HAZY

a brief introduction to CLOUDY 84

Part I Introduction and Commands

G.J. Ferland
Department of Physics and Astronomy
University of Kentucky
Lexington

CLOUDY is an evolving code. Corrections are constantly being made, while major revisions occur on roughly yearly intervals. It is a good idea to make sure that you have the most recent version of the code by checking the anonymous ftp account described later in this document.

CLOUDY 84

G. J. Ferland
Department of Physics and Astronomy
University of Kentucky
Lexington

Table of Contents

List of Figures

List of Tables

1. INTRODUCTION

This is a brief synopsis of the input, output, and assumptions for the radiative-collisional equilibrium program CLOUDY. It fully defines the commands used to drive the program and the output it generates. The methods, approximations, and assumptions used by CLOUDY are outlined, although this part, like CLOUDY itself, is still under construction.

1.1. Overview

Many environments are encountered in which dilute gas is heated and ionized by the radiation field of a central object. Under these circumstances it is possible to predict the physical conditions (that is, the run of ionization, density, and temperature) of the gas, and its resulting emission-line spectrum, in a unique and self-consistent manner. This is done by simultaneously solving the equations of statistical and thermal equilibrium, equations which balance ionization-neutralization processes, and heating-cooling processes, respectively. Osterbrock (1988) and Aller (1984) provide definitive synopses of the basic physics governing such environments, with particular emphasis on low-density nebulae ionized by relatively soft radiation (i.e., starlight), while Davidson and Netzer (1979), Halpern and Grindlay (1980), Kallman and McCray (1982), Kwan and Krolik (1981), Wills, Netzer, and Wills (1985), Ferland and Shields (1985), and Netzer (1990) provide additional details of effects of high-energy radiation and line transfer.

1.2. What Must be Specified

One powerful asset of photoionization analysis is the large number of observables resulting from only a few input parameters. Intensities of roughly 500 emission lines are predicted by CLOUDY (many of these are of negligible intensity at any one time, of course) and these result from the specification of only a) the shape and intensity of the incident continuum, b) the chemical composition of the gas, and c) the geometry of the gas, including its radial extent and the dependence of density on radius. The following subsections describe the general philosophy of the specification of each.

1.2.1. Incident Continuum

Both the shape and intensity of the incident continuum must be specified.

The shape of the continuum should be specified between an energy of 1.001×10^{-5} Ryd ($\lambda\sim$1 cm) and an energy of 100 MeV ($\sim 7.354\times 10^{6}$ Ryd). (In much of the following discussion energies will be given in Rydbergs. The ionization

potential of hydrogen is nearly 1 Rydberg. See section 1.2.1.1. below for an exact definition.) A physically motivated continuum spanning the full energy range should be specified, if possible. The continuum can be specified as a fundamental form (such as blackbody emission, optically thin bremsstrahlung emission, or a power law with optional exponential cutoff), interpolated from tables of points, or a continuum predicted by previous calculations with CLOUDY. Additionally, a set of built-in continua (for instance, some of the Mihalas and Kurucz model atmospheres, the observed Crab Nebula continuum, or several typical AGN continua) can be specified.

The intensity of the continuum must also be specified in some manner. In general, the continuum can be specified as a flux (energy or photon) per unit area of cloud, in which case the inner radius of the cloud need not be specified (a plane parallel geometry will be assumed if the inner radius is not specified), or the continuum can be specified as a luminosity (energy or photon) radiated by the central object into 4π sr, in which case the inner radius of the cloud must be specified. In the first case the predicted emission-line spectrum will give the line intensity (energy radiated per unit area of cloud) and in the second case, the total line luminosity. The intensity of the continuum can be set by specifying the flux of photons, a flux density, or a luminosity, at arbitrary energies, or by giving the absolute visual or bolometric magnitude of the continuum source.

Up to 10 continua of any form can be blended. If more than one continuum is entered, then there must be exactly the same number of shape and luminosity specifications. The code will stop if there are not.

1.2.2. Chemical Composition

The program considers hydrogen, helium, carbon, nitrogen, oxygen, neon, sodium, magnesium, aluminum, silicon, sulfur, argon, calcium, iron and nickel, in detail. All stages of ionization are treated, and all published charge exchange, radiative recombination, and dielectronic recombination processes are included as recombination mechanisms. Photoionization from valence and inner shells and many excited states, as well as collisional ionization by both thermal and supra-thermal electrons and charge transfer, are included as ionization mechanisms. The default composition is close to a solar mixture, several other standard mixtures can easily be specified, and an arbitrary composition can be entered.

1.2.3. Geometry

The geometry is always spherical, but can be made effectively plane parallel by making the inner radius much larger than the thickness of the cloud. The default is for the gas to be constant density and to fully fill its volume, but several other pressure laws and models with only part of the volume filled can be computed as well.

CLOUDY normally assumes an open geometry, or one in which the gas has a very small covering factor (these terms are defined in section 2. below). This can be changed with the SPHERE command, which sets the covering factor to a large enough value for continuous radiation escaping the cloud in the direction towards the central object to always interact with gas on the other side (a closed geometry). Line photons which cross the central hole interact with gas on the other side if SPHERE STATIC is set, but do not interact (because of a Doppler shift due to expansion) if SPHERE EXPANDING is set (this case is the default when SPHERE is specified).

1.2.4. Velocity Structure

Normally, CLOUDY assumes only thermal broadening of lines, the absence of any sort of internal velocity structure, and that the gas covering factor is so small that photons escaping the computed ionization structure do not interact with other emitting gas (i.e., an open geometry is assumed).

These assumptions can be changed in several ways. A component of microturbulence can be added with the TURBULENCE command. A WIND model, in which case a Sobolev (large velocity gradient) model is assumed, can be computed.

1.3. What is Computed and Printed

CLOUDY is driven by a set of command lines which are four letter keywords (either upper or lower case) followed by free-format numbers which may be mixed with letters. Often CLOUDY is executed as a stand-alone program. In this case Fortran unit 5 is read for input, and unit 6 is used for output. It is also possible for a larger program to drive CLOUDY directly by treating it as a subroutine.

The program begins by echoing the input commands (with the exception of lines beginning with an #, %, or *; these lines are treated as comments and are ignored). The input stream ends with either a blank line or the end-of-file. Some properties of the incident radiation field, such as luminosity and number of photons in certain frequency ranges, are then printed.

CLOUDY works by dividing a spherical nebula into a set of thin concentric shells. The shells are chosen to have thicknesses which are small enough for the physical conditions to be nearly constant within; the physical thicknesses of the shells are continuously adjusted to ensure this. Each of these shells is referred to as a zone, and typically ~100 to 200 zones are computed in a optically thick model. The physical conditions in the first and last zones are always printed and intermediate zones may be printed if needed (this is governed by the PRINT EVERY command). The output for each zone begins with a line giving the zone number, its temperature, the distance from the center of the spherical nebula to

the center of the zone, and some other properties of the solution. The next line gives some intensities of selected emission lines, while the following line gives the relative contributions of various emission lines to the radiation pressure, if this amounts to more than 5% of the gas pressure. The next lines give the ionization fraction and level populations of hydrogen excited states (2s and 2p are printed separately), and the remaining lines give the relative populations of ionization stages of the remaining elements. Many details about the conditions within the zone are intermixed with these relative populations.

After the zone calculations are complete and the model is finished, some warnings, cautions, or notes about the calculation may follow. The code is designed to check that its range of validity is not exceeded, and to complain if this occurs, or if it feels that some parameter has been miss-set. Next, optional plots of the incident and emergent continua, gas opacities, or heating-cooling curves, etc, may follow.

The final print out begins with a recapitulation of the commands, followed by the predicted emission-line spectrum. The first two columns of the emission-line spectrum give the ion and wavelength, the third column is the log of the luminosity or intensity of the emission-line, and the last column gives its intensity relative to the reference line, which is usually Hβ (others can be chosen with the NORMALIZE command). The third column will be either the luminosity or intensity. The luminosity (energy radiated by a shell of gas covering Ω sr of the central object) is predicted if the continuum luminosity is specified as energy radiated into 4π sr. The line intensity (energy emitted per square centimeter of the gas slab) is predicted if the incident continuum is specified as a flux. If the geometry is spherical, but the continuum is specified per unit area, then the line intensities will be expressed relative to the inner radius. Only the strongest emission lines are printed; the relative intensity of the weakest line to print is adjusted with the PRINT FAINT command.

Finally, the last page of the print out gives some averages of the ionization fractions over the slab, the optical depths in various lines and continua, the intensity of the continuum emerging from the cloud, and other properties of the nebula.

1.4. Acknowledgments

CLOUDY's development has been added by conversations with far too many people to list here. The roles of Peter G. Martin and Hagai Netzer were special, however. Peter added several of the commands which deal with ordering of supplemental line lists and the luminosity option on the blackbody command, insisted that CLOUDY run on a VAX, and provided access to the University of Toronto VAX 11/780 at a crucial time. Hagai and I have spent countless hours arguing over methods, assumptions, and just whose code had the bug. These comparisons are the only way to debug codes as large as CLOUDY or ION. My

collaborators, J. Baldwin, R. Boyd, E. Capriotti, R. Carswell, S. Cota, M. Elitzur, A. Fabian, C. Gaskell, R. Johnstone, K. Korista, D. Lambert, W. Mathews, J. Mihalszki, R. Mushotzky, S. Persson, B. Peterson, M. Rees, G. Shields, J. Shields, and J. Truran contributed to the development of various parts of CLOUDY. Portions of the code were written by R.F. Carswell, S.A. Cota, P.G. Martin, P.T. O'Brien, and K. Volk. Sections of the code are taken from published work of Hummer (1988) and reverse engineered from Press et al. (1986). Significant problems or suggestions which led to the improvement of CLOUDY were discovered / made by N. Arav, S. Daines, M. Diaz, F. Elizalde, B. Espey, C. Everall, A. Fabian, M. Gaskell, R. Johnstone, S. Morris, G. Perola, C. Stevenson, M. Voit, K. Volk, T. Woods and W. Zheng.

Finally, the development of CLOUDY would not have been possible without the continued support of The National Science Foundation, through grants AST 80-2522, 83-05094, 85-12414, 87-19607, and most recently AST 90-19692, and by NASA through its LTSA program. A generous allotment of time on the University of Kentucky Center for Computational Sciences IBM 3090 is also gratefully acknowledged.

2. DEFINITIONS

This section outlines many of the definitions used by CLOUDY. As much as possible the code tries to follow standard notation, such as that used by Mihalas (1978) or Osterbrock (1989). Part II of this document goes into many of these quantities in greater detail.

2.1. Continua

Figure 1 shows several of the continua computed in the calculation.

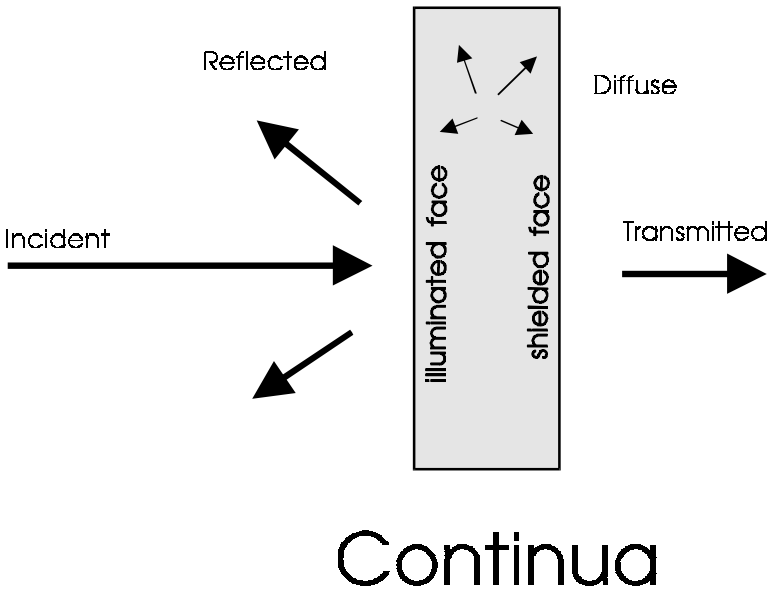


Figure 1 This figure illustrates several of the continua which enter in the calculations. Individual continua can be output by use of the "punch" command. continua

Incident continuum. The incident continuum is the external continuum emitted by the central object, which strikes the illuminated face of the cloud. It is usually specified in the initial conditions for the calculation. Usually absorption of the incident continuum is the only energy source for the cloud. Within the cloud the incident continuum is diminished by extinction.

Diffuse continuum. The diffuse continuum (often referred to as the diffuse field) is the radiation field emitted by gas and grains within the nebula. Examples include the Lyman, Balmer, or two-photon continua emitted by hydrogen. These fields are very nearly isotropic, and can be significant sources of ionizing radiation under some circumstances.

The main difference between the calculation of a stellar atmosphere and a photoionized nebula is in the treatment of the diffuse fields. In a nebula photoionized by an external continuum, the diffuse fields must be weaker than

the attenuated incident continuum, and the gas albedo is generally small. By contrast, in a stellar atmosphere the local mean intensity is often dominated by the diffuse field. As a result the diffuse fields can be treated by lower order approximations in a nebula than in a stellar atmosphere.

Transmitted continuum. The transmitted continuum is the net continuum emergent from the shielded face of the cloud. It includes both the attenuated incident continuum and the transferred diffuse continuum.

Reflected continuum. The reflected continuum is the continuum emitted from the illuminated face of the cloud in the direction towards (i.e., within 2π sr of) the source of the incident continuum. This continuum is only computed for an open geometry (defined below).

2.2. Geometry

The geometry is always spherical, but can be changed to effectively plane parallel by making the inner radius much larger than the thickness of the cloud. In addition, it is possible to make the geometry nearly cylindrical, and a simple wind can be computed. The summary at the end of the calculation will say whether the geometry was plane parallel (i.e., the thickness over the inner radius, $\Delta r / r_o < 0.1$), a thick shell ($\Delta r / r_o < 3$), or spherical ($\Delta r / r_o \geq 3$).

2.2.1. Illuminated and shielded faces of the cloud.

The side of the cloud in the direction towards the source of ionizing radiation is referred to as the illuminated face of the cloud while the opposite side of the cloud is referred to as the shielded face of the cloud.

2.2.2. Covering factor

The covering factor is the fraction of 4π sr covered by gas, as viewed from the central source of ionizing radiation. It is normally written as $\Omega / 4\pi$ (Osterbrock 1989), has the limits $0 \leq \Omega / 4\pi \leq 1$, and is the fraction of the radiation field emitted by the central object which actually strikes nebular gas. Many of the predicted luminosities are for a shell covering Ω sr, while line intensities are per unit area.

2.2.3. Filling factor

The filling factor accounts for the presence of small clumps within the emission-line region. When a filling factor is set the hydrogen density applies to the regions containing gas, while the surrounding regions are assumed to be in vacuum. The specific effects of a filling factor are described by Osterbrock and Flather (1959) and section 4.8.3. below.

2.2.4. Radii

The radii used here to are illustrated in Figure 2. The inner radius is referred to as r_o. The thickness is referred to as Δr, and the radius as r.

2.2.5. Hydrogen density

The total hydrogen density (cm^{-3}) is given by

$$n(H) = n(H^o) + n(H^+) + n(H^-) + 2n(H_2) + 2n(H_2^+) + 3n(H_3^+) \ . \quad (1)$$

2.2.6. Column densities

The hydrogen column density is given by

$$N(H_{tot}) = \int \left\{ n(H^o) + n(H^+) + n(H^-) + 2n(H_2) + 2n(H_2^+) + 3n(H_3^+) \right\} f(r)\, dr \quad (2)$$

where *f(r)* is the filling factor.

2.2.7. Open vs. closed geometry

Two limiting cases can be identified for the geometry and its influence upon the ionization calculations. Here, they are referred to as "open" and "closed" geometries. Figure 2 shows examples of both. Which is the best approximation largely depends on the gas covering factor. The choice mainly affects the calculation of the diffuse fields. These are defined in the following sections.

Open geometry. An "open" geometry is one in which the covering factor of the gas is small and all radiation which escapes from the illuminated face of the cloud, towards the source of continuous radiation, then escapes from the system without further interaction with the gas. This is thought to be the case in, for example, the broad-line region of active nuclei or the filaments in the Crab Nebula. In this case Lyβ and higher lines can escape from the nebula, and the "on-the-spot" assumption cannot be used for the innermost regions of the nebula. This geometry is the default condition for the code, and will be assumed if the "SPHERE" command (described below) is not specified.

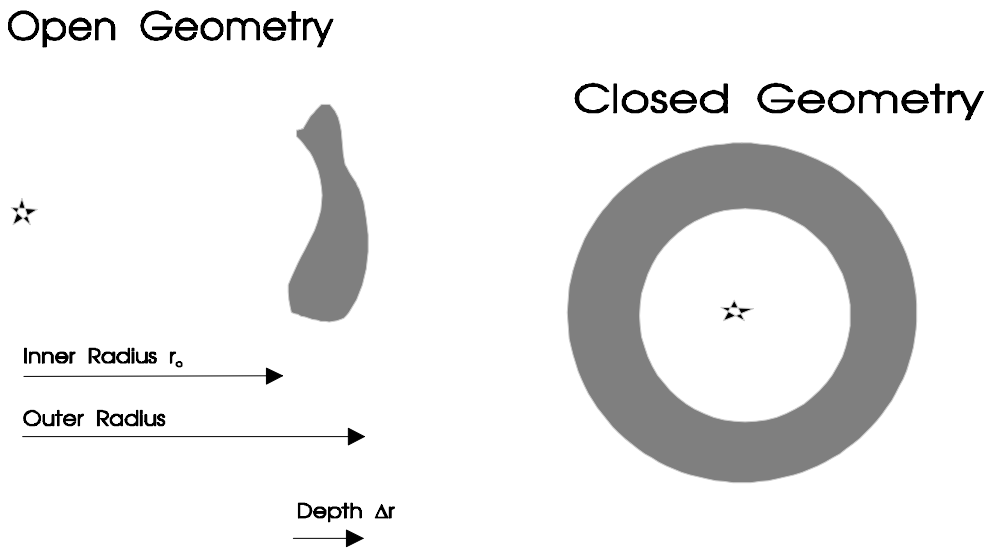


Figure 2 This figure shows the two limiting geometries which can be assumed in the calculations. The hatched area represents nebular gas. An open geometry is the default, and a closed geometry will be computed if the "sphere" command is entered. geometry

Closed geometry. Here, emission-line gas covers ~4π sr as seen by the central star. If the star is small relative to the nebula, then all diffuse fields, which escape from the illuminated face of the cloud towards the star, go on to strike the other side of the nebula. This geometry is implicitly assumed in most calculations of planetary nebulae and H II regions. Here, the "on-the-spot" assumption provides an excellent description of the hydrogen ionization balance (see, for example, Van Blerkom and Hummer 1967; Bässgen et al. 1988; Osterbrock 1989). This geometry will be assumed if the "SPHERE" command is entered.

Static vs. expanding. The SPHERE command has two optional arguments, "STATIC" and "EXPANDING", which determine how line photons from either side of the shell interact. The "STATIC" option causes the code to assume that the shell is stationary, so that all lines interact across the nebula. In this case, Lyman line interaction should ensure that case B emissivity is reached. If $\Omega/4\pi \sim 1$ but the nebula is expanding then the diffuse continua interact across the nebula, but the expansion velocity of the shell ensures that diffuse line photons do not; in this case the "EXPANDING" option should be set. This second case is the default when SPHERE is specified with no options.

These geometrical considerations make differences in the predicted emission-line spectrum at the ≈10% level, largely because of the different treatments of the diffuse fields and line optical depths.

2.2.8. Matter-bounded and radiation-bounded geometries

Matter-bounded geometry. The nebula is said to be matter bounded if the outer limit to the emission-line region is marked by the outer edge of the cloud and the cloud is ionized throughout. The cloud is optically thin to the incident continuum. In this case the intensity of a recombination line is set by the volume and density of the cloud and is not directly related to the luminosity of the ionizing continuum.

Radiation-bounded geometry. The nebula is said to be radiation bounded if the outer limit to the emission-line region is defined by a hydrogen ionization front, so both warm ionized and cold neutral regions exist. Nearly all of the incident continuum has been absorbed by the cloud, which is optically thick to the incident continuum. In this case the intensity of a recombination line is set by the luminosity of the ionizing continuum.

2.2.9. Is a starting radius necessary?

It is possible to normalize the incident continuum to either a luminosity or number of photons radiated into 4π sr, or as an intensity or surface flux of photons at the illuminated face of the cloud. In the first case it is necessary to specify a starting radius, and the emission lines will be predicted as luminosities. In the second case a starting radius need not be specified (although one may be). The lines will be predicted as intensities (i.e., per unit area of cloud) if the starting radius is not given. A default starting radius of 10^{25} cm will be assumed if one is not specified.

3. LIMITS, ASSUMPTIONS, AND RELIABILITY

This section outlines some of the assumptions and limits which define the range of validity of CLOUDY. The code is designed to check that the limits of its validity are not exceeded during a calculation. CLOUDY should print a warning after the last zone results if any aspects of the calculation are on thin ice.

3.1. Time Steady

Although it is possible to follow the time-dependent recombination and cooling of an optically thin cell of gas following the rapid extinction of the radiation field with the TIME command, steady-state is generally assumed. Various time scales characterize the approach to equilibrium of an ionized gas (see Spitzer, 1962, and Ferland 1979 for a specific application); generally, the longest is the H^+ recombination time scale,

$$T_{rec} = \frac{1}{\alpha(T_e) n_e} = 1.15 t_4^{0.8} \; n_9 \text{ hours} \qquad (3)$$

where t_4 is the temperature in units of 10^4 °K, and n_9 is the density in units of 10^9 cm^{-3}.

For situations where molecules are important the time scales are usually far more ponderous. Generally among the longer of the time scales is the time to form H^-, an important pace-setter for H_2 formation in grain-free environments. This time scale is roughly given by

$$T_{molecule} = \frac{1}{\alpha_{rad}(T_e) n_e} = 0.3 t_3^{-0.8} \; n_9 \text{ years} \qquad (4)$$

where t_3 is the temperature in units of 10^3 °K.

CLOUDY is not appropriate for the treatment of situations where conditions change more rapidly than these two time scales.

3.2. Atomic Database

This section outlines some of the atomic / molecular physics issues which affect the reliability of numerical simulations of nebulae. These uncertainties underscore the importance of atomic / molecular theory for the interpretation of astrophysical spectroscopy.

3.2.1. Collisional processes

By its nature, the electron temperature of a photoionized gas is low compared with the ionization temperature of the mixture of atoms and ions, as defined by the Saha equation (if the two were comparable, the gas would be collisionally

ionized). Because of this, the rate coefficients describing collisional effects, such as the production of cooling emission lines, are often dominated by the cross section near threshold. This is where laboratory experiments are difficult and *ab initio* quantum theory must often be used. As a result, the collision strengths undergo constant revision, towards better and more reliable values. To cite one extreme example, the collision strength for transitions within the ^{3}P ground term of Ne^{+4} has undergone three revisions between 1984 and 1991, each by a factor of 10, because of theoretical uncertainties in positions of autoionizing states which have not been observed (Lennon and Burke 1991). The intensities of all emission lines can be affected by major changes in the atomic data for only one line for some conditions. This is because (in this case) the infrared fine structure lines of Ne^{+4} can be important coolants in low-density high-ionization gasses such as planetary nebulae, and changing their cooling rate alters the thermal structure of the entire nebula. Such changes often give even models of time-steady objects such as planetary nebulae certain time-dependent characteristics.

At present, there are fairly reliable calculations of collision strengths and transition probabilities for the majority of the important coolants in moderate ionization nebulae.

3.2.2. Photoionization cross sections, recombination rate coefficients

Reliable photoionization cross sections, recombination coefficients, and charge transfer rate coefficients do not now exist. Photoionization cross sections for inner electron removal by high energy radiation are fairly well known; the uncertainties are in the valence cross sections. To cite one extreme example, the cross sections for removal of outer electrons of atoms and ions of sulfur have been calculated by Chapman and Henry (1971) and by Reilman and Manson (1979). The Chapman and Henry results are consistently larger than those of Reilman and Manson, often by factors approaching 10. These differences result in a factor of four difference in the predicted intensity of [S II] 6731 in certain H II region calculations, where valence shell photoionization is especially important. The differences are smaller for planetary nebulae or active galactic nuclei where inner electrons are energetically accessible (because the radiation field is much harder). CLOUDY uses unpublished cross-sections of Mendoza; these are intermediate between the two published extremes. Fortunately, the photoionization-recombination cross section database will improve dramatically with the completion of the Opacity Project and its extension to recombination processes, in a few years.

Similarly, low-temperature (through low-lying autoionizing states) dielectronic recombination rate coefficients have not been computed for most third row elements and iron and nickel. Extensions to the Opacity Project (Seaton 1987) should soon correct this situation.

3.2.3. Charge transfer

The rate coefficients for charge transfer are another uncertainty in the atomic / molecular data base. This process is sometimes the dominant neutralization mechanism for singly or doubly ionized heavy elements. At present some charge exchange rate coefficients are the result of Landau-Zenner calculations using semi-empirical potential curves; these are thought to be accurate to better than a factor of three. Even the best quantal calculations of charge transfer rate coefficients are not thought to have an accuracy much better than 50 percent. Unpublished tests suggest that these uncertainties affect many line intensities at the ~20% level, and some by more than this.

3.3. Continuous Opacity

All significant continuous opacity sources are treated for the energy range considered by the code, 1.001×10^{-5} Ryd to 7.354×10^{6} Ryd. These opacity sources include inverse bremsstrahlung, grains (when present), H^- absorption, electron scattering, the damping wings of strong resonance lines (i.e., Rayleigh scattering), pair production, photoelectric absorption by the ground and excited states of the 15 elements included in the calculation, and photoabsorption by molecules. This treatment should be adequate as long as the optical depths to electron scattering are not large; CLOUDY is not now designed to model Compton-thick regimes.

A warning will be issued after the last zone calculation if the nebula is optically thick to an opacity source which is not fully treated.

3.4. Temperature Range

CLOUDY assumes that the electrons are non-relativistic, which limits it to temperatures below roughly 10^9 °K. Tests (presented below) show that CLOUDY goes to the Compton temperature of the radiation field to great accuracy in the limit of very high levels of ionization for blackbody radiation fields between 3 °K and 10^{10} °K. There is no formal lower temperature limit to its validity, but the approximations used for ionic recombination coefficients (Pequignot and Aldrovandi 1986) were not intended for temperatures below 10 °K, (gas this cold is generally molecular, however) and the approximations for most charge transfer rate coefficients were not intended to be used below temperatures between 10^2 °K to 10^3 °K. The expressions for the free-free gaunt factors, taken from Hummer (1988), do not extend above ~10^8 °K or below roughly 10^3 °K.

The present range of validity of the code is now approximately from 10 °K to 10^9 °K. Temperatures outside this range can still be treated, although with

greater uncertainty. The code will not permit temperatures below 3 °K or above 10^{10} °K.

3.5. Density Range

There is no formal lower limit to the density which CLOUDY can treat. The set of heavy element fine structure lines, which dominate cooling at low densities, is complete for low and moderate stages of ionization, and fine structure optical depth and maser effects are fully treated using the escape probability formalism. Note that for very low density models ($n(H) \leq 10^{-1}$ cm^{-3}) with typical values of the ionization parameter (defined below) it is usually necessary to also consider diffuse sources of radiation such as the cosmic x-ray background, diffuse interstellar starlight, and the cosmic ray background. These must be specified independently as part of the incident continuum.

There is no formal high-density limit, other than the (inexact) treatment of radiative transfer (see Avrett and Loeser 1988) and the approximate treatment of the collisional-radiative ionization processes for excited levels of the heavy elements. Hydrogen and atoms and ions of helium are treated as 10-level atoms, including all of the physical processes which allow the approach to LTE (see, for example, Mihalas 1978). Tests with a hydrogen density of 10^{19} cm^{-3} show that CLOUDY's hydrogen and helium atoms do go to LTE at high densities; thus there is no formal high density limit to its validity. The treatment of Stark broadening for hydrogen lines follows Puetter (1981), so radiative transfer is treated correctly (in the context of the escape probability formalism) for densities above ~10^{10} cm^{-3}. The treatment of the other 13 elements is presently not as complete as hydrogen and helium, but 3-body recombination is included as a general recombination process, so the treatment of these elements is approximately correct at high densities.

CLOUDY has been tested at densities of 10^{-4} cm^{-3} and 10^{19} cm^{-3} on 32-bit machines. The numerical (not physical) limit to the density will actually be set by the limits to the range of the floating point numbers allowed by the machine in use (densities of 10^{-6} cm^{-3} and 10^{20} cm^{-3} don't work on IEEE 32-bit machines for this reason). The physics incorporated in the code imposes no lower limit to the density. The physical high-density limit is roughly 10^{13} cm^{-3}, and is set by the approximate treatment of three-body recombination - collisional ionization for the heavy elements, and the approximate treatment of line transfer (CLOUDY uses escape probabilities). Non-LTE ionization, thermal equilibria, and line transfer at high densities is an area of on-going research.

3.6. Radiative Transfer

Line intensities are predicted with stellar atmosphere conditions in mind. Radiative transfer effects, including possible maser emission, are treated.

Nebular approximations, such as the approximation that all atoms are in the ground state, are not made. Collisional effects, including excitation and de-excitation, continuum florescence, recombination, etc, are all included as general line excitation mechanisms. The treatment of level populations is designed to go to LTE in the high density case.

Line and continuum transfer is currently treated using escape probabilities. This is probably the weakest assumption in the present prediction of the spectrum. Work is now underway to begin the conversion to formally correct transport methods. There is no way to judge the error introduced by the escape probability approximation, although it is known to be exact if the conditions do not vary across the line forming region (Elitzur 1982).

3.7. Hydrogen

Hydrogen is treated as a ten level (plus continuum) atom. The 2s and 2p states are treated separately, so Lyα and 2-photon emission are computed properly in low-density nebulae. Quantum numbers between 3 and 6 are treated assuming full l-mixing, as in Seaton (1959), but with all collisional and radiative transfer effects included. Levels between 7 and 100 are treated by substituting three pseudo-states with properties chosen to mimic these high-n states. Tests show that the hydrogen line emissivity predicted by CLOUDY agrees with all of Seaton's results to ~0.1%, and with Hummer and Storey's (1987) case B Hβ emissivity predictions to ~1% for $n(H) \leq 10^{10}$ cm^{-3}.

Although the Hβ emissivity is predicted by CLOUDY with great precision for all densities, this is not true of the infrared hydrogen lines at low densities. The intensities of these lines are somewhat sensitive to the degree of l-mixing of the upper levels. They are predicted with precision in the context of the *full l-mixing* approximation, but this approximation is not valid for low densities. The differences can be judged by comparing Seaton's (1959) calculation (which CLOUDY reproduces to three significant figures) with the *l*-state calculations presented by Pengelly (1964). One of the worst cases is Paschen α, for which Seaton predicts intensities 21% smaller than Pengelly. Beware.

The full set of hydrogen level balance equations are solved by working with LTE departure coefficients. As a result, the departure coefficient of the ground state diverges for very low temperatures when the gas is ionized yet cold, so it is not possible to treat hydrogen line transfer in detail for temperatures below 1000 °K on 32-bit machines. For very low temperatures CLOUDY uses a special set of approximations (fitted to the results of Martin 1988) to solve for the hydrogen ionization balance and predict emissivities. The intensities of these lines are reliable for temperatures above ~10^2 °K as long as radiative transfer and optical depth effects are not important. (It is unlikely that significant H II emission will occur for gas colder than this 10^2 °K limit.) If such low temperatures occur, and

the matrix solution is not used, then a comment is printed after the last zone calculation.

Finally, the hydrogen density used by CLOUDY is the *total* hydrogen density, usually referred to by the label HDEN, and is given by

$$n(H) = n(H^o) + n(H^+) + n(H^-) + 2n(H_2) + 2n(H_2^+) + 3n(H_3^+) \quad . \qquad (5)$$

3.8. Helium

Model atoms. Helium is treated as three separate atoms / ions; ionized helium (a ten level atom), the singlets (a ten level atom), and the triplets (presently a five level atom). The treatment of the three ions is entirely analogous to that of hydrogen; it goes to LTE in the limits of large photon or particle densities. The low-temperature limit to the matrix treatment of the He^o singlets and He^+ are 1000 °K and 1500 °K respectively. Below these temperatures approximations to case B results are used.

As with hydrogen, these model singlet and He^+ atoms assume complete *l*-mixing for levels $3 \le n \le 100$. As mentioned above, this is not a good approximation for low densities. For instance, the intensity of λ4686 is exact at high densities, but differs by nearly 40 percent from low density case B predictions. For the time being, it is probably better to use the case B predictions, rather than the results of the 10-level atom calculations, for He II line emission at low densities, when line transfer and collisional excitation are not important. The predictions of the ten-level atom are better when either process is important, or the density is high enough for complete l-mixing to be a good approximation.

Helium Radiative Transfer. The helium line and continuum transfer problem is one whose importance in determining the intensities of many ultraviolet lines is generally underestimated (see, for example, the discussion by Netzer and Ferland 1983). Recombinations to the He^+ ground and first excited state, and HeII Lyα, all ionize hydrogen, and the He II Lyα line undergoes Bowen fluorescence (Osterbrock 1989; Netzer, Elitzur, and Ferland 1985). Unfortunately these continua, and especially the Bowen lines, can be the main source of photoelectric heating in the He^{++} zone of some high-ionization nebulae. Fundamental uncertainties in the treatment of the Bowen problem introduce substantial uncertainties in the local heating rate, and hence in the intensities of some ultraviolet lines, such as C III] λ1909 and C IV λ1549, because these lines are very temperature sensitive. My experience is that minor changes in the treatment of the Bowen problem typically results in ~20% changes in the intensities of these ultraviolet lines in certain low density nebulae, and in the near ultraviolet [Ne V] lines.

3.9. Atoms and Ions of the Heavy Elements

Most heavy elements are treated as two level systems (ground term and continuum) although photoionization from excited states is included for those cases where it is sometimes important (O^{++} and N^{+} are two examples). All published charge transfer, radiative and dielectronic recombination, collisional ionization, and three-body recombination processes are included in the ionization balance.

The treatment of the heavy element ionization balance should be exact in the nebular limit, but approximate for very high photon or particle densities because of the two-level approximation.

3.10. Molecules

At the present time a major effort is being made to complete the treatment of the heavy-element molecular equilibria and cooling in the code. The treatment of the hydrogen molecules/ions H^-, H_2, H_2^+, H_3^+, and HeH^+ is now fairly complete. The equilibrium of the heavy-element molecules is now treated with various levels of approximation. The predictions are thought to be correct for nebular ($n<10^8$ cm^{-3}) conditions, but do not now go to LTE in the high nucleon-photon limits, and the code may have convergence problems in the fully molecular limit.

3.11. Reliability

There are several issues to address in regards to the general question of reliability of the code. The first is the effects of the bugs which surely must exist in a code the size of CLOUDY. I have seldom found bugs in sections of the code older than roughly two to three years. Younger sections of the code sometimes contain bugs that only manifest themselves in exceptional situations. It is my belief that the issue of reliability in the face of complexity will increasingly be the single major problem limiting the development of large-scale numerical simulations. New methods of writing code will have to be developed if we are to take full advantage of the power of future machines. Machines are getting faster more quickly than people are getting smarter.

The second issue is the validity of the numerical methods used to simulate conditions in the nebulae. Fundamental uncertainties arise for cases where the density is high ($n >> 10^{10}$ cm^{-3}). The radiative transfer techniques used by CLOUDY are approximate (see the discussion by Avrett and Loeser 1988). Unfortunately, no definitive calculation now exists for the complete non-LTE equilibrium and emission for an intermediate density (~10^{10} to 10^{13} cm^{-3}) cloud. For less extreme conditions ($n < 10^{10}$ cm^{-3}) nebular approximations are valid,

and the comparisons presented in Part III show good agreement between CLOUDY and other codes designed to work in this limit.

Uncertainties in the atomic data base are a third concern. A great deal of progress will result over the next few years with the completion of the Opacity Project (Seaton 1987) and its extensions to collisions and recombination. Charge transfer, a collision process normally treated on a molecular basis, will remain an uncertainty.

Test cases which are designed to exercise the code in certain well-posed limits are presented in Part III of this document. Calculations of certain standard nebulae are also shown there. The code is well-behaved in these simple limits, and agrees well with predictions of similar codes when applied to nebular situations.

In the end the uncertainties can probably best be judged by looking at both the dispersion among the various photoionization calculations presented in Part III, and the changes that have occurred in the predictions made by CLOUDY itself over the past few years (see also Part III). Much of the dispersion is due to changes in the atomic data base, changes which are likely to settle down with the completion of the Opacity Project and its extensions to recombination and collision processes.

There can be little better way to close a discussion of reliability than to quote the warning included in Kurucz's (1970, page xiii) description of ATLAS5, a code nearly an order of magnitude smaller than CLOUDY:

WARNING

> "There is no way to guarantee that ATLAS5 does not contain errors. In fact, it is almost certain that it does, since the code is so long. There also may be truncation or underflow problems on computers like an IBM 360, even though all those known at present have been allowed for. We also point out that the computation of a model atmosphere should be considered a physical experiment. The program may not be able to calculate a model for conditions that do not occur in real stars or for conditions that violate the initial assumptions on which the program is based."

3.12. The Future

The eventual goal is for CLOUDY to give reliable results for all extremes of conditions between and including the intergalactic medium and stellar atmospheres. I estimate that the code is now well over halfway complete.

Current work centers on making the code formally correct in the optically thin limit for all extremes of radiation and matter densities. Much has already been done, and present efforts center on helium, molecules, and the heavy elements.

Line transfer is now treated with escape probabilities, an approximation which is not formally correct when conditions vary across the line forming

region (see, for instance, the discussion in Avrett and Loeser 1988). A major change, to be completed within the next few years, is to transfer Lyα correctly, using the proper redistribution function, using an approach similar to that of Hummer and Kunasz (1980).

By the time this work is complete, the Opacity Project (Seaton 1987) and its extensions to recombination should also be finished, and attention will return to the heavy elements. An approach similar to that now used for hydrogen and helium (employing several pseudo-states to allow the model atom to correctly approach LTE) will be used to ensure that the treatment of the heavy elements is correct for all densities and temperatures. An Opacity Distribution Function approach will probably be used to incorporate the Opacity Project results into CLOUDY.

The two major remaining concerns will be the continuum transport (especially in the infrared) and line transfer (complete redistribution is a good approximation for most lines). Both can be treated in a straightforward manner using standard radiative transfer techniques.

4. COMMANDS

This section summarizes the commands which drive CLOUDY. They are grouped together by purpose, and individual commands are discussed after examples of their use. the section begins by outlining default conditions, and then goes on to discuss the various classes of commands (i.e., those that set the continuum shape, luminosity, or the geometry).

4.1. Default Conditions

CLOUDY is designed to be easy to use, so that a minimum number of commands are needed to drive it. The general philosophy is for a reasonable set of initial conditions to be assumed by default. These default conditions are summarized in Table 1.

Table 1 Default Conditions

Variable	Value	Quantity
rdfalt	10^{25} cm	default inner radius
router	10^{30} cm	default outer radius
telow	10 °K	lowest allowed temperature
tehigh	10^{10} °K	highest allowed temperature
tend	4000 °K	lowest temperature to allow in model
thlo	1000 °K	lowest temperature in H^o matrix
the1lo	1000 °K	lowest temperature in He^o singlet matrix
the2lo	1500 °K	lowest temperature in He^+ matrix
flxfnt	10^{-10}	relative flux of high energy to consider
cylind	10^{35} cm	half-thickness of cylinder in geometry
toler	0.02	tolerance in heating-cooling match
faint	10^{-4}	relative intensity of faintest line to print
emm	1.001×10^{-5} Ryd	low energy limit to radiation field
egamry	7.354×10^{6} Ryd	high energy limit to radiation field
nend	400	limiting number of zones
colend	10^{30} cm^{-2}	limiting total hydrogen column density
colpls	10^{30} cm^{-2}	limiting ionized hydrogen column density
colnut	10^{30} cm^{-2}	limiting neutral hydrogen column density
grains?	no grains	grain mixture

The code is also designed to check that its assumptions are not violated, and to complain if problems occur, if its limits are exceeded, or if the input parameters are misused.

4.2. Command Format

When executed as a stand-alone program, CLOUDY reads Fortran unit 5 for input and produces output on unit 6. The code is also designed to be used as a subroutine of other, much larger, programs. In this case the input stream is entered using the subroutine calls described in a section in Part III. In either case, this input stream must contain the commands used to drive the program. These commands are described next.

