Molecular hydrogen in star forming regions

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OUTLINE

- Hydrogen Molecule & Cloudy
  - Energy diagram of H_2
  - Formation of H_2
  - Destruction of H_2
  - Ortho-Para conversion

- Our results on high redshift Damped Lya absorbers (DLAs)

Hydrogen Molecule

….Why is it so important ?

- About **90%** of the current Baryonic matter is in the form of **Hydrogen**.

- **Molecular hydrogen plays an important role in astrophysics.**

  - It is the first and the most abundant neutral molecule to be formed in the Universe.

  - As a highly efficient coolant, it increases the rate of formation of galaxies in primordial gas

  - Molecular hydrogen is a major constituent of giant molecular clouds.

Hydrogen Molecule

- Hydrogen molecule (H_2) is the simplest neutral molecule consisting of two protons and two electrons.

Fermi statistics

- Total (nuclear × electronic) wave function must be anti-symmetric under the exchange of nuclei

- Ortho states : Total spin I =1, Degeneracy : 3 × (2J+1)
  Nuclear spin wave function : symmetric
  Spatial wave function : anti-symmetric

- Para states : Total spin I=0, Degeneracy : 2J+1
  Nuclear spin wave function : anti-symmetric
  Spatial wave function : symmetric

Ground state

Even J : Para state Odd J : Ortho state

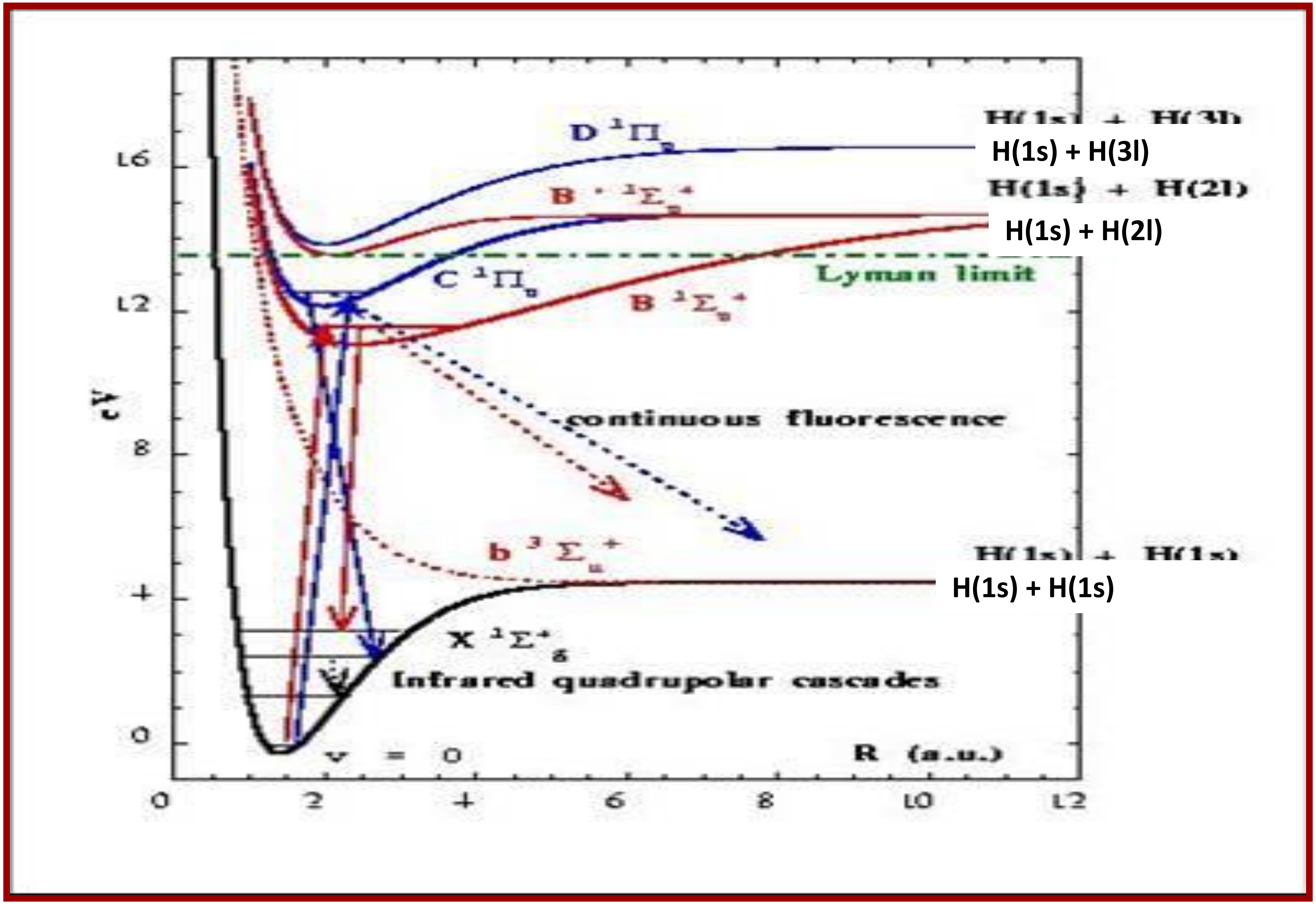
Hydrogen Molecule

- Hydrogen molecule (H_2) is the simplest neutral molecule consisting of two protons and two electrons.
- It is a symmetric molecule and does not have a permanent electric dipole moment.

