Elementární procesy a reakce v plazmatu

24.5.2016

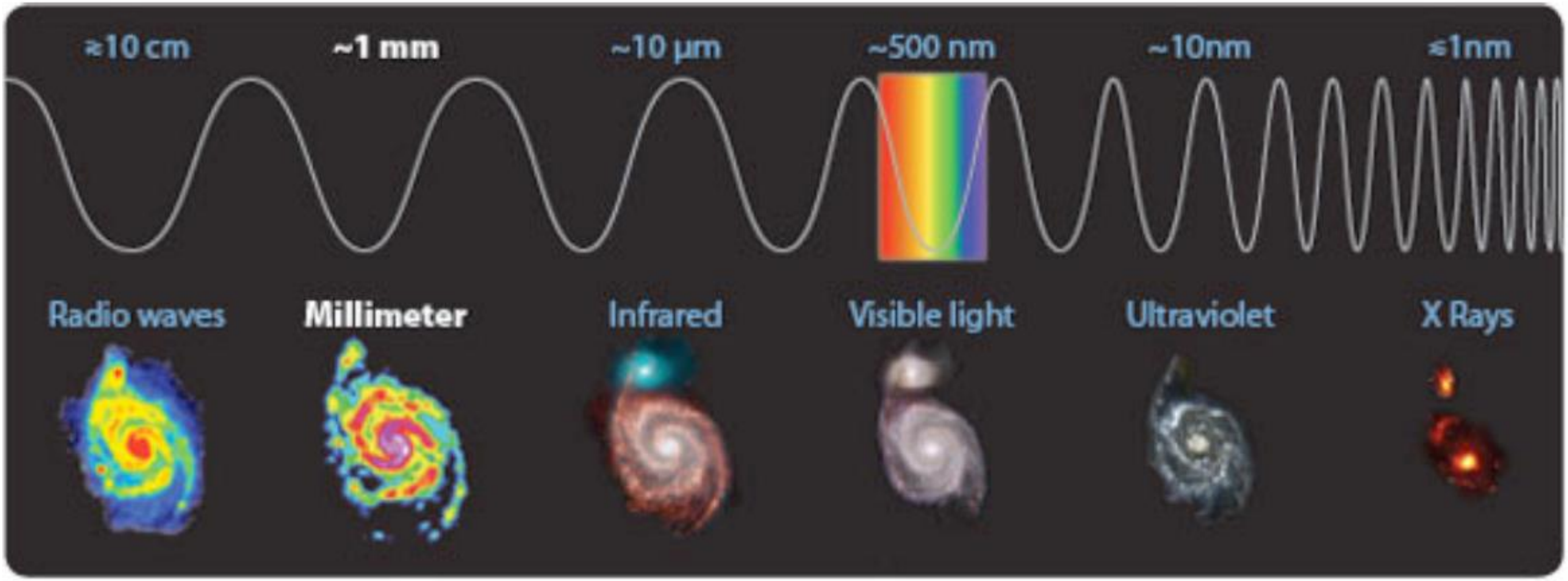
Zdroj

- Cyklus prednášek "Molecular Astrophysics: from Lab to Theory to Observations", Heidelberg University (2012), Holger Kreckel and Dmitry Semenov

http://www.mpia.de/homes/semenov/Lectures/Lectures.html

Detecting molecules

- Molecular lines: (far-)UV–millimeter wavelengths
- Rotational, vibrational, electronic transitions (and their combination)
- Atmosphere transparency windows at IR: blocked by OH, H_2O, etc.



Physical conditions in various astrophysical objects

- Diffuse clouds: T_{kin}~100 K, n ~100 cm^{-3}
- Dense clouds: T_{kin}~10–100 K, n ~10^4–10^8 cm^{-3}
- Hot cores: T_{kin}~100–1000 K, n ~10^6–10^8 cm^{-3}
- Protoplanetary disks: T_{kin}~10–1000 K, n~10^4–10^{13} cm^{-3}
- Circumstellar shells of evolved stars: T_{kin} ~300–3,000 K, n<10^{14} cm^{-3}
- More: HII regions, photo-dissociation regions, supernova remnants, ...

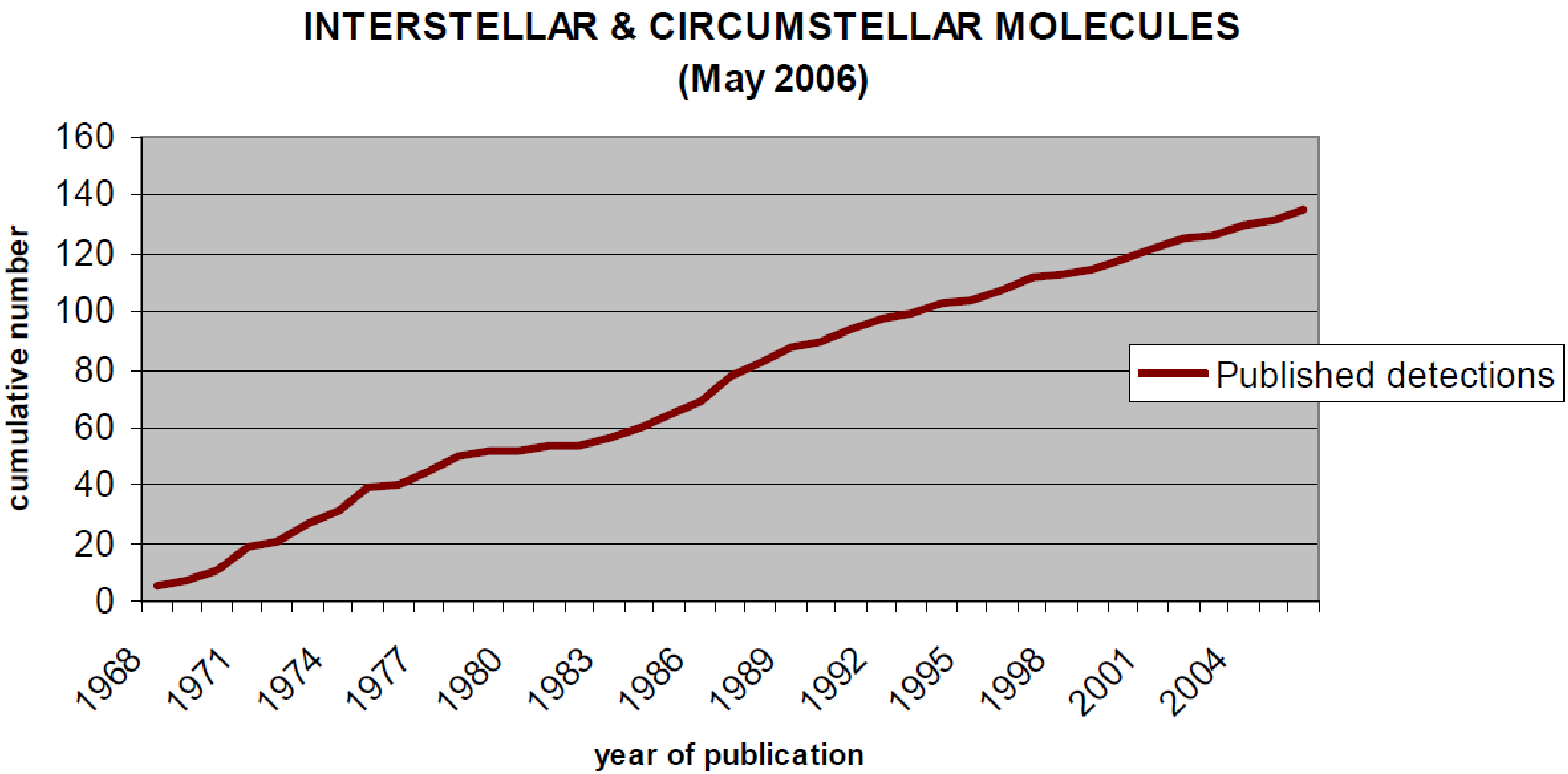
- Earth atmosphere at sea level: T_{kin}~300 K, n~3 10^{19} cm^{-3}

Typical timescales

- Collision time: ~1 month at 10 K and 10^4 cm^{-3}
- Chemical time: >10^4–10^5 years (molecular clouds)
- Life-time of a cloud: ~1–10 x 10^6 years
- Low-mass star formation: ~10^6 years

Chemistry is slow yet there are many molecules in the interstellar medium!

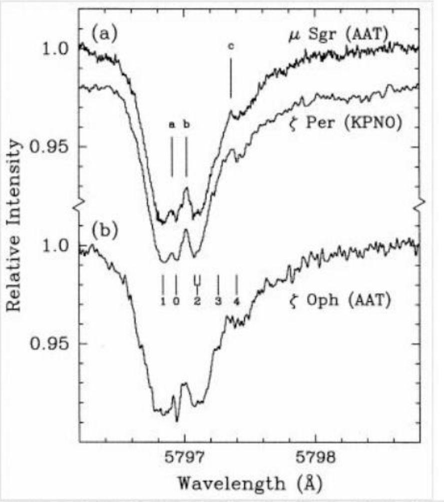
History of molecules in space



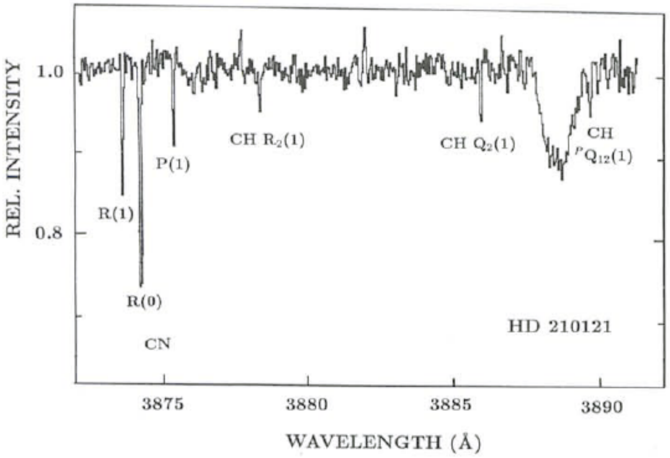
M. Guelin, Nobel Symposium, June 2006

History of molecules in space

- Diffuse Interstellar Bands (DIBs), optical:
  - Discovered by Heger (1922) and Merill (1934):
  - Remains unidentified till 2012 (polyaromatic hydrocarbons?)