All commands are entered as free-format lines, beginning with a four character key word in columns 1 to 4. This keyword specifies the purpose of the command, and is usually followed by one or more numbers or keywords. Up to 100 separate commands may be entered; this is limited by the variable NKRD which appears in several parameter statements throughout the code. Most commands use cgs units. The command lines can be in any order, and can be up to 80 characters long, in either lower or upper case. The end of each line is marked either by column 80, the end-of-line, a colon ":", a semi-colon ";", or a percentage sign "%". The input stream ends with either a blank line or the end-of-file. In the following examples the individual command keywords are shown extending beyond column 4, and these extra characters are completely ignored (except for some special commands which use optional keywords).

4.2.1. Example formats

Sections describing each of the commands are introduced by examples of their use. In these examples optional parameters are shown surrounded by square brackets ("[" and "]"). Examples are shown below.

```
*following needs flux density, but frequency is optional
f(nu) = -12.456 [at .1824 Ryd]
*the luminosity command has several optional keywords
luminosity 38.3 [solar, range, linear]
*the phi(h) command has the range option
phi(h) = 12.867 [range ...]
```

These square brackets indicate only that the parameters are optional, and the brackets need not be placed on the command line.

Most commands and keywords require four character matches to be recognized. In some cases the leading or trailing character is a blank, which is indicated by an underscore ("_"; an example is the keyword _LTE). Other examples are shown below. The underscore should not be typed, only the space character. Only one space is needed between words.

```
*blackbody with T=50,000, in strict TE
blackbody 50,000 _lte
*use ism radiation field
table _ism
```

4.2.2. The continue option

It is sometimes not possible to enter all the required values on a single line for the INTERPOLATE and ABUNDANCES commands. In these two cases the original command line can be continued on following lines with a series of lines beginning with the keyword CONTINUE. The format on a CONTINUE line is unchanged, and there is no limit to the number of CONTINUE lines which can be included.

4.2.3. Numerical input

Numerical parameters are entered on the command line as free-format numbers, and exponential notation cannot be used. For instance, the entry "1E20" will be interpreted as the numbers 1 and 20, and no error message will result. Generally, CLOUDY avoids exponential notation on input by entering numbers as logs, so 1E20 is usually entered as 20.0. Commas can be freely embedded in input numbers and they may be preceded or followed by characters to increase readability (i.e., T=1,000,000K and 1000000, and usually T=6, are equivalent, but T=1E6 is not). A period or full stop (.) by itself is interpreted as a character, not numeral or number. Default values are often available. As an example, the POWER LAW command has three parameters, the last two being optional. The following are all acceptable (but not equivalent) forms of the command;

```
power law, slope-1.4, exponen cutoffs at 9 Ryd, 0.01 Ryd
powe -1.0 5
power law, slope=-1.4 .
```

The last version uses the default cutoffs, i.e., none. Note that implicit negative signs (for instance, for the slope of the power law) *do not* occur in any of the following commands.

4.2.4. Comments

Comments may be entered among the input data in several ways. Anything on a line which occurs after a colon, semi-colon, or percentage sign is completely ignored; this can be used to document parameters on a line. Any line beginning with a #, %, or a * is totally ignored; it is not even printed. A line beginning with c_ is ignored, but printed (note that there is a space after the c). There is also a TITLE command, to enter a title for the model, as described below.

4.2.5. Some systematics

An attempt has been made to keep the input quantities as logical as possible. Most quantities are entered as the log of the number, but some are linear. Many commands have the sub-keywords "_LOG" and "LINEAR" to force one or the

other interpretation to be used. The following outlines some systematics of how these are entered.

Temperature. CLOUDY will interpret a temperature as a log if the number is less than or equal to 10, and linear if greater than 10. Many commands have the optional keyword "LINEAR" to force temperatures below 10 °K to be interpreted as the linear quantity rather than the log.

Linear vs. log for other parameters The pattern for other quantities is not as clear as for the case of temperature. Generally, quantities are interpreted as logs if negative, but may be linear or logs if positive (depending on the command).

4.2.6. An example

Specific commands to describe the continuum (luminosity and shape), and geometrical details are discussed in the following section. As a minimum, the hydrogen density, continuum shape, continuum luminosity or intensity, and possibly the starting radius, must be specified. As an example, a simple model of a planetary nebula could be computed by entering the following input stream.

```
title - this is the input stream for a planetary nebula
* this is the temp and total luminosity of central star
black body, temp = 100,000K, luminosity=38;[log(L)- ergs/s]
radius 17   ;log of starting radius in cm
hden 4      ;log of hydrogen density - cm^-3
filling factor 0.3 ;set a filling factor of 30 percent
sphere ; this is a sphere with large covering factor
```

4.3. Defining the Continuum

4.3.1. Defining a single continuum

A single continuum is specified by two quantities, its shape and its intensity (surface flux at the illuminated face of the cloud). The two are specified independently in most cases, although both can be specified by the same command in some cases (the cosmic background is an example of the latter). The continuum shape can be set by interpolating on tables of points, read in from predictions of previous calculations, and / or by specifying fundamental forms such as blackbody, power law, or bremsstrahlung emission. The intensity of the continuum at the illuminated face of the cloud can be specified as either an intensity (energy or photon flux per unit area) or by specifying *both* the luminosity and inner radius (i.e., separation between the continuum source and the illuminated face) of the cloud.

4.3.2. Combining several continua

It is possible to combine up to 10 continua of any shape.[1] When more than one continuum is entered, the series of luminosity and shape commands must be in the same order (i.e., map one to one). There must always be exactly the same number of continuum luminosity and shape specifications; CLOUDY will stop if there are not.

As an example, the following would be a rough approximation of an accretion disk and boundary layer around a white dwarf:

```
black body, temp=500,000K
luminosity (total) 37.3
*the following is a rising power law
power law, slope = 1.333, cutoff = 0.6 Ryd
luminosity (total) 37
```

The 500,000 °K blackbody is given a total luminosity of $10^{37.3}$ erg s^{-1}, while the power law continuum is given a luminosity of $10^{37.2}$ erg s^{-1}.

It is not usually necessary to keep the ordered pairs of shapes and intensity commands together, but this is a good practice since some commands (those given in Table 2) specify *both* the continuum shape and intensity. Problems arise if one of the commands giving both shape and intensity is entered between another pair of shape and intensity commands. For instance, the following will produce unintended results,

```
black body, temp = 500,000K
background, z=2
luminosity (total) 37
```

The background command enters both the shape and intensity. In this example it comes after the black body command specifies a shape, but before the luminosity command specifies the luminosity. As a result, the intensity entered by the background command will apply to the hot blackbody continuum rather than the cosmic background. This problem cannot occur if the shape and intensity commands are kept together, as in the previous example.

Table 2 is a list of all continuum shape commands which *also* enter a luminosity or intensity.

Up to 10 continua may be entered. CLOUDY will stop if more than 10 continua are entered. This limit is set by the variable LIMSPC which occurs in several PARAMETER statements throughout the code. Increase LIMSPC everywhere if more than 10 continua are required.

---

[1]Restrictions on the number of tables which could be entered existed in CLOUDY versions 73 and before, but have been lifted. Restrictions on which types of continua could be combined existed in CLOUDY versions 67 and before, but have been lifted.

Table 2
Continua Shape + Intensity Commands

background
blackbody, energy density
blackbody, lte
blackbody, luminosity
blackbody, radius
fireball
table ism

4.4. Continuum Intensity or Luminosity

The commands setting the intensity or luminosity of the continuum are described here. CLOUDY actually works with continuum fluxes in units similar to photons cm^{-2} s^{-1} Ryd^{-1}, to avoid single-precision floating-point exponent limits on 32-bit IEEE machines. The intensity of the incident continuum can be set by specifying a luminosity, the number of photons, a flux density f_ν, or the absolute visual or bolometric magnitude. These can be the quantity emitted by the central object into 4π sr (with units s^{-1}) or the surface flux at the illuminated face of the cloud (with units cm^{-2} s^{-1}). The intensity of the predicted emission lines will be either the luminosity radiated by a shell covering Ω sr, where Ω is the angular coverage of the nebula and $\Omega/4\pi$ is the covering factor, or the intensity (energy radiated per unit area of cloud). Which is predicted depends on whether the incident continuum is specified as a luminosity or intensity.

4.4.1. The RANGE Option

For most of the intensity commands the default is for the quantity entered to be the number of photons or luminosity *in ionizing radiation* ($13.6\ eV \le h\nu \le 100$ MeV). Other energy intervals can be specified with the RANGE option, an optional keyword on the LUMINOSITY, INTENSITY, Q(H), and PHI(H) commands.

The range option appears on the line specifying the luminosity or intensity and is invoked by entering the keyword RANGE. When RANGE is specified there are an additional two parameters, the low and high energy limits to the energy range in Rydbergs. These appear as the second and third numbers on the line. The position of the keyword RANGE on the command line does not matter, but the order of the numbers on the line does. If the first optional number is negative or the keyword _log appears then *both* of the extra numbers are interpreted as logs. If either parameter is zero then the low (1.001×10^{-5} Ryd) or high (7.354×10^{6} Ryd) energy limit of the continuum will be substituted. If both energies are specified then the second number must be larger than the first

(unless the second is zero). If only one parameter appears then only the lower limit of the range will be changed, and the high energy limit will be left at its default of 7.354×10^6 Ryd. If the keyword TOTAL (equivalent to RANGE TOTAL) appears with no parameters then the full energy range considered by the program will be used.

The following are some examples of the use of the range option in modifying the range on the LUMINOSITY command. The default condition on the LUMINOSITY command is for the single parameter to be the log of the luminosity (erg s^{-1}) in ionizing (1 Ryd $\le h\nu <$ 7.354×10^6 Ryd) radiation.

```
* this will use the default range, only ionizing radiation
luminosity 38 ;log of luminosity in erg/sec

* either will be the total luminosity
luminosity total 38
luminosity range total 33.4

* this will be the luminosity in visible light
luminosity 37.8 range .15 to .23 Ryd

* the luminosity in radiation more energetic than 0.1 Ryd
luminosity 38.1 range -1

* this will be the luminosity in non-ionizing radiation
luminosity 39.8 range 0 1
```

4.4.2. absolute [visual, bolometric] magnitude -2.3

It is possible to specify the luminosity in magnitudes, a quaint unit of historical interest. One of the keywords “bolometric” or “visual” must also appear. The absolute bolometric magnitude M_{bol} is related to the total luminosity by

$$L_{total} = 3.826\times10^{(4.72-M_{bol})/2.5} \quad \mathrm{erg\,s^{-1}} \quad . \tag{6}$$

The absolute visual magnitude M_V is approximately related to the flux at 5550Å by

$$\nu F_\nu(5500\text{Å}) \approx 3.086\times10^{33}\times10^{(4.79-M_V)/2.5} \quad \mathrm{erg\,s^{-1}} \quad . \tag{7}$$

The conversion between flux and absolute visual magnitude is approximate, with typical errors of roughly a percent, because CLOUDY assumes that the V filter has an isophotal wavelength of 5550Å, and does not actually integrate over the incident continuum using a V-filter transmission function.

The starting radius for the calculation must be specified since this command specifies the luminosity radiated into 4π sr.

4.4.3. energy density 50,000K [linear]

This command is used to specify the energy density of a component of the incident radiation field. The number is the equivalent energy density temperature, defined as $T_u = (u/a)^{1/4}$ where *u* is the total energy density in all radiation (erg cm^{-3}) and *a* is the Stefan radiation density constant. The number is interpreted as the temperature itself if it is greater than 10, (or if less than 10 and the optional keyword LINEAR appears on the line), and as the log of the number if it is less than or equal to 10.

If the energy density at the illuminated face of the cloud is specified then the predicted emission-line intensities will also be per unit area of gas. It is not necessary to specify a starting radius.

4.4.4. f(nu) = -12.456 [at .1824 Ryd]

This command allows the flux density f_ν to be specified. The first number is the log of the surface flux density at the illuminated face of the cloud (with units erg s^{-1} Hz^{-1} cm^{-2}), $4\pi J_\nu$, where J_ν is the mean intensity of the incident continuum.

The optional second number is the frequency in Rydbergs where f_ν is specified; the default is 1 Ryd, and in the example above the continuum is specified at 0.1824 Ryd = 5000Å. The frequency can be any within the energy band considered by the code, presently 1.001×10^{-5} Ryd to 7.354×10^{6} Ryd. If the energy is less than or equal to zero then it is interpreted as the log of the energy in Rydbergs, and as the linear energy itself if positive.

It is not necessary to also specify the starting radius when the flux is specified using this command.

4.4.5. intensity 8.3 [range, linear]

This command specifies the surface energy flux, and is the per unit area equivalent of the luminosity command. Unlike the majority of the commands, the first five characters of the line must be entered. The number is the log of the surface energy flux (erg cm^{-2} s^{-1}) at the inner face of the cloud

$$I = \int_{\nu_1}^{\nu_2} 4\pi J_\nu \, d\nu \quad . \tag{8}$$

The number is interpreted as the intensity itself, rather than a log, if the optional keyword LINEAR appears on the line. Note that the quantity referred to as the intensity here is actually 4π times larger than the intensity defined in most radiative transfer calculations.

The default range is over hydrogen-ionizing energies (1 Ryd $\le h\nu \le 7.354\times10^{6}$ Ryd). The RANGE option can be used to adjust the values of ν_1 and ν_2. If the integrated mean intensity (equation 8) at the illuminated face of the cloud is

specified then the predicted emission-line intensities will also be per unit area of gas.

Some of the interstellar medium and photo-dissociation region (PDR) literature specifies the incident continuum in units of the Habing (1968) field (see, for instance, Tielens and Hollenbach 1985a, 1985b). This radiation field has an integrated intensity of 1.6×10^{-3} erg s^{-1} cm^{-2} (Tielens and Hollenbach), between the limits of roughly 1000Å and 2400Å. This intensity is sometimes referred to as G_o. The continuum described by Tielens and Hollenbach, but with an intensity of 1 G_o, could be roughly generated with the commands:

```
c generate the Habing 1968 radiation field
blackbody 30,000K
intensity -2.8, range 0.1 to 0.38 Ryd
extinguish by 24, leakage = 0
```

The code will print a comment at the end if the incident continuum is less than ten times the intensity of the Habing field.

It is not necessary to specify a starting radius if the intensity is specified with this command. Emission-line intensities rather than luminosities will be predicted if no inner radius is specified.

4.4.6. ionization parameter = -1.984

The ionization parameter is the dimensionless ratio of photon to hydrogen densities, and is defined as

$$U \equiv \frac{Q(H)}{4\pi r_o^2 n(H) c} \equiv \frac{\Phi(H)}{n(H) c} \qquad (9)$$

where r_o is the separation between the source of ionizing radiation and the cloud, n(H) is the total hydrogen density (ionized, neutral, and molecular), c is the speed of light, Q(H) is the number of hydrogen-ionizing photons emitted by the central object (s^{-1})[2] and Φ(H) is the surface flux of ionizing photons (cm^{-2} s^{-1}). The number entered is the log of the ionization parameter. The ionization parameter is a useful quantity in plane parallel constant-density models, because of homology relations between models with different photon and gas densities but the same ionization parameter (see Davidson 1977).

It is not necessary to also specify a starting radius since the ionization parameter and hydrogen density together uniquely determine the flux of ionizing photons.

---

[2]Before version 65 of the code the electron density was used rather than the hydrogen density. Before version 75 n(H) was the atomic/ionic hydrogen density, and did not include molecules.

4.4.7. L(nu) = 38.456 [at .1824 Ryd]

This command allows the specific luminosity L_ν to be specified. The first number is the log of the specific luminosity radiated by the central object into 4π sr (erg s^{-1} Hz^{-1}).

The optional second number is the frequency in Rydbergs where L_ν is specified; the default is 1 Ryd, and in the example above the continuum is specified at 0.1824 Ryd = 5000Å. The frequency can be any within the energy band considered by the code, presently 1.001×10^{-5} Ryd to 7.354×10^{6} Ryd. If the energy is less than or equal to zero then it is interpreted as the log of the energy in Rydbergs, and the linear energy itself if positive.

It is necessary to also specify the starting radius if the specific luminosity is specified using this command.

4.4.8. luminosity 38.3 [solar, range, linear]

The number is the log of the luminosity emitted by the central object into 4π sr, (erg s^{-1})[3]

$$L = 4\pi R_{star}^2 \int_{\nu_1}^{\nu_2} \pi F_\nu \, d\nu \qquad (10)$$

or the log of the total luminosity in solar units, if the SOLAR keyword is specified. The number is interpreted as the luminosity itself, rather than a log, if the optional keyword LINEAR appears on the line.

The default range is over hydrogen-ionizing energies (1 Ryd $\le h\nu \le 7.354\times10^{6}$ Ryd). The RANGE option can be used to adjust the values of ν_1 and ν_2.

If the continuum luminosity is specified then the emission-line luminosity will be predicted, and the starting radius must also be specified.

If the optional keyword SOLAR appears, the number is interpreted as the log of the *total* luminosity, relative to the luminosity of the sun (unless the LINEAR keyword is also used, in which case the quantity will be the relative luminosity itself). The range option cannot be used if the luminosity is specified in solar units (it will be ignored if it appears).

The following are examples of the luminosity command.

```
*log of luminosity (erg/s) in ionizing radiation
luminosity 36
```

[3]Before version 83 of the code, the luminosity command was used to enter either luminosity or intensity. The code decided between the two by checking on the resulting ionization parameter. There are now separate intensity and luminosity commands.

```
* roughly the eddington limit for one solar mass
luminosity total 38

* both are a total luminosity 1000 times solar
luminosity solar 3
luminosity linear solar 1000

* this will be the luminosity in visible light
luminosity 37.8 range .15 to .23 Ryd
```

4.4.9. nuf(nu) = 13.456 [at .1824 Ryd]

This command allows the flux density νf_ν to be specified. The first number is the log of the surface flux density at the illuminated face of the cloud (erg s^{-1} cm^{-2}), at an arbitrary frequency. The number is $4\pi \nu J_\nu$, where J_ν is the mean intensity of the incident continuum.

The optional second number is the frequency in Rydbergs where f_ν is specified; the default is 1 Ryd, and in the example above the continuum is specified at 0.1824 Ryd = 5000Å. The frequency can be any within the energy band considered by the code, presently 1.001×10^{-5} Ryd to 7.354×10^{6} Ryd. If the energy is less than or equal to zero, it is interpreted as the log of the energy in Rydbergs, and the linear energy if positive.

It is not necessary to specify a starting radius when the flux density is specified.

4.4.10. nuL(nu) = 43.456 [at .1824 Ryd]

This command allows the specific luminosity νL_ν to be specified. The first number is the log of the specific luminosity radiated by the central object into 4π sr (erg s^{-1}). It can be expressed at an arbitrary frequency.

The optional second number is the frequency in Rydbergs where L_ν is specified; the default is 1 Ryd, and in the example above the continuum is specified at 0.1824 Ryd = 5000Å. The frequency can be any within the energy band considered by the code, presently 1.001×10^{-5} Ryd to 7.354×10^{6} Ryd. If the energy is less than or equal to zero, it is interpreted as the log of the energy in Rydbergs, and the linear energy if positive.

It is necessary to specify a starting radius when this command is used.

4.4.11. phi(h) = 12.867 [range ...]

This command is used to specify the log of Φ(H), the surface flux of hydrogen-ionizing photons (cm^{-2} s^{-1}) striking the inner face of the cloud. It is defined as

$$\Phi(H) \equiv \frac{Q(H)}{4\pi r_o^2} \equiv \frac{R_{star}^2}{r_o^2} \int_{\nu_1}^{\nu_2} \frac{\pi F_\nu}{h\nu}\, d\nu \qquad (11)$$

as in Ferland, Netzer, and Shields (1979), and is proportional to the optical depth in excited lines, such as the Balmer lines. The RANGE option can be used to change the default energy range in equation 11.

The inner radius need not be specified if this command is used since this command specifies the photon flux (i.e., per unit area).

4.4.12. Q(H) = 56.789 [range ...]

The log of the total number of ionizing photons emitted by the central object (with units s^{-1}) can be specified rather than the luminosity;

$$Q(H) = 4\pi R_{star}^2 \int_{\nu_1}^{\nu_2} \frac{\pi F_\nu}{h\nu}\, d\nu \qquad (12)$$

where the default value for ν_1 is 1 Ryd, and the default value for ν_2 is the high energy limit to the code, presently 7.354×10^6 Ryd. The RANGE option can be used to change the energy bounds ν_1 and ν_2. The photon flux (per unit area of cloud surface) can be specified with the PHI(H) command, described above[4].

It is necessary to specify a starting radius if this command is used.

4.4.13. ratio -3.4 0.3645 Ryd to 147 Ryd [alphaox]

The current continuum source will be given an intensity defined relative to the *previous* continuum source. The ratio of the flux densities f_ν (energy per unit frequency, time, and area) of the current to the previous continuum source is given by the first number. It is assumed to be linear unless it is less than or equal to zero, in which case it is assumed to be a log. The second parameter is the energy (Rydbergs) where the first continuum source is evaluated, and the optional third parameter is the energy where the second (and current) continuum is evaluated. If the second energy is not entered then the same energy is used for both.

This command was introduced to provide a mechanism to specify the optical to X-ray spectral index α_{ox}. This is defined as in Zamorani et al. (1981), except

---

[4]Before version 83 of the code the phi(h) and q(h) commands were the same. The code decided which was specified by checking the order of magnitude of the resulting ionization parameter.

for a difference in sign convention. α_{ox} is the spectral index which would describe the continuum between 2 keV (147 Ryd) and 2500Å (0.3645 Ryd) if the continuum could be described as a single power-law, that is,

$$\frac{f_\nu(2\text{ keV})}{f_\nu(2500\text{ Å})} = \left(\frac{\nu_{2\text{ keV}}}{\nu_{2500\text{ Å}}} \right)^\alpha = 403.3^\alpha \quad . \tag{13}$$

The definition of α_{ox} used here is slightly different from that of Zamorani et al. since implicit negative signs are *never* used by CLOUDY. Typical AGN have α_{ox} ~ -1.4 . If no X-rays are present then α_{ox} = 0. There is an optional keyword on the RATIO command which allows α_{ox} to be specified directly. If the keyword ALPHAOX appears then only one parameter is read, the value of α_{ox}. A generic AGN continuum could be produced with the following,

```
blackbody 50,000   ;the big blue bump
ionization parameter -2
table power law    ;an alpha=-1 power law
ratio alphaox -1.4
```

Note that α_{ox} depends on the luminosity of the quasar, as described by Avni and Tananbaum (1986). The solid line in their Figure 8 corresponds to

$$\alpha_{ox} = -1.32 - 0.088 \log\left(\frac{L_o}{10^{28}\text{ ergs}^{-1}\text{ Hz}^{-1}} \right) \quad . \tag{14}$$

where they define L_o as the monochromatic optical luminosity at 2500Å in the source rest frame.

Notice that the net continuum will have a smaller than specified ratio of second to total continuum, since the command specifies the ratio of the second to the first, not the ratio of second to total.

4.5. Continuum Shape

The continuum should be specified between an energy of 1.001×10^{-5} Ryd ($\lambda \approx$ 1 cm; the low-energy continuum is important for Compton cooling, photoionization from excited states of hydrogen and helium, free-free heating, H^- heating, and grain heating) and 100 MeV ≈ 7.354×10^6 Ryd (where the Klein-Nishina electron-scattering cross section is small, pair production is a competitive heating and opacity source, and the hard continuum is usually well rolled-over). CLOUDY will complain, but compute the model if possible, if the continuum is not specified over the full energy range. An intensity of zero will be assumed for missing portions of the continuum.

4.5.1. background, z=1.825, [f=100; no fireball]

This command will specify a continuum shape and intensity chosen to mimic the cosmic radio to X-Ray background, as described by Ostriker and Ikeuchi (1983) and Ikeuchi and Ostriker (1986). Their ultraviolet continuum shape is a α =-1 power-law, with a mean intensity J_ν at 912Å given by

$$4\pi J_\nu(912\text{Å}) = 4\pi\times10^{-21}\left(\frac{1+z}{3.5}\right)^4 \quad f \quad \text{erg Hz}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1} \tag{15}$$

where z is the redshift and f an optional scale factor entered as the second parameter. Its default value is f=1, and z=0 (i.e., now) is assumed if no redshift is entered. Judging from Bechtold et al. (1987) and Bajtlik, Duncan, and Ostriker (1988), f is within a factor of 10 of unity.

This command specifies *both* the shape and intensity of the continuum. It is important that any previously occurring ordered pairs of shape and intensity commands be complete before this command is given.

Primordial fireball radiation is included in the generated background. This radiation field is assumed to be a blackbody radiation field, in strict thermodynamic equilibrium, with temperature given by

$$T_{fireball} = 2.756(1+z)\ ^\circ\text{K} \tag{16}$$

where the redshift dependence is from Peebles (1971) and the present temperature of the background is assumed to be $T_{\text{fireball}} = 2.756 \pm 0.016$ °K (Wilkinson 1987). This background can be an important source of Compton cooling for low density clouds. If the optional keyword NO FIREBALL appears on the line then the background due to the primordial fireball radiation will not be included.

Thermal background radiation can also be specified independently with the FIREBALL command, described below.

If a starting radius is not specified, then a value of 10^{25} cm will be assumed. Some objects, such as Lyα forest clouds, may be very large. Note that for the geometry to be plane parallel it is necessary to make sure that $\delta r / r \ll 1$ (if $\delta r / r \gg 1$ then the incident continuum will be attenuated by the r^{-2} geometric factor). It may be necessary to specify a larger starting radius in some circumstances.

4.5.2. blackbody t=100,000 [linear; luminosity.]

The continuum will be a blackbody with temperature given by the input number, the temperature in degrees Kelvin. The temperature may be entered directly, or as a log. The number is assumed to be a log if it is less than or equal to 10 and linear if greater than 10. (As a result, temperatures less than or equal to 10 °K are entered as logs, i.e., 5 °K = 0.69897, 10 °K = 1). Temperatures lower than 10 °K will be interpreted as the linear quantity rather than as a log if the

keyword LINEAR appears. Embedded commas can improve readability, such as

```
black body, Temp = 1,000,000K
```

which is equivalent to

```
black body t=6  .
```

Blackbody luminosity options. The luminosity of the black body can also be specified with options which may occur on this command line. (This option was added by P.G. Martin.) If the luminosity is specified with any of these options, then it must not also be specified with another luminosity command for this continuum source. The keywords which can appear on the line are as follows:

blackbody 5, luminosity = 38. If the keyword LUMINOSITY appears then the second number is the log of the *total* luminosity (erg s^{-1}) of the black body, $4\pi R_{star}^2 \sigma T_{eff}^4$. This example would be a 10^5 °K planetary nebula nucleus at the Eddington limit.

blackbody 5, radius = 10. The log of the radius of the blackbody R_{star} (in cm) is used to set the total luminosity when the keyword RADIUS appears. The total luminosity is $4\pi R_{star}^2 \sigma T_{eff}^4$. This example is also typical of a planetary nebula nucleus.

blackbody 50,000K, energy density = 500K. The energy density of the blackbody radiation field, expressed as the equivalent blackbody temperature T_u in degrees K, is used to set the luminosity when the ENERGY DENSITY keyword appears anywhere on the line. The energy density temperature is defined from Stefan's law and the actual energy density of the radiation field *u* (erg cm^{-3}):

$$T_u \equiv \left(\frac{u}{a} \right)^{1/4} \quad ^\circ\mathrm{K} \tag{17}$$

where *a* is the Stefan's radiation density constant.

The second number is assumed to be a log if it is less than or equal to 10 and linear otherwise. Numbers smaller than 10 °K will be interpreted as the linear temperature rather than as a log if the keyword LINEAR appears. (Note that if the linear option is used, then the blackbody temperature must also be linear since the key triggers both.) Note also that cosmic background radiation should also be included if $T_u \leq 2.8(1+z)$ °K. CLOUDY will complain, but compute the model, if the energy density of the incident continuum corresponds to a temperature less than the present energy density temperature of the universe.

blackbody, t = 50,000K, _lte The keyword _LTE (note the leading space) with no second number is equivalent to the ENERGY DENSITY option with T_u set to the color temperature of the radiation field. This is a quick way to check that

ionization and level populations go to LTE in the high radiation field limit. (This corresponds to strict thermodynamic equilibrium, not LTE, of course.)

blackbody, t = 100,000K, dilution factor = -14 Here the second parameter is the dilution factor *W*, defined as

$$W \equiv \frac{J_\nu}{B_\nu} \approx \frac{\pi R_{star}^2}{4\pi r_o^2} \tag{18}$$

where R_{star} is the radius of the star and r_o is the separation between the illuminated face of the cloud and the center of the star. The approximation on the RHS assumes that $R_{star} \ll r_o$. The dilution factor can be entered either directly or as a log (if the latter, then it will be negative). The example above is a rough approximation of the radiation field within a typical planetary nebula.

Starting radius If the radiation field is normalized by specifying the equivalent energy density T_u, either explicitly or with the _LTE option, or by setting a dilution factor, then it is not necessary to also specify the starting radius since the intensity of the incident continuum is uniquely determined. An inner radius of 10^{25} cm will be assumed if the inner radius is not set; this usually will result in a plane parallel geometry. It *is* necessary to set a starting radius for the luminosity or radius options, however, since these specify luminosity and not intensity.

4.5.3. bremsstrahlung, temp = 8

The continuum will be (approximately) characteristic of optically thin hydrogen bremsstrahlung emission. The assumed form is given by;

$$f_\nu \propto \nu^{-0.2} \exp(-h\nu / kT) \quad . \tag{19}$$

The temperature may be entered directly, or as a log. In this example the temperature would be 10^8 °K. The argument is assumed to be the log of the temperature if it is less than or equal to 10, and linear otherwise. The form of the continuum is approximate since a simple power-law gaunt factor is assumed, and the emission from an optically thin gas with cosmic abundances is actually characterized by hundreds of overlapping emission lines (see, for example, Kato 1976).

4.5.4. extinguish column dens = 23, leak = 0.05, low =4 Ryd

After the continuum has been fully generated and normalized to the correct intensity, this command will modify the shape by extinguishing ionizing energies by photoelectric absorption by a cold neutral slab with column density $N(H) = \int n(H) f(H) dr$ (cm^{-2}) given by the first argument (entered as a log; f(r) is the filling factor). The form of the extinction is a simple single power-law fit to the absorption curves calculated by Cruddace et al. (1974);

$$f'_\nu(\nu \geq 1\,\mathrm{Ryd}) = f_\nu \left\{ \eta + (1-\eta) \exp\left(6.22 \times 10^{-18}\, \nu_{Ryd}^{-2.43}\, N(H) \right) \right\} \tag{20}$$

where f_ν and f_ν' are the incident and attenuated continua, N(H) is the total hydrogen column density, ν_{Ryd} is the frequency in Rydbergs, and η is the leakage. The non-ionizing ($h\nu < 1$ Ryd) continuum is not extinguished by this command.

The second optional number is the fractional leakage through the absorber η (see Ferland and Mushotzky 1982), which has a default value of 10^{-4}. This second number is interpreted as a log if it is negative and linear otherwise. A comment is printed if the leakage is zero, since it is possible that there will be no ionizing radiation in this case. If temperature failures occur or the solutions seem unphysical when the EXTINGUISH command is given then it is likely that nearly all ionizing radiation has been attenuated. A plot of the generated continuum (with the PLOT CONTINUUM command) may prove interesting.

The third optional number is the lowest energy for the absorption to occur. It must be greater than 1 Ryd (the default) and is entered as linear Rydbergs. The continuum with energies below this will be unaffected by the absorption. The optional arguments may be omitted from right to left.

The command acts by first generating the continuum shape, neglecting extinction. The continuum is then normalized using any of the luminosity commands (i.e., Q(H), IONIZATION PARAMETER, LUMINOSITY, etc.), *then* the continuum is extinguished. The continuum which actually strikes the illuminated face of the cloud *does not* have the ionization parameter or luminosity actually entered. (These values would be correct were the extinction not present.) Physically, the luminosity of the central object is not changed by the presence of an absorbing cloud along the line of sight.

4.5.5. fireball [redshift = 2000]

This command generates a blackbody radiation field in strict thermodynamic equilibrium (i.e., $T_{color} = T_u$, where u is the energy density). The optional argument is the redshift z; if it is not entered then z = 0 is assumed. The temperature of the blackbody is given by

$$T_{fireball} = 2.756(1+z)\,^\circ\mathrm{K} \qquad (21)$$

where the redshift dependence is from Peebles (1971) and the present temperature of the background is assumed to be $T_{fireball} = 2.756 \pm 0.016$ °K (Wilkinson 1987). This command specifies *both* the shape and intensity of the radiation field. A starting radius of 10^{25} cm will be assumed if no starting radius is specified.

4.5.6. interpolate [ν(Ryd) or log ν(Hz)], log(f_ν)

Under most circumstances the continuum will actually be entered as a table of points. CLOUDY interpolates upon this table using straight lines in log-log

space. Up to 500 ordered pairs of points can be entered, with CONTINUE lines used to continue entering values after the initial INTERPOLATE line is filled. The first of each pair of points is *either* the energy in Rydbergs (either linear or as a log) *or* the log of the frequency (in Hertz); the second number of each pair is the log of the relative flux density per unit energy interval (f_ν) at that energy. CLOUDY assumes that the log of the energy in Rydbergs was entered if the first number is negative; that the log of the frequency was entered if the first number is greater than 5; and linear Rydbergs otherwise. Any of the three styles can be chosen, but must be used consistently within the command. If the first energy is entered as zero then it is interpreted as the low energy limit of the code. In this case the remaining energies will be interpreted as linear Rydbergs if the second number is positive, and the log of the energies in Rydbergs if negative. An energy of zero Ryd is not allowed (except for the first), and the energies must be in increasing order. The luminosity of the continuum is then set by any one of the luminosity commands.

Unlike the majority of the commands, the first five characters of the command must be entered.

The INTERPOLATE command can be freely mixed with other continuum shape commands, and a total of up to 10 INTERPOLATE and TABLE (see below) commands can be entered.[5] Note that TABLE and INTERPOLATE are actually two forms of the same command. The total number of TABLE and INTERPOLATE commands entered together cannot exceed 10, the current value of the variable LIMSPC, which occurs in parameter statements throughout the code.

As an example, the following approximates a metal-poor 45,000 °K stellar atmosphere; the energies are entered in Rydbergs:

```
* following is 45000k atmosphere from Shields and Searle
interpolate (0.00001 -11.106) (.58 -1.5792) (.99 -1.44)
continue (1.01 -1.7018) (1.8 -1.905) (1.81 -1.939)
continue (2.57 -2.208) (2.59 -2.247) (3 -2.3994)
continue (3.02 -2.8193) (3.49 -2.9342) (3.51 -4.143)
continue (3.99 -5.582) (4.01 -6.3213) (6 -9.9) (10 -17.3)
continue (20 -30) (10,000,000 -30)
q(h) = 52.778151
```

Note that the continuum should be specified between 1.001×10^{-5} Ryd and 7.354×10^{6} Ryd even if the intensity is small; if it is not fully specified then a warning will be issued and a model computed with the unspecified continuum set to zero intensity, if this is possible. As a further note, it is important that the continuum be physically correct. For instance, stellar model atmospheres emit

[5]Limits to the use of the INTERPOLATE command existed in versions 73 and before, but have been lifted.

almost no X-rays, while real OB stars *are* X-ray sources (although neglecting X-rays for these stars is generally a safe approximation). See page 43 for a further discussion.

CLOUDY will stop if more than 500 frequency points are entered. The maximum number of frequency points allowed is set by the variable NTERP which occurs in several PARAMETER statements throughout the code. NTERP is presently 500. If more points are needed then NTERP should be increased everywhere this parameter occurs in the code.

4.5.7. laser, frequency = 3.5 Ryd

The intensity of the continuum will be very small, except within ±5% of the specified energy, where it will be very large.[6] The energy is specified in Rydbergs, and it is interpreted as a log if it is negative. This is a useful way to check on the computation of the photoionization rate integrals.

4.5.8. power law, slope=-1.4 [high cut=6 Ryd low cut=.01]

N.B. IT IS VERY DANGEROUS TO USE THIS COMMAND. The continuum will be a power law, with optional low and high energy exponential cutoffs, parameterized by the cut-off frequencies $\nu_{\text{high cut}}$ and $\nu_{\text{low cut}}$, expressed in Rydbergs. The form of the continuum is

$$f_\nu = \nu^{+\alpha} \exp\left(-\nu / \nu_{high\ \ cut}\right) \exp\left(-\nu_{low\ \ cut} / \nu\right) \quad . \tag{22}$$

The first number on the command line is the slope α. Note that there is no implicit negative sign in this exponent; typical AGN have α_{ox}~ -1.4, (Zamorani et al. 1981). The second (optional) number is the high energy cutoff $\nu_{\text{high cut}}$ expressed in Rydbergs. The default value of $\nu_{\text{high cut}}$ is 10^{10} Ryd~10^{11} eV. The third optional number is the low energy cutoff $\nu_{\text{low cut}}$; the default value is 0 eV.

There is an optional keyword KELVIN, to cause the command to interpret both the cutoff energies as degrees Kelvin, rather than in Rydbergs. The temperature is a log if less than or equal to 10, and the linear temperature if greater than 10.

It is generally a *very bad* idea to use this command. CLOUDY treats the entire continuum between *very* low and *very* high energies. Extrapolating reasonable continua past the optical-ultraviolet region into microwave or γ-ray energies will have unexpected effects. Power-law continua with slopes smaller than -1 will have unphysically large photon occupation numbers and brightness temperatures at very low energies, probably producing catastrophic Compton cooling and / or free-free heating. Continua with slopes greater than -1 will be

[6]The luminosity normalization for this command was not exact before version 74.

dominated by the radiation field at energies of many MeV, resulting in large Compton heating and pair production rates. A further problem is that the exponential cutoffs can drive the continuum to zero intensity when either argument in the exponential becomes large. This is unphysical, and can cause numerical problems.

It is *much* better to use the INTERPOLATE command, and enter physically reasonable low and high energy continua. There is a special version of the command, TABLE POWER LAW (see below) for entering a well behaved $f_\nu \propto \nu^{-1}$ power-law continuum.

4.5.9. table, [agn, akn120, ...]

Any of several continuum shapes which are stored as a permanent part of the code in BLOCK DATA SCALAR can be entered with this command. This is a special version of the INTERPOLATE command, described above. The same interpolation on a table of input frequencies and fluxes described there is done when this command is entered. The TABLE command can be freely mixed with other shape commands, and a total of up to ten TABLE and INTERPOLATE commands can be entered.

Table 4 AGN Continuum

ν(Ryd)	log (F_ν)	slope
1.00(-5)	-3.388	+2.50
9.12(-3)	4.0115	-1.00
0.206	2.6576	-0.50
1.743	2.194	-1.00
4.130	1.819	-3.00
26.84	-0.6192	-0.70
7.35(+3)	-2.326	-1.67
7.40(+6)	-7.34	-

Table 3 Power Law Continuum

ν(Ryd)	log (F_ν)	slope
1.00(-5)	-5.	+2.50
9.115(-3)	-0.5604	-1.00
3676.	-6.166	-2.
7.40(+6)	-12.77	-

table _agn If the keyword _AGN appears (note the presence of a leading space), then a continuum similar to that deduced by Mathews and Ferland (1987) will be used. The continuum is meant to be similar to typical radio quiet active galaxies. The points used to describe this continuum are given in Table 4.

This continuum differs from the Mathews and Ferland (1987) continuum only in that the continuum is assumed to have a sub-millimeter break at 10 microns. For wavelengths longer than 10 microns the continuum is assumed to have a slope $f_\nu \propto \nu^{+2.5}$, appropriate for a self-absorbed synchrotron continuum (Rybicki and Lightman 1979). Note that this is the observed continuum, and may not be directly related to the continuum actually striking BLR gas.