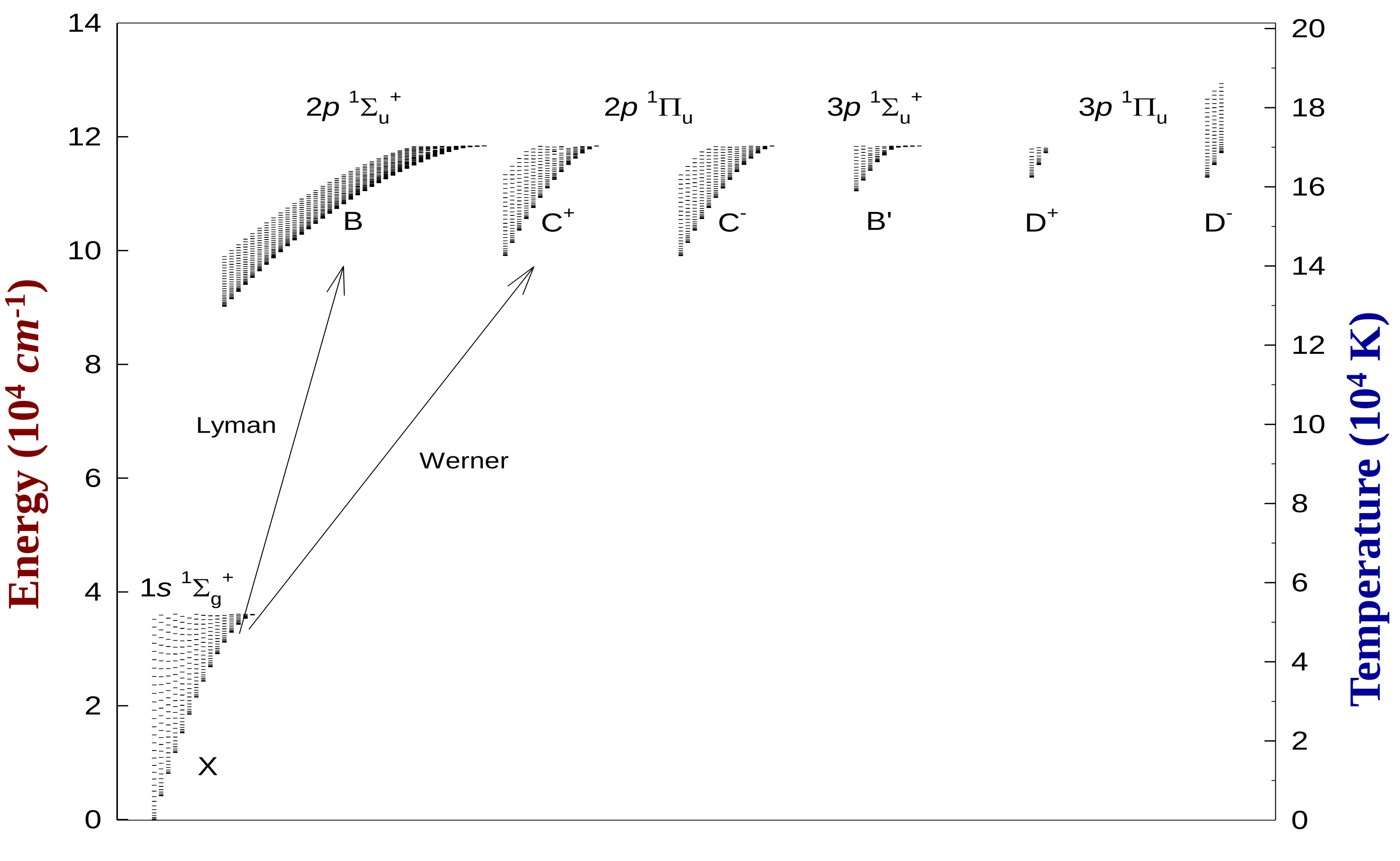
In ground state rovibrational transitions can occur only via

quadrupole transitions with ΔJ=0, ±2.

Potential curves involved in the Lyman and Werner bands (Roueff 00)



Energy levels of H_2



Molecular Hydrogen lines
"Atom H2"

Branch Notation

Branch $J_{up} - J_{lo}$

O........... -2

P ....-1

Q............. 0

R.............+1

S .... +2

Spectroscopic notation

H2 17.03m 0-0 S(1)
H2 12.28m 0-0 S(2)
H2 9.665m 0-0 S(3)
H2 8.025m 0-0 S(4)
H2 6.909m 0-0 S(5)
H2 2.12099m 1-0 S(1)
H2 2.22269m 1-0 S(0)
H2 2.41307m 1-0 Q(2)
H2 2.42307m 1-0 Q(3)
H2 2.43683m 1-0 Q(4

Micro-physics of H_2

Formation of H_2	Destruction of H_2
• Catalysis on the grain surface $H + H + grain \rightarrow H_2 + grain$ • Radiative association processes *i.* $H^- + H \rightarrow H_2 + e^-$ *ii.* $H_2^+ + H \rightarrow H_2 + H^+$	• Solomon process • Direct photo-dissociation • Collisional dissociation

Shaw et al. 2005

DESTRUCTION OF H_2

- **Collisional dissociation**

  Collisional dissociation by H, He, H_2 and e^- are also possible from higher vib-rotational state

- **Pumping via X-ray electrons**

  Molecular hydrogen is excited to $B^1\Sigma u^+$ or $C^1\Pi_u^{\pm}$ state by secondary electrons.