- Sharp absorption bands (optical):
  - CH: Swings & Rosenfeld (1937)
  - CN: McKellar (1940)
  - CH^+: Douglas & Herzberg (1941)



- First theory by Bates and Spitzer (1951), Herbst & Klemperer (1973)

History of molecules in space

- Radio telescopes:
  - H I 21 cm: Ewen & Purcell (1951)
  - OH 18 cm: Weinreb et al. (1963)
  - NH_3 1 cm: Cheung, Townes et al. (1968)
  - H_2O 1 cm: Cheung et al. (1969)

- UV telescopes: Copernicus (1970): H_2 at ~125nm (1970), later N_2

- (Sub-)millimeter telescopes: CO at 115 GHz (1970), H_2CO (1970), and many others

History of molecules in space

- IR telescopes:

  - IRAS (1983): 0.6 m, 12–100 μm, first sky survey, dust (β Pictoris disk)

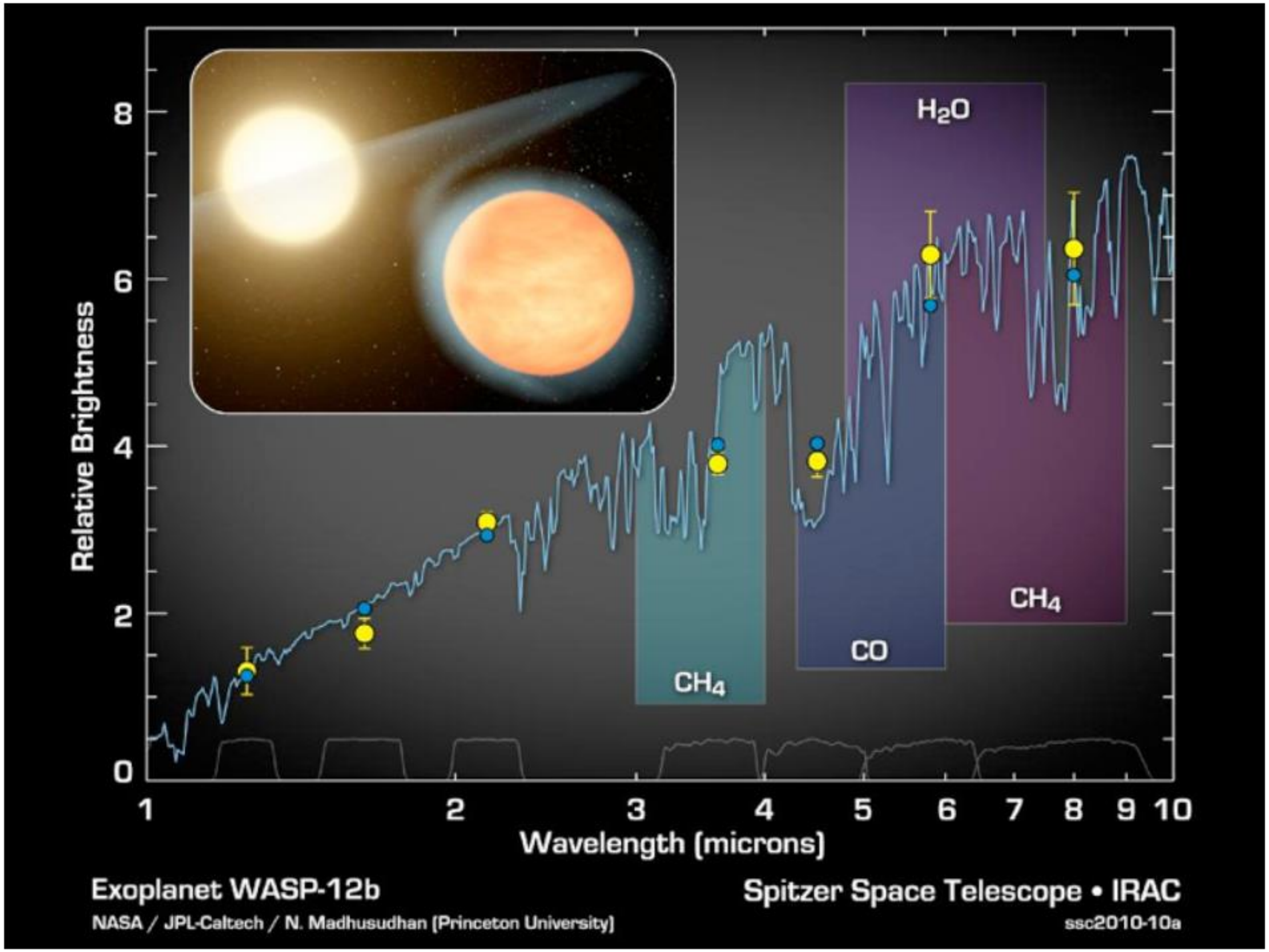
  - Infrared Space Observatory (1995–1998): 0.6 m, 2.5–240 μm, dust & molecules (H_2O, HF, OH, OI, C_6H_6, CH_3, CO_2, ...), infrared cirrus clouds

  - Spitzer Space Telescope (2003–2009): 0.8 m, 3–180 μm, high-sensitivity imaging and mapping, dust & molecules (OH, H_2O, C_2H_2, ...)

  - Herschel Space Observatory (2009–2012): 2.4 m, 60–670 μm, high-sensitivity imaging and mapping, dust & molecules (CH_3OH, H_2S, HCN, SO_2, H_2CO, H_2O, ...)

  - Ground-based: Keck, VLT, ...

Molecules, exoplanet WASP-12b, Spitzer



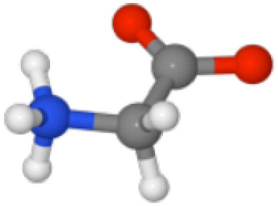
Detected molecules (~170)

as of 2013

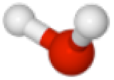
H2	**H3+**	CH3	CH4	CH3OH	CH3NH2	HCOOCH3	(CH3)2O	(CH3)2CO
CO	CH2	NH3	CH2NH	CH3SH	CH3CCH	CH3C3N	C2H5OH	CH3C5N
CS	NH2	**H3O+**	**H2CCC**	C2H4	CH3CHO	HC6H	C2H5CN	CH3CH2CHO
CN	H2O	H2CO	c-C3H2	CH3CN	c-CH2OCH2	**C7H**	CH3C4H	(CH2OH)2
C2	H2S	H2CS	CH2CN	CH3NC	CH2CHCN	HOCH2CHO	**C8H**	HCOOC2H5
CH	**CCH**	c-C3H	NH2CN	CH2CHO	**HC5N**	CH3COOH	**HC7N**	**HC9N**
CH+	**HCN**	**l-C3H**	CH2CO	NH2CHO	**C6H**	H2CCCHCN	CH3CONH2	CH3C6H
HF	HNC	C2H2	HCOOH	HC3NH+	CH2CHOH	**H2C6**	CH3CHCH2	C6H6
CF+	HCO	**HCNH+**	**C4H**	**H2CCCC**	**C6H-**	CH2CHCHO	**C8H-**	C3H7CN
SiO	**HCO+**	H2CN	**HC3N**	**C5H**		NH2CH2CN		**HC11N**
SiS	**HOC+**	HCCN	HCCNC	HC4H				C2H5OCH3
SiC	**N2H+**	HNCO	HNCCC	HC4N				
SiN	HNO	HOCN	**H2COH+**	c-C3H2O				
NH	**HCS+**	HCNO	**C4H-**	CH2CNH				
NO	**C3**	HNCS	SiH4	**C5N-**				
SO	**C2O**	HSCN	**C5**	**C5N**				
SO+	**C2S**	**C3N**	**SiC4**					
CP	SO2	**C3O**	CNCHO					
PO	N2O	**C3S**						
PN	CO2	**C3N-**						
HCl	**H2O+**	**HCO2+**						
KCl	**H2Cl+**	CNCHO						
AlCl	OCS	C-SiC2						
OH	MgNC				AlF	AlNC	AlOH	NaCl
OH+	MgCN				SiNC	CCP	HCP	FeO
SH	NaCN				CO+	O2	N2	
CN-	SiCN							

http://www.astro.uni-koeln.de/cdms/molecules

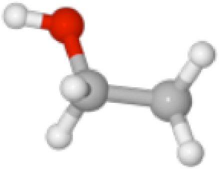
Detected molecules



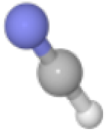
- 170 interstellar & circumstellar molecules
- 41 extragalactic molecules
- Up to 11 atoms (since 2010 => 70)!



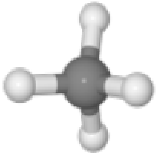
- 20 positive ions (cations)
- 6 negative ions (anions)



- ~30 free radicals
- ~20 isomers
- 6 linear and 6 cyclic species (including simplest PAH, C_6H_6)

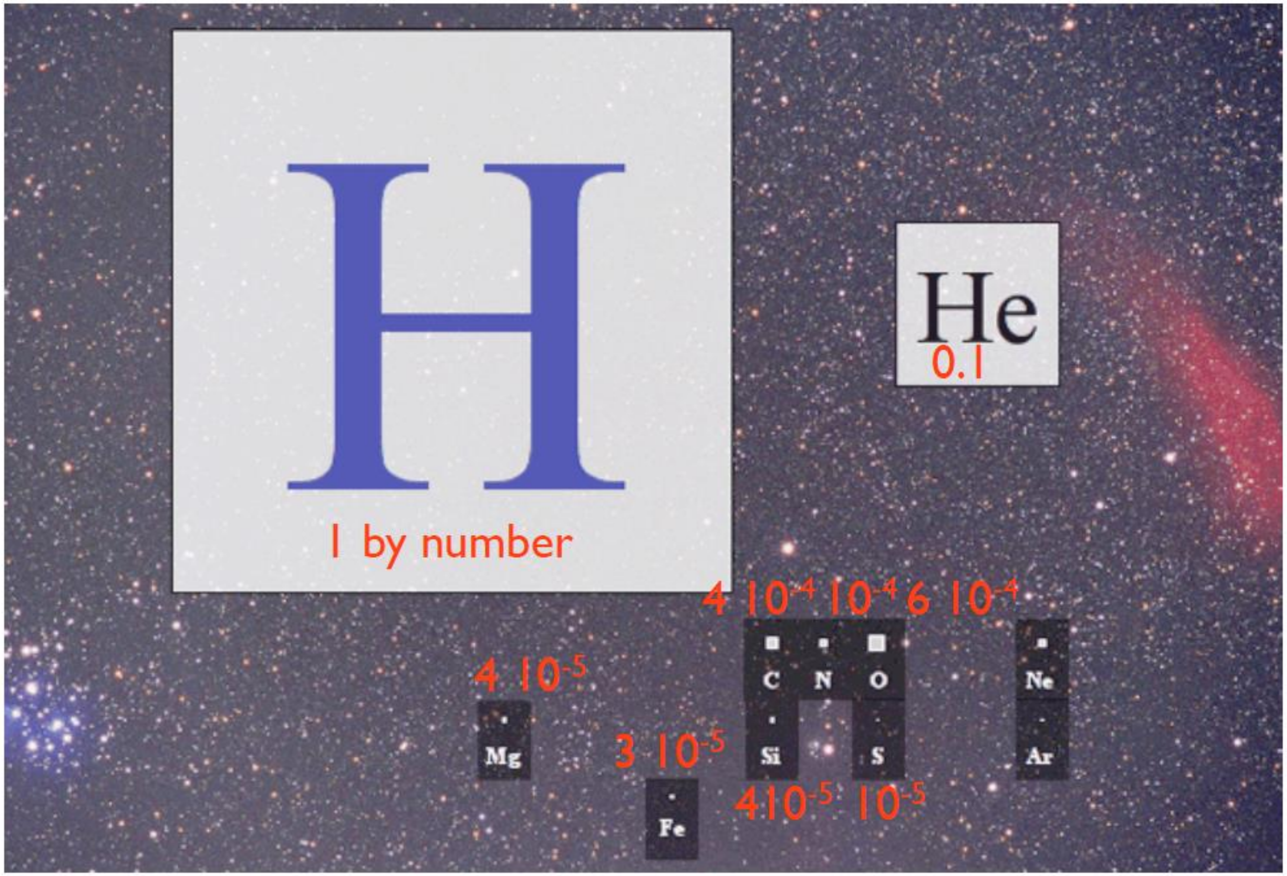


- 11 Si-, 6 P-, and 5 Cl-bearing species
- 11 metal-bearing species
- 10 species with deuterium



- Organic molecules: ethers, acids, alcohols, aldehydes, ...