The energy of the sub-millimeter break is not well determined observationally, but has a major impact on high density, high ionization parameter models, as discussed by Ferland and Persson (1989) and Ferland et al. (1992). The energy of the break can be adjusted with the BREAK keyword. The break can be adjusted between the limits of 0.2 Rydberg and 1.001×10^{-5} Ryd by entering the keyword BREAK, followed by a number specifying the energy of the break. The number is interpreted as the log of the energy in Rydbergs if it is negative, as linear Rydbergs if positive, and as the (linear) wavelength of the break in microns if a second keyword MICRONS appears. If no number appears, but the keywords NO BREAK does, then a break at an energy of 1.001×10^{-5} Ryd is assumed. The following shows equivalent ways of generating a continuum with a break at 10 microns;

```
table agn break .00912  ; energy in Ryd
table agn break -2.04   ; log of energy in Ryd
table agn break 10 microns ; wavelength in microns
table agn no break      ; no sub-millimeter break
```

Note that the nature of the continuum in AGN is still an open question. The continuum given here is very simplistic, and quite uncertain in the ionizing ultraviolet. Moreover, it would not be surprising if the BLR sees a far different continuum than we do. Recent work suggests this continuum may not be correct for low redshift Seyfert galaxies (Binette et al. 1989; Clavel and Santos-Lleo 1990). It is probably best to only use this continuum in exploratory situations, and to generate a specific AGN continuum using the RATIO command, as described on page 31.

table power law [spectral index -1.4, low=.01, hi=20] This option produces a power law continuum which is well-behaved at both the high and low energy ends. The default condition (when no numbers occur on the input line) is for the form $f_\nu \propto \nu^\alpha$ with α=-1 for the spectral midrange, between 10 microns and 50 keV, and has slopes $\alpha=\nu^{5/2}$ at lower energy, and $\alpha=\nu^{-2}$ at higher energies. Table 3 summarizes the default continuum.

Three optional numbers may appear on the command line. The first number sets the slope of the mid-range spectral component (infrared to X-ray) and has a default of -1. Note that implicit negative signs are never used in CLOUDY. The second optional number is the energy (in Rydbergs) of the infrared break; the default is 10 microns. If this second number is zero then the low energy limit to the continuum (1.001×10^{-5} Ryd) will be used. The number is interpreted as the log of the energy in Rydbergs if it is negative, and linear otherwise. The third optional number is the energy of the break in the X-ray continuum. The default is 50 keV, and if it is zero then the high energy limit of the continuum (7.354×10^{6} Ryd) is used. The number is interpreted as a log if the energy of the infrared break is entered as a log and linear otherwise. The numbers may be omitted from right to left.

Table 5 Crab Continuum

ν(Ryd)	f_ν
1.0(-5)	3.77E-21
5.2(-4)	1.38E-21
1.5(-3)	2.10E-21
0.11	4.92E-23
0.73	1.90E-23
7.3	2.24E-24
73.	6.42E-26
7.3(+3)	4.02E-28
1.5(+6)	2.08E-31
7.4(+6)	1.66E-32

Table 6 Akn 120 Continuum

ν(Ryd)	f_ν
1.0(-5)	1.5(-26)
1.9(-5)	1.6(-26)
3.0(-4)	1.4(-23)
2.4(-2)	8.0(-25)
0.15	1.6(-25)
0.30	1.8(-25)
0.76	7.1(-26)
2.0	7.9(-27)
76.	1.1(-28)
7.6(+2)	7.1(-30)
7.4(+6)	1.3(-34)

table crab If the keyword CRAB appears then the continuum summarized by Davidson and Fesen (1985) is generated. The luminosity of the continuum *is not* specified by this command. This is the net observed continuum, originating in both the pulsar and nebula, and not the pulsar continuum alone. The continuum is entered in the block data as the observed flux at Earth (erg cm^{-2} s^{-1} Hz^{-1}) and is given in Table 5.

According to Davidson and Fesen, the total luminosity of the Crab is $L_{tot} = 10^{38.14}$ erg s^{-1}, so the Crab continuum could be generated by combining the commands

```
luminosity (total) 38.14
table Crab
```

table cooling flow The keyword COOL generates the continuum described by Johnstone et al. (1992). It is a co-added series of Raymond-Smith collisional equilibrium continua, chosen to represent the spectrum at a point within a typical cooling flow.

table akn120 If the keyword AKN120 appears then the continuum summarized by Peterson et al. (in preparation) is used. This is the net continuum, as observed with a small beam, and may not be the continuum actually striking emitting gas. The continuum is described by the observed flux at Earth (erg cm^{-2} s^{-1} Hz^{-1}) and is given in Table 6.

According to Peterson the specific luminosity at 1320Å is $\nu L_\nu = 1.84 \times 10^{44}$ h^{-2} erg s^{-1}, where $h \equiv H_o / 100$ km s^{-1} mpc^{-1}, so, setting h = 0.75, the AKN120 continuum could be generated by the commands

```
nul(nu) = 44.514 at 0.6906 Ryd
table akn120
```

table star [Kurucz; Mihalas] Two sets of emergent continua from stellar atmosphere calculations are available as built-in blocks within CLOUDY. These are accessed with the keyword STAR, followed by a sub-keyword (Mihalas or Kurucz) to indicate which set of atmospheres is to be used. At present subsets of the Mihalas (1972) non-LTE OB stellar atmospheres and the Kurucz (1979; with supplements) line-blanketed LTE atmospheres are available. Both are static plane-parallel atmospheres. The parameters of the models now included are summarized in Tables 7 and 8. The temperature and author of the calculation (presently Kurucz or Mihalas) must be specified; these can be in any order.

Table 7 Mihalas (1972) Continua

T_*	log(g)
30,000	4.0
32,500	4.0
35,000	4.0
37,500	4.0
40,000	4.0
45,000	4.0
50,000	4.0
55,000	4.0

Table 8 Kurucz (1979) Continua

T_*	log(g)	[Z]	Reference
30,000	4.0	0.0	Kurucz (1979)
35,000	4.5	0.0	priv comm
40,000	4.5	0.0	priv comm
45,000	4.5	0.0	Kurucz (1979)
50,000	4.5	0.0	Kurucz (1979)

Any temperature between the lowest and highest temperatures listed in the tables can be interpolated, but only the listed gravities and metalicities can be generated at present. If the specified temperature is within a tenth of a percent of one of the temperatures listed in the tables then exactly the published continuum will be used, otherwise a linear interpolation in temperature magnitude (Mihalas) or log(f_ν) (Kurucz) space will be done. Extrapolation is not performed; the temperature must be between the lowest and highest values.

The following would roughly correspond to θ^1 C Ori, the ionizing star in the Orion Nebula;

```
table star Kurucz 39,000
q(h) 49   .
```

Note that these stellar atmospheres emit little energy above 4 Ryd, while real OB stars are actually X-Ray sources. Sciortino et al. (1990) find a correlation between the X-ray and bolometric luminosities which can be fitted by

$$\log(L_x) = 1.08(+0.06/-0.22)\log(L_{bol}) - 9.38(+2.32/-0.83) \quad (23)$$

i.e., the X-ray luminosity is typically 6.4 dex fainter than the bolometric luminosity. A source temperature of 0.5 keV is quoted by Sciortino et al. This X-ray continuum must be explicitly added as an independent continuum source. Tests show that the high energy light has little effect on conditions in the HII region, but *does* affect the ionization in the surrounding PDR.

table star atlas, temp=40,000 [log(g)=4.5] The Kurucz (1991) grid of Atlas models has been incorporated into CLOUDY by Kevin Volk. This command asks the code to interpolate on this grid to generate an incident continuum produced by an atmosphere with the specified temperature and gravity. The first number on the command line is the temperature, interpreted as a log if less than or equal to 10, and the second optional number is the log of the surface gravity. A gravity of log(g)=5 will be used if none is specified. All models are for solar abundances.

This grid is far too large to actually store within the code. Instead it is stored as an ancillary file. It is necessary to compile this file before it can be used by CLOUDY. If the code is executed from directories other than the one containing the compiled file containing the star data then it is also necessary to set the path to the directory containing the files with the SET PATH command, as described on page 108 of this section of HAZY. These issues are discussed further in Part III of this document, in the section entitled *Machine Environment*. That section describes how to access and compile the file of star data.

Table 9 lists the temperatures and surface gravities stored within this set.

Table 9 Kurucz (1991) Continua

Teff\log(g)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
3500	x	x	x	x	x	x	x	x	x	x	x
3750	x	x	x	x	x	x	x	x	x	x	x
4000	x	x	x	x	x	x	x	x	x	x	x
4250	x	x	x	x	x	x	x	x	x	x	x
4500	x	x	x	x	x	x	x	x	x	x	x
4750	x	x	x	x	x	x	x	x	x	x	x
5000	x	x	x	x	x	x	x	x	x	x	x
5250		x	x	x	x	x	x	x	x	x	x
5500	x	x	x	x	x	x	x	x	x	x	x
5750	x	x	x	x	x	x	x	x	x	x	x
6000	x	x	x	x	x	x	x	x	x	x	x
6250		x	x	x	x	x	x	x	x	x	x
6500		x	x	x	x	x	x	x	x	x	x
6750		x	x	x	x	x	x	x	x	x	x
7000		x	x	x	x	x	x	x	x	x	x
7250		x	x	x	x	x	x	x	x	x	x
7500		x	x	x	x	x	x	x	x	x	x
7750			x	x	x	x	x	x	x	x	x
8000			x	x	x	x	x	x	x	x	x
8250			x	x	x	x	x	x	x	x	x
8500			x	x	x	x	x	x	x	x	x
8750				x	x	x	x	x	x	x	x
9000				x	x	x	x	x	x	x	x
9250					x	x	x	x	x	x	x
9500					x	x	x	x	x	x	x
9750					x	x	x	x	x	x	x
10000					x	x	x	x	x	x	x
10500					x	x	x	x	x	x	x
11000						x	x	x	x	x	x
11500						x	x	x	x	x	x
12000						x	x	x	x	x	x
12500						x	x	x	x	x	x
13000						x	x	x	x	x	x
14000					x	x	x	x	x	x	x
15000						x	x	x	x	x	x
16000						x	x	x	x	x	x
17000						x	x	x	x	x	x
18000						x	x	x	x	x	x
19000						x	x	x	x	x	x
20000							x	x	x	x	x
21000							x	x	x	x	x
22000							x	x	x	x	x
23000							x	x	x	x	x
24000							x	x	x	x	x
25000							x	x	x	x	x
25000							x	x	x	x	x
26000							x	x	x	x	x
27000								x	x	x	x
28000								x	x	x	x
29000								x	x	x	x
30000								x	x	x	x
31000								x	x	x	x
32000									x	x	x
33000									x	x	x
34000									x	x	x
35000									x	x	x
37500										x	x
40000										x	x
42500											x
45000											x
47500											x
50000											x

It may take the machine some time to find the desired atmosphere, and interpolate to the correct temperature and gravity. If the same atmosphere is to be used repeatedly then it would save a lot of time if you save the interpolated

atmosphere with the PUNCH TRANSMITTED CONTINUUM command, and then read this in for later calculations with the TABLE READ command, as shown below;

```
*this input stream is just to get the right continuum
hden 0   ;the first 4 lines get the code to run at all
ionizat -1
constant temper 4
stop zone 1
;set very small largest thickness so nebula does not
;affect the transmitted continuum
set drmax -5
punch transmitted continuum
table star atlas, t=33,375 log(g)=4.26
```

This would then be followed by the real calculation, reading in the output from this run with the TABLE READ command, described on page 47 of this document.

table _ism [factor = 0.7] The local interstellar radiation field is generated with the keyword _ISM. This uses Figure 2 of Black (1987) to represent the *unextinguished* local interstellar radiation field. This command specifies *both* the shape and luminosity of the radiation field. The continuum generated by CLOUDY is exactly that given by Black, except that the radiation field between 1 and 4 Ryd is interpolated from the observed / inferred values. Actually, it is thought that this part of the radiation field is heavily absorbed by gas in the ISM, so that little 1 to 4 Ryd radiation exists, at least in the galactic plane. Such absorption can be introduced with the EXTINGUISH command, described elsewhere.

The TABLE ISM command also specifies the intensity of the incident radiation field, since this is also directly observed. There is an optional parameter which specifies a scale factor for the intensity of the entire radiation field. It is the log of the scale factor if less than or equal to zero, and the scale factor itself if positive. The default is zero (i.e., Black's radiation field). The actual numbers used by CLOUDY to interpolate on Black's table are given in Table 10. The frequencies are in Hz, and the product νf_ν in erg cm^{-2} s^{-1}.

The actual ISM radiation field incident on a typical region in the galactic plane would be generated by:

```
table ism
extinguish by 22  .
```

table read [Fortran unit 8] This command is used to read in the continuum predicted from previous calculations using CLOUDY. Here, the initial calculation is used to predict the continuum transmitted through a cloud. This command is then used in subsequent calculations, in which the transmitted continuum from the first calculation is to be included in the incident radiation field of the second calculation. The file containing the previously computed continuum must have been produced by the current version of CLOUDY by including the PUNCH TRANSMITTED CONTINUUM command in the initial calculation. This PUNCH command is described starting on page 90, and produces a file containing the frequency (in Rydbergs) and the transmitted flux νf_ν. This continuum is the sum of the attenuated incident continuum and the fraction of the diffuse emission from the cloud which is transmitted in the outward direction.

This table can be freely mixed with all of the other continuum shape commands, but only one table can be read in using this command. If more than one TABLE READ command occurs, only the last will be honored. The default is for the file containing the continuum points to be FORTRAN I/O unit 7 (i.e., named fort.7 on UNIX machines, or assigned with the ASSIGN NAME FOR.007 statement on VMS machines). The I/O unit number is changed with the optional argument on the line.

When this command is used, punch output (using the PUNCH command) must not also be produced on the same Fortran I/O unit number; the input file

Table 10 ISM Radiation Field

log(ν)	log(ν f_ν)	log(ν)	log(νf_ν)
9.00	-7.93	14.14	-2.30
10.72	-2.96	14.38	-1.79
11.00	-2.47	14.63	-1.79
11.23	-2.09	14.93	-2.34
11.47	-2.11	15.08	-2.72
11.55	-2.34	15.36	-2.55
11.85	-3.66	15.54	-2.62
12.26	-2.72	16.25	-5.68
12.54	-2.45	17.09	-6.45
12.71	-2.57	18.00	-6.30
13.10	-3.85	23.00	-11.30
13.64	-3.34		

will be overwritten if this occurs. The first two lines of the input file contain header information, and are skipped. They should not be deleted.

The following gives an example of first creating a file containing the transmitted continuum, then using this file as one of the continua in a later calculation.

```
title this finds transmitted continuum due to warm absorber
hden 9
ionization parameter 1
stop effective column density 24
table agn
punch transmitted continuum
```

Now use this continuum in a second calculation:

```
table read
luminosity 45
radius 18
hden 9
```

table star Werner, temp=140,000 [log(g)=7.4] The Klaus Werner (Werner and Heber 1991) grid of non-LTE model planetary nebula nuclei atmospheres was incorporated into CLOUDY by Kevin Volk. This command asks the code to interpolate on this grid to generate an atmosphere with the specified temperature and gravity. The first number on the command line is the temperature, interpreted as a log if less than or equal to 10, and the second optional number is the log of the surface gravity. A gravity of log(g)=8 will be used if none is specified.

Table 11
Klaus Werner (1992) Continua

Temp \ log g	5	6	7	8
80,000°K	*	*	*	*
100,000°K	*	*	*	*
120,000°K		*	*	*
140,000°K		*	*	*
160,000°K			*	*
180,000°K			*	*
200,000°K			*	*

This grid is far too large to actually store within the code, so instead is stored as an ancillary file. It is necessary to compile this file before it can be used by CLOUDY. If the code is executed from directories other than the one containing the compiled file then it is also necessary to set the path to the directory containing the files with the SET PATH command. These issues are discussed further in Part III of this document, in the section on machine environment. The treatment of these files is entirely analogous to that of the TABLE STAR ATAS command (see page 45).

Table 11 lists the temperatures and surface gravities stored within this set. The discussion of the TABLE STAR ATLAS command describes a way to save one of these atmospheres for later use.

4.6. Chemical Composition

The composition will be solar (defined in Table 12; these are taken from Grevesse and Anders 1989) unless a different mixture is specified. Abundances are always specified by number relative to hydrogen, not by mass.

4.6.1. abundances he c n o ne na mg al si s ar ca fe ni

The chemical composition is entered with a line beginning with the command ABUNDANCES, followed by: a) a set of 14 abundances; b) a single number to set all of the abundances, or c) a second keyword to select one of several stored abundance sets. Abundances are always by number relative to the total hydrogen density (the sum of atomic, ionic, and molecular).

Table 12 Solar Composition

Atom	Solar	Old Solar
Key	default	OSOLar
He	0.098	0.10
C	3.63(-4)	4.7(-4)
N	1.12(-4)	9.8(-5)
O	8.51(-4)	8.3(-4)
Ne	1.23(-4)	1.0(-4)
Na	2.01(-6)	1.0(-9)
Mg	3.80(-5)	4.2(-5)
Al	2.95(-6)	2.7(-6)
Si	3.55(-5)	4.3(-5)
S	1.62(-5)	1.7(-5)
Ar	3.63(-6)	3.8(-6)
Ca	2.29(-6)	2.3(-6)
Fe	4.68(-5)	3.3(-5)
Ni	1.76(-6)	1.0(-9)
grains?	no	no

Arbitrary abundances. An arbitrary abundance set can be specified by entering all fourteen abundances with the ABUNDANCES command. The elements must be in exactly the same order as indicated in Table 12, and all fourteen abundances must be specified. Abundances of zero are not allowed; CLOUDY will stop. The code may crash due to floating point underflow, followed by division by zero, if an abundance is made too small (i.e., such that the volume number density (cm^{-3}) of the element underflows to zero). The composition can be specified on several lines with CONTINUE lines following the initial ABUNDANCES line.

The best way to enter abundances is as the log of the abundance by number relative to hydrogen;

```
abundances he=-1 c=-4.3 n=-5 o=-2.3 ne=-1.2 na=-3 mg=-8
continue al=-8 si=-8 s=-8 ar=-8
continue  ca=-8 fe=-8 ni=-8; (deplete Fe, 3rd row).
```

The abundances can also be entered as a set of scale factors indicating the desired abundances relative to solar;

```
abundances he=1 c=1 n=10 o=1 ne=1.2 na1.2 mg=1 al=.93
continue si=1 s=1 ar=1 ca=1 fe=0.00001 ni.01; (deplete iron)
```

In general it is better to use the first style since the default solar composition changes from time to time. The code decides which type is used by checking the sign of each number. The numbers are interpreted as linear scale factors relative to solar if *all* are positive, and as logs of the abundance relative to hydrogen if *any* are negative. Be sure to check the abundances listed in the printed header to confirm that the composition has been entered correctly.

If more than one abundance line is entered then those later ones which enter the abundances as scale factors will multiply the abundances which resulted from previous commands. Later abundance lines which enter the abundances themselves (not scale factors) will take precedence over previous commands.

Setting all at once. If exactly one number is entered on the ABUNDANCES line then all of the elements heavier than hydrogen are given this abundance; the number can be either the relative abundance or its log. The number will be interpreted as a log if it is less than or equal to zero, and as the abundance if positive. Either of the following commands will give all elements between and including helium and nickel an abundance of 10^{-10} by number relative to hydrogen:

```
abundances -10
abundances 0.000,000,000,1
```

This is useful for debugging the hydrogen atom. The METALS command, described below, is useful for changing abundances of all elements heavier than helium.

Stored abundance sets. Table 13 lists the abundance sets which are stored as a permanent part of the code. These sets are entered if there are no numbers on the line, but a keyword occurs, as in the following examples. The four character part of the keyword which must be matched for the key to be recognized is capitalized in the second line of the table.

```
abundances Cameron
abundances hii region [no grains]
abundances h ii region [no grains]
abundances nova
abundances planetary nebula [no grains]
abundances primordial
abundances NLR
```

The assumed abundances are from a variety of sources, and their present values are given in Table 13, by number relative to hydrogen. The default solar abundance used pre-1990 (Table 12) can be entered by using the OSOLAR keyword. The abundances of elements which were not included before 1990 have been given very small abundances in the OSOLAR mixture.

CAMERON abundances are from Cameron (1982; note that the helium abundance is *very* low, either it or the Big Bang is wrong).

Table 13 Stored Abundance Sets

Atom	H II Region	Planetary	Nova	Cameron	Primordial	ISM
key	HII, H II	PLANetary	NOVA	CAMEron	PRIMordial	_ISM
He	0.095	0.10	0.10	0.0677	0.072	0.098
C	3(-4)	7.8(-4)	9.4(-3)	4.22(-4)	1.0(-10)	2.51(-4)
N	7(-5)	1.8(-4)	9.8(-3)	8.72(-5)	1.0(-10)	7.94(-5)
O	4(-4)	4.4(-4)	1.7(-2)	6.93(-4)	1.0(-10)	5.01(-4)
Ne	1.1(-4)	1.1(-4)	2.0(-3)	9.77(-5)	1.0(-10)	1.23(-4)
Na	3.0(-7)	3.0(-7)	2.1(-6)	2.25(-5)	1.0(-10)	3.16(-7)
Mg	3(-6)	1.6(-6)	4.2(-5)	3.98(-5)	1.0(-10)	1.26(-5)
Al	2(-7)	2.7(-7)	2.7(-6)	3.20(-6)	1.0(-10)	7.94(-8)
Si	3(-6)	1.0(-5)	4.3(-5)	3.76(-5)	1.0(-10)	3.16(-6)
S	1(-5)	1.0(-5)	1.7(-5)	1.88(-5)	1.0(-10)	3.24(-5)
Ar	3(-6)	2.7(-6)	3.8(-6)	3.99(-6)	1.0(-10)	2.82(-6)
Ca	2(-8)	1.2(-8)	2.3(-6)	2.35(-6)	1.0(-10)	1.0(-10)
Fe	3(-6)	5.0(-7)	3.3(-5)	3.38(-5)	1.0(-10)	6.31(-7)
Ni	1.8(-8)	1.8(-8)	1.76(-6)	1.80(-6)	1.0(-10)	1.82(-8)
grains?	Orion	AGB	no	no	no	ISM

The nova abundances are roughly those derived by Ferland and Shields (1978) for the classical nova V1500 Cygni.

The H II region abundances are a subjective mean of the Orion Nebula abundances determined by Baldwin et al. (1991), Rubin et al. (1991), and Osterbrock et al. (1991). The grains are the large-R grains described by Baldwin et al. (1991).

The planetary nebula abundances are from the paper by Aller and Czyzak (1983), with high depletions assumed for elements they do not list. The grains are from unpublished work of Kevin Volk, and is deduced from observations of post-AGB stars.

The ISM mixture is an average from the work of Cowie and Songaila (1986) for the warm and cold phases of the interstellar medium. The grains are the default interstellar medium grains.

Some mixtures have certain elements, especially Si, Ca, Al, Mg, and Fe in H II regions and planetary nebulae, with gas-phase compositions reduced by depletion onto grains. Specifying H II REGION, _ISM, or PLANETARY NEBULA will invoke grains and the gas phase mixtures given in Table 13. Grains set in this manner will have the properties appropriate for the type of grains indicated (see bottom line of the Table, and the section on grains below). Grains can also be specified separately with the GRAINS command. If grains are set by both the GRAINS and ABUNDANCE commands then the parameters set by the GRAINS command are used.

In some circumstances, it is interesting to explore the effects of grain-free mixtures, with the opacity / thermal effects of the grains suppressed, but with the (depleted) gas-phase abundances unchanged. The optional keyword NO GRAINS can be placed in the ABUNDANCES line. In this case grains will not be included in the calculation, but the observed (depleted) gas-phase abundances will still be used.[7] This is, of course, not self-consistent.

4.6.2. metals 0.05 [_log, linear, grains]

This command multiplies the entire mixture of metals (elements heavier than helium) by the scale factor entered on the line. This is useful when the effects of global enrichments or depletions are to be investigated. If the number is zero or negative then it is assumed to be the log of the number; if positive then a linear scale factor. If the LINEAR keyword appears then the number is interpreted as linear (unless negative). If the _LOG keyword appears then the number is interpreted as the log of the metal abundance, no matter what sign the number has.

Combinations such as

```
abundances planetary nebula
metals 3
```

or

```
metals 3
abundances planetary nebula
```

would multiply the planetary nebula gas-phase abundances by three,[8] while

```
metals -10
```

would multiply the default solar mixture by 10^{-10}.

---

[7] In versions 77 and before, the abundances of depleted elements were set to solar values when “no grains” was set.

[8] Limits to the ordering of the ABUNDANCES and METALS commands existed before version 72 but have been lifted.

It seems likely that the grain to hydrogen ratio somehow scales with the total gas-phase metalicity. There is an optional keyword on the METALS command, "GRAINS", which causes the grain abundance to also be scaled by the factor on the line. The basic assumption here is that the grain to metals ratio does not depend on metalicity while the grain to gas (hydrogen) ratio depends linearly on the metalicity. It is still necessary to turn on grains with either the GRAINS command or by specifying a chemical composition which contains grains (with the ABUNDANCES command). The scale factor which appears on the METALS command will further multiply the grain abundance specified on the GRAINS command. That is, the combination

```
grains .5
metals and grains .5
```

(in any order) will result in a grain abundance which is a quarter of the default.

In the following example the ISM gas phase *and* grain abundances are each increased by a factor of two over their default values;

```
abundances ism
metals and grains 2  .
```

The metal depletion factor is stored as the variable DMETAL, in the common block of the same name. The grains depletion factor is stored as the variable GRMETL. Both have default values of unity.

4.7. Density Laws

Several commands specify the run of hydrogen density with radius. The default condition is constant density, with the total hydrogen density (atomic, ionic, and molecular, given by the command HDEN) held constant. Power law and sinusoidal density distributions, as well as constant gas pressure, constant total (gas and radiation) pressure models, or an arbitrary density law, can also be computed.

4.7.1. constant density, pressure, gas pressure

This command has several optional keywords, depending on what is to be held constant. These are described next.

4.7.2. constant density

This is the default. The hydrogen density, the sum

$$n(H) = n(H^o) + n(H^+) + n(H^-) + 2n(H_2) + 2n(H_2^+) + 3n(H_3^+) \quad (24)$$

is kept constant. This is not quite an isochoric density law because the total particle density is not constant. This is because the electron and molecular

fraction varies with the run of ionization. I prefer this type of model because the homology relations with the ionization parameter (Davidson 1977) are preserved. The hydrogen nucleon density is set with the HDEN command, which has as an option a power-law dependence on radius. Within the code the total hydrogen density is referred to by the variable name HDEN.

4.7.3. constant gas pressure [index=-1]

An isobaric density law is specified with this command. The gas pressure

$$P_{gas} = n_{tot} k T_e \qquad (25)$$

where n_{tot} is the total particle density, is kept constant. This type of model is trendy today in active nuclei, but not really warranted since the ionizing continuum is seldom constant over the sound travel time across a typical cloud. (The latter is several months for standard BLR clouds, and constant pressure is really only approached after conditions have been stable for several sound travel times.) The optional index α will force the pressure to change as a power-law of the radius;

$$P_{gas}(r) = P_o \left(\frac{r}{r_o} \right)^{\alpha} \qquad (26)$$

where P_o is the pressure at the inner radius.

The results of this command are not exact; the actual gas pressure will vary from zone to zone with an rms scatter of typically 0.7 percent.

4.7.4. constant pressure [no continuum]

If you are holding the pressure constant, you really should hold the total pressure, particle and radiation, constant. This option turns on the physics discussed by Ferland and Elitzur (1984), and Elitzur and Ferland (1986).

The pressure is the *total* pressure, the sum of the gas and radiation pressure;

$$P_{tot}(r) = P_{tot}(r_o) + \int a_{rad} \rho \, dr = P_{gas} + P_{lines} \qquad (27)$$

where a_{rad} is the radiative acceleration due to the incident continuum and ρ is the density (gm cm^{-3}). This pressure law includes thermal gas pressure (P_{gas}), the nearly isotropic pressure due to trapped emission lines (P_{lines}), and the outward force due to the attenuation of the incident radiation field (the integral; this can be turned off by specifying the "NO CONTINUUM" option on the command line).

CLOUDY will stop if the internal line radiation pressure builds up to more than half of the total pressure, since such clouds would be unstable unless they are self-gravitating. It is necessary to do at least a second iteration when radiation pressure is important since the total line optical depths must be known to compute line widths, escape probabilities, and level populations, reliably. If

more than one iteration is to be done then the radiation pressure will not be allowed to exceed the gas pressure on any except the last iteration.

The results of this command are not exact; the actual total pressure will vary from zone to zone with an rms scatter of typically 0.7 percent. It is not possible to specify the optional power-law index for this pressure law.

4.7.5. dlaw p1, p2, p4 ... p10

An arbitrary density law, specified by the user, is used. There are up to ten parameters, which are stored as a vector in the common block DLAW. A new function FUNCTION FABDEN(R1) must be provided, and the version of FABDEN already in CLOUDY must be deleted. The code will stop if the initial version of FABDEN is not replaced. The argument of the function is the radius in centimeters, and the function returns the hydrogen density (cm^{-3}). The code provided in the function must use the ten or fewer parameters in COMMON/DLAW/ DLAW(10) to compute the density at R1. Both the vector DLAW and argument to the function are double precision, although the function value is single precision.

The following is an example of a function.

```
      FUNCTION FABDEN( RADIUS )
      COMMON/DLAW/ DLAW(10)
      DOUBLE PRECISION RADIUS , DLAW
*
*     vector dlaw and radius are double precision,
*     density (fabden) is not
      FABDEN = DLAW(1) * RADIUS
*
      RETURN
      END
```

Note that it is not consistent to specify the density or density law with both this command and others, such as HDEN, CONSTANT PRESSURE, etc. There is no telling what will happen if this is done.

4.7.6. fluctuations log(period), log(max den), log(min den)

This command specifies a model in which the density varies as a sine wave. This is useful to check on the effects of inhomogeneities upon the emission-line spectrum. The first number is the log of the period of the sine wave, in centimeters. The second two numbers are the logs of the largest and smallest hydrogen densities over the sine wave. (See Mihalszki and Ferland 1983).

4.7.7. globule [density=2, radius=16, power=3]

The density law will be appropriate for a power-law density gradient, irradiated from the outside. The total hydrogen density n(r) is given by

$$n(r) = n_o\left(\frac{r}{r-\Delta r}\right)^{\alpha} \qquad (28)$$

where n_o is the background density outside the cloud, with default value 1 cm^{-3}, and Δr is the depth into the cloud, measured from the illuminated face. The log of n_o is the optional first number on the command line. r is the radius of the cloud, and has a default of one parsec, $r = 3.086\times10^{18}$ cm. Other radii are specified by the optional second parameter, which must be entered as a log, in cm. The optional third argument is the index α, which has the default $\alpha = 2$. The arguments can be omitted from right to left.

4.7.8. hden = 5.6, [proportional to R -2, ...]

The first number is the log of the total (ionic, atomic, and molecular) hydrogen density. This is the sum

$$n(H) = n\left(H^o\right) + n\left(H^+\right) + n\left(H^-\right) + 2n\left(H_2\right) + 2n\left(H_2^+\right) + 3n\left(H_3^+\right) \quad \mathrm{cm}^{-3} \quad . \qquad (29)$$

If the optional keyword LINEAR appears then the number is the density itself and not its log.

For situations where the hydrogen atom is close to LTE and the gas is hot, there is a problem in defining the neutral hydrogen density because of the well-known divergence of the partition function, as discussed, for instance, by Mihalas (1978). To avoid this difficulty, the present version of CLOUDY defines the atomic hydrogen density as the total population in levels $n \le 6$, while ionized hydrogen (which contributes to the free electron sum) includes all hydrogen atoms in $n \ge 7$ states. In most circumstances (i.e., $n(H) \ll 10^{13}$ cm^{-3} and $T \le 10^4$ °K) the ambiguity is much less than 1%.

Several options are available to specify optional power-law dependencies on depth variables. These are described further in the next sub-sections.

Power-law radial dependence The second (optional) number is the exponent α for a radial density dependence

```
hden 9, power=-2
```

i.e.,

$$n(r) = n_o(r_o)\left(\frac{r}{r_o}\right)^{\alpha} \quad \mathrm{cm}^{-3} \quad . \qquad (30)$$

If α= -2 (i.e., a power law with index alpha=-2 is entered as in the example above), the density will be proportional to the inverse square of the distance to

the central object, and spherical models will tend to have the same ionization parameter (and hence physical conditions) across the ionized zone.

For an inverse square law density dependence, there is a critical value of the number of ionizing photons emitted by the central object,

$$Q_{crit}(H) = \alpha_B(T_e) n_o^2 \, 4\pi \, r_o^2 \quad \text{s}^{-1} \tag{31}$$

where $\alpha_B(T_e)$ is the hydrogen case B recombination coefficient and n_o and r_o are the inner density and radius respectively. An ionization front will not be present (and the model will extend to infinite radius) when $Q(H) \geq Q_{crit}(H)$. Generally, an ionization front will not be present if the density falls off faster than an inverse square law, but rather the level of ionization will tend to *increase* with radius. CLOUDY is not designed to treat this case. In either case, if a reasonable outer radius is not set, the calculation will extend to very large radii, an unphysically small density will result, and usually the code will crash due to floating point underflow, followed by division by zero. It is usually necessary to set an outer radius when the density falls off with an index $\alpha \leq -2$, since, for most circumstances, the cloud will remain hot and ionized to infinite radius.

Power-law dependence on depth The density will depend on the depth into the cloud rather than the radius if both the optional exponent *and* the keyword DEPTH appears:

```
hden 9, power=-2, scale depth = 13
```

The depth is the distance (in cm) between the point in question and the illuminated face of the cloud. Here the density is given by

$$n(r) = n_o(r_o)\left(1 + \frac{\Delta r}{r_{scale}}\right)^{\alpha} \quad \text{cm}^{-3} \tag{32}$$

where r_{scale} is the scale depth and Δr is the depth. The scale depth is entered as the third number on line, and is the log of the depth in centimeters.

Power-law dependence on column density The density will depend on the column density if both the optional exponent *and* the keyword COLUMN appears;

```
hden 9, power=-2, scale column density = 21
```

Here the density is given by

$$n(r) = n_o(r_o)\left(1 + \frac{N(H)}{N(H)_{scale}}\right)^{\alpha} \quad \text{cm}^{-3} \tag{33}$$

where N(H) is the total hydrogen column density from the illuminated face to the point in question, and $N(H)_{scale}$ is the scale column density. The scale column density is entered as the third number on the line, and is the log of the column density (cm^{-2}).

4.8. Geometry

The geometry is always spherical, but can be made effectively plane parallel by making the radius much greater than the thickness of the nebula. It is also possible to compute a model in which the emission-line region is almost a disk.

4.8.1. covering factor 0.3

This command sets a covering factor $\Omega/4\pi$ for the emission-line region. The argument is interpreted as the log of the covering factor if less than or equal to zero, and the covering factor itself if positive. It is impossible to specify a covering factor of zero. The covering factor can also be set as an optional argument on the SPHERE command.

The covering factor affects both the luminosity and the radiative transfer of lines and continua. If a covering factor is set and the line or continua are predicted as luminosities, then the luminosities will be for a shell covering Ω sr, where $\Omega/4\pi$ is the covering factor. The covering factor does not directly affect the line intensities, (the emission per unit area) if these are predicted rather than luminosity. This covering factor is referred to as the geometric covering factor, and is stored as the variable COVGEO in the common block COVER. A second covering factor, COVRT, affects the transfer of lines and continua. Both covering factors are set by the number on this command line.

If no covering factor is entered and SPHERE is not set then the default is for a geometric covering factor of unity (the shell fully covers the continuum source) but a radiative covering factor of zero (i.e., an open geometry). Both the COVERING FACTOR and SPHERE commands should not be used in the same input stream; if they are then only the second will be honored.

4.8.2. cylinder log(semithickness)=9.12

The model will be spherical, but truncated so as to simulate a cylinder (See Ferland et al. 1982). Figure 3 gives an example of the assumed geometry.

The inner and outer radii of the cylinder are set by the RADIUS command described elsewhere in this section. This command sets the full height of the cylinder to twice the number entered on the command. The argument is the log of the semi-height in cm.

The effective volume element used to compute the emissivity is given by

$$dV = 4\pi r_o^2 \left(\frac{r}{r_o} \right) \left(\frac{\min\left(r, h_{cyl}\right)}{r_o} \right) f(r)\, dr \qquad (34)$$

where r_o is the inner radius, h_{cyl} is the cylinder half-height, and f (r) is the filling factor. The half-height h_{cyl} is stored as CYLIND, the sole element of the common block with the same name. The default value is $h_{cyl} = 10^{35}$ cm.

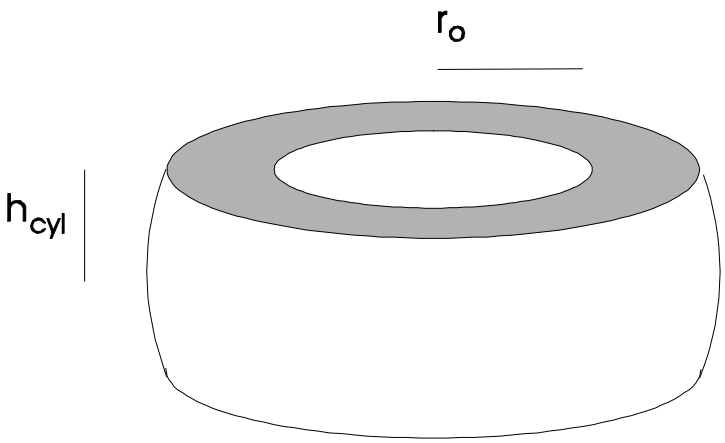


Figure 3 This figure shows the geometry assumed when the cylinder command is used. cylin

Changing the emissivity as described by equation 34 is the only effect of this command. It does not alter the radiative transfer methods, and is only formally correct when the gas is optically thin.

4.8.3. filling factor = 0.05 [index=-1]

The first number is the filling factor for a clumpy model. It can be either the filling factor itself (which is greater than zero and less than or equal to one) or the log of the filling factor (in which case it will be less than or equal to zero). The second number is optional, and is the index α for a power-law variation of the filling factor f(r), i.e.,

$$f(r) = f(r_o)\left(\frac{r}{r_o}\right)^{\alpha} \tag{35}$$

where $f(r_o)$ and r_o are the filling factor and inner radius of the cloud.

The filling factor is used in two ways. The first is to modify the volume emissivity of the cloud,

$$dI = 4\pi\, j\, f(r)\, dV \frac{\Omega}{4\pi} \tag{36}$$

where $\Omega/4\pi$ is the covering factor. The second is to modify the optical depth scale

$$d\tau = \alpha_{l,u}\left(n_l - n_u \frac{g_l}{g_u}\right) f(r)\, dr \tag{37}$$

(see Osterbrock and Flather 1959). Filling factors greater than unity are not allowed; CLOUDY will set a filling factor of unity if a value greater than one is entered.

4.8.4. radius log r(inner) [outer radius, thickness; parsec; linear]

The first number is the log of the inner radius. The second number sets a stopping radius and is optional. This can be either the log of the outer radius (if it is larger than the first number) or the log of the thickness of the cloud (if it is less than or equal to the first number).

The numbers are normally interpreted as the log of the radius in cm. If the optional keyword LINEAR appears on the line then the numbers are interpreted as the numbers themselves and not their log. The default units are centimeters, but the arguments will be interpreted as the log of the radii in parsecs if the keyword PARSECS appears anywhere on the line. Arguments will be interpreted as linear parsecs if both keywords appear. The following gives examples of its use.

```
radius 19.5      ; log of inner radius in cm
radius 19.5 18.5 ; as above, but a thickness of 3x10^18 cm
radius 19.5 20   ; inner radius as above, outer radius 10^20 cm
radius 100 linear; inner radius of 100 cm
radius 0 parsecs ; log of radius in parses, so inner rad 1 pc
radius 1 to 3 linear parsecs ; inner radius 1pc, outer 3pc
```

The default value for the outer radius is effectively infinite (actually 10^{30} cm). If the RADIUS command is not entered and the surface flux or ionizing radiation field is set in some unambiguous manner (for instance, with the ionization parameter or energy density temperature), then a radius of 10^{25} cm will be set by default. Under most circumstances this radius will result in an effectively plane parallel geometry.

4.8.5. sphere [expanding ; static; covering factor=.4]

CLOUDY normally assumes that the gas covering factor is small, as is the case in the BLR of AGNs. The SPHERE command should be included if the covering factor of the gas is large and the model spherical. This command tells CLOUDY to take into account ionization by the diffuse emission in the H and He Lyman continua and He Lyα lines produced in the far side of the nebula (i.e., from beyond the central object), and not to attenuate the ionizing continuum by pure scattering opacities, such as electron scattering, back scattering by grains, or Rayleigh scattering.

This option should be set when the geometry is spherical and gas nearly fully covers the continuum source. It should not be set when the covering factor is small, and emission from a cloud is unlikely to encounter another cloud. This latter case is the default. In the language of Van Blerkom and Hummer (1967), SPHERE causes CLOUDY to assume the symmetric case (their equation 2.14), rather than the default zero case (their equation 2.13) for diffuse continua. Here these are referred to as closed and open geometries, respectively.