- **Excitation to the triplet b state**

  Molecular hydrogen is excited to triplet b state by energetic secondary electrons and is dissociated

- **Cosmic ray ionization**

$$H_2 + CR \rightarrow H_2^+ + e^-$$

Collisional cross-sections

Rate coefficient fits for collisional de-excitation processes:

Le Bourlot et al. (1999; http://ccp7.dur.ac.uk)

Nonreactive transitions

$$H_2(v, J) + H \longrightarrow H_2(v', J') + H$$

$$H_2(v, J) + He \longrightarrow H_2(v', J') + He$$

$$H_2(v, J) + H_2 \longrightarrow H_2(v', J') + H_2$$

Gerlich 1990

$$H_2(v, J) + H^+ \rightarrow H_2(v', J') + H^+$$

Shaw et.al 2005

Ortho-Para conversion

- No Radiative decay

- Exchange collisions between H_2 and H, H^+ and H_3^+

  - $H_2(v, J) + H \rightarrow H_2(v', J') + H$ (Sun & Dalgarno 1994)

  - $H_2(v, J) + H^+ \rightarrow H_2(v', J') + H^+$ (Gerlich 1990)

  - $H_2(v, J) + H_3^+ \rightarrow H_2(v', J') + H_3^+$ (Same as H^+)

- **On grain surfaces (below critical temperature)**

Some important reactions

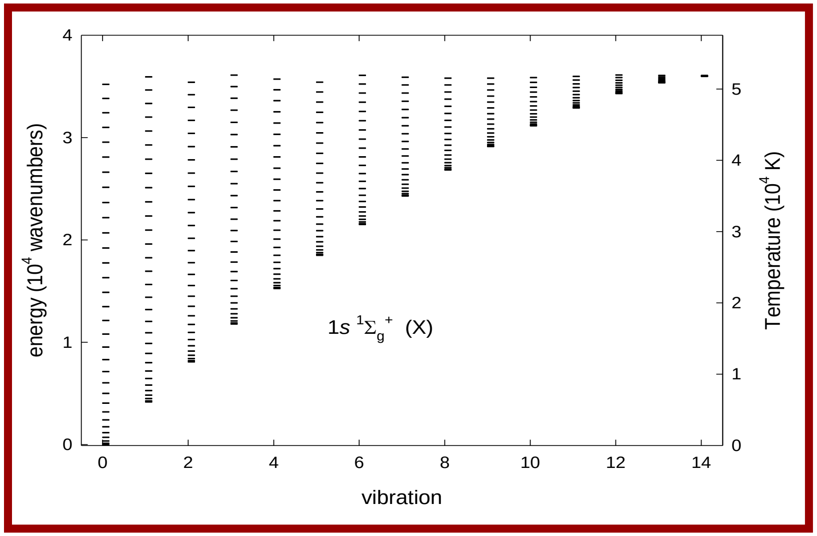
H_2 helps to form other molecules in PDRs.

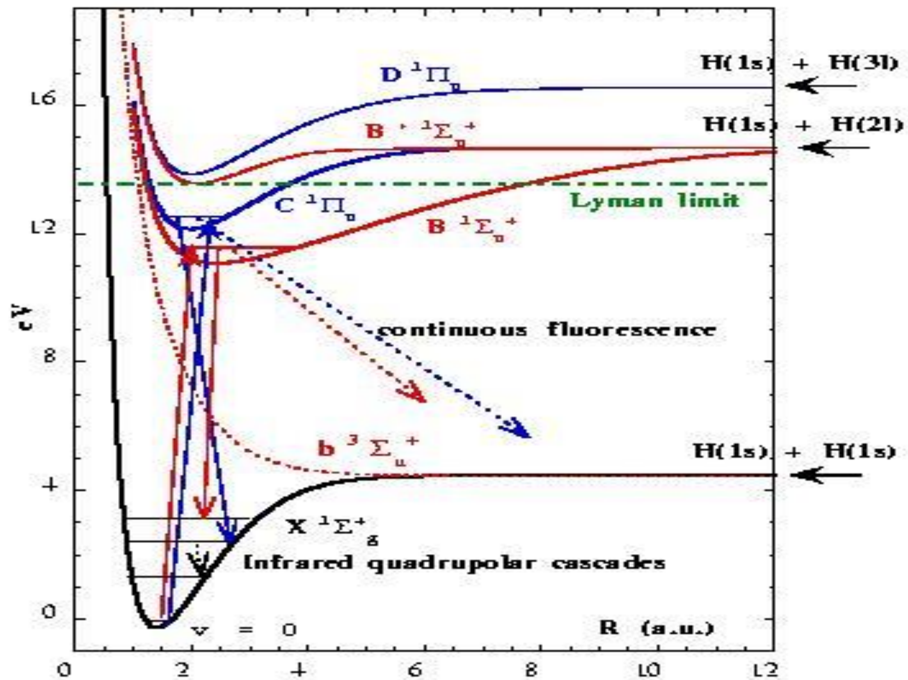
$$H_2^* + O \rightarrow OH + H$$
$$OH + C^+ \rightarrow CO^+ + O$$
$$CO^+ + H \rightarrow CO + H^+$$
$$H_2^* + C^+ \rightarrow CH^+$$

FUV and formation pumping of Molecular Hydrogen

- ❖ H_2 has small moment of inertia.
- ❖ H_2 energy levels are widely spaced.