Astronomer's periodic table



- 99% gas, 1% dust (by mass), depletion of refractory elements

McCall (2001)

Cosmological Redshift

The redshift z is defined as

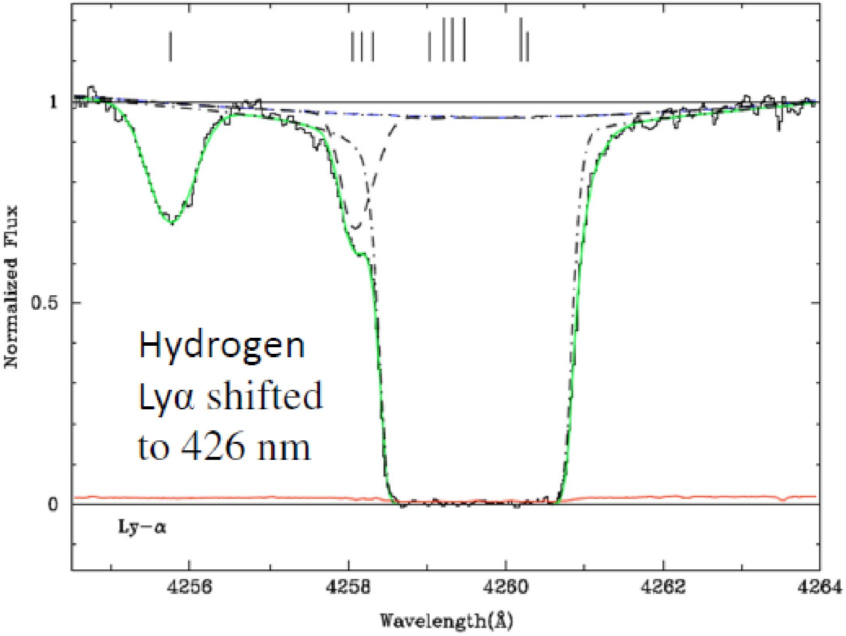
$$z = \Delta\lambda/\lambda = \frac{\lambda_{obs} - \lambda_{emit}}{\lambda_{emit}}$$

The observed wavelength is shifted by: $\lambda_{obs} = \lambda_{emit} + z\,\lambda_{emit}$

Example:

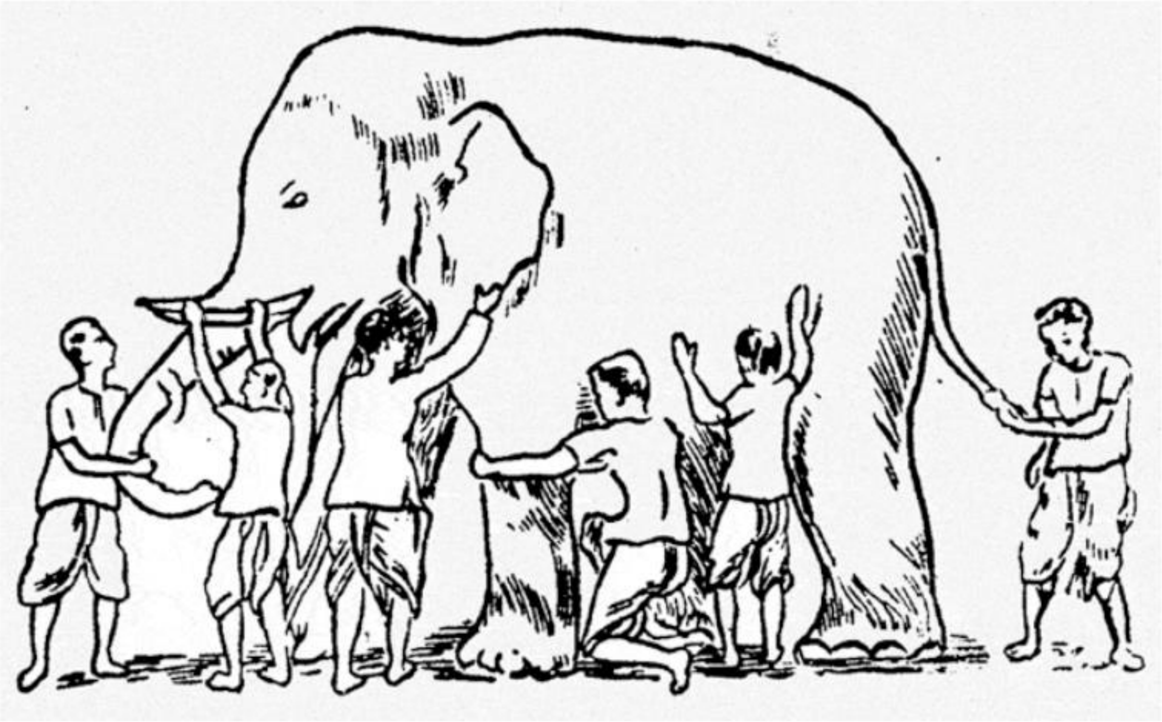
Lyα absorption, observed with Hubble Space Telescope at z =2.5

Burles and Tytler, ApJ 507, 732 (1998)



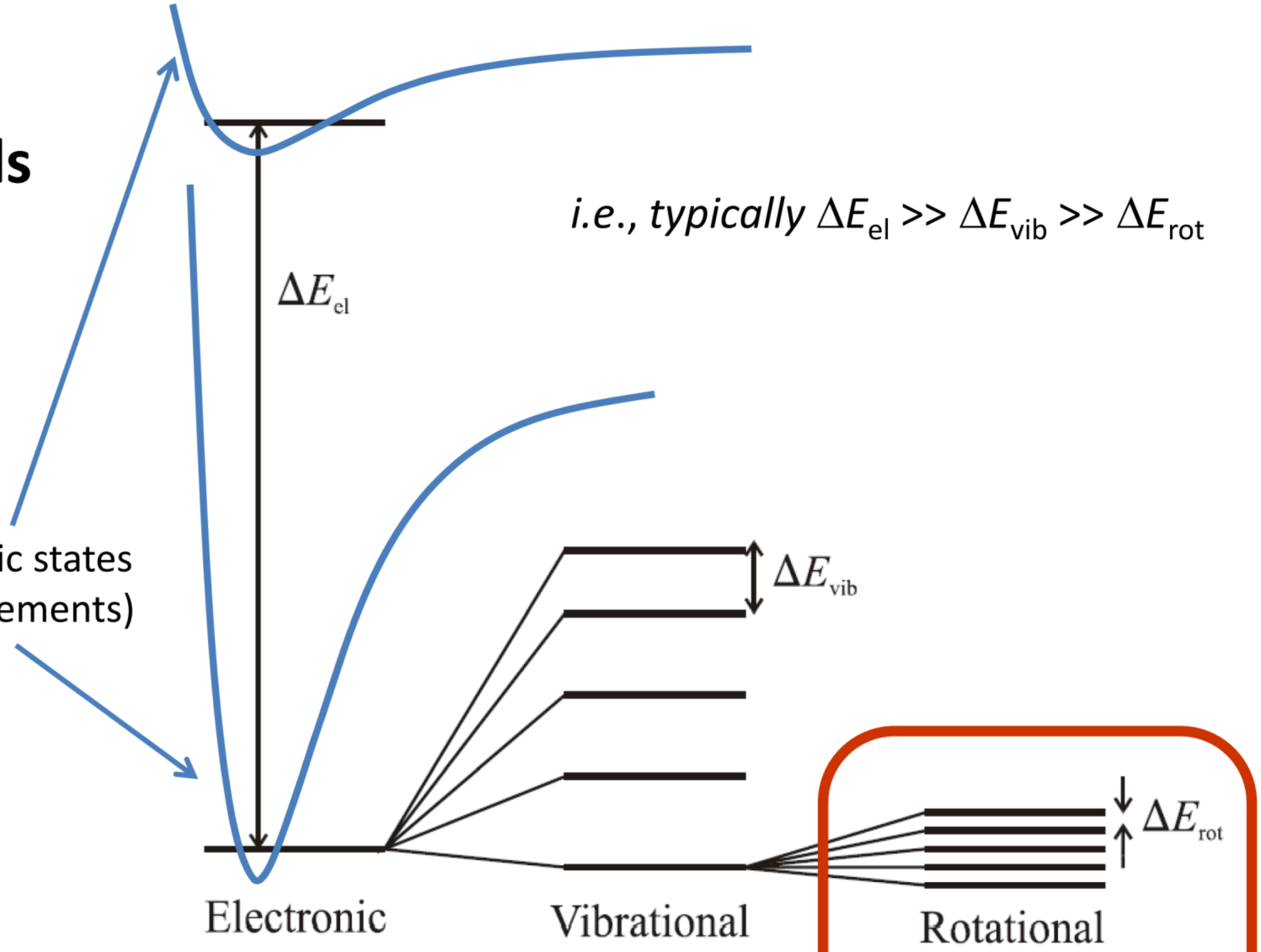
Hydrogen
Lyα shifted
to 426 nm

How do we detect particular species in space?



- Molecules emit & absorb radiation at characteristic frequencies
- Spectroscopy from the ground and space
- Laboratory spectra need to be known in advance