Two optional keywords EXPANDING and STATIC determine how line transfer is handled. If EXPANDING (the default when SPHERE is entered) is set then CLOUDY assumes that line photons escaping from the illuminated face of the cloud do not interact with absorbing material on the other side. This is the case if the expansion velocity exceeds the Doppler-width by large amounts. If STATIC[9] is set then line photons do interact on both sides, so that the escape probability at the illuminated face of the cloud is small for optically thick lines. It is necessary to iterate at least one time when the STATIC option is used, since the total line optical depths are not known on the first iteration. The optical depths for all lines are determined self-consistently on second and further iterations. Lyα radiation pressure in the H^+ region will probably be significant if SPHERE STATIC is set.

The optional number on the line is the covering factor for the emission-line region. It is interpreted as the log of the covering factor if it is less than or equal to zero, and the covering factor itself if positive. The covering factor can also be set using the COVERING FACTOR command. The effects of the covering factor are described further on page 58. Both the COVERING FACTOR and SPHERE commands should not be used in the same input stream; if they are then only the last will be honored.

When a covering factor of unity is set the specific effects of SPHERE are; a) the total continuous optical depths are assumed to be twice the computed optical depths, and the initial optical depth is half the total, b) all diffuse reemission (bremsstrahlung, free-bound, etc.) is counted in the outward beam rather than only half, c) scattering opacities are not considered in the attenuation of the incident radiation field, d) when STATIC is set, the optical depth in Lyα in the inner direction is set to 10^5 on the first iteration; otherwise it is 10^{-20}, and e) include ionization by He I and He II lines from the other side of the nebula. At the end of the iteration, all inward optical depths are set to half of the total value computed from the previous iteration. The diffuse continua are transferred using methods described in later sections.

4.8.6. wind v=300 km/sec [mass=1.4]

The model will be a large velocity gradient (v~R Sobolev approximation) wind. The line widths and escape probabilities are modified in the appropriate manner, i.e., the effective optical depth is given by

$$\tau_{l,u}(R) = \alpha_{l,u} \min(r, \Delta r)\left(n_l - n_u \frac{g_l}{g_u} \right)\left(\frac{\nu_{th}}{\nu_{\exp}} \right) \qquad (38)$$

where v_{th} and v_{exp} are the thermal and expansion velocities respectively, and the radius used is the smaller of the depth or the radius (This is necessary to keep

[9]Sphere static did not work correctly in versions 74 and before.

the line optical depths from becoming exceedingly large when the radius is very large and the expansion velocity small.)

The first parameter on the command line is the expansion velocity v_o at the inner edge of the cloud. It must be greater than zero, and is entered in km/sec. The density at the illuminated face of the cloud is entered with the HDEN command, and the density is varied across the model to conserve mass flux (i.e., the product $\rho(r)r^2v(r)$ is kept constant). Because of this, a filling factor would not make physical sense and should not be used. The optional second parameter is the mass of the central star in solar units; its default value is one solar mass.

The equations of motion of the gas are solved. Acceleration due to the continuous opacity of the gas and deceleration due to the gravity of the central object, are included. The calculation will stop if the gas comes to rest, or if any of the other stopping criteria are met. Further details are presented in a section below. Really, something like 10^6 absorption lines are needed for a realistic calculation (see, for example, Abbott 1982).

4.9. Optical Depths and Radiative Transfer

In some classes of nebulae, such as H II regions and planetary nebulae, line transfer is relatively unimportant. In other objects, such as nova shells and the broad-line region of active nuclei, excited states of hydrogen have significant populations and subordinate lines become optically thick (see Ferland and Netzer 1979; Weisheit et al 1981; Kwan and Krolik 1981; Canfield and Puetter 1980). In other cases grains are present and all lines are destroyed by the background opacity. The present version of CLOUDY treats line radiative transfer in the escape probability formalism (Hummer 1968; Hummer and Kunasz 1980; Elitzur 1982; Netzer, Elitzur, and Ferland 1985). Further details are given in Part II.

CLOUDY is fairly fast, so there is no reason not to iterate at least one time when line transfer is important. The default is for a single pass through the cloud, and this is often adequate for low-density nebulae such as planetary nebulae or H II regions. A second iteration is usually enough to establish a fairly accurate line optical depth scale for most transitions, so that the proper escape probabilities can be computed, when line transfer is important. If Lyα or Hα optical depths change by more than ~20% on the last iteration then a warning that the model has not converged will be printed at the end of the last iteration.

Line radiation pressure cannot be computed accurately until the total line optical depths are known, so this quantity is meaningful only after at least one iteration. CLOUDY will stop if the radiation pressure exceeds half of the surface gas pressure in a constant pressure model, since such a geometry is unstable unless it is self-gravitating. On the initial iterations of a multi-iteration constant pressure model, the radiation pressure is constrained to never exceed half the gas pressure; this is to prevent the calculation from stopping when the optical depth scale is not yet well converged.

4.9.1. case b [tau ly alpha = 9;Hummer and Storey]

With no options, this command sets the inner optical depth for hydrogen and helium Lyα to 10^9, so that even a one-zone model will be close to case B. The optional number is $\log(\tau_{Ly\ \alpha})$, so it is possible to change this assumption. One-sided escape probabilities are used in this case, so the total escape probability is simply that for the inward direction. The CASEB command also suppresses optical depths in excited states, in keeping with the case B approximation. This is useful for checking the behavior of the hydrogen and helium atoms in the low density limit.

Normally, the treatment of the hydrogen and helium atoms includes all collisions between the ten levels considered for each atom/ion. Case B does not define the population of the ground or first excited state, so a true comparison with case B results should have collisions from these levels turned off. This is

done with the Hummer and Storey option, to allow comparison with their 1987 paper. Collisions from the ground and first excited states *are* included if this second option is not specified. Collisions between $n \geq 3$ levels *are* always included unless the HYDROGEN COLLISIONS OFF command is given. Collisions between the 2s and 2p states are always included unless the NO 2S2P command is given.

4.9.2. double optical depths

This command simulates a geometry in which ionizing radiation strikes the plane parallel cloud from both sides, such as a Lyα forest cloud. At the end of the iteration, the total line and continuum optical depths are set to twice the computed optical depth. The computed model is then one half of the cloud, and the other half of the cloud is assumed to be a mirror image of the first half. Doubling the total line and continuum optical depths at the end of the iteration is the *only* effect of this command. Physical quantities such as the dimension, column densities, or line emission *are not* affected.

These approximations only make sense if the cloud is optically thick in lines, but optically thin (or nearly so) in the continua. Lines such as the Lyα transitions of He I and He II can be important sources of ionizing radiation; their transport will be handled correctly in this limit when this command is used. Continuum transport out of the cloud will also be treated correctly, but attenuation of the incident continuum will *not* be if the cloud is optically thick in the continuum.

4.9.3. escape __K2; incomplete; [emit; destroy]

This command specifies how line escape probabilities are to be handled. One of the keywords __K2 or INCOmplete must appear. If no other keywords appear then both the emission and destruction probabilities are set to either of the specified cases. If either keyword EMIT or DESTroy appear, then only the emission or destruction probability is changed.

4.9.4. grains [-2; planetary; orion; no heating; type...]

The effects of grains can be included, either with this command, or by using an abundance mixture which includes grains by default. The GRAINS command takes precedence over the default grains set with the ABUNDANCES command.

The treatment of grains was developed in close collaboration with P.G. Martin. Details are provided in a section below, and in Baldwin et al. (1991). Seven populations of grains, summarized in Table 14, are presently incorporated in the code.

Table 14 Grain Populations

Index	Type	Property
1	graphite	ISM
2	silicate	ISM
3	graphite	Orion
4	silicate	Orion
5	silicate	0.01 micron
6	silicate	0.1 micron
7	silicate	Volk AGB
8	gray	Volk gray

The temperature, potential, and drift velocity of the grains are determined using standard assumptions, as described, for instance, by Martin (1979) or Spitzer (1948; 1978), and in a section of Part II of HAZY. Heating by direct absorption of the continuum, Lyα, and all other lines and continua included in the OTS fields, and gas collisions, are included as heating mechanisms in the calculation of the grain temperature. The balance between this heating process and cooling by collisions with the gas and by radiative cooling is used to establish the grain temperature. Gas heating by grain photoionization, and cooling by free particle capture onto the grain surface, are also included. The grain potential is determined by solving the photoionization-recombination balance equation, and heating/cooling of the gas by grain photoionization-recombination is determined self-consistently.

The default condition for the code is to not include grains, and when grains are enabled the default grain mixture has ISM properties. The optional keyword ORION makes the grains more similar to the large-R grains in the Orion Nebula, which have a fairly gray ultraviolet extinction. The two grain populations marked Orion in Table 14 are used in this case.

The keyword _AGB makes the grains more similar to those observed in post AGB stars or proto planetary nebulae. These grain opacities for the silicate population are taken from unpublished work by Kevin Volk. This population is referred to as AGB in the printout. ISM graphite grains are also used. The mass in grains is a bit less than the ISM case, but may be an overestimate for classical planetary nebulae if grains are destroyed as the nebula ages. The AGB grains are also turned on with the "ABUNDANCES PLANETARY NEBULA" command. To be compatible with this abundances command, the program will also accept the command "GRAINS PLANETARY NEBULA" to turn on the post-AGB star grains.

The abundances of the grain populations can be changed with the optional number on the command line. This is a scale factor used to multiply the stored grain opacities. The scale factor is the log of the opacity relative to the standard value if less than or equal to zero, and the scale factor itself if positive (i.e., both GRAINS -2 and GRAINS .01 would use ISM grains with each of the two constituents having only 1 percent of the standard abundance).

It is also possible to turn on each species independently. If two numbers occur on the line *and* the grain type is not specified with a keyword, then the first is interpreted as the abundance, and the second is a pointer to the grain type.

The other grain types are not turned off by this option, so it is possible to turn on several grain types with successive GRAINS commands.

The optional keyword NO HEATING turns off photoelectric heating of the gas by grain photoionization. The optional keyword NO COOLING turns off free particle recombination cooling of the gas by grain collisions.

The following are some examples;

```
*ism grains with ism abundance
grains

*orion grains with half their standard abundance
grains orion .5

*turn on ism graphite and orion silicate
grains abundance=1, type=1
grains abundance=1, type=4

*only include opacity effects of ism grains
grains no heating, no cooling
```

Line Intensities with Grains. For a closed geometry, in which the SPHERE option is set, the predicted emission-line spectrum will be the *intrinsic* spectrum of the nebula. Photon destruction by all background opacity sources (including grains) is fully treated using escape probabilities (i.e., Hummer 1968), and the predicted intrinsic intensities include this physics. The intensities *do not* include the reddening effects of any external grains which lie outside the line-forming region, however. For an open geometry, the full intrinsic emission-line spectrum is again printed, following the predicted emergent line intensities. In this case the first set of lines is the observed spectrum, including absorption and scattering by grains, as observed from the illuminated face of the cloud.

In general the effects of grains external to the emission-line region are very difficult to model, since they are very geometry dependent. The best approach is to de-redden the observed spectrum, to obtain an intrinsic spectrum, and to then compare this intrinsic spectrum with that computed by the code. In no case is the possible presence of large amounts of grains within cold neutral regions outside the computed structure taken into account.

4.9.5. helium collisions; radiation...

helium collisions off This turns off collisions within the helium singlets and helium ion.

helium radiation pressure on This turns on radiation pressure due to trapped He II Lyα. This line undergoes Bowen fluorescence and strong destruction by the background continuum, and as a result its line radiation pressure is very difficult to compute. Normally it is neglected. The

approximations used when the option is turned on are correct when the gas is highly ionized and oxygen is depleted (as in a Lyα forest cloud).

4.9.6. hydrogen; redistribution; data . .

This allows some details of the treatment of the hydrogen atom to be changed. Unlike the vast majority of the commands, the entire keyword HYDROGEN must match for this command to be recognized.

hydrogen redistribution.. Lyα transfer can be treated with either complete or incomplete redistribution (see, for example, Hummer 1962); the default is incomplete redistribution, and can be changed by entering

```
hydrogen redistribution complete
hydrogen redistribution incomplete  .
```

There is at present a fundamental uncertainty in the computation of the line radiation pressure for transitions such as Lyα. For a simple two-level atom with incomplete redistribution, it has long been known that the line-width is proportional to $(a\tau)^{1/3}$ (Adams 1972, Harrington 1973; a is the damping constant). It is also easily shown that for complete redistribution and a frequency independent source function that the line width would be determined by inverting the Voigt function, and hence proportional to $(a\ \tau)^{1/2}$. Line interlocking, whereby scattered Balmer line radiation broadens the upper level of Lyα (Hubbard and Puetter 1985), can alter the line width, as can collisional effects when the density is high enough for distant collisions to broaden the line. The difference in radiation pressure and emergent flux is major (factors of several) for Lyα, which can easily have an optical depth of 10^7 - 10^9, when Balmer lines are also optically thick. This command determines which approximation is used. The default condition is incomplete redistribution, which minimizes the line width and radiation pressure. This issue is discussed further in Elitzur and Ferland (1986).

hydrogen lowest temp 200 Normally the level populations are determined by solving the equations of statistical equilibrium using departure coefficients. These diverge at low temperatures when hydrogen is ionized, in which case fits to Martin's (1988) results are used. The lowest temperature considered by the 10 level hydrogen atom is machine dependent, and can be altered with this command. The default value of the lowest temperature is 1000 °K. There is a single argument, and the number is interpreted as the log of the temperature if it is less than or equal to 10. Tests show that numerical instabilities in the matrix inversion routine limit the lowest temperature to only slightly below the default value, even with 64 bit words. There is no lower limit to the temperature on a CRAY Y-MP when double precision is enabled on the compile step, so the lowest temperature can be made arbitrarily low.

hydrogen data ... The collision data set can be changed from the default, which uses quantal calculations where possible, supplemented by data from Vriens and Smeets (1980). The commands

```
hydrogen data Vriens and Smeets
hydrogen data Johnson
```

will change between the Vriems and Smeets values and those of Johnson (1972). These collision cross sections differ by factors ~2 to 3 for *high-n* states; this is also, at present, a fundamental uncertainly, although the Vriems and Smeets data are based on more recent experimental results.

hydrogen collisions off Collisions within the hydrogen atom can be turned off with this command. All collisions *except* 2s-2p are turned off by this command. (These are turned off for H and He with the NO 2S2P command.)

hydrogen damping off Continuum scattering due to the extreme damping wings of Lyman lines (i.e., Rayleigh scattering) can be turned off with the DAMPING OFF option. Rayleigh scattering is a significant opacity source in clouds which have large column densities of neutral material ($N > 10^{23}$ cm^{-2}).

4.9.7. iterate [2 times]

This command specifies the number of iterations to be performed. The default is a single pass through the model. A second iteration should be performed in order to establish the correct optical depth scale when line transfer or radiation pressure is important. Two iterations are often sufficient, and will be done if no numbers are entered on the command line. No more than 10 iterations can be performed because of the present limits to the sizes of several vectors used to store information. A comment will be printed after the last iteration if the total optical depth scale has not converged and another iteration is needed.

iterate to convergence [max=7, error=.05] This is a special form of the ITERATE command, in which the code will continue to iterate until the line optical depth scale has converged, or ten iterations have been computed. The optional first number on the line is the maximum number of iterations to perform, and the default is 10. It is not possible to specify more than ten iterations. The second optional number is the convergence criterion. Normally, it is that the Hα optical depth has not changed by more than 10 percent on the next-to-last iteration. The optional numbers may be omitted from right to left. The iterations will stop when the changes in the Hα optical depth are less than the second number, unless Hα is optically thin, in which case only a second iteration is performed.

4.9.8. no scattering opacity

This command turns off several pure scattering opacities. These include scattering by grains, electron scattering, and the extreme damping wings of Lyman lines (Rayleigh scattering). When scattering opacity is included and an open geometry is to be computed, the scattering opacity is assumed to attenuate the incident radiation field as $(1+0.5\tau_{scat})^{-1}$ rather than $\exp(-\tau)$ (Schuster 1905).

Scattering should be neglected in a spherical geometry with gas fully covering the source of ionizing radiation, since photons absorbed by a pure scattering process are not really lost, but continue to diffuse out with (perhaps) a slight shift in energy. Electron scattering is generally the most important scattering opacity in a grain-free mixture. If $\tau_{scat} \leq 1$ then it is reasonable to consider electron scattering as a heating and cooling process, but not as an absorption mechanism, if the energy shifts are not large (i.e., $h\nu << mc^2$) and the geometry spherical (this is not correct for γ-ray energies, of course). CLOUDY is not now designed to work in environments which are quite Compton thick, but the approximation of neglecting electron scattering opacity for spherical geometries should work well for nebulae where the electron scattering optical depths are less than or of order unity. If this command is given then Compton energy exchange and recoil ionization are still included as heating, cooling, and ionization processes, but not as opacity sources. (Thermal and ionization effects of Compton scattering are turned off with the NO COMPTON command.) The NO SCATTERING OPACITY command is automatically generated when SPHERE is specified.

4.9.9. turbulence = 100 km/sec [_log]

The input number is the turbulent velocity (assumed to be microturbulence) expressed in kilometers per second. This velocity field affects the line width and optical depth scale through the Doppler width $v = \sqrt{v_{th}^2 + v_{turb}^2}$, where $v_{th} = \sqrt{2kT/m}$ is the projected line width due to thermal motions of particles of mass m, and the turbulent line width v_{turb} is normally zero. If the optional keyword "_LOG" appears then the number is interpreted as the log of the turbulence.

In general line pumping by the continuum will be increasingly important for larger turbulent line widths. Continuum fluorescence is included as a general excitation mechanism for all hydrogen and helium lines, using the formalism outlined by Ferland (1992). It is *not* included for the majority of the metal lines. Those for which it is included can be identified by the existence of a line contribution with the "pump" label.

4.10. Thermal Solutions

This section describes options which affect the thermal solution. These deal with the accuracy of the solution (changes in the tolerance, or permitting more or fewer temperature failures), or with additional sources of heat, such as cosmic rays or turbulence.

4.10.1. cextra -14.231 [temp to the 1.5 power]

It is possible to add an extra source of cooling (due to some unspecified physical process) with this command. The first number is the log of the cooling rate in erg cm^{-3} s^{-1}. The second number is an optional exponent to specify a temperature dependence. The cooling will be given by

$$\Lambda = 10^{c_1} \times \left(\frac{T_e}{10^4 \ ^\circ\mathrm{K}} \right)^{c_2} \quad \mathrm{erg\ cm^{-3}\ s^{-1}} \tag{39}$$

where c_1 and c_2 are the two numbers entered with this command. If the second optional argument c_2 is not specified then zero (i.e., constant cooling) is assumed.

4.10.2. constant temperature, t=10,000K [linear]

A constant temperature calculation will be performed. The number can be either the electron temperature itself, or the log of the temperature (the latter is assumed if the argument is less than or equal to 10). If the optional keyword LINEAR appears on the line then the number is always interpreted as the temperature itself, and not its log.

Collisional ionization of all atoms and ions is included, so this option can produce clouds in coronal or collisional equilibrium. For technical reasons, the photon array must be defined for all energies which contribute to photoionization of all stages of ionization with significant abundances. For instance, to do models of the solar corona it is necessary to include both the cool blackbody from the solar photosphere (important for excited state induced recombination, photoionization, and Compton cooling) as well as a weak ~10^8 °K bremsstrahlung continuum to define the photon array at all possible coronal energies (see the CORONAL EQUILIBRIUM command, described below).

If this command is used, then it is usually necessary to specify other stopping criteria. Many calculations stop when the electron temperature falls below some lowest value, set with the STOP TEMPERATURE command and with the default value 4000 °K. This cannot happen with a constant temperature model. For instance, a constant temperature model of a planetary nebula will continue until the limit to the number of zones (now 400) is reached. The *vast* majority of the model will consist of predominantly neutral gas well outside the Strömgren sphere, and this gas will have an small ambient level of ionization and emission

due to collisional ionization. The resulting emission-line spectrum would be surprising since the neutral gas contributes significant emission. A solution would be to use the STOP EDEN or STOP EFRAC commands to stop the calculation when the hydrogen ionization front is reached, or STOP ZONE to stop the calculation at a particular zone number.

4.10.3. coronal equilibrium, T=10,000,000K [linear]

A model in coronal equilibrium, in which the gas is mainly collisionally ionized, will be computed. The number is either the temperature or the log of the temperature (the argument is interpreted as a log if it is less than or equal to 10). If the optional keyword LINEAR is specified then the number is always interpreted as the linear temperature.

This calculation is very similar to those presented by, for instance, Raymond, Cox, and Smith (1976) or Gaetz and Salpeter (1983).

The command in the example above actually issues the following commands;

```
constant temperature t=10,000,000K
stop zone 1
drmax = 0
drmin = 0
stop Lyman continuum optical depth = -6
brems, t=8
ionization parameter -15
```

4.10.4. cosmic rays, background, density=1.2 [index, etc]

This command turns on energy deposition and ionization due to relativistic particles, as described by Ferland and Mushotzky (1984) and Part II. The first number is the log of the cosmic ray density (n(cr), cm^{-3}). The second optional number is a power-law index α, describing the variation of the cosmic ray density with radius, i.e.,

$$n(cr, r) = n(cr, r_o)\left(\frac{r}{r_o}\right)^{\alpha} \quad \mathrm{cm}^{-3} \quad . \tag{40}$$

The default value of the index is α =0, or constant density. The third optional number is the log of the temperature of the fast electrons, if they are not relativistic. If this third number is specified then expressions from Balbus and McKee (1982) will be used to evaluate the electron heating rates. The options can be omitted from right to left.

Collective effects are not included in the heating and ionization rates, but they may not be important either (Rephaeli 1987).

If no numbers appear on the line, but the keyword BACKGROUND does, then a constant cosmic ray density of n(cr) = 2×10^{-9} cm^{-3} will be used. This

density will produce a neutral hydrogen ionization rate of ~2×10^{-17} s^{-1}, the value quoted by Tielens and Hollenbach (1985a) for the galactic cosmic ray ionization rate. *This value is quite uncertain*. If cosmic rays are not included in the calculation, but the neutral hydrogen ionization rate falls below 10^{-17} s^{-1}, the code will print a comment stating that the ionization rate fell below the galactic background rate.

4.10.5. failures 100 times

A temperature failure occurs when the heating-cooling balance is not within a certain tolerance, set by the TOLERANCE command, after 20 tries. Normally CLOUDY will punt after an excessive number of temperature failures (presently 20) occur. This command increases the number of allowed failures to the value entered as a parameter.

When CLOUDY stops because of excessive failures it first produces a map of heating-cooling space to give an indication of where the equilibrium temperature should have been. A section in Part III describes thermal failures in more detail, and describes the output produced before the program stops.

Failures occur most often when the code needs to jump over the peaks in the cooling function which occur near 2000 °K and 10^5 °K, or if it trips over an ionization front because the zones are too large. Increasing the number of allowed failures in these circumstances, by using this command, is permissible as long as the global energy balance is preserved. A warning will be issued at the end of the calculation if there is a discrepancy in the global heating balance.

The default limit to the number of failures is 20, which is stored as the variable LIMFAL.

4.10.6. force temperature to 3400K

This command forces the initial estimate of the temperature of the first zone to the value entered. The temperature is interpreted as a log if it is less than or equal to 10 and the linear temperature if greater than 10. This command is useful if more than one temperature solution is possible. It forces the first guess of the temperature to the specified value, but *does not* hold the temperature constant; the temperature is determined by energy balance thereafter. (Constant temperature is set with the CONSTANT TEMPERATURE command.)

4.10.7. hextra -14 [scale r=18]

This command turns on extra heating due to some unspecified energy source, such as dissipation of turbulence. The first number is the log of the volume heating rate (erg cm^{-3} s^{-1}). The second number is the log of the scale radius r_{scale},

such that the extra heating rate varies as $\exp\left(-r_{scale}/\left(r-r_o\right)\right)$, where r_o is the inner radius. The default, when r_{scale} is not specified, is constant extra heating.

4.10.8. high temperature approach

This command tells the code to search for the first temperature by approaching the thermal solution from the high temperature extreme of 10^6 °K. Normally the approach is from low temperatures. This can be useful when more than one thermal solution is possible.

4.10.9. lowest temperature = 300K [linear]

The search for the temperature of the first zone can find temperatures as low as TELOW, which has a default value of 10 °K. This command can be used to change the value of TELOW. CLOUDY will not allow initial temperatures below the value of TELOW. The argument is interpreted as a log if it is less than or equal to 10, otherwise as the temperature itself. There is an optional LINEAR keyword to force all values to be linear, rather than logs. The number is the sole element of common block TELOW.

After the first zone the temperature can fall to values as low as TEND, which has a default value of 4000 °K. TEND is changed with the STOP TEMPERATURE command.

4.10.10. magnetic field, log(B) = 5

The argument is the log of the magnetic field strength in Gauss. Magnetic effects are not normally included; when this is specified, cooling due to cyclotron emission, using equations from Fabian, Pringle, and Rees (1976; these assume optically thin emission) are included. The volume cooling rate is given by

$$\Lambda_{cyclotron} = n_e \frac{B^2}{8\pi}\frac{4}{3}\sigma_{\rm Thom} c\left(\frac{v_e}{c}\right)^2 = 4.5433\times10^{-25} B^2 T_e \quad \text{erg cm}^{-3}\ \text{s}^{-1} \tag{41}$$

where σ_T is the Thomson cross-section and

$$v_e = \left(\frac{8kT_e}{\pi m_e}\right)^{1/2} = 6.2124\times10^5\, T_e^{1/2}\ \text{cm s}^{-1} \tag{42}$$

is the mean electron speed. See, however, Masters, Pringle, Fabian, and Rees (1977). They show that this emission process is likely to be optically thick under some circumstances. Cyclotron optical depth effects are not now included.

Cosmic rays should not be included when a magnetic field is specified, since the effects of a field on cosmic ray transport are not now included. A warning will be printed if both are included.

4.10.11. map 4 [range 2000, 5000]

This command tells the code to compute a heating-cooling map of the specified zone. This is a useful way to check for the existence of more than one thermal solution. If no zone is specified, or if the zone is less than or equal to 0, then only a thermal map is produced for the illuminated face of the cloud, and no zone calculations are performed. The calculation of the heating and cooling is self-consistent, except that no attempt is made to converge the electron density.

The optional keyword RANGE specifies the temperature range of the map. If this option is specified then the first number on the line must be the zone for the map, zero if only a map of the first zone, and the next two numbers must be the lower and upper limits to the map. These temperatures will be interpreted as logs if the first number is less than or equal to 10. Normally about 20 steps occur between the lowest and highest temperature in the map. This is controlled by the variable NMAPS, and can be reset with the SET NMAPS command.

The thermal map can be punched with the PUNCH MAP command. This will produce a form of the output which is suitable for later processing by other software.

The code is left in a disturbed state after a map is computed. It is best to begin a calculation over again after a map is computed, rather than try to continue with the current model. This can be done with the STOP ZONE command.

4.10.12. neutrons -2 [efficiency=-2]

This command adds energy deposition and ionization by secondaries, due to the fast neutrons proposed by Sikora, Begelman, and Rudak (1989). The argument is the luminosity in fast neutrons, expressed as a fraction of the *total* photon luminosity of the incident continuum. It is interpreted as a log if less than or equal to zero, and a linear scale factor if positive.

The second argument is optional, and is the heating – ionization efficiency of the neutrons. Its default is unity. Both quantities are interpreted as logs if less than or equal to zero, and linear if greater than zero.

4.10.13. print coolants, zone 135

See page 84.

4.10.14. print heating

See page 85.

4.10.15. time dependent model of zone 3

A time-dependent model of the specified zone is performed, as discussed by Ferland and Truran (1981). The model follows the recombination and cooling after the ionizing radiation is instantaneously cut off. The initial conditions are those appropriate for the zone specified as the argument. Collisional ionization is included, so this calculation is somewhat like a shock.

This command does not now work, and will not function again until development work on helium is complete.

4.10.16. tolerance 0.001

The equilibrium temperature is set by balancing the heating and cooling rates. This command is used to change the error tolerance in the heating-cooling match. The default tolerance (the fractional error) is 0.02. This will be the error in the heating-cooling balance allowed in each zone; the total error or energy conservation mismatch over a model will be much smaller, usually of order ten times smaller than the tolerance specified.

The tolerance is given by the variable TOLER, which is the sole variable in the common block TOLER.

4.11. Stopping Criteria

In some nebulae ionized by starlight, such as certain planetary nebulae or H II regions, the outer limit of the cloud is well-defined by a hydrogen ionization front (the nebula is said to be radiation-bounded), and setting an outer limit is not necessary. In these cases the model stops because nearly all ionizing radiation has been attenuated, and the temperature falls below 4000 °K, the default lowest allowed electron temperature. This choice of lowest temperature was made with optical emission lines in mind; if lines with very low ionization and excitation potentials (i.e., the [C II] or [O I] far infrared lines) are of interest, then it is probably necessary to lower this ending temperature with the STOP TEMPERATURE command.

In other circumstances, particularly X-ray ionized nebulae, the gas is optically thin to hard radiation and an outer limit must be specified. In other situations, optically thin models, or ones in which only part of the hydrogen Strömgren sphere is present, must be computed (in this case the nebula is said to be matter-bounded). In these cases stopping criteria must be specified. More than one stopping criteria can be specified, and the calculation will stop as soon as the first one is met. CLOUDY will say why it stopped after the last zone calculation is printed.

If no stopping criteria are set, then the calculation will usually stop because the default lowest temperature (4000 °K) or the default greatest number of zones (400) was reached.

4.11.1. Danger! Understand why the calculation stopped!

There are circumstances in which the predicted emission-line spectrum will depends strongly on the stopping criteria. This occurs when the calculation ends within a line's creation zone. This is nearly always the case for some lines in an X-ray irradiated gas, and for any radiation field and low-ionization infrared lines.

There are several checks that should be made, to make sure that the spectrum is the one expected, and not an artifact of the stopping criteria. The first and most important is to understand *why* the calculation stopped. This is explained in the first comment after the last zone is printed. In its default state the code will probably stop because the temperature fell below the default lowest temperature of 4000 °K. This was chosen with optical and ultraviolet lines in mind, but infrared lines continue to form at far lower temperatures. It is also possible that the calculation will stop because of an internal error, in which case the results are suspect.

It is a good idea to check whether, if the model were made thicker, the lines would increase in strength. It is safe to assume that a line no longer depends on the thickness of the cloud if either a) the final temperature is well below the

excitation potential of the line, or b) that ionization of the gas has fallen below that of the species of interest.

4.11.2. radius inner=18 [thickness=16; parsecs; linear]

The RADIUS command is discussed above. The optional second number is the log of the thickness of the cloud (if the second number is less than the first) or the log of the outer radius (if the second number is greater than the first). The default outer radius is 10^{30} cm. The default units are centimeters, but the arguments will be interpreted as the log of the radius and thickness in parsecs if the keyword PARSECS appears anywhere on the line. The numbers are interpreted as logs unless the optional keyword LINEAR appears. If both keys appear then linear parsecs result.

4.11.3. stop column density=23 [neutral; ionized; total; ...]

This command causes the calculation to stop when the specified hydrogen column density (N(H), cm^{-2}) is reached. There are several optional keywords, which determine whether the column density is the total (the default), the ionized hydrogen column density, the neutral hydrogen column density, or the effective column density (defined in this subsection). For all cases the default stopping column density is 10^{30} cm^{-2}.

stop column density=23 The number is the log of the total hydrogen column density (atomic, ionic, and molecular hydrogen), defined as the integral

$$N(H) = \int \left\{ n\left(H^o\right) + n\left(H^+\right) + n\left(H^-\right) + 2n\left(H_2\right) + 2n\left(H_2^+\right) + 3n\left(H_3^+\right) \right\} f(r)\, dr \qquad (43)$$

where f(r) is the filling factor.

stop neutral column density=23 The number is the log of the neutral (atomic) hydrogen column density, i.e.,

$$N\left(H^o\right) = \int n\left(H^o\right) f(r)\, dr \ . \qquad (44)$$

stop ionized column density=23 The number is the log of the ionized hydrogen (H^+) column density, i.e.,

$$N\left(H^+\right) = \int n\left(H^+\right) f(r)\, dr \ . \qquad (45)$$

stop effective column density=23 This command is actually a form of the STOP OPTICAL DEPTH command. Usually, low energy cutoffs in X-ray spectra are parameterized by the equivalent column density of a cold neutral absorber with cosmic abundances. Actually, what is measured is an optical depth at some energy, generally around 1.0 keV. If the gas is ionized then a much larger column density will be needed to produce the observed absorption, and the difference is often more than an order of magnitude. Using this command, it is possible to stop the calculation when the incident continuum has been attenuated by the appropriate absorption at 1.0 keV. The calculation will stop

when the absorption optical depth at 1.0 keV (neglecting all scattering) reaches a value of

$$\tau_{abs}(1.0\ \text{keV}) = N_{effec}\, 2.14 \times 10^{-22} \quad (46)$$

at 73.5 Ryd. N_{effec} is the effective column density. The absorption cross section per proton for cold neutral gas is taken from Morrison and McCammon (1983). Scattering opacities *are not* included in this optical depth. If the gas is highly ionized than the actual column density will be greater than the effective column density. If the abundances of the heavy elements are greatly enhanced, then it will be less.

4.11.4. stop eden 3 [linear]

The model will stop if the electron density falls below the indicated value. The number is entered as a log; in this case the model will stop if $n_e < 10^3$ cm^{-3}. There is an optional keyword LINEAR which will force the argument to be interpreted as the quantity itself, not its log. This command is a useful way to stop constant temperature models. For instance the calculation can be forced to stop at the H^+-H^o ionization front by setting the stopping electron density to approximately half of the hydrogen density.

The following examples show a case which will stop near the He^{2+}-He^+ ionization front (for solar abundances) and a case which will stop hear the H^+-H^o ionization front.

```
*
* stop at the He++ - He+ ionization front
hden 9
stop eden 9.06 ;stop when helium (10% by number) is He+
*
* stop at H+ - Ho ionization front
hden 5
stop eden 4.5 ;stop when elec dens falls below H density
```

The default is an electron density of -10^{30} cm^{-3}. (The negative sign is not a typo.) It is stored as the variable ENDEDN, the sole variable in common block ENDEDN.

4.11.5. stop efrac=1.05

The model will stop when the electron fraction, defined as the ratio of electron to total hydrogen densities, falls below the indicated value. This is another way to stop calculations at ionization fronts, and is useful if the hydrogen density there is not known (this occurs in constant pressure calculations, for instance). The argument is interpreted as the fraction itself if it is greater than zero, and the log of the fraction if less than or equal to zero.

The default is an electron fraction of -10^{37} cm^{-3}. (The negative sign is not a typo.) It is stored as the variable EFREND, the sole variable in common block EFREND.

4.11.6. stop line 6300 reaches 0.1 relative to 5007

The model will stop when the emission line with the wavelength given by the first number exceeds an intensity given by the second number, relative to a second emission line with wavelength given by the third number, in this example [O III] λ5007. If a third number is not entered, this second emission line will be Hβ (not the normalization line). This command is useful for stopping matter-bounded models. This results of this command are not exact; the final intensity ratio will be slightly larger than the ratio specified.

Up to 10 different stop line commands may be entered. This limit is controlled by the variable MXSTPL which appears in parameter statements throughout the code. If more than one stop line command is entered then the code will stop as soon as one of the limits is reached.

4.11.7. stop optical depth -1 at 2.3 Ryd

This command stops the calculation at an arbitrary *absorption* optical depth. The first number is the log of the optical depth, and the second number is the energy in Rydbergs. The optical depth is always a log, and the optical depth does not include scattering opacities. The second number is interpreted as a log if it is negative, as linear Rydbergs if positive, and must be within the energy bounds considered by the code (presently 1.001×10^{-5} Ryd to 7.354×10^{6} Ryd). At present, only one stopping optical depth can be specified; if more than one is entered then only the last is honored.

It is traditional in X-ray astronomy to characterize low-energy cut-offs as the equivalent *completely neutral* column density for *solar* abundances. This is not correct when the gas is ionized (since the high energy absorption opacity is diminished) or when the abundances of the heavy elements are enhanced (the high energy opacity is increased). For extreme cases these effects can be more than an order of magnitude. The deduced column density is underestimated by the same amount. It is better to convert the deduced column density back into an optical depth at 0.5 or 1 keV (this is actually the observed quantity), and use this optical depth and energy as the stopping criteria, than to use the deduced column density as a stopping criteria. Either this command, or the STOP EFFECTIVE COLUMN DENSITY command (which is actually a form of the STOP OPTICAL DEPTH command) can be used to stop the calculation at an X-ray optical depth corresponding to a certain low-energy absorption.

The optical depth used in this command is the absorption optical depth τ_{abs}, and does not include scattering opacities. The most important scattering opacity

in grain-free environments is usually electron scattering, which is gray when $h\nu \ll mc^2$. As a result this scattering opacity does not affect the usual X-ray analysis. In general, the effects of scattering opacities are much more geometry dependent than absorption opacities.

stop Balmer optical depth = -.3 This command is a special case of the STOP OPTICAL DEPTH command, in which the energy does not need to be specified, but the keyword BALMER is given. It will cause CLOUDY to stop when the log of the absorption optical depth at the Balmer edge (ν = 0.250 Ryd) reaches the specified value. The default is $\tau_{Bac} = 10^{20}$, and the optical depth is always interpreted as a log. This is the *total absorption* optical depth at the Balmer edge, and includes all computed opacity sources such as grains or free-free absorption.

stop Lyman optical depth = 5 This is a special case of the STOP OPTICAL DEPTH command, in which the energy does not need to be specified, but the keyword LYMAN is given. In this case the model will stop at an absorption optical depth of 10^5 in the Lyman continuum. The number entered is the log of the Lyman limit optical depth, τ_{912}. The default value is $\tau_{912} = 10^{20}$. The stopping criterion is *really* the total 912Å absorption optical depth, and *not* the hydrogen Lyman limit optical depth at 912Å. These are not exactly the same, especially when grains are present or the abundances of the heavy elements are enhanced.

4.11.8. stop temperature=1,000K [linear, exceeds]

The model will stop if the electron temperature drops below T_{low}, the argument of this command. The temperature is interpreted as a log if the argument is less than or equal to 10, and as the linear temperature if greater than 10, or if the LINEAR keyword appears. The default value is T_{low} = 4000 °K. Gas cooler than this produces little optical emission, but may be a strong emitter of infrared lines such as the [C II] 158 μm or the [O I] ^{3}P lines. The lowest temperature allowed, T_{low}, should be adjusted so that $h\nu \gg kT_{low}$ for the lowest excitation potential ($h\nu$) transition to be considered. Note that more than one temperature is sometimes possible when T~10^3 °K, so thermal stability problems may develop if T_{low} is lowered below a few thousand degrees Kelvin. If stability problems occur then it may be necessary to increase the number of thermal failures allowed, with the FAILURES command. This issue is discussed further in a section in Part III. The lowest temperature allowed is stored as the variable TELOW, the sole variable in common block TELOW.

It is possible to use a form of this command to stop a calculation if the temperature *exceeds* the input value. This might be necessary if an entire grid of models is to be computed by calling the code as a subroutine, but those in the coronal phase (i.e., $T_e > 10^5$ °K) are not of interest. If the keyword EXCEEDS appears then the temperature specified by the command will be the highest allowed temperature. The other rules for the command are unchanged.

4.11.9. stop thickness 9.3 [parsecs; linear]

This command sets an upper limit to the thickness of the model. The argument is interpreted as the log of the thickness unless the keyword LINEAR appears. The default units are centimeters, but it will be interpreted as the log of the thickness in parsecs if the keyword PARSECS appears on the line. The STOP THICKNESS command has the same effect as the optional second number on the RADIUS command. This command makes it possible to set a thickness when the inner radius is not specified, such as when the ionization parameter is given.

4.11.10. stop zone 123 [21 on sec iteration, ...]

In this example the calculation will stop after computing 123 zones. The default value is 400. Up to ten numbers may be entered, each being the ending zone for consecutive iterations. If fewer numbers are entered than iterations performed, then the last number will be used for all further iterations.

4.12. Controlling Output

CLOUDY is capable of keeping a printer going for hours. Several commands vary the printer's mass-loss rate, and are described here. A description of the meaning of the output follows in section 3.

4.12.1. normalize to 1216 [scale factor = 100]

Emission-line intensities are usually listed relative to the intensity of Hβ. This command changes the reference line to any of the other predicted lines. The entire emission-line spectrum will have its relative intensity normalized to the intensity of the line whose wavelength is given by the argument.