➢ FUV pumping can excite higher levels.





➢Formation pumping

H_2 formation on dust grain surfaces is exothermic process and can excite higher levels.

Shaw et al. 2005

Damped Lyα Absorbers (DLAs)

DLAs are defined as absorption-line systems having large neutral hydrogen column density $N(HI) \geq 2\times10^{20} cm^{-2}$ when seen against the emission of background QSOs.

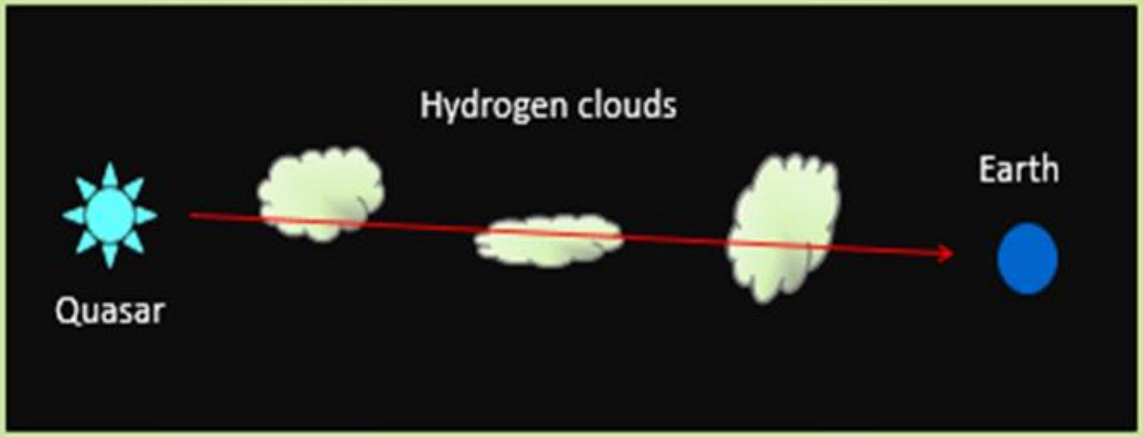


Fig. 1: Schematic representation of absorbers at different redshifts along the line-of-sight to a quasar

Damped Lyα Absorbers (DLAs)

- ***DLAs are believed to be the progenitors of present day disk galaxies.***

- ***Study of DLAs at high redshift provides information about :***
  - ***early evolution of galaxies,***
  - ***intergalactic medium,***
  - ***early star formation,***
  - ***evolution of chemical elements.***

UVES Observations at VLT

- ***DLA at z_{abs} = 2.3377 observed in absorption along the sightline towards the quasars LBQS 1232+0815***
- ***DLA at z_{abs} = 2.41837 observed in absorption along the sightline SDSS J143912.04+111740.5***

H_2 has been detected in both DLAs, and CO has also been observed in the DLA at z_{abs} = 2.41837.

OUR MODEL

We perform our simulation using the spectral synthesis code CLOUDY.

Model assumptions

- ***A plane parallel slab of gas irradiated from both sides.***
- ***We included,***
- ***Haardt-Mada metagalactic radiation of background galaxies and QSOs***
- ***CMB***
- ***cosmic ray ionization***
- ***radiation from in-situ star formation.***