Molecular Energy Levels

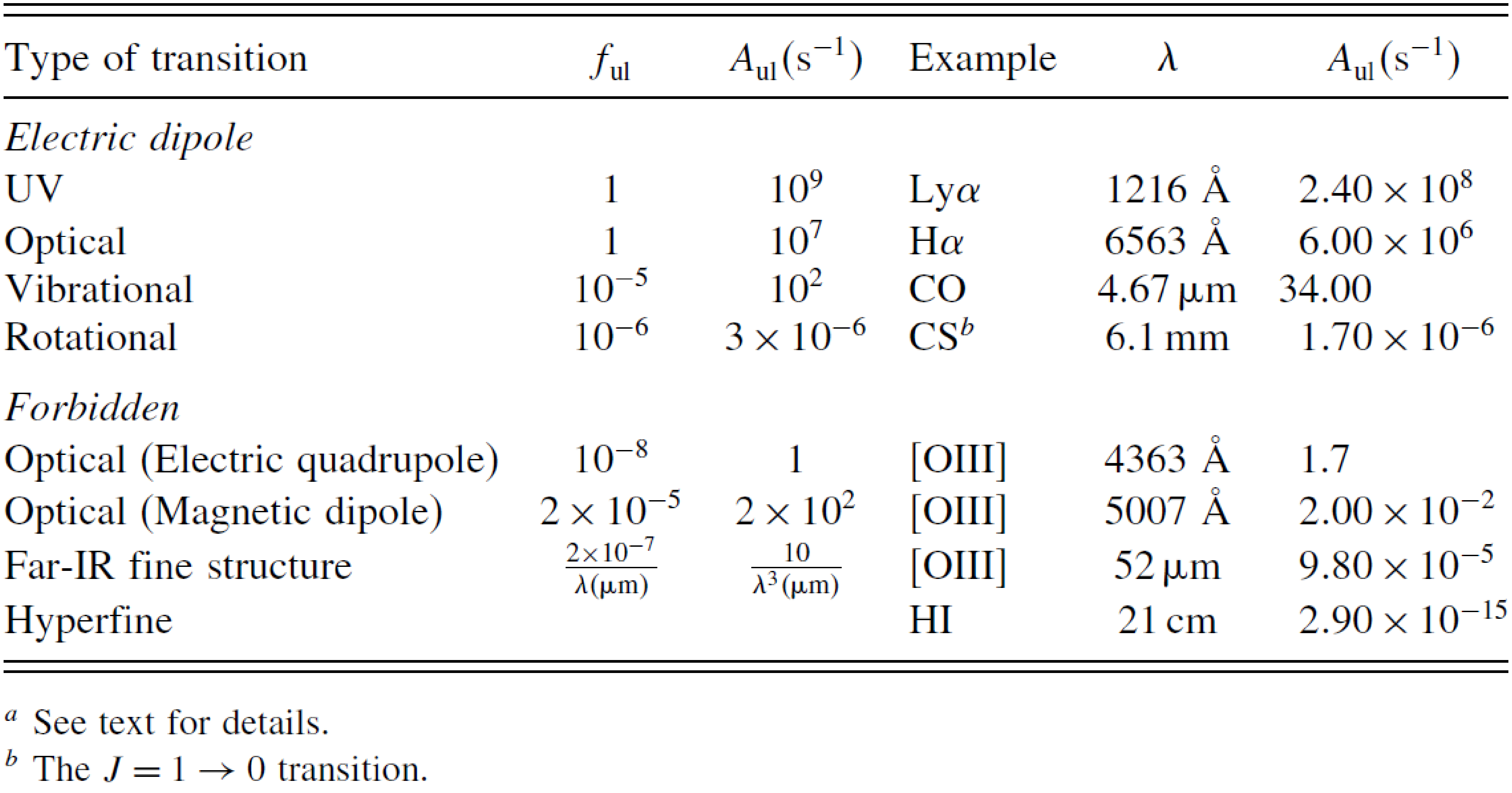


i.e., typically $\Delta E_{el} >> \Delta E_{vib} >> \Delta E_{rot}$

Different electronic states
(electronic arrangements)

$\Delta E \approx$	**2×10^4 – 10^5 cm^{-1}**	**10^2 – 5×10^3 cm^{-1}**	**3 – 300 GHz** **(0.1 – 10 cm^{-1})**
Transitions at $\lambda \approx$	**500 – 100 nm**	**100 μm – 2 μm**	**10 cm – 1 mm**
	Vis – UV	**infrared**	**microwave**

Typical values of A_{ul} and f



Type of transition	f_{ul}	$A_{\mathrm{ul}}(\mathrm{s}^{-1})$	Example	λ	$A_{\mathrm{ul}}(\mathrm{s}^{-1})$
Electric dipole					
UV	1	10^9	Lyα	1216 Å	2.40×10^8
Optical	1	10^7	Hα	6563 Å	6.00×10^6
Vibrational	10^{-5}	10^2	CO	4.67 µm	34.00
Rotational	10^{-6}	3×10^{-6}	CS[b]	6.1 mm	1.70×10^{-6}
Forbidden					
Optical (Electric quadrupole)	10^{-8}	1	[OIII]	4363 Å	1.7
Optical (Magnetic dipole)	2×10^{-5}	2×10^2	[OIII]	5007 Å	2.00×10^{-2}
Far-IR fine structure	$\frac{2\times10^{-7}}{\lambda(\mu\mathrm{m})}$	$\frac{10}{\lambda^3(\mu\mathrm{m})}$	[OIII]	52 µm	9.80×10^{-5}
Hyperfine			HI	21 cm	2.90×10^{-15}

[a] See text for details.

[b] The $J = 1 \rightarrow 0$ transition.

Lifetime of an excited level: $\sum A_{ul}^{-1}, l<u$

Tielens' book (2005)

Timeline: The First Second of the Universe

Time

Temp.

10^{30} K

< 10^{-37} s Universe is filled with high energy density, expanding, cooling

10^{-37} s **Inflation**, the Universe expands exponentially

< 10^{-11} s The Universe is filled with a **Quark-Gluon plasma**, elementary particles are being created and destroyed continuously

Baryogenesis: creates in imbalance in the matter / antimatter ratio of 100,000,001 to 100,000,000 → **the universe is matter-dominated**

10^{-6} s Quarks and Gluons combine, **Protons** and **Neutrons (Baryons) form** and annihilate immediately, leaving 10^{-10} of the initial baryons due to the matter / antimatter imbalance

1 s **Electrons and positrons (leptons) form**, annihilate, leaving 10^{-10} of the leptons as electrons

10^{10} K

Big Bang Nucleosynthesis (BBN): Ways to form Deuterium

has to overcome Coulomb force

weak interaction

1) $p + p \longrightarrow D + e^+ + \nu_e$

2) $n + n \longrightarrow D + e^- + \bar{\nu}_e$

3) $p + n \longrightarrow D + \gamma$

Good approximation:

all neutrons are used up to form deuterium via Reaction 3)

BBN: Beyond Deuterium

$$D + p \longleftrightarrow {}^{3}He + \gamma$$

$$D + n \longleftrightarrow {}^{3}H + \gamma$$

$$D + D \longleftrightarrow \mathbf{{}^{4}He} + \gamma$$

$$D + D \longleftrightarrow {}^{3}H + p$$

$$D + D \longleftrightarrow {}^{3}He + n$$

$${}^{3}He + p \longleftrightarrow \mathbf{{}^{4}He} + \gamma$$

$${}^{3}He + n \longleftrightarrow \mathbf{{}^{4}He} + \gamma$$

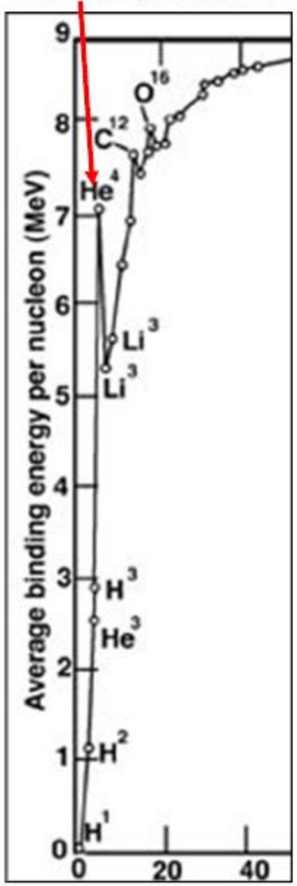
$${}^{3}H + D \longleftrightarrow \mathbf{{}^{4}He} + n$$

$${}^{3}He + D \longleftrightarrow \mathbf{{}^{4}He} + p$$

all D, ${}^{3}He$, ${}^{3}H$ rapidly converted to ${}^{4}He$

Nucleosynthesis Roadblocks

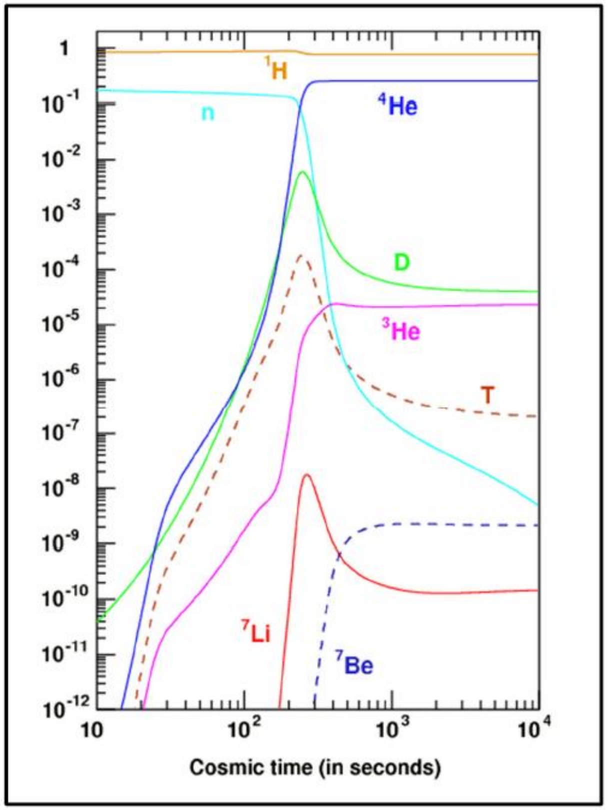
Universe filled with protons and ^{4}He:


^{4}He very stable

$$p + {}^4\mathrm{He} \longrightarrow {}^5\mathrm{Li} + \gamma$$

$$^4\mathrm{He} + {}^4\mathrm{He} \longrightarrow {}^8\mathrm{Be} + \gamma$$

BBN predictions (t = 3 - 20 min)



Recombination

$T < 380000$ yr

Ionization potentials [in eV]

	1st	2nd	3rd	4th
H	13.6			
He	**24.6**	54.4		
Li	5.4	75.6	122.5	

$Li^{3+} + e \rightarrow Li^{2+} + \gamma$

$Li^{2+} + e \rightarrow Li^{+} + \gamma$

$Li^{+} + e \rightarrow Li + \gamma$

$He^{2+} + e \rightarrow He^{+} + \gamma$

$He^{+} + e \rightarrow \mathbf{He} + \gamma$

$H^{+} + e \rightarrow \mathbf{H} + \gamma$

He^{+} recombines first to form the first neutral atoms **He**

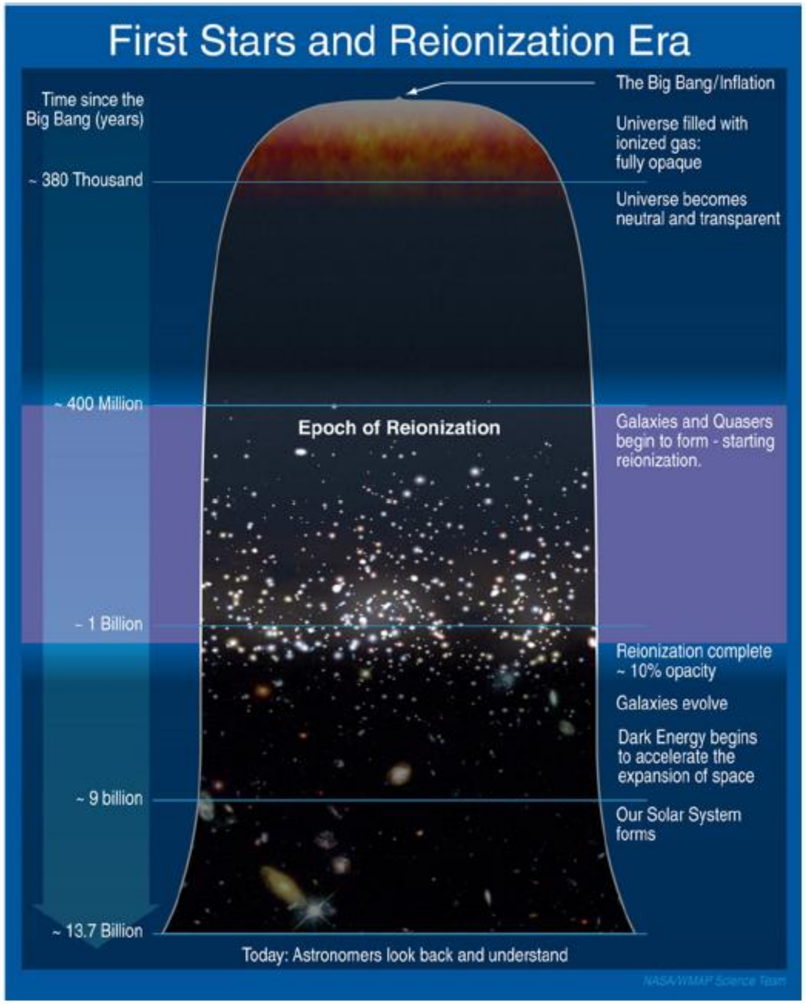
H^{+} recombines second to form **neutral H**