The optional second number is a scale factor for the relative intensity array. If it is equal to 100, as in this example, then all intensities will be relative to a reference line intensity of 100. The default value is 1. The example given above will cause the intensities to be expressed relative to a Lyα intensity of 100.

4.12.2. plot [type, range]

A plot of any of several properties of the calculation can be made. One of the keywords described below (continuum, map, or opacity) must appear on the command line. Up to ten plots can be generated; this limit is set by the variable NDPLOT which appears in several parameter statements throughout the code. The keyword TRACE will turn on a great deal of information concerning the mechanics of generating the plot.

Publication-quality plots can be produced using the PUNCH commands (described below) to produce a file which can then be post-processed using plotting software.

4.12.3. plot continuum [_raw, trace, range]

If CONTINUUM is entered then the continuum (usually 1.001×10^{-5} Ryd$\leq h\nu\leq$ 7.354×10^{6} Ryd) is plotted, unless the range is altered by entering the two optional numbers. The default is for both the incident continuum (in units of νf_ν) entering the cloud (plotted as .'s) and that transmitted through the cloud (the o's) to be plotted.

Plot continuum keywords It is possible to plot specific components of the continuum with the following series of keywords.

Plot diffuse continuum If the keyword DIFFUSE appears then the diffuse emission per unit volume, for the last computed zone, will be plotted. This continuum is only that emitted by the gas and grains in the optically thin limit and unity filling factor.

Plot emitted continuum If the keyword EMITTED appears, then the net integrated continuum produced by the cloud is plotted. This is the sum of the continuum emitted in the inward and outward directions from the computed ionization structure, and does not include the incident continuum.

Plot reflected continuum If the keyword REFLECTED appears, then only the continuum emitted from the illuminated face of the cloud is plotted. This includes the back-scattered portion of the incident continuum, along with diffuse emission from the cloud. This is meaningful only for non-spherical (open) geometries. If the option _RAW is specified, then the continuum in units actually used inside CLOUDY (cm^{-2} s^{-1} $cell^{-1}$) will be plotted. If the keyword PHOTON appears, then the units of the plotted continuum will be photons cm^{-2} s^{-1} Ryd^{-1}).

4.12.4. plot opacity [type, range]

If the keyword OPACITY is entered then the opacity of the first and last zones (per hydrogen atom) is plotted. The continuum between 1.001×10^{-5} Ryd $\leq h\nu <$ 7.354×10^{6} Ryd is usually plotted, unless this is adjusted by entering the optional energy range.

There are three optional keywords; ABSORPTION, SCATTERING, and TOTAL, to change which opacity is plotted. If none appear, then the total opacity is plotted.

plot range options For the OPACITY and CONTINUUM options, there is a further keyword RANGE to specify the energy range of the plot. If one number occurs on the command line then it is interpreted as the lowest energy (in

Rydbergs) on the plot. If the first number is zero, then it is interpreted as the lowest energy in the continuum, presently 1.001×10^{-5} Ryd. The optional second number is interpreted as the highest energy shown on the plot. If the second number is omitted or zero, then it is interpreted as the high-energy limit of the code, presently 7.354×10^{6} Ryd. If either number is negative then both are interpreted as the log of the energy, otherwise they are assumed to be the linear energy in Rydbergs. If the first number is zero (i.e., interpreted as the lowest energy considered by the code) then the second number is interpreted as the energy of the upper limit to the plot, and not its log.

The following give specific examples of the range option.

```
*plots the absorption opacity between 0.1 to 10 Ryd.
plot absorption opacity, range=.1 to 10 Ryd
*
*plot the opacity between 1 Ryd and
*the high energy limit of the code.
plot scattering opacity, range=1
*
*the range will be the full energy limit of the code
plot opacity
```

4.12.5. plot map [Tmin=3,000K, Tmax=20,000K, linear, range]

If the keyword _MAP (note the leading space) appears then a plot of the heating and cooling rates as a function of temperature will be made. This will follow the last zone calculated, and will be appropriate for the attenuated continuum and physical conditions in that zone.

plot map range options The high and low temperatures on the map can be changed by entering the keyword RANGE and one or two optional numbers. If no numbers appear then a range of 10 °K to 10^{9} °K is used. If only one number appears then only the lower temperature limit is changed. If two numbers appear then both lower and upper limits are changed.

If the first number is less than or equal to ten then both numbers are interpreted as logs of the temperature. If the first number is greater than ten then both numbers are interpreted as the temperature itself. If the keyword LINEAR appears then both numbers are interpreted as the temperature itself no matter how large or small they may be.

4.12.6. print _all

This command tells the code to print many emission lines whose intensities are simply scaled from lines usually printed, such as the higher Balmer lines, and many helium lines. These assume case B emissivities, and are not reliable at high densities, or when lines are optically thick. This option was added by P.G Martin.

4.12.7. print arrays

This option tells the code to print the ionization balance arrays for all elements heavier than helium. The first line is the vector of ionization rates, in units s^{-1}. The second line is the vector of recombination rates, also s^{-1}. These lines are the two diagonals of the bi-diagonal matrix used in the solution of the ionization balance equation, and include *all* ionization and recombination processes. If too many numbers need to be printed then the first number will indicate how many ionization stages are off the page to the left (i.e., if the first number is 11, then the first ionization stage is 12).

4.12.8. print coolants, zone 135

This turns on an option to print the emission-line cooling arrays for the specified zone. If no zone number or 0 appears on the line then the coolants for *all* zones will be printed. The numbers printed are the log of the cooling per unit volume. Only the strongest coolants are printed, as indicated in the header of the printed array. For each coolant, a four character label gives an indication of the spectroscopic origin of the coolant, and the following integer gives its wavelength, with a 0 to indicate a continuum. The following number is the fraction of the total carried by that agent.

This command sets the variable NZDUMP, the sole element of block DUMP, to the entered number. If set, then routine DMPARY is called.

4.12.9. print continuum

This command tells the code to print the transmitted continuum at the end of the calculation. The information includes the integrated Balmer and Lyman continua, the transmitted X-ray continuum, and frequency by frequency continuum intensities. Generally it is more useful to “punch” the continuum (see the discussion following page 87) and use other software to post-process this file.

4.12.10. print departure coefficients

This command tells the code to print departure coefficients in addition to the relative populations for the lowest seven of the ten levels of hydrogen, H^-, helium, and some molecules.

4.12.11. print every 1000 [5 37 93]

CLOUDY will always print the results for the first and last zones. This command can be used to vary the number of zones printed in between. In the example above, it will print every 1000 zones on the first iteration, every 5 zones on the second iteration, etc. Normally about 100 to 200 zones are computed per

model, so printing every five or ten zones on the last iteration may sometimes be useful. If there are fewer numbers entered than iterations performed, then the last number entered will be used for all further iterations. The default condition is to print only the first and last zones.

4.12.12. print faint -2 [_off]

CLOUDY will normally print the intensities of all emission lines with intensities greater than 10^{-4} of the reference line, which is usually Hβ. This command changes the limit to the relative intensity of the weakest line to be printed. The argument is either the log (if less than or equal to zero) or the linear value of the intensity of the weakest line to print (if positive), relative to the reference line. The reference line is usually Hβ, and can be changed with the NORMALIZE command. In the case shown here, only lines with intensities greater than 1% of Hβ will be printed.

If no numbers are entered, but the keyword _OFF appears, then all lines are printed, even those with zero intensity.

4.12.13. print heating

This tells the code to print the relative heating due to each stage of ionization or physical process. The number is the fraction of the total heating due to this particular stage of ionization, and is printed directly below the relative abundance of that stage.

4.12.14. print last

Normally, results for every iteration are printed as they are computed. If this command is entered then only results for the last iteration will be printed.

4.12.15. print line 1909

The relative intensities of a few selected lines are given for every printed zone. It is possible to have one extra emission-line intensity printed by entering this command, whose argument is the wavelength of the extra line. This is a useful way to follow the buildup of a line across a model.

4.12.16. print only [header, zones]

The keyword ONLY shortens the printout somewhat by stopping the calculation prematurely. If it appears, then another keyword, presently HEADER or ZONES, must also appear. The command PRINT ONLY HEADER will cause the code to stop after printing the header information. The command PRINT ONLY ZONES will cause the code to stop after printing the zone results on the first iteration.

4.12.17. print quiet

This command sets CLOUDY's quiet mode, in which nothing is printed at all. Specifically, it sets the variable TALK in common block CALLED to false. Printing can be turned off and then restarted at a particular zone by using the PRINT STARTING AT command described below.

4.12.18. print short

The detailed final printout is shortened when the SHORT keyword appears. Only the emission lines, and a short summary of some thermal properties of the model, will be printed.

4.12.19. print sort

This option causes the output spectrum to be sorted by wavelength rather than by ion. It was added by Peter G. Martin. It doesn't work.

4.12.20. print starting at 61

This option turns off *all* printout *until* the specified zone is reached. This should come last in the input stream since command lines appearing after it will not be printed.

4.12.21. print _sum

This option adds an extra entry, the sum of the intensities of an arbitrary set of emission lines, to the final integrated emission-line spectrum. This can be useful for applications such as the Stoy (1933) energy balance method of determining stellar temperatures, which rely on the sum of a set of observed line intensities. The sum is printed as the last entry in the emission-line array as an entry with the label Stoy and a wavelength of 0.

The set of emission lines to be summed are entered one per input line, beginning on the line after the PRINT SUM command appears. It continues until a line with END in the first three columns appears. The line label must be the first four characters on each line, and the line wavelength is the following integer. The following gives an example of its use.

```
print sum
o  3 5007
totl 3727
o  1 6300
s  3 9532
end of lines
```

Up to 30 lines can be entered into the sum. This limit is set by the variable NRDSUM which appears in parameter statements throughout the code.

4.12.22. punch option [unit=8]

Punch (output on an arbitrary FORTRAN logical output unit) any of several possible pieces of information. The options are many; physical quantities such as temperature, ionization, density, for each zone are produced for some options, for other cases the continuum or other quantities predicted by the code can be output. In all cases, the general idea is for the file produced by this command (called fort.n in UNIX, where n is the integer on the command line) to then be post-processed by other plotting programs to produce final plots.

Punch output is a primary output mechanism for CLOUDY. Several of the most important options are describing in following subsections. Other options which are not described in great detail are summarized in Table 16. One of the keywords must appear, and only one keyword per line is recognized. The four character key which must be matched is capitalized. This command causes a subroutine called PUNCHR to be called after every zone calculation. If SPECial is specified then a portion of the subroutine will be used, which can be changed to fit the circumstances.

Up to 10 PUNCH commands can be entered. This limit is stored as the variable LIMPUN which appears in parameter statements throughout the code. The optional number on the line is the FORTRAN I/O unit number used for the output. Unit 7 will be used for the first file if no number appears on the line. If no I/O unit number appears on subsequent PUNCH commands the unit number will be incremented by one on each call (i.e., the second file will be fort.8). This is to ensure that no more than one PUNCH command writes to a given file.

Normally the results are produced for every iteration. Only results from the last iteration will be produced if the LAST keyword appears on the line.

Note that CLOUDY uses FORTRAN logical unit 6 for output, and unit 5 for input. These units cannot also be used for punch output, and the same logical output unit cannot be used for more than one punch option. The code also performs other I/O at various times, and punch units greater then 90 are reserved for this purpose. These units cannot be used for punch output.

The following sections outline the more frequently used punch commands, and Table 16 lists all others.

4.12.23. punch continuum [unit=9, last iteration]

This command is the primary mechanism for saving the continuum predicted by the code. The first column of the resulting output is the energy in Rydbergs. The second column is the intensity of the incident continuum at the illuminated face of the cloud. The third column is the transmitted (attenuated) portion of the incident continuum, and does not included reemission from the nebula. The 4th column is the diffuse thermal continuum emitted by the computed structure. Only this column includes a covering factor if one was specified (so that the total

emission from the nebula is this multiplied by the inner area of the cloud). This column does not include the attenuated or reflected portions of the incident continuum. The 5th column gives the net transmitted continuum, the sum of the attenuated incident (column 3) and diffuse (column 4) continua. This would be the observed continuum if the geometry were viewed through the gas, and includes the covering factor. The 6th column is the reflected continuum, and is only predicted if the geometry is not spherical.

All continua are expressed as the flux (units of νf_ν are erg cm^{-2} s^{-1}) and are relative to the inner radius of the cloud (i.e., the specific luminosity is the predicted quantity multiplied by $4\pi r_o^2$).

In most cases an observer at large distance from the computed structure would observe the quantity listed in column 5.

4.12.24. punch continuum bins [unit=12]

This command is used to punch the continuum array. The first number is the frequency of the center of the bin ν, and the second number is its width $\delta\nu$. The bin extends from $\nu-\delta\nu/2$ to $\nu+\delta\nu/2$.

4.12.25. punch transmitted continuum [unit=12, last iteration]

This command is used to save the transmitted (attenuated incident and outward component of diffuse) continuum at the end of the calculation.

This punch file can then be used as part of the incident continuum in a later calculation, by reading in this file with the TABLE READ command (see page 47). Three cautions when reading this file as an input continuum: a) if the keyword LAST does not appear on the line then the continuum from each iteration will be punched. Probably results from only the last iteration are needed, so either the LAST option should the used, or the file must be edited after the initial calculation to leave only the last computed continuum; b) punch output should not be created on the same FORTRAN unit number as the input file during the second calculation. It will overwritten if this occurs; c) the program expects the first two lines to contain header information and skips them. They should not be deleted from the input file.

4.12.26. punch emitted continuum [unit=12, last iteration]

The emitted continuum is punched. The first column is the energy in Rydbergs. The second column is the total emitted continuum (the sum of the transmitted, reflected, and diffuse emitted continua). This would be the observed emission from the nebula if the central continuum source were not in the beam. The third column is the total outward emitted continuum with no optical depth effects included. The attenuated incident continuum is not

included in either of these component. The last column is not a directly observable quantity. All continua are in units νf_ν (erg cm^{-2} s^{-1}).

4.12.27. punch diffuse continuum [unit=12, last iteration]

This command is used to punch the diffuse continuum (νf_ν erg cm^{-2} s^{-1}) at the end of the calculation. This is the locally produced diffuse emission from the gas, per unit volume with no filling factor. Optical depth effects are not included.

4.12.28. punch ionizing continuum [unit=12, last, energy]

This command is used to punch the ionizing continuum at the end of the calculation. The first column is the frequency, the second is the total number of photons within this frequency bin (*not* per unit frequency) and the third number is this photon flux multiplied by the gas opacity. This quantity has units s^{-1} $cell^{-1}$, and is basically a radiation field interaction rate. The next number is the ratio of this quantity to the total integrated radiation field interaction rate, and the last number is the cumulative interaction. This allows the portions of the radiation field which have the dominant interaction with the gas to be identified.

The first optional number on the command line is the punch unit number. The second optional number is the lowest energy to consider in the resulting output. If missing or zero, the lowest energy considered by the code will be used.

4.12.29. punch _raw continuum [unit=12, last iteration]

This command is used to punch the "raw" continua at the end of the calculation. The first number is the frequency. The next four columns are the contents of the arrays FLUX, OTSLIN, OTSCON, and OUTCON at this energy. Each is the number of photons stored in that cell, with units s^{-1} cm^{-2} $cell^{-1}$.

4.12.30. punch [carbon, helium, etc, unit=12, last]

There are a series of punch commands which will produce the ionization structure of various elements. Table 15 lists the elements now included. The part of the element name which must be present for the keyword to be recognized is capitalized. The resulting punch output will have one line per zone, and give the relative ionization of each successive stage.

Table 15 Punch Element Ionization

Keyword	Output
CALCium	NSTEP, CA(1, 2, 3, 4)
CARBon	NSTEP, radius, depth, CARB(1-7)
HELIum	NSTEP, radius, depth, HeI, HeII, HeIII
HYDRogen	NSTEP, TE, HDEN, EDEN, (HI, HII, H2, H2+, H3+, H-)/HDEN
IRON	NSTEP, -log10(rel ioniz)*100
NITRogen	ionization fractions
OXYGen	NSTEP, oxy(1,2,3,4)

4.12.31. punch reflected continuum [unit=12, last iteration]

This command is used to punch the reflected continuum at the end of the calculation if SPHERE is not set. The first column is the frequency in Rydbergs, and the second the reflected continuum at that energy (νf_ν; erg cm^{-2} s^{-1})

4.12.32. punch map unit

If the keyword _MAP (note the leading space) appears then the heating and cooling rates as a function of temperature will be made. This will follow the last zone calculated, and will be appropriate for the attenuated continuum and physical conditions in that zone.

Table 16 Punch Options

Keyword	Output
_DR_	logic behind choice of zone thickness
GRAIN OPACity	nu, extinction, absorption, scattering
GRAIN PHYSical	te, potential, drift velocity, frac heat
GAUNt factors	ν(Ryd), free-free gaunt factor
HTWO	H2 formation, destruction, processes
LYMAn alpha	tau (Lyα), n(2p)/n(1s), T(excitation)
MOLEcules	H2/HDEN, CO/H, H2O/H, OH/H, CH/H
OPTIcal depths	nu, total, absorption, scattering optical depths
_OTS	nu, flux, otscon, otslin, outcon
_QS_	nu, qabs, qscat
PHYSical cond	NSTEP, R-R_o, TE, HDEN, EDEN, rad accel
PRESsure	NZONE, depth, P(gas), P(rad), Pinteg
RADIus	NZONE, R, R-Ro, dr
RECOmbin effic	τ(912), rec effic to n=1
SOURce function	nu(R), diffus, opacity, source fcn, black body ratio
SPECial	Specially defined
TEMPerature	NZONE, T, dT/dr
WIND	Radius, thickness, velocity, accel, force multiplier

4.12.33. punch lines, cumulative [unit=10, last iteration, relative]

This option on the PUNCH LINES command tells the code to punch the log of the cumulative intensity of up to 15 emission lines as a function of depth into the cloud. The emission lines are specified on the following input lines, and end with a line with the keyword END in columns 1-3. The label used by CLOUDY to identify each line (see section 6. starting on page 130) must appear in column 1-4 of the line, and the integer used to identify the line wavelength appears as a free-format number in later columns. The line labels and wavelengths are then punched. The depth into the cloud, and the integrated intensities of the lines (erg cm^{-2} s^{-1}) are then punched for each zone. This information can then be used to follow the build up of emission lines across a computed structure.

The following illustrates its use;

```
punch lines, structure
totl 4861
o  3 5007
totl 3727
o  1 6300
end of lines
```

There is an optional keyword RELATIVE; if specified then the punched quantities will be the intensity relative to the normalization line. If not specified, then the absolute intensity will be punched.

The PUNCH LINES CUMULATIVE and PUNCH LINES STRUCTURE commands use the same line array, so both commands cannot be used in the same run.

4.12.34. punch _PDR

This command is used to output a set of quantities relevant to photodissociation region (PDR) calculations. The first column gives the depth into the cloud in centimeters, the second is the total hydrogen column density (cm^{-2}), the third column is the total extinction in magnitudes in the V filter, then follows the temperature. These are followed by the abundance ratios of atomic to total hydrogen, H_2 to total hydrogen, atomic carbon to total carbon, carbon monoxide to total carbon, and water to total oxygen. The total hydrogen density is defined throughout CLOUDY as the total number of protons per unit volume, so a fully molecular gas will have $H_2/H=1/2$.

4.12.35. punch map [range]

This command is used to produce a map of the heating cooling rates as a function of temperature. The details of this map are described above, in the

description of the MAP command. The range option is not implemented in the punch map command.

Normally about 20 steps occur between the lowest and highest temperature in the map. This is controlled by the variable NMAPS, and can be reset with the SET NMAPS command.

4.12.36. punch lines, structure [unit=10, last iteration]

This option on the PUNCH LINES command tells the code to punch the emissivity of up to ten emission lines as a function of depth into the cloud. The emission lines are specified on the following input lines, and end with a line with the keyword END in columns 1-3. The label used by CLOUDY to identify each line (see section 6. starting on page 130) must appear in column 1-4 of the line, and the integer used to identify the line wavelength appears as a free-format number in later columns. The line labels and wavelengths are then punched. The depth into the cloud, and the volume emissivity (erg cm^{-3} s^{-1}, for unit filling factor) is then punched for each line. This information can then be used by other codes to reconstruct the surface brightness distribution of a resolved emission-line object.

The following illustrates its use;

```
punch lines, structure
totl 4861
o  3 5007
totl 3727
o  1 6300
end of lines
```

The PUNCH LINES CUMULATIVE and PUNCH LINES STRUCTURE commands use the same line array, so both commands cannot be used in the same run.

4.12.37. punch lines, intensity [unit 7, every 5 zones, last iteration]

This option on the PUNCH LINES command tells the code to punch the entire emission-line array, in the format used for the final printout (line label, wavelength, intensity). The default is for this to be done after the last zone is computed. Intermediate results can be punched if the additional keyword EVERY appears. In this case the first number on the line must be the IO unit number, and the second number is the interval between zones to punch, as in the PUNCH EVERY command.

4.12.38. punch opacities [total, element]

The total gas opacity will be punched if the keyword TOTL appears, and cross sections for individual stages of ionization will be produced if the (first four characters of the) name of the element appears. Each stage of ionization is punched in successive fort.n files.

4.12.39. punch results [unit 7, last iteration]

All emission lines and column densities predicted during a calculation can be saved at the end of the calculation by entering the command PUNCH RESULTS LAST ITERATION. This is the best way to save the results of a large number of calculations (such as when the code is being used to generate a large grid of models). The resulting file contains all of the input stream as well. The input stream, and the predicted emission lines and column densities, can then be read at a later time by calling the subroutine CDGETT. There is a common block, GETT, associated with this subroutine. This common block contains information specified in the input stream, such as the ionization parameter, hydrogen density, stopping column density, flux of ionizing photons, etc. The general strategy behind calling the code as a subroutine, generating large grids of output files, and then reading this output with CDGETT, is described in the section on calling the code as a subroutine, in Part III of this document.

4.12.40. title This is a title

The argument is a title for the calculation, and can be useful for organizing the models in some manner. The title is reprinted several times.

4.12.41. trace zone 94 [iteration 2;hydrogen;helium;carbon;...]

This command turns on trace printout beginning *after* the zone given by the first number on the line. The trace follows the logical flow within CLOUDY, and is a useful way to follow the internal decisions CLOUDY makes. CLOUDY uses adaptive logic to control many choices, such as the run of zone thickness with radius. This command allows these decisions to be followed in detail. If the zone is zero, or if no numbers occur on the line, then the trace is turned on at the beginning of the calculation. The second (optional with default=1) number is the iteration on which the trace should be started. It should be set to 2 to turn on the trace for the second iteration. Table 17 lists the trace keywords (column 1; the four character part of the key which must be matched is capitalized), the logical variable in CLOUDY which is affected (column 2; these are variables in the common block of the same name), and the purpose of each.

Table 17 Trace Keywords and Effects

keyword	variable	Trace
BETA	TR8446	OI 8446-Lyβ problem
CARBon	CARBUG	carbon ionization equilibrium
COMPton	COMBUG	Compton heating, cooling, and ionization
CONTinuum	CONBUG	prints out photon arrays, pointers
COOLants	COOLTR	cooling
DIFFuse fields	TRDIFF	sum of recombination coef in DIFFEM
_DR_	DRBUG	choice of next zone thickness
GRAIN	DSTBUG	details dealing with grain treatment
EDEN	NEBUG	changes in electron density
GAUNt	TRGANT	the free-free gaunt factors
IRON	FEBUG	Fe Auger - fluorescence K-alpha problem
HEATing	HEATBG	heating agents
HELIum	HEBUG	helium ionization equilibrium
HELIum IONIzed	HE2BG	helium ionization equilibrium
HELIum SINGlet	HE1BG	helium ionization equilibrium
HELIum TRIPlet	HE3BG	helium ionization equilibrium
HYDRogen	HBUG	hydrogen ionization equilibrium
Ly BETA	TR8446	Lyβ - OI 8446 pumping problem
OPACities	OPCBUG	continuous opacities, zone by zone
OPTIcal depths	OPTBUG	inner, outer optical depths in STARTR
oPTIMizer	TROPTM	steps in optimize command driver
_OTS	OTSBUG	ots ionization rates
MOLEcules	TRMOLE	rate coefficients for molecules
NEON	NEONBG	recombination, ionization for neon
THREe body	BD3BUG	three-body recombination rates for metals
TWO photon	BUG2NU	induced two photon processes

4.13. The Optimize Command

The OPTIMIZE command and its keywords tell the code to vary two or more of the initial parameters to try to find an optimal set of parameters to fit a specified emission-line spectrum, line flux or luminosity, and/or a set of column densities. The method was first implemented in CLOUDY by R.F. Carswell, who wrote most of the code for the present version. It uses the downhill simplex algorithm (Press et al. 1988) to obtain a best fit to a set of observed quantities. The desired emission-line spectrum, line flux or luminosity, and/or column densities, are specified by a series of OPTIMIZE commands. A keyword VARY can appear on several of the commands used to specify initial conditions (Table 18) to indicate which parameters are to be varied.

Table 18 Commands with Vary Option

Command	quantity varied	Min	Max	Inc.
blackbody	temperature	def	def	0.5
bremsstrahlung	temperature	def	def	0.5
energy density	energy density temp	def	def	0.1
filling factor	filling factor	def	0	0.5
hden	hydrogen density	def	def	1.0
intensity	intensity of source	def	def	0.5
ionization parameter	ionization parameter	def	def	0.5
luminosity	luminosity of source	def	def	0.5
metals	log of metalicity	def	def	0.5
phi(H)	log of photon flux	def	def	0.5
Q(H)	log of ionizing photons	def	def	0.5
radius	inner radius	def	def	0.5
stop column density	column density	def	def	0.5
table star kurucz	temperature	4.477	4.699	0.1
table star mihalas	temperature	4.477	4.740	0.1
turbulence	turbulent velocity (km/s)	def	def	0.5

At a minimum, a desired emission-line spectrum, line flux, or column density, and a specification of which parameters are to be varied, must be given. The parameters to be varied during the optimization are specified by a keyword VARY which may appear on any of the commands listed in Table 18. Up to 20 parameters may be varied at a time; this limit is set by the variable LIMPAR which appears in several PARAMETER statements throughout the code. The quantities being varied are actually entered as logs within the code, and increments to the initial guess are also logarithmic. More than one parameter must be varied because of limitations in the current optimization algorithm. It simply cannot find a solution with only a single variable parameter.

An example of the VARY option in action is given in a sample input stream in Part III of HAZY. A typical input stream follows:

```
blackbody, 50,000K
hden 4 vary
ionization parameter -2 vary
stop zone 1
*
* the following specifies observed emission lines, order is
* label, wavelength, intensity relative to H-beta, tolerance
optimize lines
O  3 5007 intensity =13.8 error =0.1
totl 3727 < 2.1 (only upper limit)
end of lines
*
* following are elements, stage of ioniz, log col density
optimize column densities
carbon 4 17.4
silicon 3 14.6
end of column densities
```

Information concerning the optimization process is fed to the code as a series of keywords on the OPTIMIZE command; these are described next. Only one keyword will be recognized per OPTIMIZE command.

4.13.1. no vary

It is sometimes useful to be able to turn off the optimizer for a given input stream, without having to change the (many) occurrences of the VARY keyword. This can be done with a command line which has the key “NO VARY” in the first seven columns. If this command is entered then the VARY keyword will be ignored, and a single model will be computed.

4.13.2. optimize, column density

This tells the code to try to reproduce a set of column densities. A series of column densities, ending with a line with the keyword END in columns 1 to 3, will be read in from subsequent lines. One column density is entered per line, and up to 100 may be specified. Columns 1 to 4 of the column density lines must contain the first four characters of the name of the element, spelled as in the output from the zone results. The first number on the line is the ionization stage, 1 indicates Atom I, 3 indicates Atom III, etc. The second number on the line is the log of the column density (cm^{-2}), and the last optional number is the relative uncertainty. It has a default of 0.05 (5 percent). A column density can be specified as an upper limit by entering < anywhere on the line. If < appears then the column density is only included in the optimization if the predicted value exceeds the upper limit.

The following gives some examples of its use;

```
optimize column densities
hydrogen 1  < 17 ;make optically thin in Lyman continuum
carbon 4 17.4 error =.001
silicon 3 14.6
end of column densities
```

4.13.3. optimize, increment = 0.5 dex

The increments are the amounts by which each variable is changed in the first step away from the initial parameter. The default increments preset in the code were chosen with typical conditions in mind. The increments are logarithmic quantities which will be added to or subtracted from the initial guess. It may be necessary to increase these if the process is unable to identify a solution. If a zero is entered as an increment, then the default increment will not be changed.

The increments entered with this command affect *only* the previously selected VARY command. The following gives some examples of changing the increments.

```
hden 4 vary
optimize increments .1 ;this sets .1 dex changes in hden
brems 6 vary           ;increments left at default
radius 13.6 vary
optimize increments .05; this sets changes in radius
```

The increments are stored in the vector variable VINCR.

4.13.4. optimize, (intensity, luminosity)=36.425 [error =0.1]

The code will try to make the predicted intensity or luminosity of the normalization line (usually Hβ, and set with the NORMALIZE command) match the entered value. The sub-keyword is either INTENSITY or LUMINOSITY, and both have exactly the same effect. The number is the log of either the intensity or luminosity of the line, in the same units as found in the third column of the final print out. The second (optional) number is the fractional tolerance allowed for the fit between the observed and computed values. If a tolerance is not specified, then a fractional uncertainty of 0.05 is assumed.

4.13.5. optimize, iterations =75

The upper limit to the number of iterations to be performed is specified with this command. The maximum number of iterations is stored as the variable ITOPTM, which has the default of 20. It is probably a good idea to reduce the number of iterations if the initial guess is far from the solution. It may be necessary to increase the limit if the process is still making progress at the end of the calculation. The limit to the number of iterations should really be some function of the number of parameters being varied.

4.13.6. optimize, lines

This command tells the code to try to reproduce a set of relative emission-line intensities, and to begin reading a list of observed lines. Up to 100 lines may be entered; the limit is stored as the variable NOBSLM which appears in several PARAMETER statements throughout the code.

One emission line is specified per input line, and the line must contain information in the following order: columns 1 to 4 of the line must list the label CLOUDY uses to identify the line; this must then be followed by the wavelength, a free format integer. Both must exactly match the identifications used inside CLOUDY and printed as line labels in the output; the code will stop if this is not the case. Section 6., starting on page 130 below, gives the emission-line or continuum labels and wavelengths. The third quantity on the line is the desired relative intensity of the line. This will be in the same units as the relative intensities normally printed at the end of the calculation. Intensities are normally relative to Hβ, but can be changed to other reference lines with the NORMALIZE` command (described elsewhere). The last (optional) number is the fractional tolerance allowed for the fit between the observed and computed values. If a tolerance is not specified, then a fractional uncertainty of 0.05 is assumed. A line can be specified as an upper limit by entering < anywhere on the line. If < appears then the line is only included in the optimization if the predicted value exceeds the upper limit.

The series of emission lines ends with a line which has the keyword END in columns 1 to 3. If this end does not appear correctly then the code will continue reading lines until the end-of-file is encountered.

Comments may be entered using any of the special characters in column 1 which were described on page 22.

4.13.7. optimize, punch =9

At the end of the optimization process the optimal input parameters are entered into a file for later use. Normally this is Fortran punch unit 7 (i.e., fort.7 in Unix). The unit number can be changed with this command.

Using this file, it is possible to make later calculations in which various quantities are also punched for plotting. Also, it is generally a good idea to confirm that a single run with CLOUDY does reproduce the final results from the many calls of the code made by the optimization method. The two should agree exactly, but would not if the code became corrupted during the many calls made during the process (this could happen if a pointer went astray, for example).

Be careful that the unit specified with this command is not the same as one of those used by the PUNCH command. The files will overlap if the same unit is used.

4.13.8. optimize, range -2.3 to 3.9

It is possible to establish limits to the allowed range over which parameters are to be varied. The limits which are preset in the code are indicated in Table 18. The entry def indicates the default limits of -1×10^{37} and 1×10^{37}.

It is sometimes necessary to establish physical limits to parameters which are varied. For instance, metalicities may be limited to the range $-1 \le \log(Z) \le 0$ by observations or physical plausibility. The optimization driver doesn't know this, but can be told a set of bounds with this command. The arguments are ordered pairs of limits, which are the log of the lower and upper limits to the allowed range of variation of the previous command with VARY specified. In this way the command is similar to the OPTIMIZE INCREMENTS command described above. Examples follow.

```
hden 4 vary
*the following sets limits to range of density
optimize range from 3 to 5
*There will be no range for this one
brems 6 vary
radius 13.6 vary
*this sets limits to radius
optimize range from 13 to 14
```

The optimizer does not actually know about the range limit; a residual of 10^{37} is returned if a parameter outside the allowed range is used. The limits to the range are stored in the vectors VARANG(1,n) (lower limit) and VARANG(2,n) (upper limit).

4.13.9. optimize, tolerance = 0.2

The tolerance, a measure of the overall agreement between the observed and specified spectra, intensity, and / or column density, is set with this command. The tolerance is stored as the variable VTOLER, with the default value 0.10.

4.13.10. optimize, trace 4

This command turns on trace printout for the n^{th} time the code is called by the optimizer. Specific aspects of the trace are still controlled by the trace command, described on page 94.

4.13.11. Convergence criteria

The sum of residuals

$$\sum \max\left[\left(\frac{\text{observed}-\text{model}}{\text{observed}\times\delta}\right)^2,\left(\frac{\text{observed}-\text{model}}{\text{model}\times\delta}\right)^2\right] \qquad (47)$$

is accumulated over all relative intensities, line intensities or luminosities, and column densities, and minimized. In this expression observed and model are the observed and computed quantities. If the model prediction is zero then a residual of 10^{37} is returned. The uncertainty δ is specified when the observed quantities are read in and has a default value of 0.05 (5 percent). For column densities and relative line fluxes the linear quantity is used to form the residuals. To avoid floating point problems on 32-bit IEEE machines, the log of the line flux or luminosity is used. The process stops when the sum of residuals is smaller than the variable entered with the OPTIMIZE TOLERANCE command, which has the default of 0.10.

4.13.12. Notes concerning commands with vary option

The keyword VARY can appear on the commands in Table 18. Notes concerning these follow.

Blackbody It is not possible to specify the luminosity of the blackbody by using the keywords on the blackbody command when the VARY option is used. It is necessary to enter the luminosity using some other command, such as LUMINOSITY or IONIZATION PARAMETER.

Filling factor Only the filling factor itself can be varied. It is possible to specify the optional power law for a radial dependence but it is not possible to vary it.

HDEN It is possible to specify the exponent for the optional power law density dependence upon radius or thickness. It is not possible to vary this additional parameter; only the initial hydrogen density is varied.

INTENSITY It is possible to specify all of the options on the intensity command, but it is only possible to vary the intensity itself.

LUMINOSITY It is possible to specify all of the options on the luminosity command, but it is only possible to vary the luminosity itself.

METALS The GRAINS keyword can also be specified.

PHI(H) and Q(H) It is possible to use the RANGE option, but only the log of the photon number will be varied.

RADIUS It is possible to specify the stopping radius on the line, but it is not possible to vary it. Only the starting radius is varied.

STOP COLUMN DENSITY All of the optional keywords (neutral, effective, etc.) are recognized.

4.13.13. Notes concerning the optimization process.

Use physically motivated initial conditions. The algorithm will not be able to find a solution if one is not physically possible. For instance, an observed

HeII λ4686 / Hβ ratio of 0.5 cannot be produced by a 20,000 °K blackbody, no matter how many other parameters are varied (it produces no He^+ ionizing radiation). It is probably necessary to start with parameters in the general area of the successful model. When far from the solution, it is also a good idea to limit the number of iterations the optimizer can perform (using the OPTIMIZE ITERATIONS command) to stop it from over-optimizing a bad solution.

Change the increment size. The initial increment will be the largest step ever taken during the optimization process. If the initial parameters are far from the solution then it may be wise to increase the increments.

Set physically motivated limits to the variable quantities. The optimizer driver uses a pure brute force method, and understands surprisingly little modern astrophysics. For instance, while trying to reproduce an observed He II λ4686 / Hβ intensity ratio of 0.5 by varying the temperature of a black-body radiator, the algorithm is likely to examine the consequences of photoionization by a 100 °K radiation field. Physically, it is known that HeII emission only occurs for stars hotter than ~50,000 °K (Osterbrock 1989), so there is little purpose in examining temperatures lower than this. The process will converge more quickly if reasonable bounds to the range of the varied quantities are set using the OPTIMIZE RANGE command.

Don't give up! My experience is that this process works about a quarter of the time. The problem is that the algorithm can easily home-in on a local minimum, which is actually a very bad solution. When this occurs, the best idea is to restart the optimization process with a different set of initial conditions. Better yet is to start the process with parameters which give answers known to be close to the solution. In order to avoid wasting time, it is also a good idea to limit the number of iterations with the OPTIMIZE ITERATIONS command.

4.13.14. Code variables.

The following is a partial list of the variables used to control the interaction between CLOUDY and the optimizer codes.

NPARM This sets which variable is being varied. It is a pointer to the number in the stack of varied variables, (1 for the first, 2 for the second, etc).

VFORMT This is a character variable. VFORMT(NPARM) is the Fortran format statement specifying how to write the control line for the NPARM variable to be varied.

VPARM VPARM(NPARM,1) is the value of first parameter on the NPARMth line to be varied, VPARM(NPARM,2) is the second value on the NPARMth line to be varied, etc.

NVARXT The number of parameters on the NPARMth line to be varied is NVARXT(NPARM).

VARANG This specifies the range of allowed variation. VARANG(1,NPARM) is the lower limit, and VARANG(2,NPARM) is the upper limit.

NVFPNT is the pointer to which place in the input stream the current line holds.

VINCR VINCR(NPARM) sets the initial increment.

4.14. Miscellaneous Commands

This section describes commands which are used to disable physical processes within the code, or to take care of housekeeping activities, like setting paths for ancillary files. These are not normally used.

4.14.1. dielectronic recombination [10]

At present rate coefficients for dielectronic recombination through low-lying autoionizing states have not been computed for most elements on the third row and higher. For the four lowest stages of ionization, the code uses the means of the rate coefficients for C, N, and O; these are $3\pm2\times10^{-13}$, $3\pm2\times10^{-12}$, $1.5\pm0.5\times10^{-11}$, and $2.5\pm1.4\times10^{-11}$, $cm^3\ s^{-1}$, for the successive stages of ionization. The uncertainty is indicated by the quoted uncertainty, which is the dispersion from the mean of the quoted atoms and ions. Because no better can be done at present, these are used for those ions which have no rate coefficients. These rate coefficients can be turned off, or the values changed by a scale factor, by entering this command. If a number is entered on the line then it is the scale factor to multiply all the above rate coefficients; if no number is entered then zero is assumed and the effect is turned off. This is a useful way to check on the importance of this recombination mechanism for specific calculations. Extensions to the Opacity Project (Seaton 1987) should soon produce all needed recombination rate coefficients.

4.14.2. drive fread, gaunts, pointers, ...

This command causes CLOUDY to enter a special debug mode, in which the program requests information and responds with deduced quantities. A flag is set when the commands are entered. Parameters for the entire model (density, continuum, and luminosity) must still be specified. This special mode is entered after the last command is specified and the input stream ends with a blank line or the end-of-file.

drive escape probabilities The command causes the code to enter a debug mode in which the user enters the log of a one-sided optical depth, the code queries three of the escape probability functions, (complete redistribution with damping wings; incomplete redistribution, and complete redistribution with

only the Doppler core), and responds with the one-sided escape probabilities. A null line exits the driver.

drive fread This command causes the code to enter a debug mode in which the free format input reader, subroutine FREAD, reads the input stream and prints the interpreted number. The program will request an input line, and print the interpreted number, until a line with the number zero is entered.

drive gaunts This command enters a CLOUDY debug mode in which a driver requests temperature and photon energies, queries the free-free gaunt factor routine, and responds with the returned gaunt factor. The gaunt factor routine was written by David Hummer, and is described in Hummer (1988).

drive molecules Here it is possible to change individual molecular abundances within the iteration loop.

drive pointers This command allows the user to interrogate the frequency array. After the continuum is generated, the driver will ask for energies in Rydbergs (interpreted as a log if negative) and respond with the cell pointer, frequency, cell width, boundaries, and the phase space factor $2h\nu^3 / c^2$. Once complete, the calculation will continue as usual.