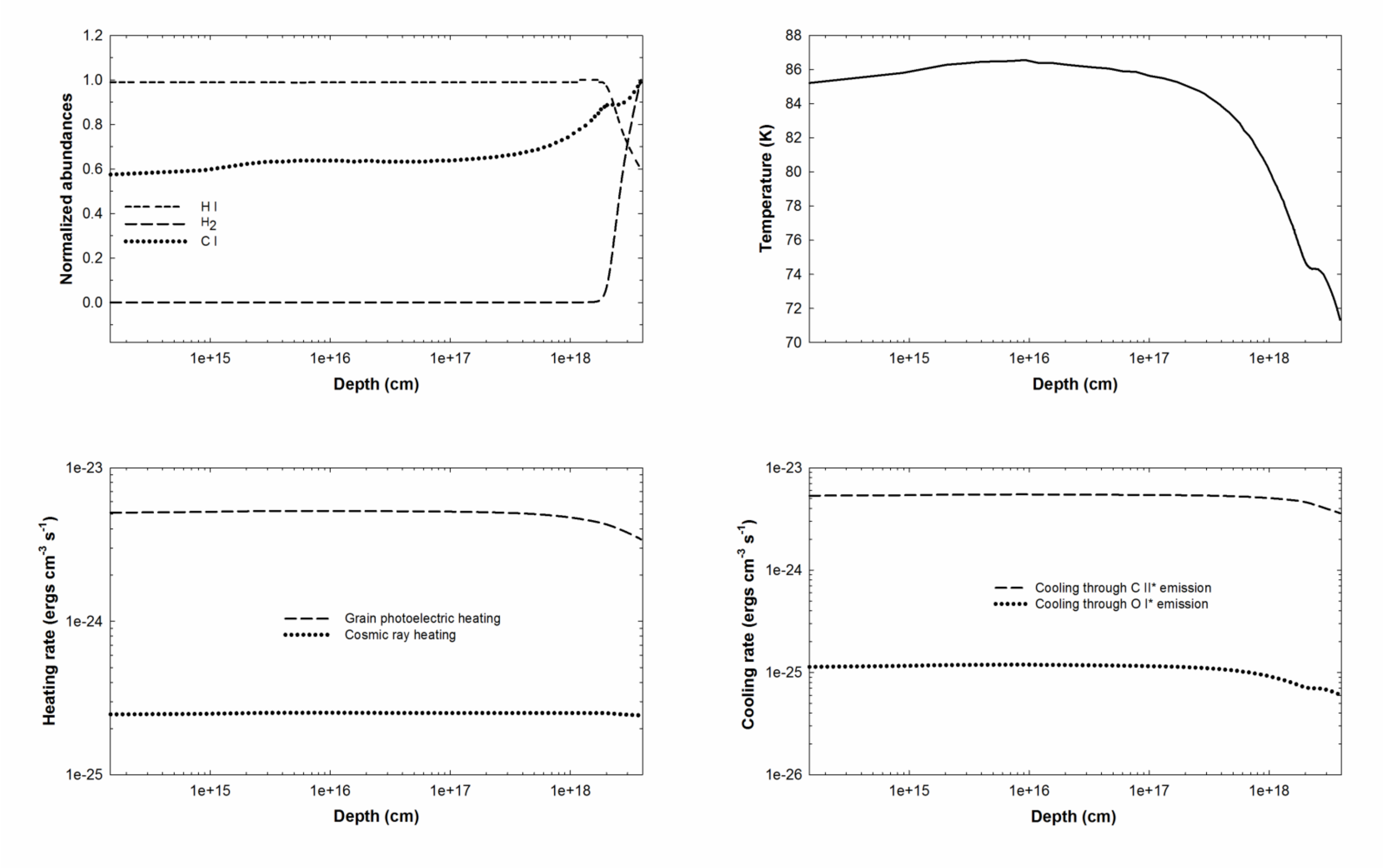
Results for DLA at z = 2.3 towards LBQS 1232+0815

Model parameter	Value
Hydrogen density	100 cm^{-3}
Intensity of radiation field	2.5×10^{-3} erg cm^{-2} s^{-1} (between 6 and 13.6 eV)
Cosmic ray ionisation rate of H I	2×10^{-16} s^{-1}
Metallicity	0.3 ISM
Turbulence	4 km/s
Grain size	0.5 ISM

Species (X)	Column density from observation log N(X) cm^{-2}	Column density predicted by model log N(X) cm^{-2}
H I	20.90±0.08[a]	20.84
H_2	$19.68^{+0.08}_{-0.10}$ [a]	19.70
H_2 (0, 0)	19.45±0.10[a]	19.43
H_2 (0, 1)	19.29±0.15[a]	19.37
H_2 (0, 2)	16.78±0.24[a]	16.99
H_2 (0, 3)	16.36±0.10[a]	15.70
H_2 (0, 4)	14.70±0.06[a]	14.63
H_2 (0, 5)	14.36±0.07[a]	14.33
CO	< 12.6[b]	12.54
C I*	13.87±0.05[c]	13.86
C I**	13.56±0.04[c]	13.72
C I***	12.82±0.07[c]	13.02
N I	14.54±0.22[b]	14.52
Mg II	15.33±0.24[b]	15.29
Si II	15.06±0.05[b]	15.02
P II	12.86±0.24[b]	12.81
S II	14.81±0.09[b]	14.76
Cl I	12.97±0.14[b]	12.66
Ar I	13.86±0.22[b]	13.81
Mn II	12.22±0.08[b]	12.19
Fe II	14.44±0.08[b]	14.40
Ni II	12.81±0.04[b]	12.82