PART II

Timeline

10000 K

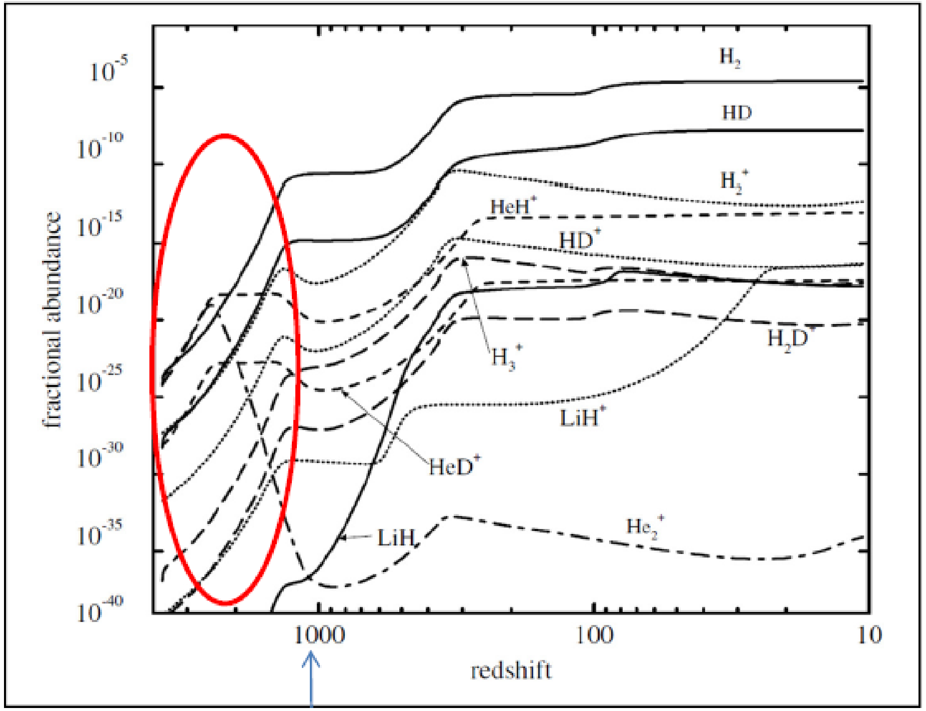
30 K



First molecules

First stars

Formation of Molecules (z > 1000)



T = 380000yr

The First Molecules

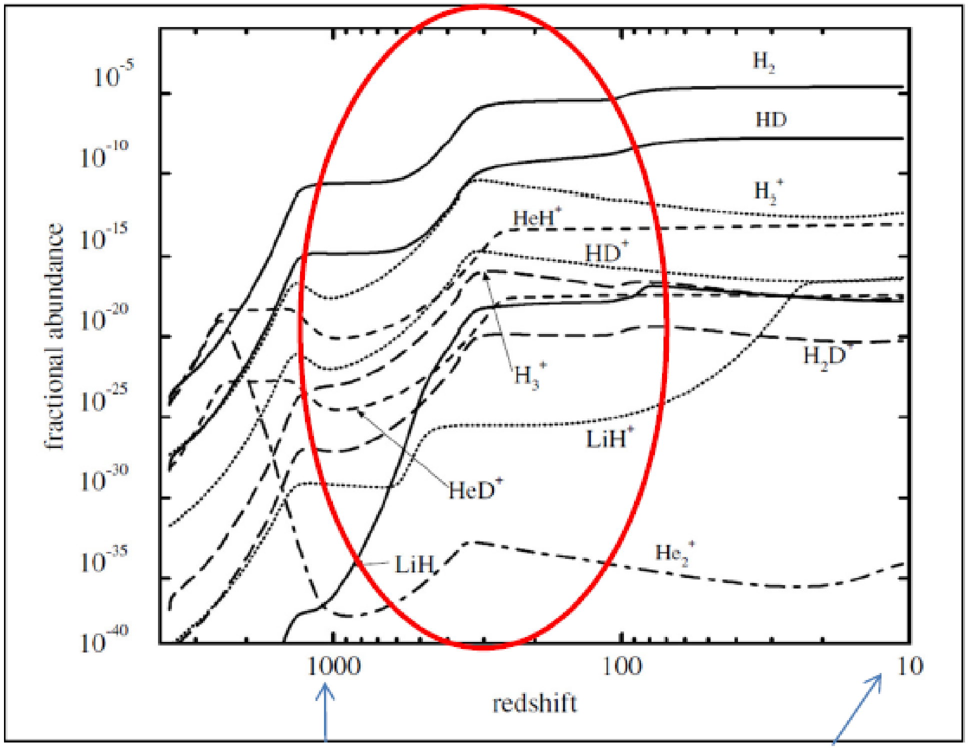
$$\begin{aligned} He + H^+ &\rightarrow HeH^+ + \gamma\,, \\ He + He^+ &\rightarrow He_2^+ + \gamma\,. \end{aligned}$$

The first neutral molecule: H_2

$$\begin{aligned} HeH^+ + H &\rightarrow H_2^+ + He, \\ H_2^+ + H &\rightarrow H_2 + H^+, \end{aligned}$$

Lepp, Stancil, Dalgarno, J. Phys. B., At. Mol. Opt. Phys 35 (2002) R57-R80

Formation of Molecules (1000> z > 100)



T = 380000yr

t = 480 x10^6 yr

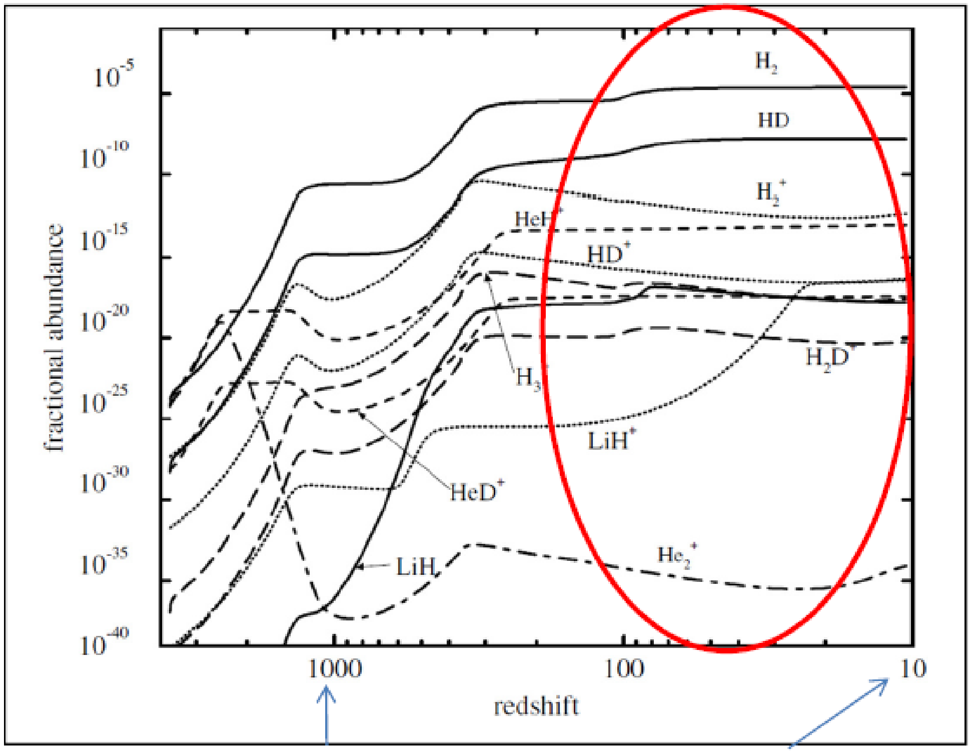
More hydrogen: the H_2^+ channel

$$
\begin{aligned}
H^+ + H &\rightarrow H_2^+ + \gamma, \\
H_2^+ + H &\rightarrow H_2 + H^+,
\end{aligned}
$$

More molecules:

D_2^+ , H_3^+, H_2D^+, D_2H^+, D_3^+
HeH^+, HeD^+, He_2^+
LiH^+, LiD^+, LiD, LiH^+

Formation of Molecules (z < 100)



T = 380000yr

t = 480 x10⁶ years

The H⁻ channel:

$$H + e^- \rightarrow H^- + \gamma,$$

0.75 eV

$$H^- + H \rightarrow H_2 + e^-.$$

H_2 associative detachment

I. Chemical Processes in Space

Name	Representation	Example	Rate*
Radiative association	$A + B \rightarrow AB + v$	$C^+ + H_2 \rightarrow CH_2^+$	$\sim 10^{-10}$-10^{-17} $cm^3\ s^{-1}$
Ion-molecule	$A^+ + B \rightarrow C^+ + D$	$CO + H_3^+ \rightarrow HCO^+ + H_2$	$\sim 10^{-7}$-10^{-10} $cm^3\ s^{-1}$
Neutral-neutral	$A + B \rightarrow C + D$	$O + CH_3 \rightarrow H_2CO + H$	$\sim 10^{-10}$-10^{-16} $cm^3\ s^{-1}$
Charge transfer	$A^+ + B \rightarrow B^+ + C$	$C^+ + Mg \rightarrow C + Mg^+$	$\sim 10^{-9}$ $cm^3\ s^{-1}$
Radiative recombination	$A^+ + e^- \rightarrow A + v$	$Mg^+ + e^- \rightarrow Mg + v$	$\sim 10^{-12}$ $cm^3\ s^{-1}$
Dissociative recombination	$AB^+ + e^- \rightarrow A + B$	$HCO^+ + e^- \rightarrow CO + H$	$\sim 10^{-7}$ $cm^3\ s^{-1}$
Ionization	$A + hv \rightarrow A^+ + e^-$	$C + hv \rightarrow C^+ + e^-$	$\sim 10^{-10}$ x RF** $cm^3\ s^{-1}$
Dissociation	$AB + hv \rightarrow A + B$	$CO + hv \rightarrow C + O$	$\sim 10^{-10}$ x RF $cm^3\ s^{-1}$

Arrhenius rate: $k = \alpha \left(\frac{T}{300}\right)^{\beta} \exp\left(-\gamma/T\right)$

II. Chemistry in the Early Universe

- Simple chemistry, only light elements: H, D, He, Li
- Almost isotropic physical conditions (no structures)
- First molecules: cooling of gas ⇒ formation of first stars (Pop III)
- High-z molecules are detected ($z \sim 7$)!