4.14.3. eden -2

This command allows an extra component of free electrons to be added to the gas. The argument is the log of the electron density (cm^{-3}). This command is used to test the behavior of CLOUDY in the limit of very low Compton temperatures. When the color temperature T_{color} is much less than 10^4 °K, the gas is almost entirely neutral, and free electrons must be artificially added to test the Compton energy exchange problem in the strict TE limit. (Remember, charge conservation is a horrible thing to violate.)

4.14.4. fudge factors 4.59678 [12.3 34.5 958 ...]

The numbers appearing on the line can be communicated to any part of the code which calls the function FUDGE. This function has a single integer argument which points to the numbers entered on the command line. In the example given above, a call to FUDGE(2) would return the value 12.3. Up to ten numbers can be entered on the command line. Extra numbers are ignored.

This option is not normally used, but can be a useful way to pass numbers to temporary or trial parts of the code. All elements of FUDGE are initially zeroed in the large BLOCK DATA. The function FUDGE is a permanent part of CLOUDY, and a warning is given at the end of the calculation if this function is ever evaluated. Also, the function checks that the pointer to the array of stored values is not larger than the number of values entered in the command line; the code will stop if too few values are entered.

4.14.5. increments 0.05 .05 [scale factor = 2]

This command adjusts the two variables used to choose the zone thickness. The thickness of the first zone is chosen so that the largest continuous optical depth through it is equal to the first number on the line. The default is 0.001. Thereafter, the zone thickness is continuously adjusted by checking that the relative ionization of hydrogen, helium, carbon, oxygen, and iron do not change by more than a factor related to the second number. The default is 0.15. If only one number appears on the line then it is interpreted as a scale factor used to multiply the default values. If either number is less than or equal to zero, then it is interpreted as the log of the quantity, and linear if greater than zero. The two numbers are referred to by the variables DTAU1 and DIDZ, the two elements of the common block SETDR.

4.14.6. no . . .

It is possible to disable physical processes as a test of their importance. If a physical process is turned off, then the logical variable PHYSOK in the common block of the same name is set to false to indicate that the treatment of physical processes is not OK. A warning is then printed at the end of the calculation, as a reminder that the results of the calculation are not to be trusted.

4.14.7. no (2p2s; 2s2p) collisions

This command turns off 2s2p collisions in the hydrogen atom and helium singlets and ion; it is mainly used for debugging the hydrogen and helium atoms. The keyword can be either 2s2p or 2p2s.

4.14.8. no Auger effect

This command turns off the Auger effect.

4.14.9. no Compton effect

This command turns off Compton heating and cooling of free electrons, and Compton recoil ionization of bound electrons. Electron scattering opacity *is not* turned off.

4.14.10. no FeII pumping

This turns off H I Lyα pumping of Fe II.

4.14.11. no fine structure line optical depths

Fine structure lines, such as the ^{3}P 52, 88 μm lines of O^{+2}, can become optically thick under certain high-luminosity conditions (see, for example, Rubin 1983).

Radiative transfer effects, including stimulated and maser emission, are fully treated by CLOUDY for all fine structure lines, using escape probabilities. This command turns off the treatment of optical depths and line transfer for these lines.

4.14.12. no free free heating

Free-free heating is turned off with this command. It sets the logical variable FREEON in the common block of the same name to false.

4.14.13. no grain neutralization

Ion recombination on grain surfaces is turned off with this command.

4.14.14. no induced processes

This command turns off induced recombination and stimulated emission for hydrogen and helium.

4.14.15. no IR pumping

This command turns off continuum pumping of infrared fine structure lines. This process can be an important heating mechanism for cool gas irradiated by a powerful infrared continuum.

4.14.16. no molecules

CLOUDY does a molecule formation network, initially based on Black (1978) and Hollenbach and McKee (1979) (see the section on molecules in Part II). It includes H^+, H^o, H^-, H_2, H_2^+, H_3^+, HeH^+, and many molecules involving heavy elements. A very brief description of the network and some results are given in Ferland (1980b). The NO MOLECULES command turns the entire network off.

4.14.17. no on the spot

This command turns on all ground state recombination coefficients, and turns off ionization by helium resonance lines. Specifically, it sets all hydrogen recombination efficiencies (in the vector HREFF(n,2)) to unity, and sets OTSMIN to 1. This last variable is then used to deduce the ionization efficiency of lines and continua; the effect of this command is to turn off such ionizations.

4.14.18. no radiation pressure

This command turns radiation pressure completely off. Radiation pressure due to trapped lines will be counted in the total pressure when the CONSTANT

PRESSURE option is used; the default is for a constant density model. Radiation pressure is not included if constant gas pressure is specified.

4.14.19. no recoil ionization

This command turns off Compton recoil ionization of hydrogen, helium, and heavy elements. Compton heating and cooling of free electrons is included, but is the only electron scattering thermal effect remaining. Bound electron scattering opacity is still included when this command is issued.

4.14.20. no secondary ionizations

This command will turn off the effects of knock-on supra-thermal electrons. Normally these are treated as in Spitzer and Tomasko (1968), Bergeron and Collin-Souffrin (1971), Shull (1979), and Shull and van Steenberg (1985). This command will make X-rays contribute 100% heat, and produce no secondary ionizations or Lyα excitations.

4.14.21. no Stark broadening

Stark broadening (important for densities larger than $\sim 10^{10}$ cm^{-3}) is treated for hydrogen lines using escape probabilities from Puetter (1981). This turns Stark broadening off.

4.14.22. no three body recombination

This turns off three body recombination for the heavy elements. It is not possible to turn off three body recombination for hydrogen or helium.

4.14.23. no vary

This command turns off the vary option set on various optimization commands. For a further discussion see page 96 above on the optimization driver.

4.14.24. set colimt=0.3

This command sets the limit to the ratio CO / C_{tot}, the ratio of the carbon monoxide abundance to the total carbon abundance. The default is 0.75 and is stored as the variable COLIMT. The code stops when the CO abundance exceeds COLIMT. Instabilities in the heavy element molecular equilibrium system of equations prevent higher carbon monoxide molecular from being successfully treated.

4.14.25. set csupra = -12.34

This command sets the secondary ionization rate due to supra-thermal electrons to the number on the line, the log of the rate (s^{-1}). The excitation rate of Lyα is assumed to be identical. This option is used to test the code in secondary-ionization dominated cases. The secondary ionization rate is denoted by the variable CSUPRA, and the rate of secondary excitation of Lyα by X12.

4.14.26. set drmax 11.2

This command sets the largest allowed zone thickness. The argument is the log of the thickness in cm, and the default is 10^{30} cm. It is possible to force the zones to have a specific thickness by combining the DRMAX and DRMIN commands.

4.14.27. set drmin 11.2

The number is the log of the minimum zone thickness (in cm). It may be necessary to specify this if CLOUDY starts to oscillate near an ionization front in a constant pressure model. If this happens and DRMIN is not set then the zones become smaller and smaller, as CLOUDY tries to damp out the oscillations. If this occurs, then, at the end of the calculation, the code will suggest using this command to establish a smallest zone size The default value is 10^{-20} cm.

4.14.28. set erredn 0.01

This command sets the convergence criterion for the electron density. The number is the largest relative change in the electron density that can have occurred during an iteration, and that iteration still be considered as having a converged electron density. The number on the line is interpreted as the relative change in the electron density if it is positive, and the log of this change if negative.

4.14.29. set flxfnt -20

The highest continuum frequency which needs to be considered in equilibrium calculations is lower for relatively soft continua, such as H II regions, than for X-ray continua, such as AGNs. The criterion used to choose the highest energy ν_{high} to be considered is that $\nu f_\nu (\nu_{high}) / \nu f_\nu(\nu_{peak}) <$ FLXFNT, where ν_{peak} is the frequency where the continuum reaches its maximum $\nu f\nu$. FLXFNT is normally 10^{-10}. This command changes the value of FLXFNT. The argument is the log of the value.

4.14.30. set nend 500

This command sets the default limit to the number of zones which will be computed. This limit is stored as the code variable NEND. The preset default value is 400, but more zones may be needed in very dense models, or ones exposed to very intense radiation fields.

The limit to the number of zones which will be computed can be set with either this command, or with the STOP ZONE XXX command. The only difference between these two commands is in the level of warning that will be generated by the code if it stops after reaching the limiting number of zones. If the code stops because it reached the number of zones set by the STOP ZONE command, then this was probably the intended stopping criteria, and no comment is generated. However, the code generates a *warning* if it stops because it reaches the default limit to the number of zones, since this probably *was not* intended. The STOP NEND command was introduced so that it is possible to increase the default limit to the number of zones when computing very large grids of models. Some of these may require more than the current default limit to the number of zones. By using this command the limit can be increased while still retaining the checking / warning generated if the code stops for an unintended reason.

4.14.31. set nmaps 50

This is used to control the number of steps in the heating cooling map which results from either the MAP or PUNCH MAP COMMANDS. Normally about 20 steps are taken between the lowest and highest temperatures. This number is stored as the variable NMAPS and can be reset with this command.

4.14.32. set path="/usr/home/cloudy"

This command sets the path CLOUDY will use to look for various ancillary files. If the path is not set then the current directory will be used. The path begins with either a single or double quote, and ends with a single or double quote, or a space.

5. OUTPUT

This section defines the output produced by CLOUDY. Each section begins with a sample of the output described, and then goes on to describe the meaning of the printout in greater detail. The output actually shown is from the Meudon (Pequignot 1986) meeting Planetary Nebula test case.

5.1. Header Information

Several lines of output echo the input commands and outline some properties of the initial continuum.

5.1.1. Initial Information

```
                                        CLOUDY 84.00

************************************93Feb 5************************************
*                                                                              *
* title "New" Paris meeting Planetary nebula                                   *
* c recompute "standard" PN model of the Pequignot Meudon Conferance           *
* sphere                                                                       *
* black body, T=150,000K radius = 10                                           *
* hden = 3.4771213                                                             *
* radius = 17                                                                  *
* abund -1 C-3.523 N-4. O-3.222 ne-3.824 na=-10 mg-4.523 al=-10                *
* continue si-4.523 s-4.824 ar-10 ca=-10 fe-10 ni=-10                          *
* plot continuum range .1                                                      *
* c parispn.in                                                                 *
* c Sun IPC                                                                    *
*                                                                              *
********************************************************************************


                                  Chemical composition
He:1.000E-01   C:2.999E-04   N:1.000E-04   O:5.998E-04   Ne:1.500E-04   Na:1.000E-10   Mg:2.999E-05
Al:1.000E-10   Si:2.999E-05   S:1.500E-05   A:1.000E-10   Ca:1.000E-10   Fe:1.000E-10   Ni:1.000E-10
```

This begins with the version number of CLOUDY. Major revisions, which have noticeable effects on the emission-line spectrum or which reflect significant improvements in the physics, are denoted by integer increases in the version number, while minor changes increment the revision number by 0.01. In a static version of the code, changes (usually bug fixes) are denoted by letters (i.e., .02a). The following line gives the date this version was created.

All of the input command lines, with the exception of those starting with a #, %, or *, are echoed before the calculation begins, and the first twelve lines are saved to be reprinted after the calculation is completed. The input information is followed by the chemical composition of the gas. The numbers are the number density of the elements, relative to hydrogen.

5.1.2. Properties of the Continuum

```
413Cell Peak3.74E+00   Lo 1.00E-05=0.9105cm   Hi-Con:3.38E+01 Ryd   E(hi):7.35E+06Ryd     E(hi):     100.01 MeV
L(nu>1ryd):  37.5397   Average nu:2.935E+00   L( X-ray):  31.4677   L(BalC):  36.1444     Q(Balmer C):  46.9767
Q(1.0-1.8):  47.1615   Q(1.8-4.0):  47.4535   Q(4.0-20):  47.0523   Q(20--):  40.7978     Ion pht flx:4.313E+12
L(gam ray):   0.0000   Q(gam ray):   0.0000   L(Infred):  34.4848   Alf(ox):   0.0000     Total lumin:  37.5572
L/Lsolar:     3.9744   Abs bol mg:  -5.2161   Abs V mag:   2.4664   Bol cor:  -7.6825     nuFnu(Bbet):  34.5868
U(1.0----):4.795E-02   U(4.0----):9.981E-03   T(En-Den):3.354E+01   T(Comp):1.436E+05     nuJnu(912A):2.909E+01
Occ(FarIR):2.254E-10   Occ(H n=6):8.356E-14   Occ(1Ryd):1.342E-15   Occ(4R):3.747E-17     Occ (Nu-hi):1.382E-30
Tbr(FarIR):3.749E-10   Tbr(H n=6):3.702E-10   Tbr(1Ryd):2.120E-10   Tbr(4R):2.371E-11     Tbr (Nu-hi):7.278E-24
```

This section gives a synopsis of the incident continuum. These quantities are evaluated at the illuminated face of the cloud, not at the center of the first zone.

The first line gives the number of numerical frequency cells in the continuum, followed by the energy (in Ryd) of the cell with the largest flux density per unit energy interval (f_ν). Next are the energies of the low and high energy limit of the continuum, both in Ryd and cm or MeV. The last two numbers are the energies of the high energy limit of the present version of the code, in Ryd and keV.

The second line gives the log of the energy (erg s^{-1} cm^{-2} or erg s^{-1}, depending on whether a flux or luminosity was specified) in the hydrogen ionizing continuum (1 Ryd ≤ hν < 100 MeV), and the average energy of the hydrogen ionizing continuum, in Ryd, weighted by photon number;

$$\langle h\nu \rangle = \frac{\int_{1\,Ryd}^{\infty} 4\pi\, J_\nu \, d\nu}{\int_{1\,Ryd}^{\infty} 4\pi\, J_\nu / h\nu \, d\nu} \quad . \tag{48}$$

The log of the energy in the X-ray continuum (20.6 Ryd ≤ hν ≤ 7676 Ryd), the log of the energy (erg s^{-1} cm^{-2} or erg s^{-1}), and the number of photons (cm^{-2} s^{-1} or s^{-1}) in the Balmer continuum (0.25 Ryd to 1.0 Ryd) is then printed.

The third line gives the log of the number of photons (cm^{-2} s^{-1} or s^{-1}) in four frequency bins (1.0 Ryd ≤ hν < 1.807 Ryd, 1.807 Ryd ≤ hν < 4.0 Ryd, 4.0 Ryd ≤ hν < 20.6 Ryd, and 20.6 Ryd ≤ hν < 7676 Ryd). The last number is the flux of hydrogen ionizing photons;

$$\Phi(H) = \frac{Q(H)}{4\pi r^2} \quad \mathrm{cm}^{-2}\ \mathrm{s}^{-1} \quad . \tag{49}$$

In this equation Q(H) is the total number of hydrogen-ionizing photons emitted by the central object (s^{-1}), and r is the separation between the center of the central object and the inner face of the cloud. Unlike the majority of the quantities printed in the header, Φ(H) (per unit area) is always printed, never Q(H) (into 4π sr).

The fourth line of the header gives some information about the low and high energy portions of the incident continuum. The first number is the log of the luminosity in the gamma-ray (7676 Ryd ~ 100 keV to 7.354×10^6 Ryd ~ 100 MeV) continuum. The second number on the line is the log of the number of photons over this energy range. The third number is the log of the luminosity in the continuum between 0.25 Ryd and the lowest energy considered, presently an energy of 1.001×10^{-5} Ryd. All of these entries are either per unit area, or radiated into 4π sr, depending on how the continuum was specified.

The next entry, "Alf(ox)", is the spectral index α_{ox}, defined as in Zamorani et al. (1981), except for the difference in sign convention. This is the spectral index which would describe the continuum between 2 keV (147 Ryd) and 2500Å (0.3645 Ryd) if the continuum could be described as a single power-law, that is,

$$\frac{f_\nu(2\text{ keV})}{f_\nu(2500\text{ Å})} = \left(\frac{\nu_{2\text{ keV}}}{\nu_{2500\text{ Å}}} \right)^{\alpha} = 403.3^{\alpha} \quad . \tag{50}$$

The definition of α_{ox} used here is slightly different from that of Zamorani et al. since implicit negative signs are *never* used by CLOUDY. Typical AGN have α_{ox} ~ -1.4 . If no X-rays are present then α_{ox} = 0.

The last number on the line is the log of the total energy in the continuum between 1.001×10^{-5} Ryd and 100 MeV; it is given as either erg cm^{-2} s^{-1} or erg s^{-1}, depending on how the continuum was defined. If the continuum is specified per unit area, then this number is 4π times the integrated intensity of the incident continuum. If it is specified as the total luminosity radiated into 4π sr, then the quantity is the luminosity.

The next line is optional, depending on whether the continuum is specified as the total luminosity or photon number radiated into 4π sr, or as an incident surface flux. If the continuum is specified in absolute terms, i.e., the luminosity or photon number radiated into 4π sr, then this optional line is generated. The first quantity is the log of the total luminosity in the continuum, in solar units. The absolute bolometric magnitude, absolute V magnitude, and the bolometric correction, are then given, followed by the log of the continuum specific luminosity (νF_ν) at Hβ (the units of νF_ν(Hβ) are erg s^{-1}).

The next line begins with two ionization parameters. The first is the dimensionless ratio of ionizing photon to hydrogen densities, defined as

$$U \equiv \frac{\Phi(H)}{n_H c} \tag{51}$$

where n_H is the total hydrogen density. The second number is defined in a similar way, but the numerator is the number of photons with energies greater than 4 Ryd (i.e., helium-ionizing). The third number is the equivalent black body temperature corresponding to the energy density u at the illuminated face of the cloud, from the incident continuum and Stefan's radiation density constant a; $T_u \equiv \left(L / 4\pi r^2 ac \right)^{1/4}$, and the next quantity is the Compton temperature of the incident radiation field[10]. The last number on the line is $4\pi\ \nu J_\nu$(912 Å), the flux at 912Å (erg cm^{-2} s^{-1}). In this equation J_ν is the mean intensity of the incident continuum as defined by Mihalas (1978).

---

[10]For a blackbody radiation field $T_{Compton}$ is roughly 4% lower than the blackbody color temperature T_{color} when the energy density temperature T_u is « T_{color}. Only when $T_u \equiv T_{color}$ does induced Compton heating cause $T_{Compton} \equiv T_{color}$. If $T_u > T_{color}$ then $T_{Compton} > T_{color}$ because of induced Compton heating. All of the relevant physics is included in the Compton temperature printed here.

The next two lines give some of the incident continuum photon occupation numbers $\eta(\nu)$, defined as

$$\eta(\nu) \equiv J_\nu(\nu)\left(\frac{2h\nu^3}{c^2}\right)^{-1} \quad , \tag{52}$$

and the incident continuum brightness temperature $T_b(\nu)$, (°K), defined as

$$T_b(\nu) \equiv J_\nu(\nu)\left(\frac{2k\nu^2}{c^2}\right)^{-1} \quad , \tag{53}$$

for five energies. These energies correspond to the lowest frequency considered (presently an energy of 1.001×10^{-5} Ryd); the ionization potential of the n=6 level of hydrogen (1 / 36 Ryd); an energy of one Rydberg; four Rydbergs, and the high energy limit of the incident continuum (this depends on the continuum shape; the energy is given by the fifth number on the first line of the continuum output).

Finally, if grains are present, then the last line gives the total grain extinction (scattering and absorption) cross section (cm^{-2}) per unit column density of hydrogen at several energies (Pα , Bα , Mg II, 1 Ryd, 4 Ryd).

5.2. Zone Results

```
#####  1 Te:1.452E+04 Hden:3.000E+03 Ne:3.612E+03 R:1.002E+17 R-R0:1.898E+14 dR:3.795E+14 NTR:  1 Htot:5.555E-17 T912: 9.991E+07###
 -3.50 4686  1.04 5876  0.00 1909  0.19 1549 13.07 6584  0.00 5007  0.34 3727  0.00 6300  0.00 2798  0.00 1035  5.01
Hydrogen    1.278E-04 9.999E-01 H+0/Hden: 1.000E+00 4.958E-12 H-     H2 3.867E-14 1.194E-12 H2+  HeH+ 9.007E-15 H col den 1.139E+18
H 2SP 3-6   2.035E-11 1.813E-17 5.615E-18 8.132E-18 1.215E-17 1.749E-17 Texc(La); 3.856E+03 T(contn): 3.332E+01 T(diffs): 1.995E+01
Helium      6.247E-07 5.451E-03 9.945E-01 He I 2S3  1.179E-08 Comp H, C 6.682E-23 6.758E-24 Fill Fact 1.000E+00 Gam 1/tot 9.952E-01
He singlet  6.130E-07 1.536E-13 5.054E-21 7.602E-21 1.164E-20 1.735E-20 He triplt 1.179E-08 1.792E-18 1.516E-20 5.243E-20 1.217E-20
HeII        5.451E-03 1.113E-11 3.235E-18 4.767E-18 7.100E-18 1.030E-17 8.295E-17 6.732E-16 1.245E-13 PRAD/GAS; 1.101E-02
Pressure    NgasTgas; 1.007E+08 P(total): 1.405E-08 P( gas ): 1.390E-08 P(Radtn): 1.530E-10 Rad accel 1.169E-06 Force Mul 3.594E+02
Carbon      0.000E+00 3.548E-05 1.128E-02 3.116E-01 6.771E-01 0.000E+00 0.000E+00 H2O+/Otot 0.000E+00 OH+/Ototl 0.000E+00
Nitrogen    0.000E+00 7.035E-06 5.485E-03 1.625E-01 4.809E-01 3.511E-01 0.000E+00 0.000E+00 O2/Ototl: 0.000E+00 O2+/Otot: 0.000E+00
Oxygen      0.000E+00 5.518E-06 6.197E-03 2.506E-01 6.158E-01 1.242E-01 3.292E-03 0.000E+00 0.000E+00 Hex(tot): 0.000E+00 A:-12.725
Neon        0.000E+00 2.788E-06 6.543E-03 2.214E-01 7.029E-01 6.907E-02 7.195E-05 0.000E+00 0.000E+00 0.000E+00 0.000E+00
Sodium      0.000E+00 8.684E-06 6.414E-03 2.092E-01 5.672E-01 2.134E-01 3.824E-03 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
Magnesium 0 0.000E+00 5.216E-05 1.511E-02 3.304E-01 4.946E-01 1.587E-01 1.148E-03 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
Aluminium 0 2.333E-06 7.971E-04 2.615E-02 4.231E-01 4.564E-01 9.297E-02 5.644E-04 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
Silicon   0 0.000E+00 1.153E-04 1.265E-02 1.961E-01 6.980E-01 9.276E-02 4.040E-04 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
Sulphur   0 0.000E+00 1.517E-06 5.054E-04 1.528E-02 1.266E-01 5.133E-01 3.443E-01 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
Argon     0 0.000E+00 2.044E-06 5.848E-04 1.973E-02 1.368E-01 3.926E-01 4.197E-01 2.921E-02 1.357E-03 0.000E+00 0.000E+00 0.000E+00
Calcium   0 0.000E+00 1.319E-06 3.237E-04 8.654E-03 5.363E-02 4.066E-01 4.550E-01 7.444E-02 1.389E-03 0.000E+00 0.000E+00 0.000E+00
Iron      0 0.000E+00 0.000E+00 0.000E+00 1.048E-04 5.359E-03 1.869E-01 6.529E-01 1.527E-01 1.991E-03 0.000E+00 0.000E+00 0.000E+00
Nickel    0 0.000E+00 0.000E+00 0.000E+00 6.043E-06 4.355E-04 7.836E-02 5.928E-01 3.143E-01 1.418E-02 0.000E+00 0.000E+00 0.000E+00
```

The results of calculations for the first and last zones are always printed. Results for intermediate zones can be printed if desired (see the PRINT EVERY command above). The following is a line-by-line description of the output produced for each printed zone.

5.2.1. Line 1

The line begins with five # characters, to make it easy to locate with an editor. The zone number is the first number, followed by the temperature of the zone ("Te"). A lower case u will appear before the "Te" if the temperature solution is possibly thermally unstable (i.e., the derivative of the net cooling with respect to temperature is negative. See the section in Part III on thermal stability problems). The total hydrogen ("Hden") and electron ("Ne") densities (cm^{-3}) follow. The next number ("R") is the distance to the center of the zone, from the

center of the central object. The depth, the distance between the illuminated face of the cloud and the center of the zone, ("R-R0", or $r-r_o$), and the width of the zone ("dR", or δr), (all are in cm), follow. The inner edge of the zone is $(r-r_o) - \delta r/2$ from the illuminated face of the cloud. The line ends with a number indicating how many iterations were needed for this zone to converge (NTR), followed by the total heating[11] ("Htot"; photoelectric and otherwise, erg cm^{-3} s^{-1}), and the optical depth between the *inner* face of the cloud and the *outer* edge of the zone at the Lyman limit (T912; the number is the *total absorption* optical depth at 912Å, and *not* the hydrogen Lyman limit optical depth).

5.2.2. Line 2 - Emission-line strengths

The first number is the log of the surface brightness in Hβ (erg cm^{-2} s^{-1}). The remainder of the numbers are ordered pairs, with the first being the wavelength of an emission line, and the second its intensity relative to Hβ. All of these are the intensities accumulated so far, with the present zone included. The selection of lines is arbitrary, and the last can be changed with the LINE command. This information is useful when dealing with a matter-bounded geometry, in which the emission-line intensities are set by the thickness of the cloud. This information is only printed if the intensity of Hβ is greater than zero.

5.2.3. [Optional] wind parameters

A line describing the velocity and acceleration of the zone is printed if the WIND option is used. The numbers are the wind velocity at the inner edge of the zone (km s^{-1}), inward gravitational acceleration (cm s^{-2}), total outward radiative acceleration, and the fraction of this acceleration caused by the incident continuum, line driving, and the gradient of the radiation pressure. The solution is probably not realistic for grain-free environments, since ~10^6 lines need to be included to do radiative acceleration properly (Abbott 1982).

5.2.4. [Optional] radiation pressure

If the ratio of line radiation to gas pressure, P(radiation)/P(gas), is greater than 5%, then a line describing the source of the radiation pressure is generated. The printed line is the vector which contains the contributors to P_{rad}, and are in the order (1)=Lyα , (2)=Mg II λ2798 , (3)=C III λ1909 , (4)=Fe II UV lines, (5)=C IV λ1549 , (6)=C II λ1335 , (7)= n>2 Lyman lines, (8)=Balmer lines, (9)=He I λ 10830, (10)=HeII Lyα , (11)=HeI Lyα , (12)=N III λ1750, (13)=O III λ1666, (14)=SI III λ1207, (15)=SI III λ1895, (16)=SI IV λ1397, (17)=S III λ1198, (18)=O VI λ1035 ,

---

[11]CLOUDY defines heating as the energy input by the freed photoelectron, or hν - IP, where IP is the ionization potential of the atom or ion, and hν is the energy of the photon. See Osterbrock (1988) for more details.

and (19)=N V λ1240. The numbers are the fraction of the total radiation pressure contributed by each line. Usually, the majority of the line radiation pressure comes from Lyα , C IV λ1549, Mg II λ2798, or the Fe II UV lines.

5.2.5. Line 3 - Hydrogen I

The line begins with the abundance of neutral and ionized hydrogen relative to all atomic-ionic hydrogen (i.e., the ratios $H^o/(H^o+H^+)$ and $H^+/(H^o+H^+)$ where H^o is the population in the lowest six levels of hydrogen. If PRINT DEPARTURE COEFFICIENTS has been specified then departure coefficients are also printed on the following line. Neutral hydrogen H^o is defined to be the total population of atomic hydrogen in the $1 \le n \le 6$ states. Ionic hydrogen includes the sum over higher levels and protons. Next comes H+o/Hden, the ratio of the density of hydrogen in atomic or ionic form (this is indicated by the label "H+o") to the total hydrogen density in all forms (including molecular).

The following five numbers are abundances of the negative hydrogen ion and several molecules (H^-, H_2, H_2^+, and HeH^+) relative to the total hydrogen abundance. The total hydrogen density is usually referred to by the label HDEN, and is the sum $H^o + H^+ + H^- + 2H_2 + 2H_2^+ + 3H_3^+$. Note that, with the definition of HDEN given here, a fully molecular gas will have H_2/HDEN=0.5. These molecular abundances are also expressed as departure coefficients if this option is set. The last number on the line is the total hydrogen column density (cm^{-2}).

5.2.6. Line 4 - Hydrogen II

The first two numbers are the populations of the H^o 2s and 2p levels relative to the ionized hydrogen density. The next four numbers are populations of levels 3 to 6, again relative to the ionized hydrogen density. The latter are computed assuming full l-mixing. The populations of three pseudo-states, chosen to represent the actual levels 7 to 100, are also computed, but not printed. All of these populations usually are relative to the ionized hydrogen density, but can also be printed as LTE departure coefficients if the PRINT DEPARTURE COEFFICIENTS command is given. The excitation temperature T_{exc} of Lyα, defined as

$$\frac{n(2p)/g(2p)}{n(1s)/g(1s)} = \exp\left(-h\nu / kT_{exc}\right) \qquad (54)$$

is given. This is followed by the temperature corresponding to the energy density of the attenuated incident continuum ("T(contn)"), and the diffuse continua ("T(diffs)"). This includes all trapped lines and diffuse continuous emission.

5.2.7. Line 5 - Helium

The first three numbers are the total populations of the three ionization stages of helium, relative to the total helium abundance. The population of atomic helium is the sum of the total population in the triplets and singlets, including the population of the lowest six levels of each. These populations can also be expressed as departure coefficients if this option is set with the PRINT DEPARTURE COEFFICIENTS command. The population of He^o 2^3S, relative to the total helium abundance, follows. The Compton heating and cooling rates (both erg cm^{-3} s^{-1}) are next, followed by the gas filling factor. The last number is the fraction of the total hydrogen ionizations which are caused by photoionization from the ground state.

5.2.8. Line 6 - Atomic Helium

The first group are the level populations of the populations of the n=1 to 6 levels of the He^o singlets. Level two is actually resolved into 2s and 2p, but the total population of 2 is printed. The next group consists of populations of the 2s, 2p, and n=3s,p,d levels of the He^o triplets. Both sets of populations are relative to the total helium abundance. Departure coefficients are also printed if requested.

5.2.9. Line 7 - Ionized Helium

The populations of the 2s, 2p, and n=3 to 6 levels are indicated. There are relative to He^{++} ; departure coefficients are also printed if requested. The ratio of radiation pressure to gas pressure follows.

5.2.10. Optional Grains

If grains are present, then lines giving some properties of the grain populations are printed. Each line gives the results of calculations for a specific type of grain. Normally, a type of graphite and silicate are included when grains are present. The line for each type gives the equilibrium temperature of the grain, the potential in volts, the charge, the drift velocity, followed by the gas heating (erg cm^{-3} s^{-1}) due to grain photoionization, and the dimensionless fraction of the total gas heating due to grain photoionization.

5.2.11. Pressure

Some information concerning the pressure is now printed. The gas equation of state includes thermal gas pressure, the radiation pressure due to trapped line emission, and the radiation pressure due to absorption of the incident continuum. The first number is the gas pressure N_{gas} T_{gas} (with units cm^{-3} °K), followed by the total pressure (dynes cm^{-2}), followed by the gas pressure in dynes cm^{-2}. The radiation pressure follows. The second to last number is the

radiative acceleration (cm s^{-2}) at the inner edge of this zone. The radiative acceleration is computed with all continuous scattering and absorption opacities included. (Work on OB winds suggests that this result is a serious underestimate for grain-free environments. See, for instance, Abbott 1982.) The last number is a force multiplier, defined as in Tarter and McKee (1973), and is the ratio of total opacity to electron scattering opacity.

5.2.12. Molecules

A line giving relative abundances of some molecules is printed if there is a significant molecular fraction. All molecular abundances are relative to either the total carbon or total oxygen abundance (this is indicated in the label for each). In order, the molecules are CH, CH^+, CO, CO^+, H_2O, and OH.

5.2.13. Carbon

The abundances of the seven stages of ionization of carbon relative to the total carbon abundance begin the line. The relative abundance of H_2O^+ and OH^+ (relative to the total oxygen abundance) follows.

5.2.14. Nitrogen

The relative populations of the eight ionization stages of nitrogen are printed first. The relative abundance of O_2 and O_2^+ (relative to the total oxygen abundance) follows.

5.2.15. Oxygen

The oxygen ionization stages are followed by the extra heat added at this zone (erg cm^{-3} s^{-1}); due to cosmic rays, turbulence, etc, and the log of the effective hydrogen recombination coefficient (cm^3 s^{-1}).

5.2.16. Neon

The neon ionization balance is printed across the line.

5.2.17. Magnesium to Nickel

There are too many ionization stages to print across the line. Although all stages with non-trivial abundances are computed, only the highest twelve stages of ionization are printed. The first number is an integer indicating how many stages are off the page to the left. If the number is 2, then the first printed stage of ionization is twice ionized, i.e., Fe^{+2}.

5.3. Calculation Stopped Because ...

```
Calculation stopped because lowest Te reached.
The geometry is a thick shell.
Photoionization of He 2TriS reached  15.2 percent of the total rate out.
Grains were not included but might survive in this environment (energy density temperature was 3.35E+01K)
Helium continuum mased.
Frequency out of range of free-free gaunt factor routine.
OI negative level populations 239 times.
The ratio of radiation to gas pressure reached  1.54E+01.  Caused by Lyman alpha.
Line radiation pressure capped by thermalization length.
```

A series of messages appear after the printout of the last zone.

The first will say why the calculation stopped. In a valid calculation the model will stop because one of the specified stopping criteria specified was met. If no other criteria are specified, then the calculation usually stops when the default lowest temperature of 4000 °K is reached. If the code stops because of a probably unintended reason (i.e., internal errors, or the default limit to the number of zones) then a note is printed saying that the calculation may have halted prematurely.

The first line explains why the calculation stopped. Only one stopping criterion message will be printed. The possible messages, and their interpretations, are:

5.3.1. ... because of radiation pressure

The default density law is for a constant density. If constant pressure is specified instead (with the CONSTANT PRESSURE command), then CLOUDY will try to keep the total pressure, particle and radiation, constant. The radiation pressure is small at the boundaries of the cloud, so the cloud will be unstable if the ratio of radiation to total pressure exceeds 0.5. The calculation stops, and this message is generated, if this occurs on the last iteration.

5.3.2. ... because lowest EDEN reached.

The calculation can be forced to stop when the electron density (EDEN) falls below a certain value, as set by the STOP EDEN command, described above. This can be used to stop the calculation at an ionization front. The default lowest electron density is negative, so this stopping criterion applies only when the command is entered.

5.3.3. ... because low electron fraction.

The calculation can be forced to stop when the ratio of electron to hydrogen densities falls below a certain value, as set by the STOP EFRAC command, described above. This can be used to stop the calculation at an ionization front when the hydrogen density there is not known (for instance, in a constant pressure model). The default lowest electron density is negative, so this stopping criterion applies only when the command is entered.

5.3.4. ... because wind velocity < 0

The code can perform a simple wind calculation (see the section below) which includes the outward force due to radiation pressure and the inward force of gravity. This message is printed if the gas comes to rest.

5.3.5. ... because code returned BUSTED

The calculation stopped because something bad happened. The results are suspect.

5.3.6. ... because DRAD small - set DRMIN

The Strömgren radius of the H^+ zone is estimated at the start of the calculation, and the smallest allowed zone thickness is then set as a very small fraction of this. The calculation will stop if the zone thickness falls below this smallest thickness. This can occur because of any of several logical errors within CLOUDY (adaptive logic is used to continuously adjust the zone thickness), although it can rarely occur for physical reasons as well. The smallest thickness can be reset to any number with the SET DRMIN command, see above.

5.3.7. ... because DR small rel to thick.

The depth into the cloud is stored as the double precision variable DEPTH and the zone thickness is stored as the double precision variable DRAD. If the zone size becomes too small relative to the depth (DRAD / DEPTH < 10^{-14}) then the depth variable will underflow such that DEPTH+DRAD=DEPTH. The calculation will stop in this case and give the above reason if this problem prevents the density from being properly evaluated. This is a fundamental numerical problem with no clear solution.

5.3.8. ... because carbon fully molecular.

For mixtures where oxygen is more abundant than carbon the atomic carbon abundance can become vanishingly small when carbon monoxide forms. The matrix inversion routine may have trouble determining the carbon balance under these conditions. If problems occur under these conditions then the code will stop with this message.

5.3.9. ... because negative mole abundan.

The matrix inversion routine can predict negative abundances of some of the heavy element molecules when the gas becomes predominantly molecular. CLOUDY is not now designed to handle this situation.

5.3.10. ... because optical depth reached.

The default value of the largest allowed continuous optical depth is unphysically large, and can be reset with the STOP OPTICAL DEPTH ... command. The command specifies both the optical depth, and the energy at which it is to be evaluated. All absorption opacity sources included in the calculation contribute to the computed optical depths. If the calculation stops because the largest continuum optical depth is reached, then this line is printed. This line is also printed if the STOP EFFECTIVE COLUMN DENSITY command is used to stop the calculation, since this command is actually a form of the STOP OPTICAL DEPTH command.

5.3.11. ... because outer radius reached.

The default outer radius is unphysically large, but can be changed with the RADIUS or STOP THICKNESS commands. If the calculation stops because the outer radius set by one of these commands is reached, then this line is printed.

5.3.12. ... because column dens reached.

The default values of the largest allowed neutral, ionized, and total hydrogen column densities are unphysically large. They can be reset with the commands STOP COLUMN DENSITY, STOP NEUTRAL COLUMN DENSITY, or STOP IONIZED COLUMN DENSITY. This message will be printed if one of these criteria stops the calculation.

5.3.13. ... because lowest Te reached.

The default value of the lowest temperature allowed is 4000 °K. This is reasonable when only optical emission-lines are of interest. The limit can be changed with the STOP TEMPERATURE command. This message is printed if the calculation stops because the lowest temperature is reached.

5.3.14. ... because highest Te reached.

The default value of the highest temperature allowed is 10^{10} °K. The limit can be changed with the STOP TEMPERATURE EXCEEDS command. This message is printed if the calculation stops because the highest allowed temperature is exceeded.

5.3.15. ... because NZONE reached.

The default condition is for up to 400 zones to be computed. This can be reset with the STOP ZONE command. This message is printed if the calculation stops because the limiting number of zones is reached. A comment will be printed at

the end of the calculation if it stops because it hits the default limit to the number of zones allowed, presently 400, since this was probably not intended.

5.3.16. ... because line ratio reached.

It is possible to set a limit to the largest value of an emission-line intensity ratio with the STOP LINE command. This message is printed if the calculation stops because the largest value of the ratio is reached.

5.3.17. ... because internal error - DR.

An internal logical error caused this message to be printed. Send the command lines, and the version number of CLOUDY to me. My internet address is gary@asta.pa.uky.edu.

5.4. Geometry

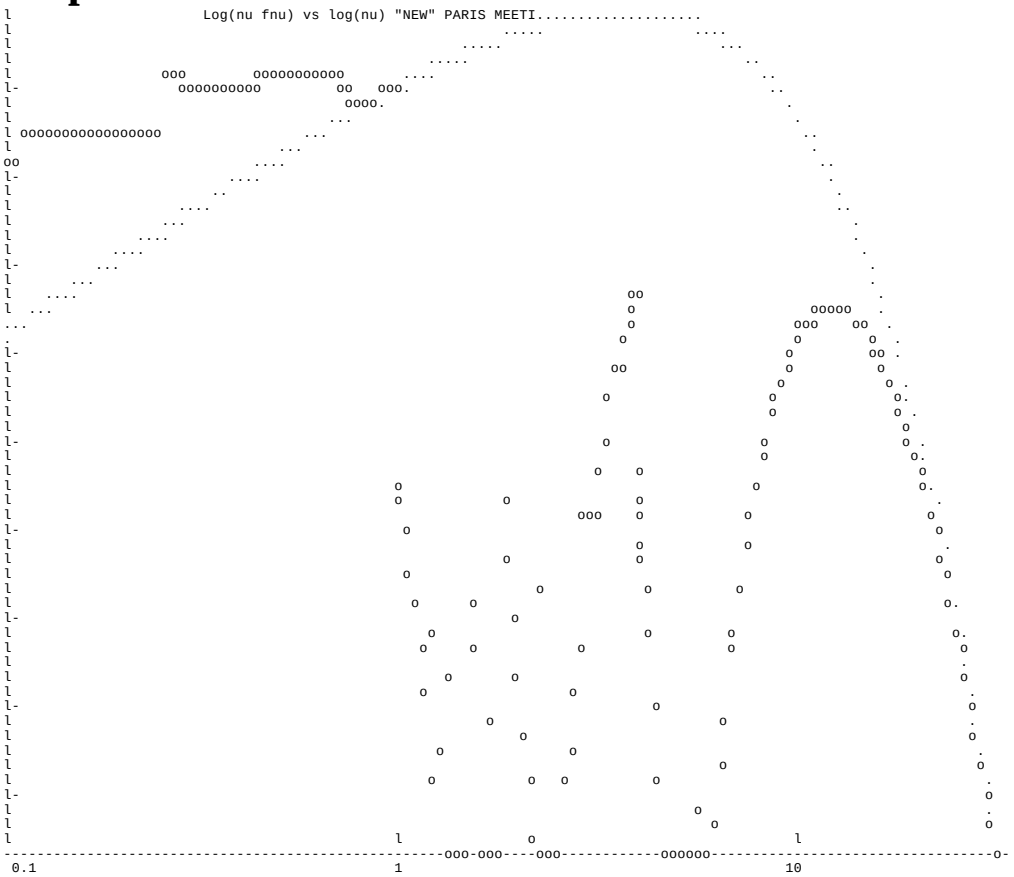
After saying why the calculation stopped, CLOUDY will say whether the geometry is plane parallel ($\Delta r / r_o < 0.1$), a thick shell ($\Delta r / r_o < 3$), or spherical ($\Delta r / r_o \geq 3$), where r_o is the inner radius and δr is the thickness of the cloud.