Ivanchik et al. 2010; Balashev et al. 2011

The physical conditions of the DLA at $z_{abs} = 2.3377$



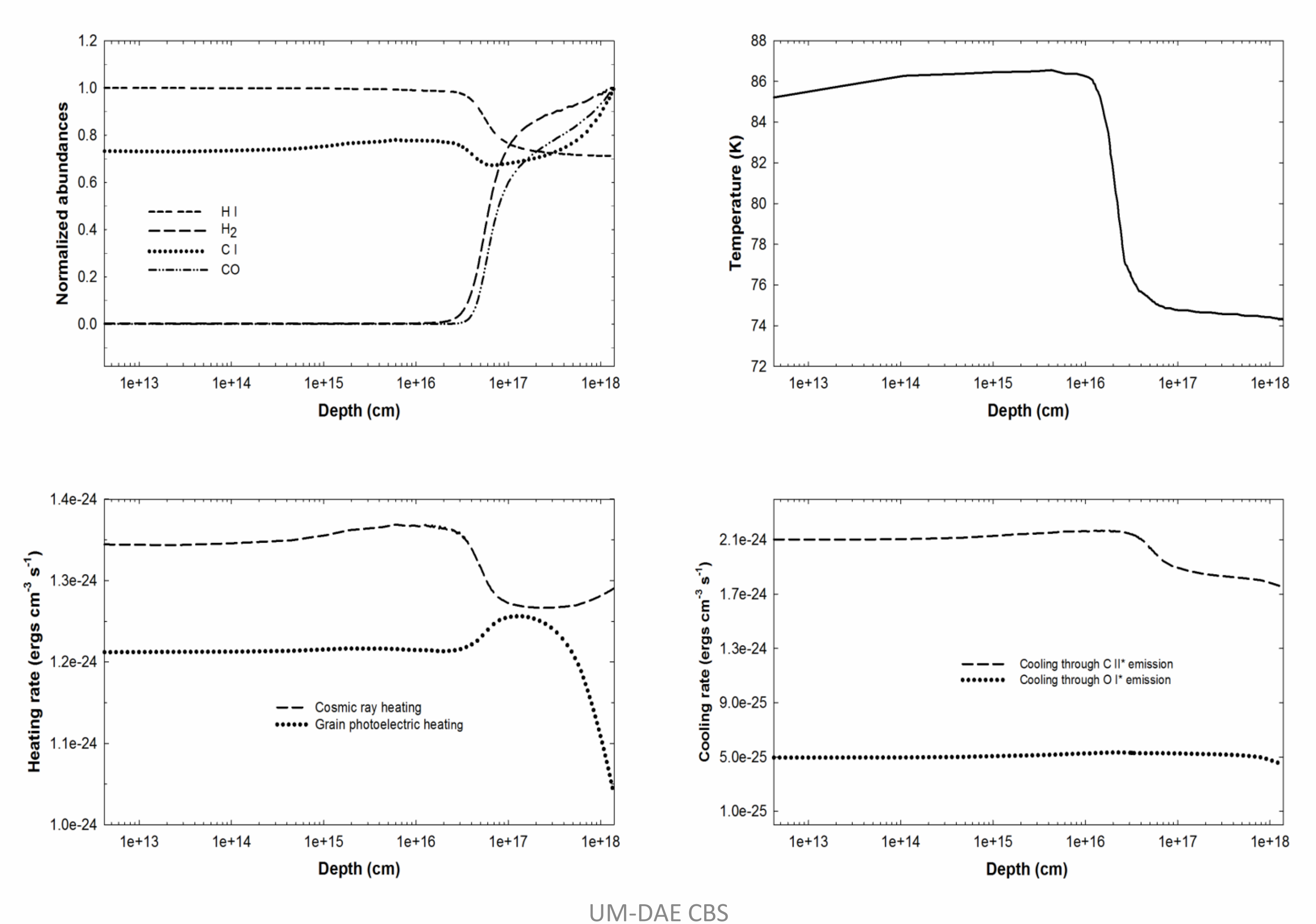
Results for DLA at z = 2.4 towards SDSS J143912.04+111740.5

Model parameter	Value
Hydrogen density	60 cm^{-3}
Intensity of radiation field	10^{-4} erg cm^{-2} s^{-1} (between 6 and 13.6 eV)
Cosmic ray ionisation rate of H I	1.4×10^{-15} s^{-1}
Metallicity	0.5 ISM
Turbulence	1.5 km/s
Grain size	0.5 ISM

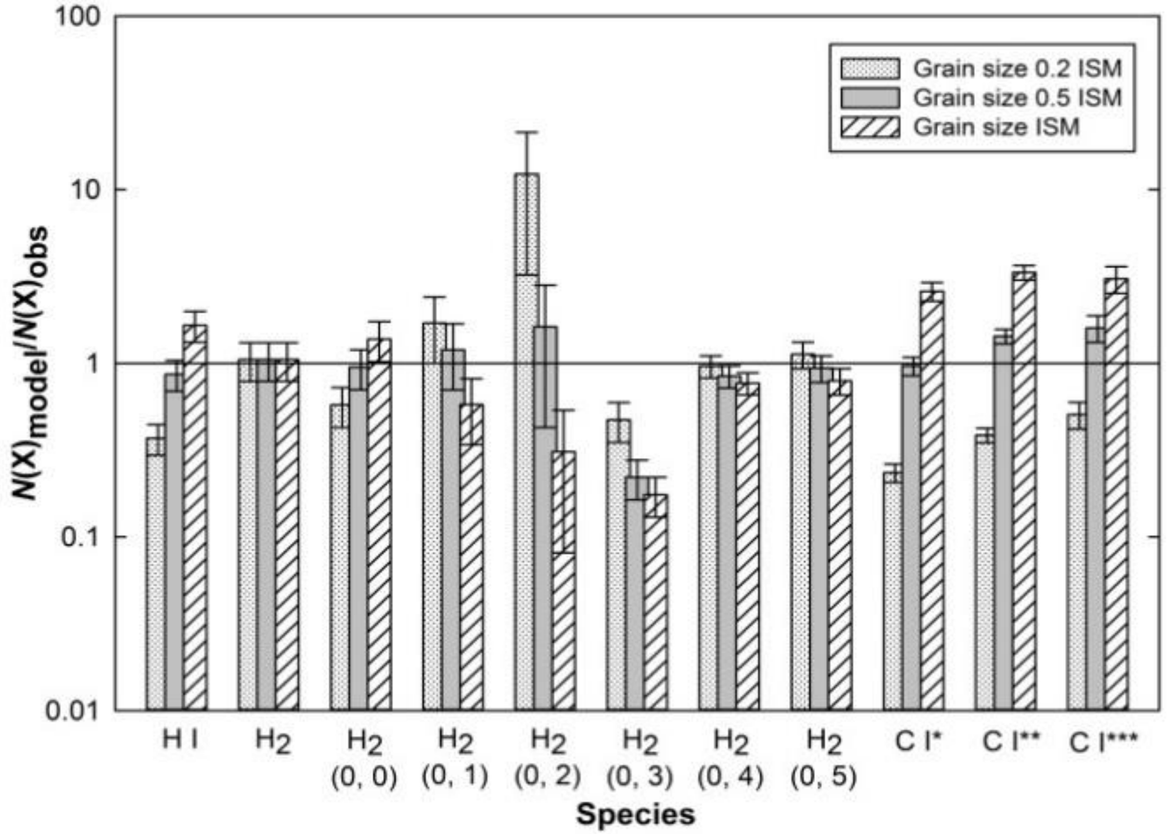
Srianand et al. 2008; Noterdaeme et al. 2008b