Standard Cosmological Model

Composition at the beginning of the matter-dominated era:
H : D : ^{4}He : ^{3}He : ^{7}Li
1 : $4\ 10^{-5}$: $8\ 10^{-2}$: 10^{-5} : $2\ 10^{-10}$
(all atoms fully ionized)

(1) $H + h\nu \rightarrow H^+ + e$, rate ~ ambient radiation field
(2) $H^+ + e \rightarrow H$, rate ~ $T^{-0.61}$

Temperature of matter $T_M = T_R$ due to Thompson scattering of photons on electrons

As Universe cools, recombination becomes more important:
$n(H^+)=n(H)$ at z=1340, $T_R=T_M=3630$ K

After that no thermodynamical equilibrium => chemical kinetics has to be considered to predict molecular abundances

Chemistry of He

He^+ recombines earlier than H^+:

$He^{2+} + e \rightarrow He^+ + h\nu$

$He^+ + e \rightarrow He + h\nu$

First molecules were He_2^+ and HeH^+:

$He^+ + He \rightarrow He_2^+ + h\nu$ (radiative association)

$He + H^+ \rightarrow HeH^+ + h\nu$ (radiative association)

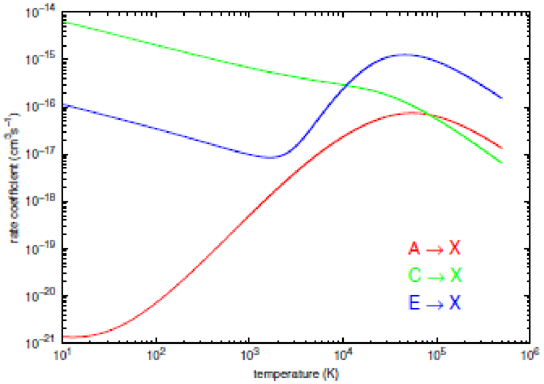


Fig. 2. Rate coefficients for spontaneous (T_b = 0 K) radiative association of He_2^+.

Excited states

They were removed by photodissociation & dissociative recombination:

$He_2^+ + h\nu \rightarrow He^+ + He$

$He_2^+ + e \rightarrow He + He$

L. Augustovicova, A&A 553, A42 (2013)

Chemistry of H

Molecular hydrogen cannot form on dust grains as at present time => slow gas-phase reactions

Direct formation by radiative association:
$H + H \rightarrow H_2 + h\nu$ is too slow

(H_2 does not have a dipole moment => difficult to get rid of excess of energy via radiation)

Formation of H_2 from HeH^+

First H_2 were formed via ion-molecule reactions with HeH^+:

$He + H^+ \rightarrow HeH^+ + h\nu$

$HeH^+ + H \rightarrow H_2^+ + He$

$H_2^+ + H \rightarrow H_2 + H^+$

(here He and H are catalysts!)

At that time, H_2 is quickly destroyed by background radiation (photodissociation)

Formation of H_2 from H^+

Later, formation H_2 involves RA & ion-molecule reaction:

$H + H^+ \rightarrow H_2^+ + h\nu$

$H_2^+ + H \rightarrow H_2 + H^+$

H_2^+ is destroyed by photodissociation and DR:

$H_2^+ + h\nu \rightarrow H + H^+$

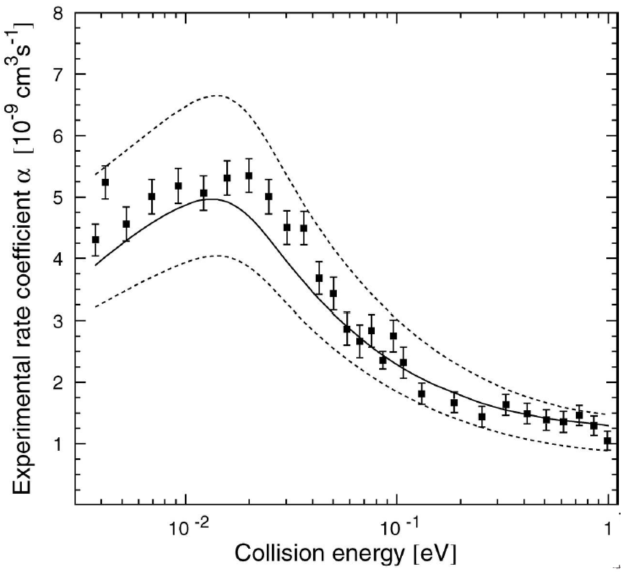
$H_2^+ + e \rightarrow H + H$

Photodissociation of H_2^+ is efficient when $T_R > 4000$ K => no H_2 at earlier times!

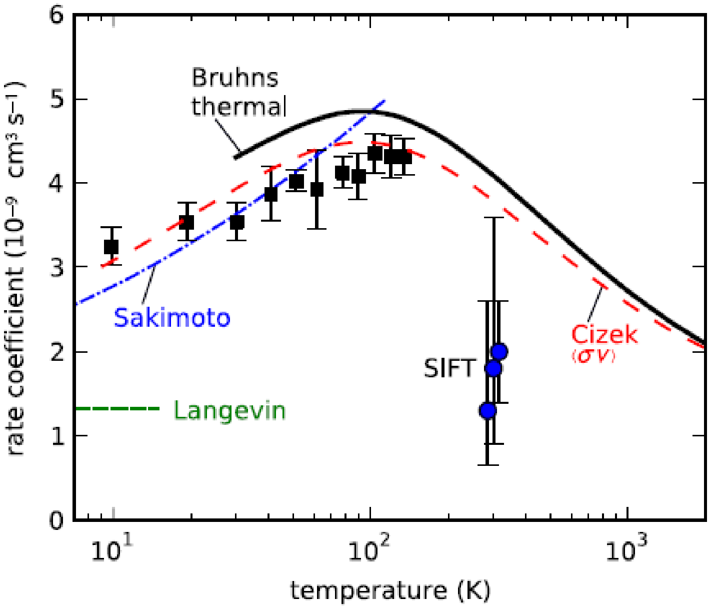
Formation of H_2 from H^-

At z~100, H_2 can be formed through H^-:
$H + e \rightarrow H^- + h\nu$ (radiative attachment)
$H^- + H \rightarrow H_2 + e$ (associative detachment)

H^- is destroyed by photodetachment reaction:
$H^- + h\nu \rightarrow H + e$ (barrier is 0.75 eV)
=> $T_R < 1000$ K are needed to slow down this process



Kreckel et al. (2010), Science



D. Gerlich, P. Jusko, Š. Roučka et al., Astrophys. J. 749 (2012) 22.

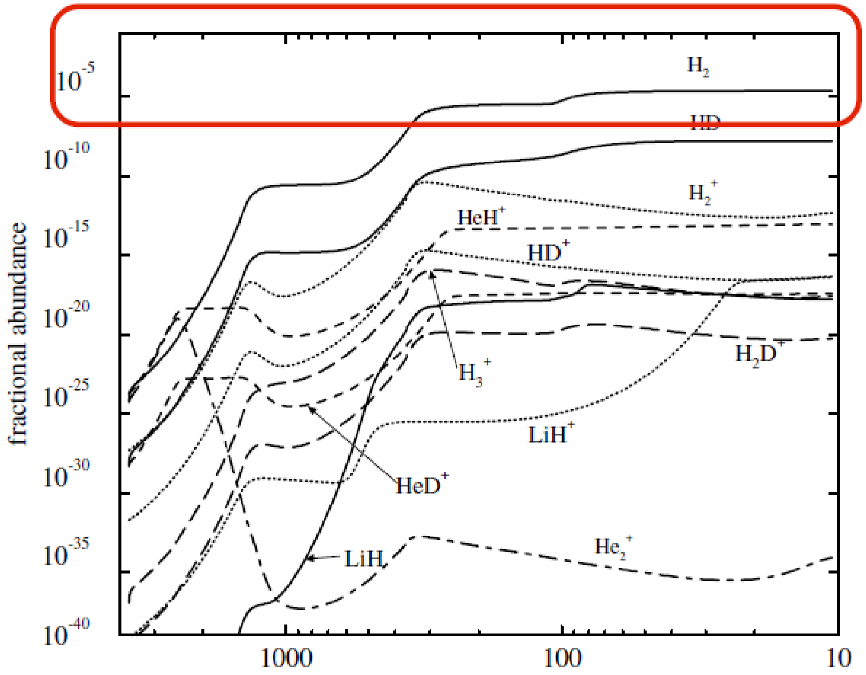
Destruction of H_2

H_2 is efficiently destroyed by photodissociation, ion-molecule reactions with H^+, and collisional dissociation:

$H_2 + H^+ \rightarrow H_2^+ + H$

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

=> small molecular fraction in the early Universe: $X(H_2) \sim 10^{-6}$



Chemistry of Li

I.P. of Li is 5.4 eV => relevant chemistry begins at $z<450$:

Major species are LiH and LiH^+:

LiH^+ chemistry:

$Li^+ + H \rightarrow LiH^+ + h\nu$ (RA)

$LiH^+ + e \rightarrow Li + H$ (DR)

$LiH^+ + h\nu \rightarrow Li^+ + H$ (photodissociation)

LiH chemistry:

$Li + H \rightarrow LiH + h\nu$ (RA)

$Li + H^- \rightarrow LiH + e$ (associative detachment)

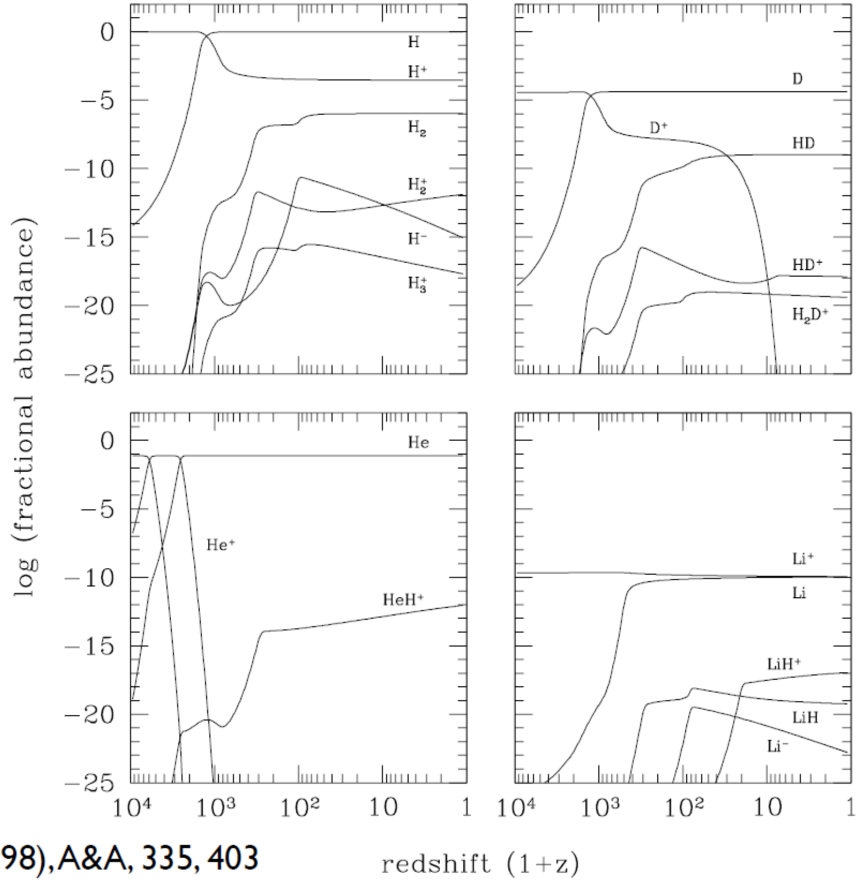
$Li^- + H \rightarrow LiH + e$ (AD)

$LiH + h\nu \rightarrow Li + H$ (PD)