5.5. Warnings, Cautions, Surprises, and Notes

The next, optional, messages fall into four categories: warnings, which begin with W-; cautions, which begin with C-; surprising results, which begin with an explanation mark (!), and notes.

CLOUDY checks that its range of validity was not exceeded in the calculation. Warnings are issued to indicate that the program has not treated an important process correctly. For instance, warnings occur if the temperature was high enough for the electrons to be relativistic, if the global heating - cooling balance is off by more than 20%, or if the code stopped for an unintended reason. I would like to hear about warnings, my e-mail address is gary@asta.pa.uky.edu. Cautions are less severe, and indicate that CLOUDY is on thin ice. Examples are when the optical depths in excited states of hydrogen change during the last iteration. Surprises begin with "!" and indicate that, while the physical process has been treated correctly, the result is surprising. An example is when induced Compton heating is more that 5 percent of the total Compton heating. Notes indicate interesting features about the model, such as maser effects in lines or continua, or if the fine structure lines are optically thick. The messages are usually self explanatory.

5.6. Optional Plot



If any of the optional plots are requested with the PLOT xxx command then they will appear next. The quantities plotted are described in the section of HAZY where the command is defined (see the discussion following page 81).

5.7. Final Printout

5.7.1. Emission-Line Spectrum

```
                  ********************************> CLOUDY 83.64  <********************************
                  * title "New" Paris meeting Planetary nebula                                      *
                  * c recompute "standard" PN model of the Pequignot Meudon Conferance              *
                  * sphere                                                                         *
                  * black body, T=150,000K radius = 10                                             *
                  * hden = 3.4771213                                                               *
                  * radius = 17                                                                    *
                  * abund -1 C-3.523 N-4. O-3.222 ne-3.824 na=-10 mg-4.523 al=-10                  *
                  * plot continuum range .1                                                        *
                  * c parispn.in                                                                   *
                  * c Sun IPC                                                                      *
                  ********************************> LOG(U): -1.32 <********************************

               Emission Line Spectrum.   Constant  Density Model.  Closed geometry.  Iteration 1 of 1.
                           Luminosity (erg/s) emitted by shell with full coverage.

TOTL 4861 35.383   1.0000      TOTL 3889 34.050   0.0465      N  2  203 32.000   0.0004      Ne 2  128 33.917   0.0342
TOTL 1216 36.821  27.4511      TOTL 7065 34.101   0.0523      N  2 4239 31.711   0.0002      Ne 3  156 35.812   2.6867
Inci    0 37.557 149.4204      CcHE    0 35.232   0.7061      N  2 5680 32.243   0.0007      Ne 3  361 34.715   0.2151
TotH    0 37.201  65.7183      He I    2 33.734   0.0225      N  2 2140 33.960   0.0377      Ne 3 3869 35.774   2.4589
BFH1    0 37.050  46.4329      DevB    2 32.750   0.0023      N  2 1084 32.365   0.0010      Ne 3 3968 35.260   0.7544
BFHe    0 36.581  15.7775      He I 5016 33.685   0.0200      N  3 1750 34.409   0.1062      Ne 3 3343 33.094   0.0051
TotM    0 35.928   3.5064      DevB 5016 33.202   0.0066      N  3   57 34.448   0.1161      Ne 3 1815 33.233   0.0071
H- H    0 32.519   0.0014      He I 3965 33.394   0.0103      TOTL  990 32.940   0.0036      Ne 4 2424 35.148   0.5818
Ca B 4861 35.385   1.0058      DevB 3965 32.676   0.0020      N 3c  990 32.925   0.0035      Ne 4 4720 33.375   0.0098
Ca B 1216 36.925  34.8068      He I 3614 33.110   0.0053      N 3p  990 31.467   0.0001      Ne 4 1602 33.991   0.0405
Q(H) 4861 35.411   1.0662      DevB 3614 32.539   0.0014      N  4 1486 34.516   0.1360      Ne 5 3426 35.020   0.4336
Q(H) 1216 36.945  36.4530      He I 3448 32.891   0.0032      N  4  765 32.121   0.0005      Ne 5 3346 34.587   0.1601
TOTL 6563 35.824   2.7614      DevB 3448 32.108   0.0005      N  4 1718 32.931   0.0035      Ne 5 2976 32.368   0.0010
TOTL 4861 35.383   1.0000      TOTL 1640 35.732   2.2354      TOTL 1240 34.263   0.0760      Ne 5 1575 32.843   0.0029
```

The final printout begins by reprinting the input commands. The box surrounding it gives both the version number of CLOUDY (at the top) and the log of the ionization parameter (the ratio of ionizing photon to hydrogen densities) at the bottom.

The line following the box summarizes some properties of the model and output. The first part of the line indicates whether the energy in the emission lines is given as the luminosity radiated by a spherical shell covering Ω sr (erg s^{-1}; $\Omega / 4\pi$ is the covering factor) or the intensity produced by a unit area of gas (erg s^{-1} cm^{-2}). Which of the two choices is printed is determined by whether the luminosity of the continuum was specified as the luminosity radiated by the central object into 4π sr or the intensity (4π J) of the incident continuum (erg cm^{-2} s^{-1}) at the illuminated face of the cloud. If the model is spherical and the incident continuum specified per unit area, then the emergent emission-line spectrum will be per unit area in units of the inner radius r_o (that is, the total line luminosity radiated by a shell covering 4π sr will be the listed intensity 4πj times 4π r_o^2). The second part of this line indicates the density structure of the model (i.e., wind, constant density, constant pressure, constant gas pressure, power-law density distribution, etc). The next section tells whether the geometry was open or closed. The last part indicates which iteration this is.

The computed emission-line spectrum follows. Emission lines are divided into two groups. The first includes the effects of grain scattering and absorption, and is indicated by the header Emergent Line Intensities. This first group is only printed if grains are present and the geometry is open (i.e., SPHERE not set). The intensities are the *total* intensities observed from the illuminated face, including both absorption and scattering by grains. The second group of lines is always printed, is usually the intrinsic intensity of the lines, and does not include the reddening effects of internal grains due to the photon's passage out of the nebula. This second group usually gives the total intrinsic intensity of the lines. Although reddening effects of internal (or external) dust are not taken into account, photon destruction by background opacity sources during the transfer process is. This predicted spectrum should be compared with the reddening-corrected observed spectrum.

The spectrum is sorted into four large groups of columns, with each large group sub-divided into four smaller sub-columns. The first sub-column is either the spectroscopic designation of the ion producing the line or an indication of how the line is formed. The second sub-column is the line wavelength, with a 0 to indicate a continuum. The third sub-column is the log of the power in the line, in the units given in the header (4π sr or cm^{-2}). The last sub-column is the intensity of the line relative to the reference line, usually Hβ , unless this is reset with the NORMALIZE command.

The following sections give overviews of the general treatment of line formation. A description of the entire line array, and a formal definition of how CLOUDY works, follows in latter sections.

Heating and cooling. The total photoelectric heating, due to photoionization of hydrogen, is given by BF H. The following entries, BFHe, and TotM, are the heating due to helium and metal photoionization. ComH and H-H , indicate the heating due to Compton scattering and absorption by the H^- ion. Comp 0 is the total cooling due to Compton scattering, and eeff 0 is the electron-electron bremsstrahlung cooling. H FB and H FF are the free-bound and free-free cooling of hydrogen.

Hydrogen lines. The first two entries are the total intensities of Hβ and Lyα, as predicted by the 10-level H atom. These intensities are the results of calculations which include all collisional, radiative, and optical depth effects. The next (CA B 4861) is the Case B intensity of Hβ, computed from the actual model ionization and temperature structure, but assuming that Hβ emits with its Case B emissivity. DU B 4861 is the Case B intensity of Hβ modified for grain destruction of Lyman lines, as described by Cota and Ferland (1988). For models of dusty low-density gas, such as an H II region, where collisional and radiative transfer effects are not important, this entry should be more reliable than the results of the ten level atom calculation when Case B is a good assumption. The two may differ at the ~ 2% level. The entry Q(H) 4861 is the intensity of Hβ predicted from the total number of ionizing photons, Q(H), assuming that each hydrogen-ionizing photon produces one hydrogen atom recombination (see, for example, Osterbrock 1989). Q(H) 1216 indicates the Lyα intensity produced if each hydrogen ionizing photon results in one Lyα photon in the high density limit (i.e., no two-photon emission).

The lines starting with TOTL are the total intensities of the indicated lines, predicted by the 10-level atom, including all physical processes. A few of the entries suggest different contributions to the TOTL hydrogen lines. LA X 1216 is an estimate of the intensity of Lyα produced by excitation of n=2 by suprathermal electrons. C 13 6563 and C 14 4861 are the intensities of these Balmer lines produced by collisional excitation from the ground state. CION 0 is the net cooling due to collisional ionization of hydrogen, and 2 NU 0 is the total two photon emission. The lines beginning Strk and e sc are the contributions to the lines from Stark broadening and electron scattering. nFnu 4861 is the total diffuse continuous emission νf_ν(4861Å) at the wavelength of Hβ. This continuum includes two-photon, free-free, and free-bound emission from the nebula. BA C 0 and PA C 0 are the integrated intensities of the Balmer and Paschen continua respectively. The entries beginning with rest and COOL are indications of the cooling due to various sets of H lines. Entries marked INWD indicate the intensity of the fraction of the line emitted in the

inward direction (that is, towards the source of ionizing radiation). This is only meaningful on second or later iterations.

Molecular cooling. H2 l 2 is the intensity of the H_2 lines near 2μm, and H2 d is the cooling due to collisional dissociation of H_2. H-FB and H-FF are the free-bound and free-free continua of the H^- ion. H2+ and HEH+ are the cooling due to formation of H_2^+ and HeH^+.

Helium lines Ionized and singlet helium are each treated as ten-level atoms. Triplet helium is currently treated as an five level atom.

HE I 4471 is the case B intensity of this He I line. TOTL 5876 is the intensity of this line, as predicted by the model helium atom. Ca B 5876 is the case B intensity of this line. This second entry is generally smaller than the TOTL intensity because of collisional excitation from $2\ ^3S$. TOTL10830, TOTL 3889, and TOTL 7065 are the intensities of these lines, predicted by the model helium atom. C HE 0 is the total cooling due to collisional excitation within the helium atom. He I 2 and DevB 2 are intensities of the 2μm He I line. The first is the case B prediction, and the second is the actual intensity. This was computed using expressions from Cota (1987; Ph.D. Thesis). He I-DevB etc are sets of lines, the first being the case B intensity, and the second the actual intensity (the deviation from case B included). HE2C 304 and ESC r 304 are the produced and emitted intensities of the He II Lyα . He II 1640, 4686 are intensities from case B calculations. For low densities, Case B is probably more accurate for HeII emission than the results of the present 10-level atom, because of the assumption of complete l-mixing. At high densities the predictions of the 10-level atom are certainly better. The entries marked TOTL are more accurate at high densities ($N \gg 10^8$ cm^{-3} or when collisional or transfer effects are important.

Heavy elements. A few notes on deciphering the heavy element lines follow. A more complete discussion is presented in section 6.. In cases where the notation is unclear a careful examination of subroutine LINES (which enters the line fluxes into the arrays) or COOLR (which actually calculates the line intensities) should clarify the meaning. In general, the line wavelengths are given in Å, although the infrared fine structure lines are an exception. Often these IR lines have their wavelength given in microns (for instance, [O III] λ 88 μ m), but sometimes it is given in microns or tenths of microns (this is because the wavelengths are integers). Notes on specific iso-electronic sequences follow.

Li-sequence. Examples include C IV λ1549, O VI λ1034, Mg II λ2798, etc. A two level atom, with full treatment of optical depths and collisional excitation, is used. The intensity is the sum of both lines in the doublet.

Be-sequence. Examples include C III] λ1909, O V] λ1215, Si III] 1895, etc. A four level atom, solving for populations of the individual ^3P_j states, is used. The first printed intensity is the total intensity of the multiplet (both j=0,1 decays),

and this is followed by the intensities of individual lines. The intensity of the permitted ^1P_o - ^1S transition is also calculated. Optical depth and collisional effects on both the permitted and intercombination lines are included.

B-sequence. Examples include C II and O IV. The ground term is treated as a two level atom, with optical depth and collisional effects included. The ^4P -^2P_o lines are also predicted with a two level atom. The intensity printed is the total intensity of the multiplet.

^{3}P- ground term. Examples include [O III] and [O I]. The infrared fine structure lines are computed with full treatment of collisional and optical depth effects. A comment is printed at the end of the model if these lines mase or become optically thick. The populations of ^1D and ^1S are computed with a three-level atom. The intensity of the ^1D - ^3P transition is only that of the individual line (i.e. 5007), not the doublet.

$^4S^o$ - ground term. Examples include [O II] and [S II]. They are treated as a five level atom. Intensities of all individual lines, as well as co-added multiplets, are given.

A list of emission lines with negative intensities may follow the main block of lines. These are lines which heat rather than cool the gas (heating is negative cooling). This is not a problem, but occurs if the line de-excitation rate exceeds the line excitation rate. The most common reason for this to occur is if the line is radiatively excited by collisionally de-excited.

5.7.2. Page two

```
Cooling:  O  3 5007:0.229  O  3 4959:0.076  O  4   26:0.056  TOTL 2798:0.061  Cool 2798:0.061
Heating:  BFH1    0:0.707  BFHe    0:0.240  TotM    0:0.053

IONIZE PARMET:  U(1-) -1.3192  U(4-): -2.0008  U(sp): -2.49  Q(ion):   43.475  L(ion):  33.766 Q(low): 47.02    P(low)   36.155
ENERGY BUDGET:  Heat:  37.201  Coolg:  37.203  Error:  0.5%  Rec Lin:  36.106  WorkF:   37.409 F-F  H 24.097    PRADMX:1.54E+01
Column density  H12:8.784E+20  H II:8.458E+20  HI:3.253E+19  H-:    7.833E+11  H2:   7.251E+13 H2+:8.642E+11    He H+:4.128E+12
               Heff:0.000E+00
                  CH:0.000E+00   CH+:0.000E+00  OH:0.000E+00 OH+:    0.000E+00  O2:   0.000E+00  C2:0.000E+00       CO:0.000E+00
                 CO+:0.000E+00   H2O:0.000E+00H2O+:0.000E+00 O2+:    0.000E+00 C2+:   0.000E+00 H3+:0.000E+00     H3O+:0.000E+00
                CH2+:0.000E+00   CH2:0.000E+00 CH3:0.000E+00
<NH>:3.000E+03  <Tp>:1.26E+04  <TO3>:1.14E+04  Ne:3.352E+03  ti(snd):2.32E+11  NeN+dl:2.90E+24 <T(C3)>:1.15E+04 <E(C3)>:3.30E+03
He/Ha:9.72E-02  =   0.97*true  N/Oap:1.90E-01  =   1.14true  T(O3R):1.135E+04  L THIN:1.00E+30 <T(S2)>:1.01E+04 <E(S2)>:2.14E+03
T He+:1.10E+04  EHe+:3.16E+03  T(O+):1.10E+04  EO+:2.81E+03  iter/zn:   1.566  Te-low:3.97E+03 Te-high:1.46E+04  Hlu/zn:1.89E+00
  <a>:0.00E+00  erdeFe0.0E+00  Tcompt8.11E+07  Tthr3.75E+08  <Tden>: 1.25E+04  <dens>:7.07E-21 <Mol>:6.44E-01
Mean Jeans      l(cm)7.49E+19  M(sun)7.81E+05  smallest:     len(cm):4.26E+19  M(sun):1.44E+05 Alf(ox-tran):     0.0000
```

Cooling: This line indicates the fraction of the total cooling (defined here as in Osterbrock 1989; that is, the energy of the freed photoelectron) carried by the indicated emission lines. The designation of the line is given as in the emission-line spectrum, and this is followed by the ratio of the energy in the line to the total cooling. This is an important indication of the fundamental power-losses governing conditions in the model.

Heating: This line indicates the fraction of the total heating produced by various processes.

IONIZE PARMET to He/Ha. The first line begins with the log of the two ionization parameters defined in the header. The next number is the log of an ionization parameter which is often used in spherical geometries, such as H II regions or planetary nebulae. It is defined as

$$U_{sph} = \frac{Q(H)}{4\pi R_s^2 n_H c} \quad (55)$$

where R_s is the Strömgren radius, defined as the point where the hydrogen neutral fraction falls to $H^o / H_{tot} = 0.5$. If no ionization front is present, then U_{sph} is evaluated at the outer edge of the computed structure. The next two numbers are the log of the number of hydrogen ionizing photons ($h\nu \geq 1$ Ryd) exiting the nebula, and the log of the energy in this ionizing continuum. The last two numbers are the equivalent quantities, for non-ionizing ($h\nu < 1$ Ryd) radiation. These are either per unit area or by a shell covering 4π sr. These have been corrected for the r^{-2} dilution if per unit area, and so are directly comparable with the numbers given at the start of the calculation.

The second line gives an indication of the energy budget of the nebula. The first number is the log of the total heating (in ergs s^{-1}, but again either into 4π sr or cm^{-2}). The second number is the total cooling, in the same units. Cooling, as defined in Osterbrock (1989), is the total energy in collisionally excited lines and part of the recombination energy, but *does not* include recombination lines. The percentage error in the heating–cooling match follows. The next number is the total luminosity in recombination lines. The number indicated by WorkF is an indication of the work function (that is, the energy needed to remove bound electrons from the atom or ion) of the cloud. The work function and the total cooling do not add up to the total energy absorbed from the incident continuum because some recombination lines of helium and heavy elements contribute to both. The next number (F-F H) is the amount of energy deposited by free-free heating, and the last number (PRADMX) is the largest value of the ratio of radiation to gas pressure which occurred in the calculation.

The third line lists the column densities (cm^{-2}) of some ions and molecules. The first number (H12) is the total hydrogen column density (both H^o and H^+). The following two numbers are the column densities in H^+ and H^o only. The last four numbers are column densities in four ion - molecules (H-, H_2, H_2^+, and HeH^+). The first number on the next line is the column density in OH, and the second is the effective column density; that needed to attenuate the incident continuum by the calculated amount at 1.0 keV, if the absorber were cold neutral gas.

The fifth line gives some average quantities. The first is the mean hydrogen density (cm^{-3}). The next number is the mean electron temperature, weighted by the H^+ density. The third number is the mean temperature of the O^{2+} zone. This is useful because it can be compared directly with the temperature indicated by the [O III] lines. The 4th number is the mean electron density, and is followed by the sound travel time (seconds) across the nebula. The 6th number is the emission measure, the integral over radius of the product $n_e\ n_p\ f(r)\ dr$, where f(r) is the filling factor. The last two numbers on this line are the mean electron temperature and electron density, weighted with respect to the C^{2+} density.

The next line mainly gives some quantities deduced from the predicted emission-line spectrum. The first (He/Ha) number is the apparent helium abundance He/H, measured from the emission-line intensities using techniques similar to those described in Osterbrock (1989);

$$\left(\frac{\mathrm{He}}{\mathrm{H}}\right)_{apparent} = \frac{0.739 \times I(5876) + 0.078 \times I(4686)}{I(H\beta)} \qquad (56)$$

The intensity of both Hβ and HeI λ5876 are the total predicted intensities, and includes contributions from collisional excitation and radiative transfer effects. The intensity of HeII λ4686 is taken from Case B results, which are better than those of the model atom at low densities. The second number (i.e., 1.07*true), is the ratio of this deduced abundance to the true abundance. This provides a simple way to check whether ionization correction factors, or other effects, would upset the measurement of the helium abundance of the model nebula.

The next two numbers are the apparent N/O abundance (as deduced from the [N II] and [O II] spectra, as described by Wilkes et al. 1981) and the ratio of this to the true N/O abundance. The fifth number is the electron temperature of the [O III] zone, as indicated by the [O III] 5007/4363 ratio assuming emissivities at the low-density limit. The next number is the wavelength (in cm) where the nebula becomes optically thin to bremsstrahlung absorption. The last two numbers are the mean temperature and electron density of the S^+ zone.

The next line gives mean temperatures and electron densities for the He^+ and O^+ zones. The next number is the average number of iterations needed to converge each zone. The next two numbers are the lowest and highest electron temperatures which occurred in the model. The last number is related to the number of iterations needed to converge each zone.

The next line of the block gives the mean radiative acceleration, if the geometry is a wind model, followed by some time scales. The first is the time scale (s) to photoerode Fe (Boyd and Ferland 1987; this number is 0s if the γ-ray flux is zero). The next two are the Compton equilibrium timescale, and the thermal cooling timescale. Both are in seconds. The density weighted mean temperature, radius weighted mean density (gm cm^{-3}), and mean molecular weight follow.

The next line gives the mean Jeans length (cm) and Jeans mass (in solar units), followed by the smallest Jeans length and mass which occurred in the calculation. The last quantity is the spectral index α_{ox}, defined as in the header, but for the transmitted continuum (attenuated incident continuum plus emitted continuum produced by the cloud).

The next, optional, lines give some information concerning grains in the calculation. These lines give the mean temperature, drift velocity, and potential, for all of the grain populations included in the calculation.

```
Contin Optical Depths: COMP: 6.55E-04    H-: 3.05E-05 R(1300): 2.18E-04 H2+ 6.05E-06  HeTri:5.74E-04
 Pfa:3.27E-04   Pa:3.27E-04   Ba:3.41E-04   Hb:3.38E-04  La:2.69E-01   1r:4.995E+07  1.8:1.15E+07  4.:1.715E+06  21R:3.170E+04
Line Optical Depths: 10830: 1.14E+02  3889: 4.84E+00  5876: 2.73E-06  7065: 1.50E-06
   C  1656 1.47E+01  C  2326 1.36E-03  C  1335 2.71E+03  C  1909 1.06E-02  C   977 2.67E+04  C  1550 1.07E+04  C   386 3.56E+03
   N  1085 2.04E+02  N  1750 4.20E-03  N   990 1.74E+03  N  1486 9.39E-03  N   765 5.71E+03  N  1240 1.10E+03  N   373 8.65E+02
   N   374 1.06E+03  N  1200 3.22E+02  O  1304 5.94E+02  O   834 6.03E+03  O  1666 8.24E-02  O   835 4.01E+03  O  1402 4.80E-02
   O   789 3.60E+03  O   630 1.23E+04  O  1214 6.65E-02  O  1035 4.24E+02  O  1039 8.44E+01  O  1025 1.74E+02 Mg  2800 6.95E+03
  Al  1860 2.09E-02 Si  2335 1.14E-02 Si  1808 4.79E+03 Si  1207 5.91E+03 Si  1895 1.58E-01 Si  1397 4.11E+03  S  1256 4.37E+01
   S  1194 1.83E+01  S  1406 6.71E-02  S -1198 7.33E-02  S   786 2.18E+02  S   933 1.01E+03 Ca  3934 1.10E-02 Ca  3969 5.52E-03
 C157: 3.97E-04  N122: 3.29E-04  N205: 4.71E-05   N57: 4.17E-03  O146:-1.19E-03   O63: 3.10E-03   O88: 2.43E-02   O52: 6.19E-02
  O26: 8.40E-02  NE13: 1.98E-03  NE36:-1.73E-03  NE16: 6.11E-02   MG4: 5.57E-03  MG14:-4.88E-06   MG6: 3.25E-03  SI35: 1.61E-03
  S19: 2.66E-03   S34: 3.45E-03   S11: 4.64E-03   AR7: 3.55E-09   AR9: 3.51E-08  AR22:-3.86E-10  AR13: 5.89E-08   AR8: 3.65E-10
  CA3: 1.37E-08  CA12:-8.26E-12   CA4: 1.05E-08  Ne14: 9.27E-03  Ne24: 5.08E-02   Si3: 1.00E-20   Si4: 1.00E-20   Fe7: 1.00E-20
 Fe61: 1.00E-20  Fe23: 1.00E-20  Fe13: 1.00E-20 Si2.5: 1.65E-07 Si6.5:-7.53E-12  C610: 2.99E-05  C370: 2.41E-05
```

Optical Depths The first two lines give the optical depth of the nebula in various continua. These are the total optical depths, including the correction for stimulated emission, and will be negative if maser action occurs. The labels, and their interpretation, follows: COMP, Thomson scattering; H-, negative hydrogen ion at maximum cross section; R(1300), Rayleigh scattering at 1300Å; H_2 , H_2^+ ; HeTri, helium triplets. These are total optical depths, including, for instance, grain opacity if grains are present. The next line gives total optical depths for various hydrogen and helium ionization edges and lines. The next two large blocks are sets of optical depths in various emission lines, and the last set of lines are optical depths in the infrared fine structure lines.

```
Old hydro optical depths:    1 9.99E+07    2 1.00E-20    3 1.00E-20    4 1.00E-20    5 1.00E-20    6 1.00E-20    7 1.00E-20
                    Lines:  2-1 9.96E+19  3-2 3.34E-02  4-3 3.33E-04  5-4 1.66E-05  6-5 2.56E-06  7-6 2.56E-07  8-7 2.56E-08
New hydro optical depths:    1 5.00E+07    2 7.91E-06    3 1.53E-05    4 4.15E-06    5 1.05E-12    6 2.44E-12    7 1.06E-11
                    Lines:  2-1 2.05E+06  3-2 9.47E-03  4-3 2.21E-09  5-4 1.73E-09  6-5-6.23E-12  7-6 2.15E-08  8-7 2.82E-07
```

Hydrogen and helium optical depths in continua and n $\rightarrow$ n-1α transitions follow. The first two lines are the optical depths assumed at the start of the present iteration, and the second pair of lines gives the newly computed total optical depths. Negative optical depths indicate maser action. For each of the pairs of lines, the first line is the optical depth at thresholds of the first seven levels of hydrogen. The second line gives the optical depths in the first seven of the n $\rightarrow$ n-1α transitions of hydrogen or helium.

```
Hydrogen  -1.102 -0.036                          Log10 Mean Ionisation (over volume)
Helium    -1.431 -0.180 -0.519
Carbon    -2.981 -0.818 -0.302 -0.548 -1.186
Nitrogen  -1.409 -0.743 -0.370 -0.573 -1.149 -1.830
Oxygen    -1.131 -0.851 -0.258 -0.795 -1.168 -2.360 -4.279
Neon      -1.898 -1.375 -0.154 -0.788 -1.102 -2.621 -6.100
Sodium    -3.019 -0.922 -0.218 -0.727 -1.105 -2.070 -4.173
Magnesium -2.302 -0.456 -0.383 -0.748 -1.327 -2.302 -4.767
Aluminum  -3.336 -0.507 -0.518 -0.471 -1.352 -2.552 -5.121
Silicon   -4.332 -0.551 -0.608 -0.480 -0.865 -2.380 -5.161
Sulphur   -3.501 -0.817 -0.430 -0.575 -1.039 -1.017 -1.662
Argon     -1.578 -1.080 -0.321 -0.632 -1.112 -1.126 -1.611 -2.661 -4.131
Calcium   -2.207 -0.903 -0.286 -0.767 -1.263 -1.045 -1.506 -2.393 -3.918
Iron      -2.607 -0.873 -0.828 -0.385 -1.220 -0.826 -1.057 -2.226 -4.470
Nickel    -3.115 -0.806 -1.353 -0.347 -1.547 -0.808 -0.833 -1.741 -3.505
            1      2      3      4      5      6      7      8      9     10     11     12     13     14     15     16     17

Hydrogen  -1.431 -0.016                          Log10 Mean Ionisation (over radius)
Helium    -1.771 -0.374 -0.251
Carbon    -3.296 -1.121 -0.449 -0.407 -0.753
Nitrogen  -1.755 -1.044 -0.500 -0.457 -0.755 -1.294
Oxygen    -1.472 -1.144 -0.384 -0.543 -0.748 -1.810 -3.634
Neon      -2.249 -1.688 -0.318 -0.554 -0.688 -2.072 -5.383
Sodium    -3.361 -1.207 -0.382 -0.519 -0.719 -1.539 -3.541
Magnesium -2.577 -0.717 -0.470 -0.493 -0.895 -1.739 -4.111
Aluminum  -3.654 -0.770 -0.612 -0.335 -0.948 -1.995 -4.450
Silicon   -4.667 -0.837 -0.725 -0.421 -0.563 -1.877 -4.516
Sulphur   -3.810 -1.128 -0.622 -0.596 -0.822 -0.666 -1.175
Argon     -1.925 -1.360 -0.519 -0.614 -0.847 -0.762 -1.116 -2.164 -3.678
Calcium   -2.521 -1.177 -0.462 -0.758 -1.023 -0.683 -1.025 -1.872 -3.488
Iron      -2.941 -1.203 -1.090 -0.539 -1.148 -0.590 -0.664 -1.691 -3.833
Nickel    -3.457 -1.135 -1.587 -0.537 -1.567 -0.653 -0.516 -1.263 -2.906
```

Mean Ionization. The two large blocks of output give the mean ionization, averaged over volume, and over radius. The numbers printed are the log of the mean ionization fraction in the various stages.

Continuum. If the PRINT CONTINUUM command is included then the following tables related to the transmitted continuum will the printed.

X-Ray Continuum. The next line gives the photon fluxes (cm^{-2} s^{-1}) in various X-ray bands, if the continuum extends to X-ray energies. The units of the energy bands are keV. The numbers are the numbers of photons exiting the cloud, integrated over the energy bands. This is the net continuum, that is, the incident continuum, less attenuation, with diffuse re-emission from the cloud added on.

Normalized Continuum. This block is a set of ordered pairs giving the emergent Balmer continuum, relative to the continuum which entered the cloud. The first number of each pair is the frequency in Rydbergs. The second is the ratio of the emergent continuum to the incident continuum (i.e., that which went into the cloud). In the absence of optical depth or diffuse emission effects, this block will be equal to 1.000 throughout.

Emergent Continuum. This block gives ordered pairs of energy (in Rydbergs) and the emergent continuum. It is expressed as photon fluxes (phot Ryd^{-1} cm^{-2}) corrected for r^{-2} dilution , so as to be directly comparable with the continuum which went into the cloud.

Lyman continuum. The last block of information gives the intensities of some of the emergent diffuse fields, and is only printed for open geometries. The first part is the energy in Rydbergs and the log of the product νf_ν for the Lyman continuum emerging from the illuminated face of the cloud (the side towards the central source of ionizing radiation). The number of Lyman continuum photons and the total energy in the Lyman continuum is then given. The end of the block gives the inward and outward diffuse fields in the Lyman, Balmer, and Paschen continua. These numbers are only meaningful for a plane parallel geometry.

6. THE EMISSION LINES

This section gives a complete list of all emission lines predicted by CLOUDY. In the following, the first column gives the four character label printed in the final array listing and the second column gives the wavelength of the line. The latter is usually in Å, although some fine-structure lines are given in microns or tenths of microns, and continua are usually indicated by a wavelength of zero. The third column item indicates whether the entry is a heat source (indicated by h), a coolant (c), a recombination line (r), or an intensity entered for information only i). The last column of the table gives a brief description of the meaning of the line prediction. More information about individual lines can usually be had by examining the comments associated with the actual calculation of the line strength (in subroutine COOLR) or in subroutine LINES, where the line intensity is entered into the storage array.