Species (X)	Column density from observation log N(X) cm^{-2}	Column density predicted by model log N(X) cm^{-2}
H I	$20.10^{+0.10}_{-0.08}$ [a]	20.08
H_2	19.38±0.10[a]	19.45
H_2 (0, 0)	18.90±0.10[a]	19.06
H_2 (0, 1)	19.18±0.10[a]	19.22
CO	13.89±0.02[a]	13.88
CO (0, 0)	13.27±0.03[a]	13.28
CO (0, 1)	13.48±0.02[a]	13.53
CO (0, 2)	13.18±0.06[a]	13.26
C I*	14.26±0.01[a]	14.23
C I**	14.02±0.02[a]	13.99
C I***	13.10±0.02[a]	13.21
N I	≥ 15.71[b]	15.86
Si II	14.80±0.04[b]	14.84
S II	15.27±0.06[b]	15.30
Fe II	14.28±0.05[b]	14.35
Zn II	12.93±0.04[b]	12.85

The physical conditions of the DLA at z_{abs} = 2.41837



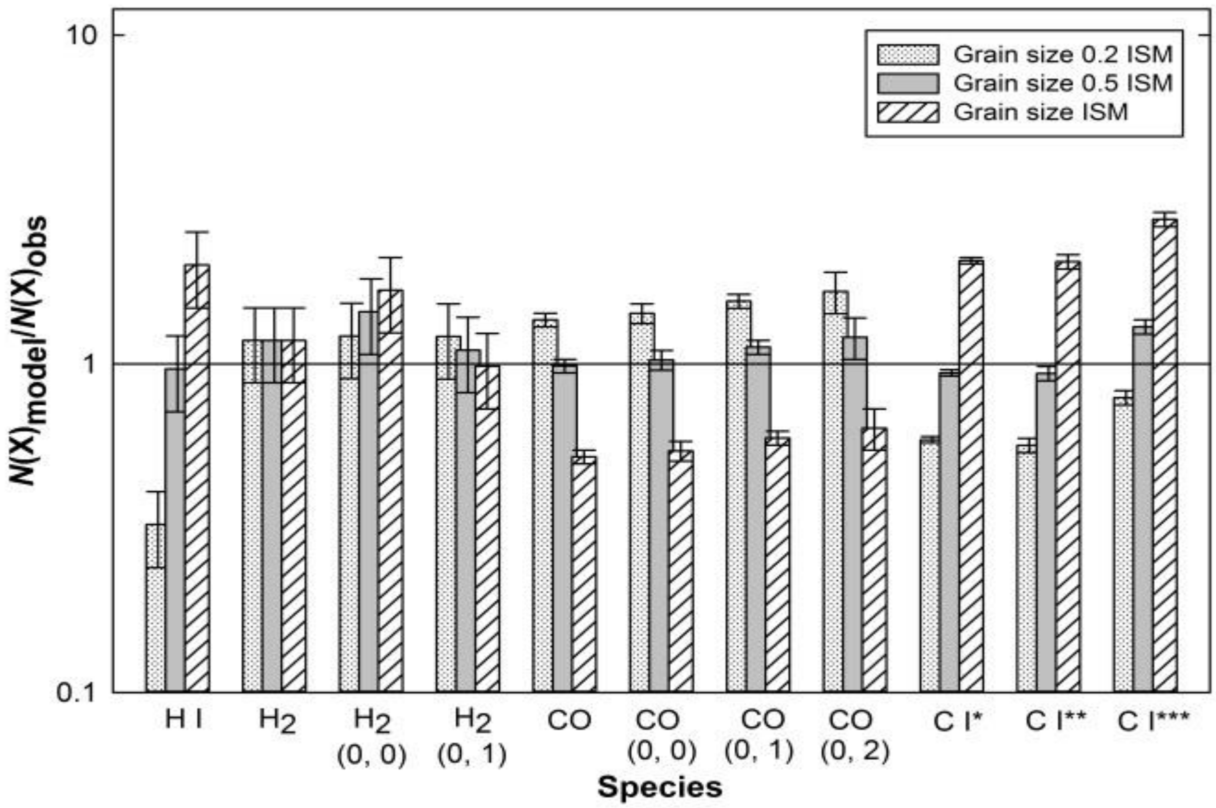
Effect of grain size on predicted column densities



The ratio of model-to-observed column densities for H I, C I and H_2 for the DLA at z_{abs} = 2.3377.The best-fitting model is clearly the one with grains of size 0.5 times the ISM grain size.