The Emission Lines

Label λ Description

```
TOTL  4861 r   total H-beta from 10-level atom
TOTL  1216 i   total Ly-a from 10-level atom
Inci     0 i   total luminosity in incident continuum
TotH     0 i   total heating, all forms, information since individuals added later
BFH1     0 h   hydrogen photoionization heating, ground state only

BFHx     0 h   hydrogen photoionization heating, all excited states
He1i     0 c   net cooling due to collisional ionization of Heo
3He1     0 h   this is the heating due to 3-body recombination
He2i     0 c   net cooling due to collisional ionization of He+
3He2     0 h   this is the heating due to 3-body recombination

BFHe     0 h   total helium photoionization heating, all stages
TotM     0 h   total heavy element photoionization heating, all stages
FF H     0 h   total free-free heating
ComH     0 h   Compton heating
H- H     0 h   H- heating

H-Hc     0 c   induced H- cooling
GraH     0 h   gas heating by grain photoionization
GraC     0 c   gas cooling by grain collisions
extH     0 h   "extra" heat added to this zone, from HEXTRA command
extC     0 c   "extra" cooling added to this zone, from CEXTRA command

pair     0 h   heating due to pair production
Ca B  4861 i   H beta recombination, assuming case B
Ca B  1216 i   case b intensity of Ly-alpha, no two photon
Q(H)  4861 i   H-beta computed from Q(H) and specified covering factor
Q(H)  1216 i   Ly-alpha from Q(H), high-dens lim, specified covering factor

TOTL  6563 r   H-alpha emission from 10-level atom
TOTL  4861 i   H-beta emission from 10-level atom
TOTL  4340 r   H-gamma emission from 10-level atom
TOTL  4102 r   H-delta emission from 10-level atom
TOTL 18751 r   P-alpha emission from 10-level atom

TOTL 12818 r   P-beta emission from 10-level atom
TOTL 10938 r   P-gamma emission from 10-level atom
TOTL 40512 r   5-4 emission from 10-level atom
TOTL 26252 r   6-4 emission from 10-level atom
TOTL 74578 r   6-5 emission from 10-level atom

2 NU     0 i   2-photon emission from 10-level atom
TOTL  1216 i   Ly-alpha from 10-level atom
```

```
TOTL  1026 r   Lyman beta is special because of OI fluorescense
TOTL   973 r   Ly-gamma emission from 10-level atom
TOTL   950 r   Ly-delta emission from 10-level atom

TOTL   938 r   Ly-epsilon emission from 10-level atom
LA X  1216 i   la contribution from suprathermal secondaries from ground
Ind2  1216 i   "Ly alpha" produced by induced two photon
C13c  6563 c   H-alpha collision cooling from ground state
C13h  6563 h   H-alpha collision heating from ground state

C14c  4861 c   H-beta collision cooling from ground state
C14h  4861 h   H-beta collision heating from ground state
Pump  4861 i   H-beta produced by continuum pumping in optically thin ld limit
CION     0 c   collision ionization cooling of hydrogen
3bHt     0 h   this is the heating due to 3-body recombination

inwd  1216 i   inward escaping Ly-alpha
inwd  6563 i   inward escaping Balmer-alpha
inwd  4861 i   inward escaping Balmer-beta
inwd 18751 i   inward escaping Paschen alpha
Strk  1216 i   Stark broadening contribution to line

Strk  6563 i   Stark broadening contribution to line
Strk  4861 i   Stark broadening contribution to line
Strk 18751 i   Stark broadening contribution to line
Strk 40512 i   Stark broadening contribution to line
Dest  1216 i   portion of line lost due to absorp by background opacity

Dest  6563 i   portion of line lost due to absorp by background opacity
Dest 40516 i   portion of line lost due to absorp by background opacity
Dest  4861 i   portion of line lost due to absorp by background opacity
Dest 18751 i   portion of line lost due to absorp by background opacity
e sc  1216 i   electron scattering escape contribution to line

e sc  6563 i   electron scattering escape contribution to line
e sc  4861 i   electron scattering escape contribution to line
e sc 18751 i   electron scattering escape contribution to line
e sc 40512 i   electron scattering escape contribution to line
e-e+   511 i   511keV annihilation line

nFnu  4860 i   diffuse cont-nu.fnu(4861) due to all computed emission processes
nFnu  1215 i   diffuse cont-nu.fnu(1216) due to all computed emission processes
Inci  4860 i   incident continuum at H-beta, no attenuation
Inci  1215 i   incident continuum at Ly-alpha, no attenuation
BA C     0 i   integrated Balmer continuum emission

PA C     0 i   Paschen continuum emission
GraT     0 i   total grain reradiation, lines, collisions, and incident continuum
GraI     0 i   grain heating by incident continuum
GraL  1216 i   part of grain heating due to destruction of Ly alpha
H FF     0 c   H brems (free-free) cooling

FF X     0 i   part of H brems, in x-ray beyond 0.5KeV
ComC     0 c   total Compton cooling
Expn     0 c   expansion cooling, only non-zero for wind
eeff     0 c   electron - electron brems
H FB     0 c   H recombination cooling

Hind     0 c   cooling due to induced rec of hydrogen
He3i     0 c   cooling due to induced rec of fully ionized helium
Cycn     0 c   cyclotron cooling
Cool  1216 c   collisionally excited La cooling
Heat  1216 h   collisionally de-excited La heating

Crst   960 c   cooling due to n>2 Lyman lines
Hrst   960 h   heating due to n>2 Lyman lines
Cool  6563 c   cooling due to collisional excitation of Balmer alpha
Heat  6563 h   heating due to collisional de-excitation of Balmer alpha
Crst  4861 c   cooling due to n>3 Balmer lines

Hrst  4861 h   heating due to n>3 Balmer lines
Cool 18751 c   cooling due to collisional excitation of Paschen alpha
Heat 18751 h   heating due to collisional de-excitation of Paschen alpha
Crst     0 c   cooling due to higher Paschen lines
Hrst     0 h   heating due to higher Paschen lines
```

```
H2 l     2 c   H2 rotation lines from Lepp and Shull ApJ 270, 578.
H2dC     0 c   H2 dissociation by H atoms (not e)
H2dH     0 h   heating by H2 dissociation by Lyman continuum
H-FB     0 c   neg H ion free-bound emission
H2+      0 c   H+ + H => H2+ + photon continuum cooling

HEH+     0 i   HeH+ formation cooling
COdh     0 h   carbon monoxide co photodissociation
CO C     0 c   cooling due to coll of vib rot levels
HeFF     0 c   He brems emission
HeIn     0 c   He ionization cooling

HeFB     0 c   He recombination cooling
MeFB     0 c   heavy element recombination cooling
MeFF     0 c   metal brems emission
ToFF     0 i   total brems emission
HeIC   584 c   Helium I 584, collisional excitation only

esc    584 i   Ly alpha escaping cloud, at present includes 626
He2p   910 i   He I two photon emission from 10 level atom
He I   504 i   emission from recombination to grnd state
He I  4471 i   HeI 4471 recombination only, fit to Brocklehurst '72
TOTL  5876 i   total 5876, from n-level atom

Ca B  5876 r   He I 5876 REC, simple fit to Brocklehurst
TOTL 10830 i   10830 from n-level atom
reco 10830 i   10830 produced by radiative recombination
coll 10830 i   collisionally excited 10830 estimated from Clegg 1987 (not model atom)
inwd 10830 i   inward escaping HeI 10830

TOTL  3889 i   3889 from n-level atom
TOTL  7065 i   7065 from n-level atom
CcHE     0 c   total collisional He I triplet line cooling, from n-level atom
ChHE     0 h   total collisional de-exec He I heating, from n-level atom
He I     2 i   case B He I 2.06 micron

DevB     2 i   Cota estimate of He I 2.06 micron
TOTL     2 i   He I 2.06 micron from model atom, all physics included
He I  5016 i   case B emission
DevB  5016 i   case B corrected for Lyman line destruction
He I  3965 i   case B emission

DevB  3965 i   case B corrected for Lyman line destruction
He I  3614 i   case B emission
DevB  3614 i   case B corrected for Lyman line destruction
He I  3448 i   case B emission
DevB  3448 i   case B corrected for Lyman line destruction

HeII   228 i   Lyman continuum
HE2C   304 c   He II 304 collisionally excited
He2C   911 i   He II Balmer continuum escaping from cloud
TOTL   304 i   304 predicted by 10-level atom
TOTL  1640 i   1640 predicted by 10-level atom

TOTL  4686 i   4686 predicted by 10-level atom, only valid at high densities
TOTL  1217 i   1216 predicted by 10-level atom, only valid at high densities
Ca B  1640 i   He II 1640, case B at low densities
Ca B  4686 i   He II 4686, case B
Mion     0 c   cooling due to collisional ionization of heavy elements

C  1  1656 c   Carbon I 1656, collision strength from van Regemoter
REC   1656 i   C I 1656 recomb; n.b. coll deexcitation not included
C Ic  9850 c   C I 9850, coll excit, both 5007+4959 together
C Ir  9850 i   C I 9850, recom both 5007+4959 together, rec coef from apj sup 73, 513.
TOTL  9850 i   total intensity, all processes, C I 9850

C  1  8727 c   C I 8727; equivalent to 4363
C  1  4621 c   1S - 3P
C  1   610 c   C I 610 micron, only H0, H2 included in excitation
C  1   370 c   C I 370 micron, only H0, H2 included in excitation
C  2   158 c   C II 158 micron, both e- and H0, H2 included in excitation

C 2h   158 c   heating by absorption of 157 micron continuum
TOTL  2326 i   total CII] 2326 with correction for Balmer continuum abs
```

```
C  2  2326 c   collisionally excited CII] 2326
inwd  2326 i   inward escaping C II 2326
Phot  2326 i   photoproduction, Helfand and Trefftz

TOTL  1335 i   total intensity of C II 1335
C  2  1335 c   collisionally excited part of CII 1335
REC   1335 i   1335 recombination, coef from Ferland et al 1984
C II  3134 c   intercombination line with same upper state as 1335
C  2  4267 i   C II 4267, rate from Ferland et al.

TOTL   977 i   total CIII] 1909, recombination + collisional + pumped excitation
C3 C   977 c   collisionally excited C III 977
C3 R   977 i   recombination contribution to C III 977
C3 p   977 i   CIII 977 pumped by continuum near 386A
TOTL  1909 c   CIII  1909 collision

inwd  1909 i   inward escaping CIII] 1909
C  3  1907 i   j-2 to ground
C  3  1909 i   j-1 to ground
C3 R  1909 i   C III 1909 recombination from Storey
Phot  1909 i   C III] 1909 following relax following inner shell photoionization

C  3  2297 i   C III 2297, diel rec coef from Stickland et al
C  3  4187 i   C III 4187
C  3  4649 i   diel contr from Nussbaumer and Storey, Ast Ap '84
TOTL  1549 i   total 1549, collisions plus pumping
C  4  1549 c   C IV 1549, collisional part

Pump  1549 i   C IV 1549, pumped by continuum
inwd  1549 i   inward part of C IV 1549
DEST  1549 i   part of line destroyed by photoionization of Balmer continuum
C4 r     1 i   recombination CIV 1549 from CV
C  4  4659 i   C IV 4659, recombination

C  5    40 c   C V 40.3 A, collisionally excited, g-bar approx
C  6    34 c   C VI 33.7 A, collisionally excited, g-bar approx
C 6r    34 i   K-alpha due to recombination of stripped ion
N  1  5200 c   Nitrogen I 5200
REC   5200 i   5200 rec, both rad+di, 1/3 of total to doublets

N  1  1200 c   collisionally excited part
N  2  6584 c   N II 6584 alone
N  2  6548 c   N II 6548 alone
REC   6584 i   N II 6584 alone, recombination contribution
N  2  5755 c   N II 5755 from Seaton 75

N  2   122 c   N II fine structure line
N  2   203 c   N II fine structure line
N  2  4239 i   N II 4239 recombination, effective rec coef from Williams et al
N  2  5680 i   N II 5680 recombination
N  2  2140 c   N II 2140 intercombination line

N  2  1084 c   N II 1084, CS guess from g-bar
N3cn  4640 i   continuum pumped "Bowen" NIII, optically thin excited line
N3cn  4634 i   continuum pumped "Bowen" NIII, optically thin excited line
N3cn  4642 i   continuum pumped "Bowen" NIII, optically thin excited line
N  3  1750 c   N III 1750, collisionally excited

N  3    57 c   N III 57 micron fine structure line
TOTL   990 i   total NIII 990, both electron excitation and continuum pumping
N 3c   990 c   N III 989.8, collisionally excited
N 3p   990 i   N III 989.8, continuum pumped
N  4  1486 c   N IV 1486, collisionally excited

N  4   765 c   N IV 765, collisionally excited
N  4  1718 i   N IV 1718, diel rec coef from Stickland et al
TOTL  1240 i   NV 1240, total emission, collisions plus pumping
N  5  1240 c   N V 1240, collisionally excited part
Pump  1240 i   continuum pumping of NV 1240

N  6    29 c   N VI 29A, collisionally excited
N  7    25 c   N VII 25A, collisionally excited
N 7r    25 i   recombination K-alpha from fully stripped ion
O  1  6300 c   total Oxygen I  6300, including line optical depth
O  1  6363 c   total Oxygen I  6363, including line optical depth
```

```
O  1  5577 c   auroral OI
O  1   630 c   O I fine structure line
O 1h   630 h   heating by absorption of OI 63 micron line
O 1f   630 i   continuum fluorescent excitation of OI 63 micron line
O  1  1470 c   O I fine structure line

O  1  7774 i   estimate of rec coef, 50% of total  O I rec
TOIc     0 c   total collisional cooling due to 6-level OI atom
TOIh     0 h   total collisional heating due to 6-level OI atom
6lev  8446 i   OI 8446 from six level atom
6lev  1304 i   OI 1304 from six level atom

6lev  1039 i   OI 1039 from six level atom
6lev  4368 i   OI 4368 from six level atom
6lev    13 i   OI 1.3 micron from six level atom
6lev    11 i   OI 1.1 micron from six level atom
6lev    29 i   OI 2.9 micron from six level atom

6lev    46 i   OI 4.6 micron from six level atom
TOTL  3727 c   O II 3727, all lines of multiplet together
TOTL  7325 c   O II 7325, all lines of multiplet together
IONZ  3727 i   line produced by photoionization of Oo; already included in TOTL
IONZ  7325 i   line produced by photoionization of Oo; already included in TOTL

O II  3729 i   five level atom calculations; D5/2 - S3/2
O II  3726 i   D3/2 - S3/2 transition
O II  2471 c   both 2P 1/2 and 3/2 to ground
O II  7323 i   P1/2-D5/2 and P3/2-D5/2 together
O II  7332 i   P1/2-D3/2 and P3/2-D3/2 together

O II   834 c   O II 833.8 coll excit
O  2  4651 i   O II 4651 recombination, coef from Williams et al
O  3  1663 c   O III 1661+1666
Phot  1663 i   contribution to OIII 1664 due to inner shell (2s^2) ionization
Augr  1663 i   contribution to OIII 1664 due to K-shell ionization

Rec   1663 i   upper limit to rate coefficient for dielectronic recomb, NS84
O  3  5007 c   O III  5007 alone, collisions, tot OIII is this times 1.333
O  3  4959 c   O III  4959 alone, collisions, tot OIII is this times 4
LOST  5007 i   O III 5007 lost through excit photo
TOTL  4363 c   O III 4363,collisions from five level atom

Rec   4363 i   O III 4363 recombination, coef from Burgess and Seaton
O  3  2321 c   collisional excitation of 2321, 5-level atom
C EX  4363 i   charge exchange, Dalgarno+Sternberg ApJ Let 257, L87.
C EX  5592 i   charge exchange rate, D+S
O  3   880 c   O III fine structure line, collisions only

O  3   520 c   O III fine structure line, collisions only
O  3   834 c   O III 834A, collisions only
O  3  3341 i   Burgess and Seaton O III RECOMB, 3341+3312+3299
O  4    26 c   O IV 26 micron
O  4  1402 c   O IV 1402, collisions

InSh  1401 i   inner shell photoionization, relaxation
O  4   789 c   O IV 789A
O  4  3412 i   Burgess-Seaton O IV 3412 (whole multiplet twice as strong)
O  5   630 c   O V 630, collisional excitation
TOTL  1218 c   O V 1214, collisional excitation

O  5  1218 i   j=1 to ground
O  5  1214 i   the other line
O  5  5112 i   BS O V 5112, recombination
TOTL  1035 i   O VI 1035, total of pumping and collisional excitation
O  6  1035 c   O VI 1035, collisional excitation

Pump  1035 i   O VI 1035, continuum pumping
O  7    22 c   O VII 21.6A, collisional excitation, g-bar
TOTL    19 i   O VIII 18.97A, collisional excitation and recombination
O  8    19 c   O VIII 18.97A, collisional excitation, g-bar
O 8r    19 i   recombination from fully stripped ion

Ne 2   128 c   Neon II 12.8 micron
Ne 3   156 c   Ne III fine structure line
```

```
Ne 3   361 c   Ne III fine structure line
Ne 3  3869 c   Ne III  3869, of 3968+3869 doublet
Ne 3  3968 c   Ne III  3968, of 3968+3869 doublet

Ne 3  3343 c   NeIII auroral line
Ne 3  1815 c   NeIII auroral line
Ne 4  2424 c   Ne IV 2424, collisional excitation
Ne 4  4720 c   Ne IV N=3 lines, three level atom approx
Ne 4  1602 c   Ne IV N=3 lines, three level atom approx

Ne 5  3426 c   Ne V 3426 of 3426, 3346 doublet
Ne 5  3346 c   Ne V 3346 of 3426, 3346 doublet
Ne 5  2976 c   auroral line
Ne 5  1575 c   collisionally excited
Ne 5   242 c   Ne V 24.2, 14.3 micron

Ne 5   143 c   Ne V 24.2, 14.3 micron
Ne 5  1134 c   both components of 5S-3P 1140, 1131 doublet
Ne 6    76 c   Ne VI fine structure lines
Ne 6  1007 c   Ne VI] 1007, collisionally excited
Ne 7   895 c   Ne VII 895, collisionally excited

Ne 8   774 c   Ne VIII 774, collisionally excited
Ne 9    13 c   Ne 9 13.5A, collisionally excited
Ne10    12 c   Ne 10 12.13A, collisionally excited
NeLr    12 i   Ne Ly-alpha recombination from fully stripped ion
Na D  5893 c   sum of Na D lines

NaLr    10 i   Na Ly-alpha recombination from fully stripped ion, 10A
Mg 1  4571 c   Magnesium I 4571, O I data for coll strength and trans prob
TOTL  2798 c   Mg II 2800 tot intensity, corrected for photoionization loss
Cool  2798 c   total cooling, including absorbed photons
phot  2798 i   fraction lost due to photoionization of upper level by Balm cont

Mg 4     4 c   Mg IV 4.5 micron
Mg 5    13 c   Mg V  13.5 micron emission
Mg 5    56 c   Mg V 5.6 micron emission
Mg 5  2751 c   (Mg 7) 2571, 2893
Mg 6  1806 c   MG VI

Mg 7  2629 c   (Mg 7) 2510, 2629
Mg 7   433 c   Mg 7 433
Mg 8   435 c   Mg 8 435
Mg 8     3 c   Mg 8 3.03 micron
Mg 9   705 c   Mg 9 704.5

Mg 9   368 c   Mg 9 368,1
Mg10   615 c   Mg 10 614.9
Mg11     9 c   Mg 11 9.17A
Mg12     7 c   Mg 12 7.11A
MgLr     7 i   recombination from fully stripped ion

totl  2665 c   total emission in Al II] 2669.7, 2660 doublet
Al 2  2669 i   emission in Al II] 2669 alone
Al 2  2661 i   emission in Al II] 2661 alone
Al 3  1860 c   Al III
Al10   639 c   Al X

AlLr     6 i   recombination from fully stripped ion
Si 2    35 c   Silicon II 35 micron
Si 2  2335 c   SI II] 2336,
Si 2  1808 c   SI II 1808, permitted resonance line, collisionally excited
Si 3  1207 c   SI III 1207, collisionally excited

Si 3  1895 c   Si III) 1895, collisionally excited
PHOT  1895 i   photoproduction by inner shell removal
Si 4  1397 c   Si IV 1397, collisionally excited
Si 6    19 c   SI VI 1.96 micron, collisionally excited
Si 7  2148 c   SI VII, 2148, O III like, collisionally excited

Si 7    25 c   Si VII 2.48, 6.49 micron, collisionally excited
Si 7    65 c   Si VII 2.48, 6.49 micron, collisionally excited
Si 8  1446 c   SI VIII 1446, OIII like, collisionally excited
Si 8    61 c   SI 8, 61.0A, collisionally excited
Si 9  1985 c   SI IX 1985, 2150, collisionally excited
```

```
Si 9   949 c   collisionally excited
Si 9  1815 c   collisionally excited
Si 9     3 c   SI 9, 3.86, 2.84 3P fine structure lines
Si 9     2 c   SI 9, 3.86, 2.84 3P fine structure lines
Si 9   691 c   both components of 5S-3P doublet

Si 9    55 c   SI 9 55.3A, collisionally excited
Si10   606 c   SI 10 606A, actually group of 4 intercombination lines.
Si10 14300 c   SI 10 1.43 micron, collisionally excited
Si11   583 c   SI XI 582.9, collisionally excited
Si11    44 c   SI XI 43.7A, collisionally excited

Si12    41 c   SI XII 40.9A, collisionally excited
Si13     7 c   SI XIII 6.7A, collisionally excited
Si14     6 c   SI XIV 6.17A, collisionally excited
SiLr     6 i   recombination from fully stripped ion
S 1R  1807 i   this is to check whether photoexcit of S II is ever important

S  2  6720 c   S II 6731 + 6716 together
S  2  4074 c   S II 4070 +4078 together
S  2 10330 c   S II N=3 lines, all four lines together
S II  6731 i   individual line from five level atom
S II  6716 i   individual line from five level atom

S II  4070 i   individual line from five level atom
S II  4078 i   individual line from five level atom
S II 10323 i   individual line from five level atom
S II 10289 i   individual line from five level atom
S II 10373 i   individual line from five level atom

S II 10339 i   individual line from five level atom
S II  1256 c   resonance line near NV, collisionally excited
S  3    18 c   S III fine structure 18.7
S  3    34 c   S III fine structure 34
S  3  9532 c   [S III] 9532 alone

S  3  9069 c   [S III] 9069 alone
S  3  6312 c   [S III] 6312, transauroral temperature sensitive
S  3  3722 c   [S III] 3722, same upper level as 6312
S  3  1198 c   WL, other data, from Ho + Henry Ap.J. 1984
S  3  1729 c   S III intercombination line with no atomic data (wild guess)

S  4   105 c   S IV 10.5 micron, collisionally excited
S  4  1406 c   S IV 1406, collisionally excited
S  5  1198 c   S V 1198, collisionally excited
S  5   786 c   S V 786.5, collisionally excited
S  6   933 c   S VI 933+944, collisionally excited

S  9  1715 c   S IX 1715, 1987, collisionally excited
S 10  1213 c   S X 1213, 1197, collisionally excited
S 11  1826 c   S XI 1615, 1826, collisionally excited
S 12   520 c   S XII 520, group of four intercombination lines all together
S 12  7611 c   S XII 7625, WL from Moore NBS, collisionally excited

S 13   488 c   S XIII 488.4, 1909 like, collisionally excited
S LR     5 i   S 16 4.7A Ly a recombination from fully stripped ion
Ar 2     7 c   Argon II 7 micron
Ar 3  7135 c   Argon III 7136
Ar 3  7751 c   Argon III 7751

Ar 3    22 c   Argon III 21.8, 9 micron lines
Ar 3     9 c   Argon III 21.8, 9 micron lines
Ar 4  4740 c   Argon IV 4711 + 4740 together, 4740=90%
Ar 4  7335 c   [AvIV] auroral line
Ar 5  7007 c   Argon V, 3P lines, 7007, collisionally excited

Ar 5  6435 c   Argon V, 3P lines, 6435, collisionally excited
Ar 5   131 c   Argon V fine structure lines, 13.09, 7.903 micron line
Ar 5    79 c   Argon V fine structure lines, 13.09, 7.903 micron line
Ar 6     4 c   Ar VI 4.53 micron
Ar14  4413 c   Ar XIV 4413, predicted lambda, not observed(??)

Ar15   409 c   collisionally excited
ArRr     4 i   Ar 18 ly a recombination 3.7A from fully stripped ion
```

```
Ca 2  3933 c   coll excit calcium k+h
Ca 2  8579 c   infrared triplet
Ca 2  7306 c   forbidden line

Phot  3933 i   fraction H Ly-alpha destruction of excited levels
Phot  7306 i   fraction H Ly-alpha destruction of excited levels
Ca2K  3934 i   individual lines from five level atom
Ca2H  3969 i   individual lines from five level atom
Ca2X  8498 i   individual lines from five level atom

Ca2Y  8542 i   individual lines from five level atom
Ca2Z  8662 i   individual lines from five level atom
CaF1  7291 i   individual lines from five level atom
CaF2  7324 i   individual lines from five level atom
Rec   3933 i   reccombination contribution to CaII emission

Ca 4    32 c   Ca IV 3.2 micron
Ca 5     4 c   Ca V 4.16, 11.47 micron
Ca 5    11 c   Ca V 4.16, 11.47 micron
Ca 5  6087 c   Ca V optical and uv lines, collisional excitation, 3-level atom
Ca 5  5311 c   Ca V optical and uv lines, collisional excitation, 3-level atom

Ca 5  2414 c   Ca V optical and uv lines, collisional excitation, 3-level atom
Ca 5  3997 c   Ca V optical and uv lines, collisional excitation, 3-level atom
CaLr     3 i   Calcium Ly a recombination from fully stripped ion
Fe 2    48 i   emission from Netzer's 3-level atom
Fe 2     7 i   emission from Netzer's 3-level atom

Emis     3 i   emission from Netzer's 3-level atom
Fe 2  1216 r   Ly-alpha pumping of FeII, absorbed by Balmer continuum
Cool     3 i   net cooling due to UV lines
TFe2     0 c   total of all UV+optical FE II cooling
FEIR     0 c   sum of all IR cooling from 6D ground state

Fe 2     4 c   the group of [Fe II] lines near 4 microns
Fe 2     2 c   the group of [Fe II] lines near 1.7 microns
Fe 2     1 c   the group of [Fe II] lines near 1.2 microns
Fe 3     0 c   sum of 3p and 3g states together
Fe 3  5270 c   Fe III 5270, predictions cop-out from garstang et al 78

Fe 3  4658 c   Fe III 5270, predictions cop-out from garstang et al 78
Fe 3  1122 c   FeIII 1122 entire multiplet
Fe 5  3892 c   Fe V  3892+3839
Fe 6     0 c   all of 2G lines together first
Fe 6  5177 c   Fe VI 5177, approximate correct

Fe 7  6087 c   FE VII 6087
Fe 9   171 c   FE 9 171.1
Fe 9   245 c   FeIX 245 j=1 fast decay
Fe 9   242 c   FeIX 242 j=1 slower decay
Fe10   352 c   FE 10 352.1

Fe10  6374 i   total (coll, pumped)
Coll  6374 c   collisional contribution
Pump  6374 i   pumped by continuum fluorescense
 352  6374 c   collisions of E1 line
Fe11  7892 i   total intensity of line

Coll  7892 c   contribution from collisional excitation
Pump  7892 i   contribution from continuum fluorescense
Fe11     6 c   IR fine structure line
Fe11  2649 c   collisional excitation
Fe11  1467 c   collisional excitation

Fe11   354 c   Fe 11 353.8
Fe12  1242 c   Fe 12, 1242, 1349 together, collisional excitation
Fe12  2170 c   Fe 12, 2170, 2406 together, collisional excitation
Fe12  2568 c   Fe12 2904, 2567, 3567, 3073 together, collisional excitation
Fe12   357 c   Fe 12 357.3, collisional excitation

Fe13   363 c   Fe 13 363.3, collisional excitation
Fe14   347 c   Fe 14 262.3, 347, collisional excitation
Fe14   262 c   Fe 14 262.3, 347, collisional excitation
Fe14  5303 i   total intensity of line
Coll  5303 c   contribution from collisional excitation
```

```
Pump  5303 i   continuum fluorescense
 347  5303 c   collisional excitation of E1 line
Fe15   284 c   Fe 15 284.1, collisional excitation
Fe16   343 c   Fe 16 343.5, collisional excitation
Fe17    17 c   2p5 3s 17.096, 17.051, 16.775A

Fe17    15 c   2p5 3d 15.451, 15.261, 15.013A
Fe18   975 c   Fe XVIII 974.A, collisional excitation
Fe18   104 c   lines from Kato, collisional excitation
Fe19   108 c   lines from Kato, collisional excitation
Fe19   592 c   fe19 from loulergue et al '85

Fe19  7082 c   fe19 from loulergue et al '85
Fe19  1118 c   fe19 from loulergue et al '85
Fe19  1328 c   fe19 from loulergue et al '85
Fe20   120 c   fe19 from loulergue et al '85
Fe21   142 c   triplet at 129, 142, 146A, collisional excitation

Fe21  1354 c   next two 3p ground state lines, collisional excitation
Fe21  2304 c   collisional excitation
Fe22   130 c   collisional excitation
Fe22   149 c   collisional excitation
Fe23   133 c   collisional excitation

Fe22   846 c   Fe 22 845.6A
Fe23   263 c   Fe 23 1909-like 262.6
Fe24   255 c   Fe 24 255, 192 doublet all in one, collisional excitation
Fe25     2 c   Fe 25, He like, 1.85A, collisional excitation
Fe26     2 c   Fe 26, H like, 1.79A, collisional excitation

Totl     2 i   total intensity of K-alpha line
FeLr     2 i   recombination from fully stripped ion
TotH     2 i   total hot iron Ka; Auger "hot" iron, plus recom
AugC     2 i   Auger production of "cold" iron, less than or 17 times ionized
NiLr     1 i   Ni Ly-alpha recombination from fully stripped ion, 1.5A

Stoy     0 i   optional sum of certain emission lines, set with "print sum"
```

7. REFERENCES

Abbott, D.C., 1982, Ap.J. 259, 282.
Adams, T., 1972, Ap.J. 174, 439.
Aldrovandi, S., and Pequignot, D., 1972, Ast. Ap. 17, 88.
Aldrovandi, S., and Pequignot, D., 1974, Revista Brasileira de Fisica, 4, 491.
Aller, L.H., 1984, in *Physics of Thermal Gaseous Nebulae*, (Reidel: Dordrecht).
Aller, L.H., and Czyzak, S.J. 1983, Ap.J. Sup. 51, 211.
Avni, Y., and Tananbaum, H., 1986, Ap.J. 305, 83.
Avrett, E.H., and Loeser, R., 1988, Ap.J. 331, 211.
Bajtlik, S., Duncan, R.C., and Ostriker, J.P. 1988, Ap.J. 327, 570.
Balbus, S.A., and McKee, C.F., 1982, Ap.J. 252, 529.
Baldwin, J., Ferland, G.J., Martin, P.G., Corbin, M., Cota, S., Peterson, B.M., and Slettebak, A., 1991, Ap.J. 374, 580.
Bässgen, G., Bässgen, M., and Grewing, M., 1988, Ast.Ap. 200, 51.
Bates, D.R., Kingston, A.E., and McWhirter, R.W.P., 1962, Proc. R. Soc., A267, 297.
Bechtold, J., Weymann, R.J., Lin, Z., and Malkan, M.A., 1987, Ap.J. 315, 180.
Bell, K.L., Kingston, A.E., and McIlveen, W.A., 1975, J. Phys. B 8, 358.
Berger, M.J., and Seltzer, S.M., 1965, NASA SP-3012.
Bergeron, J., and Collin-Souffrin, S., 1971, Ast.Ap. 14, 167.
Bieniek, R.J., and Dalgarno, A., 1979, Ap.J. 228, 635.
Binette, L., Prieto, A., Szuszkiewicz, E., and Zheng, W., 1989, Ap.J. 343, 135.
Black, J.H., 1978, Ap.J. 222, 125.
Black, J.H., 1987, in *Interstellar Processes*, Hollenbach and Thronson, editors.
Bonihala, J.R.M., Ferch, R., Salpeter, E.E., Slater, G., and Noerdlinger, P., 1979, Ap.J. 233, 649.
Boyd, R., and Ferland, G.J., 1987, Ap.J. (Letters) 318, L21.
Broad, J.T., and Reinhardt, W.P., 1976, Phys Rev A 14, 2159.
Brown, R.L., and Mathews, W.G., 1970, Ap.J. 160, 939.
Burgess, A., and Summers, H.P., 1976, MNRAS 174, 345.
Butler, S.E., and Dalgarno, A., 1980, Ap.J. 241, 838 (LZ calc).
Butler, S.E., Heil, T.G., and Dalgarno, A., 1980, Ap.J. 241, 442 (Quantal calc).
Cameron, A.G.W., 1982, in *Essays in Nuclear Astrophysics*, ed CA Barnes, DD Clayton, and DN Schramm, (Cambridge Univ Press; London).
Canfield, R.C., and Puetter, R.C., 1980, Ap.J. 236, L7.
Castor, J.I., 1970, MNRAS 149, 111.
Chapman, R.D., and Henry, R.J.W., 1971, Ap.J. 168, 169.
Chidichimo, M.C., 1981, J. Phys. B. 14, 4149.
Clavel, J., and Santos-Lleo, M., 1990, Ast Ap 230, 3.
Clegg, R.E.S., 1987, MNRAS 229, 31p.
Cota, S.A., 1987, PhD Thesis, The Ohio State Univeristy.
Cota, S.A., and Ferland, G.J., 1988, Ap.J., 326, 889.
Cowie, L.L., and Songaila, A., 1986, Ann Rev AstAp 24, 499.
Cruddace, R., Paresce, F., Bowyer, S., and Lampton, M., 1974, Ap.J. 187, 497.
Dalgarno, A., and Kingston, A.E., 1963, Observatory 83, 39.
Dalgarno, A., and McCray, R.A., 1973, Ap.J. 181, 95.
Davidson, K., 1975, Ap.J. 195, 285.
Davidson, K., 1977, Ap.J. 218, 20.
Davidson, K., and Netzer, H., 1979, Rep. Prog. in Physics 51, 715.
Davidson, K., and Fesen, R.A., 1985, Ann. Rev. Ast. Ap. 23, 119.
Draine, B.T., 1978, Ap.J. (Sup) 36, 595.
Draine, B.T., and Lee, H.M., 1984, Ap.J. 285, 89.
Draine, B.T., and Salpeter, E.E., 1979, Ap.J. 231, 77.
Drake, S.A., and Ulrich, R.K., 1980, Ap.J. Sup. 42, 351.

7 REFERENCES

Elitzur, M., 1982, Rev. Mod. Phys 54, 1125.
Elitzur, M., 1984, Ap.J. 280, 653.
Elitzur, M., Ferland, G.J., Mathews, W.G., and Shields, G., 1983, Ap.J. (Let) 272, L55.
Elitzur, M., and Ferland, G.J., 1986, Ap.J. 305, 35.
Fabian, A.C., Pringle, J.E., and Rees M.J., 1976, MNRAS 175, 43.
Fabian, A.C., Ferland, G.J., and Johnstone, R.M., 1991, MNRAS, to be submitted.
Ferland, G.J., 1979, MNRAS 188, 669.
Ferland, G.J., 1980a, MNRAS 191, 243.
Ferland, G.J., 1980b, Bul. A.A.S. 12, 853.
Ferland, G.J., 1980c, Publ.A.S.P. 92 , 596.
Ferland, G.J., 1992, Ap.J. Letters 389, L63.
Ferland, G.J., 1993, Ap.J. in press.
Ferland, G.J., and Elitzur, M., 1984, Ap.J. (Letters) 285, L11.
Ferland, G.J., Lambert, D.L., Slovak, M., Shields, G.A., and McCall, M., 1982, Ap.J. 260, 794.
Ferland, G.J., and Mushotzky, R.F., 1982, Ap.J. 262, 564.
Ferland, G.J., and Mushotzky, R.F., 1984, Ap.J. 286, 42.
Ferland, G.J., and Netzer, H., 1979, Ap.J. 229, 274.
Ferland, G.J., and Netzer, H., 1983, Ap.J. 264, 105.
Ferland, G.J., Netzer, H., and Shields, G.A., 1979, Ap.J. 232, 382.
Ferland, G.J., Peterson, B.M., Horne, K., Welsh, W.F., and Nahar, S.N., 1992, Ap.J. 387, 95.
Ferland, G.J. and Persson, S.E., 1989, Ap.J. 347, 656.
Ferland, G.J. and Rees, M.J., 1988, Ap.J. 332, 141.
Ferland, G.J., and Shields, G.A., 1978, Ap.J. 226, 172.
Ferland, G.J., and Shields, G.A., 1985, in *Astrophysics of Active Galaxies and Quasi-stellar Objects*, J.S. Miller, Ed.
Ferland, G.J., and Truran, J.W., 1981, Ap.J. 244, 1022.
Ferland, G.J., Williams, R.E., Lambert, D.L., Shields, G.A., Slovak, M., Gondhalekar, P.M., and Truran, J.W., 1984, Ap.J. 281, 194.
Field, G. B., 1965, Ap.J. 142, 431.
Gaetz, T.J., and Salpeter, E.E., 1983, Ap.J. Suppl. 52, 155.
Ginzburg, V.I., and Syrovatskii, S.I., 1964, *The Origin of Cosmic Rays*, (Oxford: Pergamon).
Gould, R.S., 1978, Ap.J. 219, 250.
Grevesse, N., and Anders, E., 1989, *Cosmic Abundances of Matter*, AIP Conference Proceedings 183, Ed. C.J. Waddington, (New York: AIP).
Guilbert, P.W., 1986, MNRAS 218, 171.
Habing, H.J., 1968, Bull. Astr. Inst. Netherlands 19, 421.
Halpern, J.P., and Grindlay, J.E., 1980, Ap.J. 242, 1041.
Harrington, J.P., 1973, MNRAS 162, 43.
Heitler, W., 1954, *The Quantum Theory of Radiation* (Oxford: Oxford University Press).
Hollenbach, D., and McKee, C.F., 1979, Ap.J. Sup 41, 555.
Hollenbach, D., and McKee, C.F., 1989, Ap.J. 342, 306.
Hubbard, E.N., and Puetter, R.C., 1985, Ap.J. 290, 394.
Hummer, D.G., 1962, MNRAS 125, 21.
Hummer, D.G., 1968, MNRAS 138, 73.
Hummer, D.G., 1988, Ap.J. 327, 477.
Hummer, D.G., and Kunasz, 1980, Ap.J. 236, 609.
Hummer, D.G., and Seaton, M.J., 1963, MNRAS 125, 437.
Hummer, D.G., and Storey, P., 1987, MNRAS 224, 801.
Hutchings, J.B., 1976, Ap.J. 205, 103.
Ikeuchi, S., and Ostriker, J.P., 1986, Ap.J. 301, 522.
Jackson, J.D., 1975, *Classical Electrodynamics* (New York: Wiley).
Janev, R.K., Langer, W.D., Post, D.E., and Evans, K., 1987, *Elementary Processes in Hydrogen–Helium Plasmas* (Springer--Verlag; Berlin).

Johnson, L.C., 1972, Ap.J. 174, 227.
Johnstone, R.M., Fabian, A.C., Edge, A.C., and Thomas, P.A., 1992, MNRAS 255, 431.
Kallman, T.R., and McCray, R., 1982, Ap.J. Sup 50, 263.
Karzas, W.J., and Latter, R., 1961, Ap.J. Sup. 6, 167.
Kato, T., 1976, Ap. J. Supp. 30, 397.
Kellerman, K.I., 1966, Ap.J. 146, 621.
Krolik, J., McKee, C.M., and Tarter, C.B., 1981, Ap.J. 249, 422.
Kurucz, R.L., 1970, SAO Special Reports 309.
Kurucz, R.L., 1979, Ap.J. Sup 40, 1.
Kurucz, R.L., 1991, in *Proceedings of the Workshop on Precision Photometry: Astrophysics of the Galaxy*, A.C. Davis Philip, A.R. Upgren, and K.A. James (Davis, Schenectady), p 27.
Kwan, J., and Krolik, J., 1981, Ap.J. 250, 478.
Lambert, D.L., and Pagel, B.E.J., 1968, MNRAS 141, 299.
Lea, S., and Holman, G., 1978, Ap.J. 222, 29.
Lennon, D.J., and Burke, V.M., 1991, MNRAS 251, 628.
Lenzuni, P., Chernoff, D.F., and Salpeter, E.E., 1991, Ap.J. Supp. 76, 759.
Levich, E.V., and Sunyaev, R.A., 1970, Astrophy Let 7, 69.
Lightman, A.P., and White, T.R., 1988, Ap.J. 335, 57.
Lites, B.W., and Mihalas, D., 1984, Solar Physics 93, 23.
Longair, M.S., 1981, *High Energy Astrophysics*, (Cambridge, Cambridge University Press).
Lotz, W., 1967, Ap.J. Sup. 14, 207.
Martin, P.G., 1979, *Cosmic Dust* (Oxford, Clarendon Press).
Martin, P.G., 1988, Ap.J. Sup. 66, 125.
Martin, P.G., and Ferland, G.J., 1980, Ap.J. (Letters), 235, L125.
Martin, P.G., and Whittet, D.C.B., 1990, Ap.J. 357, in press.
Masters, A.R., Pringle, J.E., Fabian, A.C., and Rees, M.J., 1977, MNRAS 178, 501.
Mathews, W.G., Blumenthal, G.R., and Grandi, S.A., 1980, Ap.J. 235, 971.
Mathews, W.G., and Ferland, G.J., 1987, Ap.J. 323, 456.
Mathis, J.S. Rumpl, W., and Nordsieck, K.H., 1977, Ap.J. 217, 425.
Mathis, J.S., and Wallenhorst, S.G., 1981 Ap.J. 244, 483.
Nahar, S.N., and Pradhan, A.K., 1992, Ap.J. 397, 729.
Neufeld, D.A., and Dalgarno, A., 1989, Phys Rev A, 35, 3142.
Mendoza, C., 1983, in *Planetary Nebulae*, IAU Sym 103, D.R. Flower, Ed., p 143, (Dordrecht: Reidel).
Mihalas, D., 1972, *Non-LTE Model Atmospheres for B and O Stars*, NCAR-TN / STR-76.
Mihalas, D., 1978, *Stellar Atmospheres*, 2nd Edition (W.H. Freeman: San Francisco).
Morrison, R., and McCammon, D., 1983, Ap.J. 270, 119.
Mihalszki, J.S., and Ferland,G.J., 1983, Publ A.S.P. 95, 284.
Netzer, H., 1990, in *Active Galactic Nuclei, Saas-Fee Advanced Course 20*, Courvorsier, T.J.-L., and Mayor, M., (Springer-Verlag; Berlin).
Netzer, H., Elitzur, M., and Ferland, G.J., 1985, Ap.J. 299, 752.
Netzer, H., and Ferland, G.J., 1984, Publ.A.S.P. 96, 593.
Nussbaumer, H., and Storey, P.J. 1983, Ast. Ap. 126, 75.
Nussbaumer, H., and Storey, P.J. 1986, Ast. Ap. Suppl. 64, 545.
Nussbaumer, H., and Storey, P.J. 1987, Ast. Ap. Suppl. 69, 123.
Oliveira, S., and Maciel, W.J., 1986, Astro. Space Sci. 126, 211.
Osterbrock, D.E., 1951, Ap.J. 114, 469.
Osterbrock, D.E., 1989, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*, University Science Press.
Osterbrock, D.E., and Flather, E., 1959, Ap.J. 129, 26.
Osterbrock, D.E., Tran, H.D., and Veilleux, S., 1992, Ap.J. in press.
Ostriker, J.P., and Ikeuchi, S., 1983, Ap.J. (Let) 268, L63.
Pacholczyk, A.G., 1970, *Radio Astrophysics* (San Francisco: Freeman).

7 REFERENCES

Palla, F., Salpeter, E.E., and Stahler, S.W., 1983, Ap.J. 271, 632.
Peebles, P.J.E., 1971, *Physical Cosmology*, (Princeton U. Press; Princeton).
Pengelly, R.M., 1964, MNRAS 127, 145.
Pequignot, D., 1986, *Wordshop on Model Nebulae*, (Paris: l'Observatoire de Paris) p363.
Pequignot, D., and Aldrovandi, S.M.V., 1986, Ast.Ap. 161, 169.
Peterson, J.R., Aberth, W., Moseley, J., and Sheridan, J., 1971, Phys Rev A, 3, 1651.
Press W.H., Flannery, B.P., Teukolsky, S.A., and Vetterling, W.T., 1986, (Cambridge University Press; Cambridge).
Puetter, R.C., 1981, Ap.J. 251, 446.
Raymond, J.C., Cox, D.P., and Smith, B.W., 1976, Ap.J. 204, 290.
Rees, M.J., Netzer, H., and Ferland, G.J., 1989, Ap.J. 347, 640.
Rephaeli, Y., 1987, MNRAS 225, 851.
Reilman, R.F., and Manson, S.T., 1979, Ap.J. Sup. 40, 815.
Rossi, B., 1952, *High-Energy Particles* (New York; Prentice-Hall).
Rubin, R.H., 1983, Ap.J. 274, 671.
Rubin, R.H., Simpson, J.R., Haas, M.R., and Erickson, E.F., 1991, Ap.J. 374, 564.
Rybicki, G.B., and Lightman, A.P., 1979, *Radiative Processes in Astrophysics* (Wiley, New York).
Saraph, H.E., 1970, J.Phys.B. 3, 952.
Sciortino, S., et al., 1990, Ap.J. 361, 621.
Scott, J.S., Holman, G.D., Ionson, J.A., and Papadopoulos, K., 1980, Ap.J. 239, 769.
Schuster, A., 1905, Ap.J. 21, 1.
Schwarzschild, M., 1965, *Structure and Evolution of the Stars*, (New York: Dover).
Seaton, M.J., 1959, MNRAS 119, 90.
Seaton, M.J., 1987, J.Phys. B 20, 6363.
Shine, R.A., and Linsky, J.L., 1974, Solar Physics 39, 49.
Shull, J.M., 1979, Ap.J. 234, 761.
Shull, J.M., and Van Steenberg, M.E., 1982, Ap.J. Suppl 48, 95.
Shull, J.M., and Van Steenberg, M.E., 1985, Ap.J. 298, 268.
Sikora, M., Begelman, M.C., and Rudak, B., 1989, Ap.J. (Let), 341, L33.
Spitzer, L., 1948, Ap.J. 107, 6.
Spitzer, L., 1962, *Physics of Fullly Ionized Gasses*, (Interscience: New York).
Spitzer, L., 1978, *Physical Processes in the Interstellar Medium*, (Wiley: New York).
Spitzer, L., and Tomasko, M.G., 1968, Ap.J. 152, 971.
Stoy, R.H., 1933, MNRAS 93, 588.
Storey, P.J., and Hummer,D.G., 1991, Comput.Phys.Commun. 66, 129.
Swings, P., and Struve, O., 1940, Ap.J. 91, 546.
Tarter, C.B., and McKee, C.F., 1973, Ap.J. Letters 186, L63.
Tielens, A.G.G.M., and Hollenbach, D., 1985a, Ap.J. 291, 722.
Tielens, A.G.G.M., and Hollenbach, D., 1985b, Ap.J. 291, 746.
Van Blerkom, D., and Hummer, D.G., 1967, MNRAS 137, 353.
Vernazza, J.E., Avrett, E.H., and Loeser, C.B., 1981, Ap.J. Sup. 45, 635.
Vriems, L., and Smeets, A.H.M., 1980, Phys Rev A 22, 940.
Watson, W.D., 1972, Ap.J. 176, 103.
Weisheit, J.C., 1974, Ap.J. 190, 735.
Weisheit, J.C., and Dalgarno, A., 1972, Ap. Letters, 12, 103.
Weisheit, J., Shields, G.A., and Tarter, C.B., 1981, Ap.J. 245, 406.
Werner, K., and Heber, U., 1991, in *Stellar Atmospheres: Beyond Classical Models*, p 341, NATO ASI Series C, eds. L. Crivellari, I. Hubney, and D.G. Hummer, (Kluwer; Dordrect)..
Wilkes, B.J., Ferland, G.J., Truran, J., and Hanes, D., 1981, MNRAS 197, 1.
Wilkinson, D.T., 1987, in *13th Texas Symposium on Relavistic Astronphysics*, M.P. Ulmer, ed., (World Scientific; Singapore), p209 .
Williams, R.E., 1967, Ap.J. 147, 556.
Wills, B., Netzer, H., and Wills D., 1985, Ap.J. 288, 94.

Winslow, A.M., 1975, Lawrence Livermore Lab. report UCID-16854.
Wishart, A.W., 1979, MNRAS 187, 59p.
Wyse, A.B., 1941, Publ.A.S.P. 53, 184.
Zamorani, G., et al. 1981, Ap.J. 245, 357.

8. INDEX

D

J

K

L

M

N

S

T

W

X

Z

8