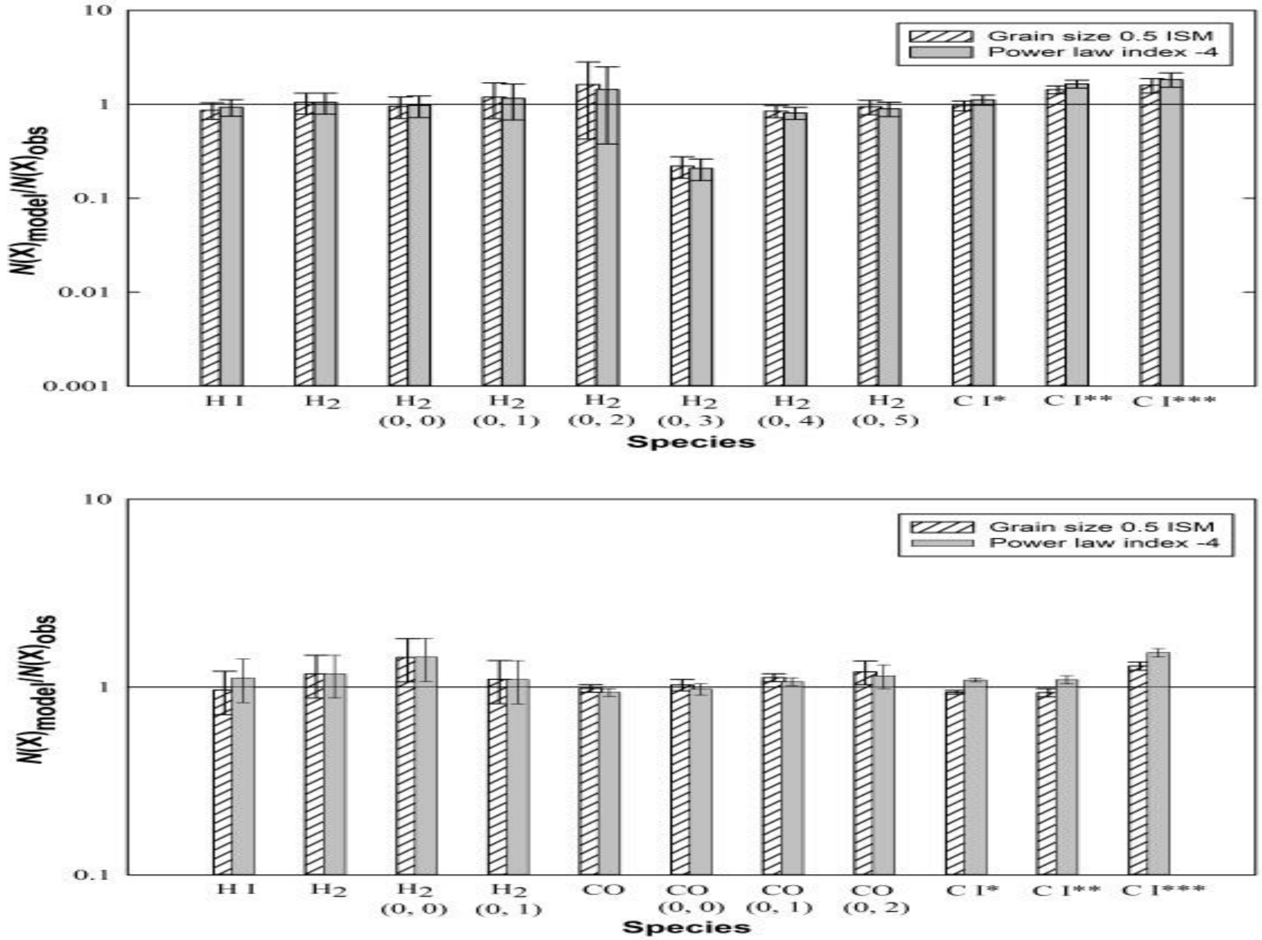
Katherine et al. 2015

Effect of grain size on predicted column densities



The ratio of model-to-observed column densities for H I, H_2, CO and C I for the DLA at z_{abs} = 2.41837. The best-fitting model is clearly the one with grains of size 0.5 times the ISM grain size.

Katherine et al. 2015



Ratio of model-to-observed column densities of C I and H_2 for the 2 DLAs for two different models – one, with grain sizes in the range 0.0025–0.125 μm following the MRN size distribution with exponent -3.5; and two, with grain sizes in the range 0.005–0.250 μm, following a power-law distribution with exponent -4.

Conclusions

- *We have performed detailed numerical simulation of 2 DLAs: at z_{abs} = 2.3377 towards Q 1232 + 082, at z_{abs} = 2.41837 towards SDSS J143912.04+111740.5 We have reproduced most of the observed column densities satisfactorily.*

- *DLAs with H_2 have high density ($n_H > 10$ cm^{-3}) and stars are forming there.*

- *The two DLAs are constant-pressure clouds with in-situ star formation.*

- *We find that grains in the high-redshift DLAs that we have modelled are smaller in size than in the local ISM.*

Conclusions

The smaller grains can be due to,

- ***smaller grains distributed by the MRN size distribution***
- ***ISM-sized grains following a power-law distribution with an index lower than the MRN distribution.***

The two scenarios produce almost identical column densities for various species and hence it is not possible to single out one of them as the more likely case.

The cosmic ray ionization rates in the 2 systems we have modelled span a range > 1.5 dex. This clearly indicates that the ionization produced by cosmic rays is not uniform everywhere, and encourages further probing of cosmic ray ionization along various sightlines.

Katherine et al. 2015

Thank you