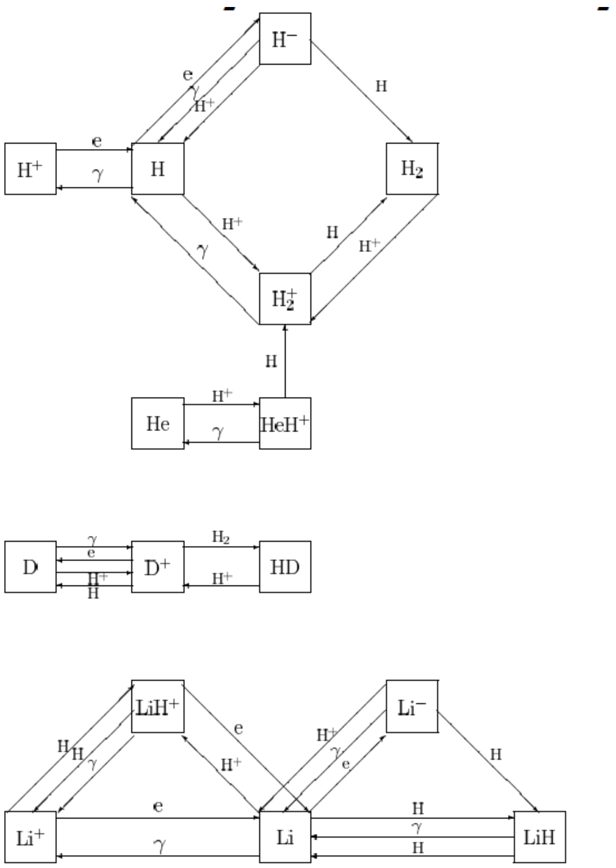
$LiH + H \rightarrow Li + H_2$ (PD)

Minor species: X(LiH) ~ 1% of $X(LiH^+) \sim 10^{-18}$

Summary: abundances of early molecules



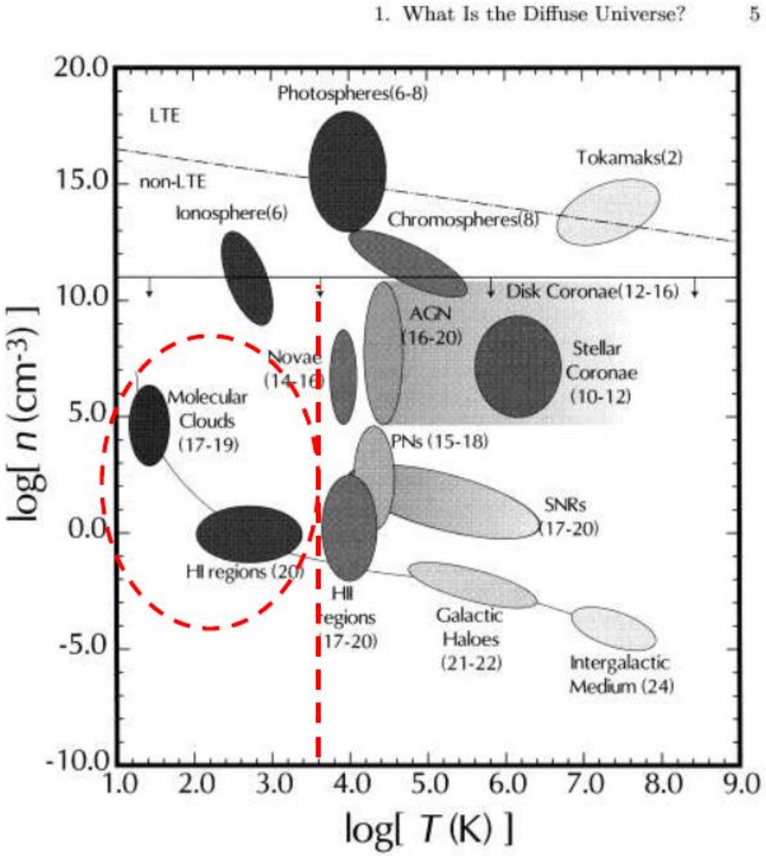
Galli, Palla (1998), A&A, 335, 403



Scheme: chemistry in the early Universe

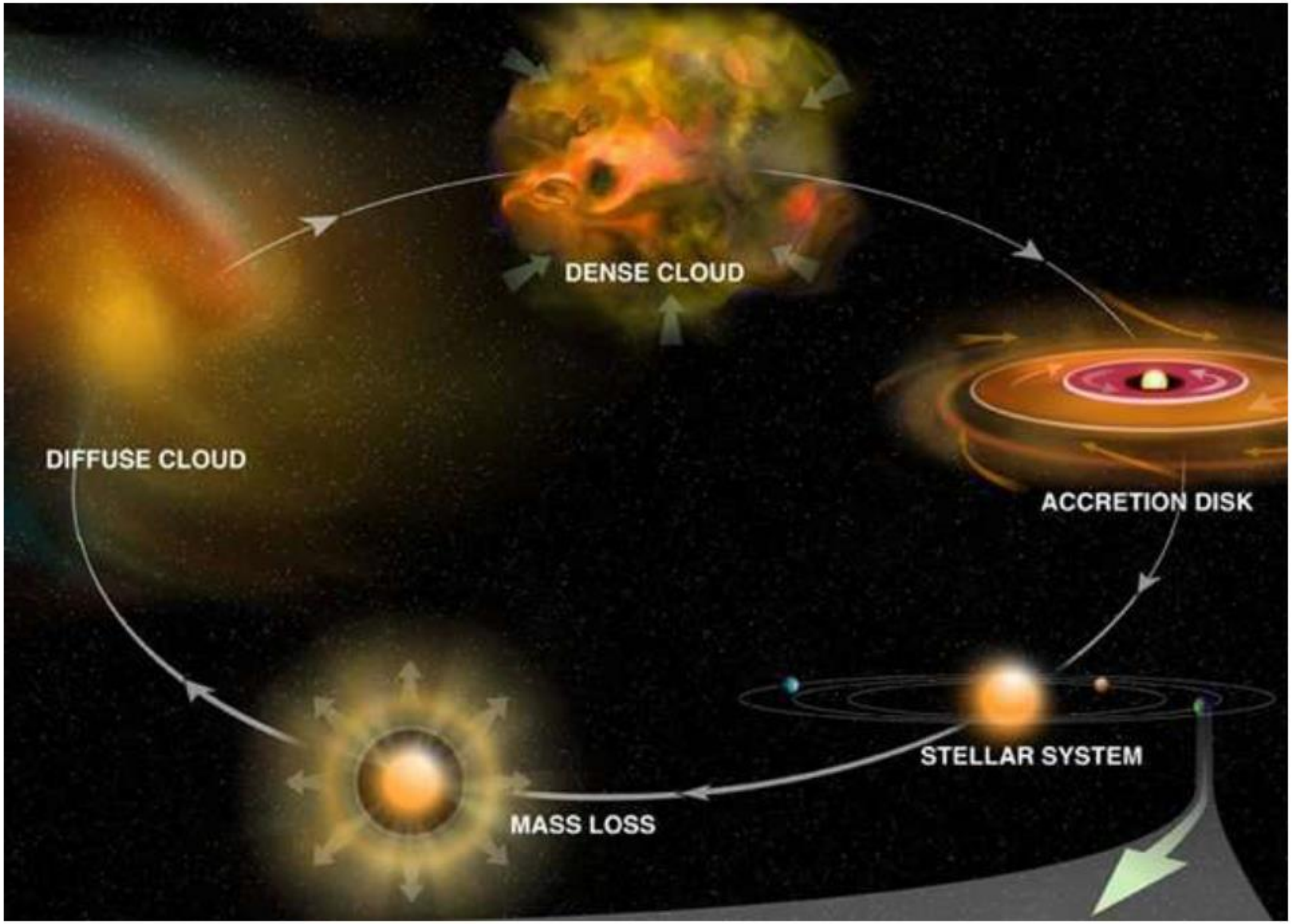
Physics and chemistry of diffuse interstellar medium

What is the Diffuse Interstellar Medium?



Picture from Dopita / Sutherland, “Astrophysics of the Diffuse Universe”, Springer

The Cosmic Chemistry Cycle



Credit: NRAO

Diffuse medium vs. terrestrial conditions

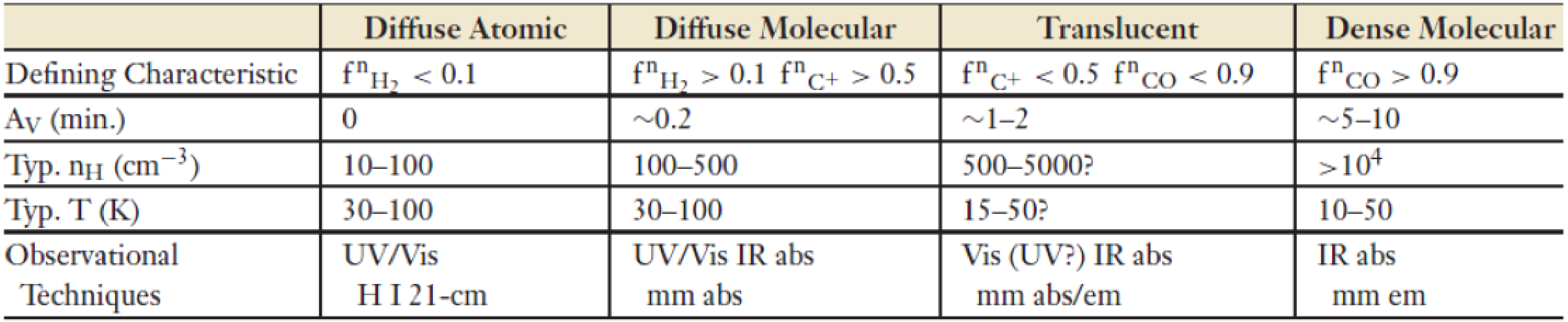
	Earth's atmosphere	Interstellar Medium
Density	10^{19} cm^{-3}	$10^2 - 10^6$ cm^{-3}
Collision time scale	nanoseconds, 3-body collisions likely	hours – years for binary collisions, no 3-body collisions
statistics	Boltzmann $\frac{N_j}{N_1} = \frac{g_j}{g_1} \exp\left(\frac{-\Delta E_m}{kT}\right)$	Often local thermodynamic equilibrium is not reached, radiative lifetimes can be much shorter than average collision times → many species in ground state, irrespective of kinetic temperature

Modern Classification of Interstellar Cloud Types

Snow & McCall, Annu. Rev. Astron. Astrophys. 2006. 44:367-414

Definitions:

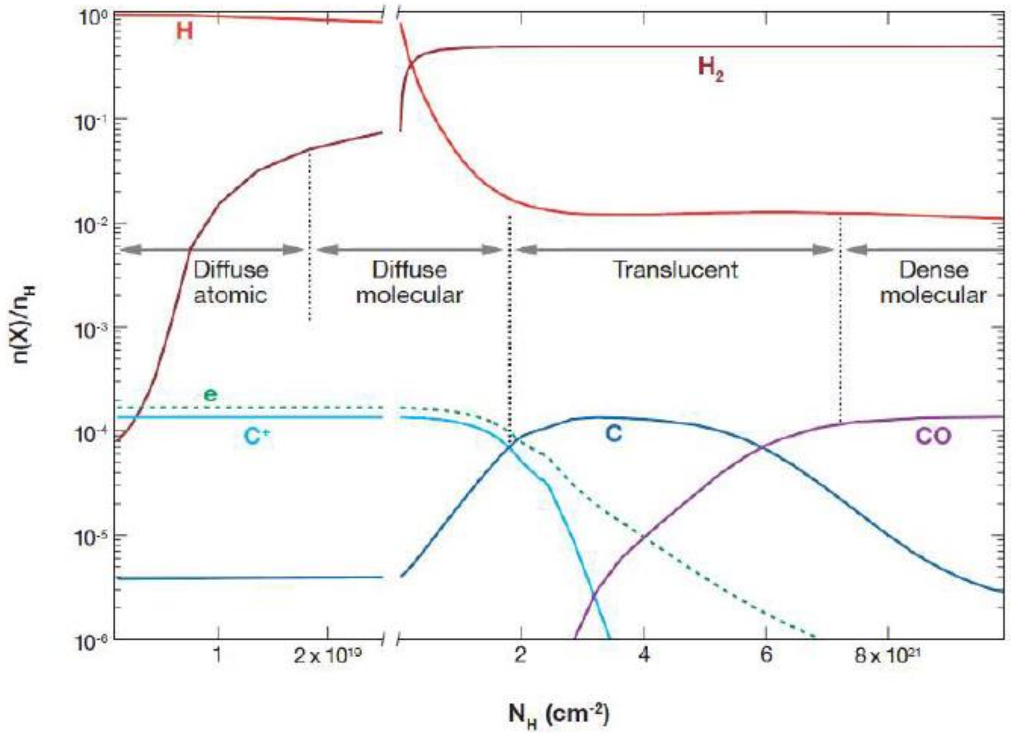
Number density of species X:	$n(X)$	$[cm^{-3}]$
Column density: Integral of $n(X)$ along sightline	$N(X)$	$[cm^{-2}]$
Total nuclei number density: example: $N_H = n(H) + 2n(H_2)$, $n_C \approx n(C^+) + n(C) + n(CO)$	n_X	$[cm^{-3}]$
Local fraction: example: $f^n_{H2} = 2n(H_2)/n_H$, $f^n_{CO} = n(CO)/n_C$, etc …	f^n	



	Diffuse Atomic	Diffuse Molecular	Translucent	Dense Molecular
Defining Characteristic	$f^n_{H_2} < 0.1$	$f^n_{H_2} > 0.1$ $f^n_{C+} > 0.5$	$f^n_{C+} < 0.5$ $f^n_{CO} < 0.9$	$f^n_{CO} > 0.9$
A_V (min.)	0	~0.2	~1–2	~5–10
Typ. n_H (cm^{-3})	10–100	100–500	500–5000?	$>10^4$
Typ. T (K)	30–100	30–100	15–50?	10–50
Observational Techniques	UV/Vis H I 21-cm	UV/Vis IR abs mm abs	Vis (UV?) IR abs mm abs/em	IR abs mm em

The diffuse ISM can be explored by Visible and UV observations!
Easy to study? Still a lot of problems …

Transition between Cloud Types



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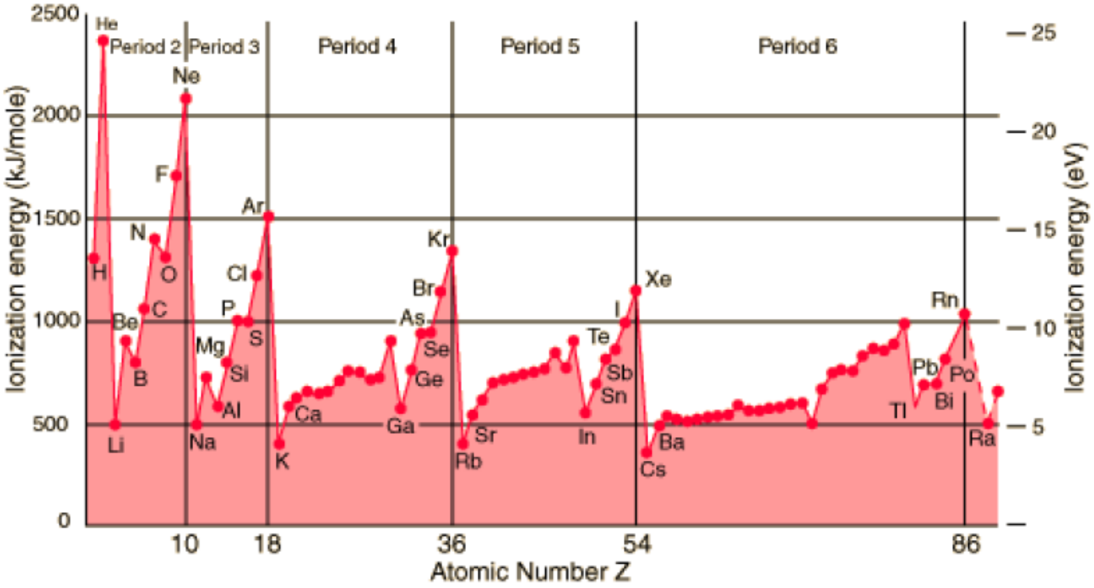
Observational Techniques	UV/Vis H I 21-cm	UV/Vis IR abs mm abs	Vis (UV?) IR abs mm abs/em	IR abs mm em

Snow & McCall, Annu. Rev. Astron. Astrophys. 2006. 44:367-414

Diffuse Atomic Clouds

- Part of the diffuse interstellar medium that is fully exposed to radiation field
- Nearly all molecules quickly destroyed by photodissociation
- Hydrogen in neutral atomic form (H).
- Elements with Ionization potential < 13.6 eV almost fully ionized (e.g. C -> C^+)
- Hardly any molecules, **but strong Diffuse Interstellar Bands (Mystery!)**



Diffuse Molecular Clouds

- Interstellar radiation field is sufficiently attenuated in the UV regime for H_2 to survive,
- typically surrounded by diffuse atomic gas,
- Most diffuse molecular sightlines will also cross atomic sightlines,
- densities 100-500 cm^{-3},
- temperature 30-100 K,
- Almost all carbon ionized (C^+)
- High ionization fraction, $n(C^+) \approx n(e)$
- Electron recombination dominant destruction route for many ions

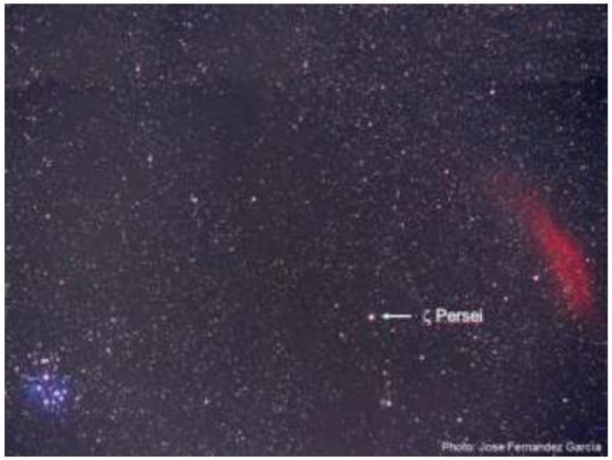
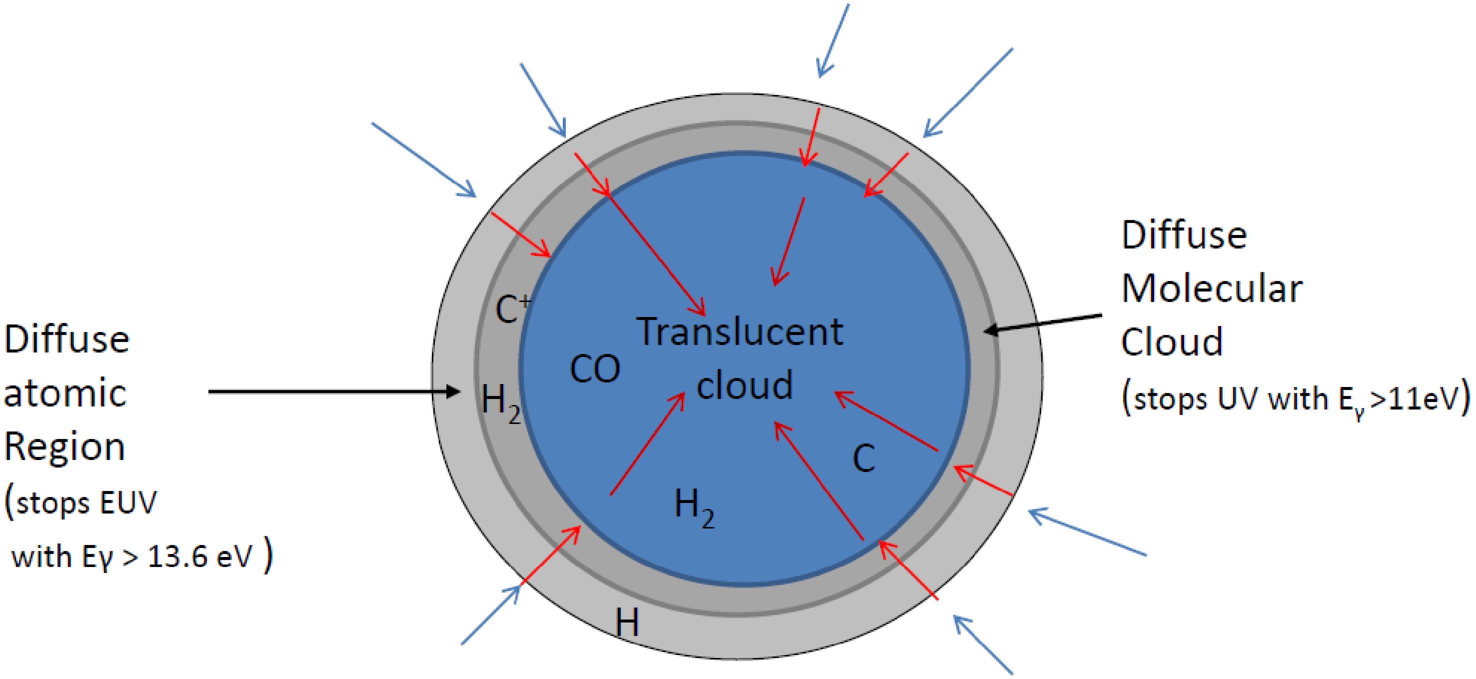


Photo: Jose Fernandez Garcia

Translucent Clouds

- Characterized by the transition from ionized C^+ to neutral C and CO
- Introduced by Van Dishoeck and Black (1989),
- Translucent regime not well understood,
- Lack of observational data,
- Chemical models do not agree in the C, Co transition regime,

- Interstellar radiation field is sufficiently attenuated at energies <13.6 eV that carbon becomes neutral (C) or molecular (CO)
- Typically surrounded by diffuse molecular gas,



Diffuse
atomic
Region
(stops EUV
with Eγ > 13.6 eV)

Diffuse
Molecular
Cloud
(stops UV with E_γ>11eV)

Dense Molecular Clouds

- With increasing extinction, carbon becomes completely molecular (CO),
- No longer observable in the visible or UV regime,
- Much lower ionization fraction than diffuse medium,
- Electron recombination is much less important due to lack of electrons,
- Main source of ionization: Cosmic rays!
- Most of the detected interstellar molecules are observed in dense clouds,
- Places of star formation.

H_3^+: the Engine of Interstellar Chemistry

Molecular clouds:

It's cold and (relatively empty)

temperatures: **10-100 K**

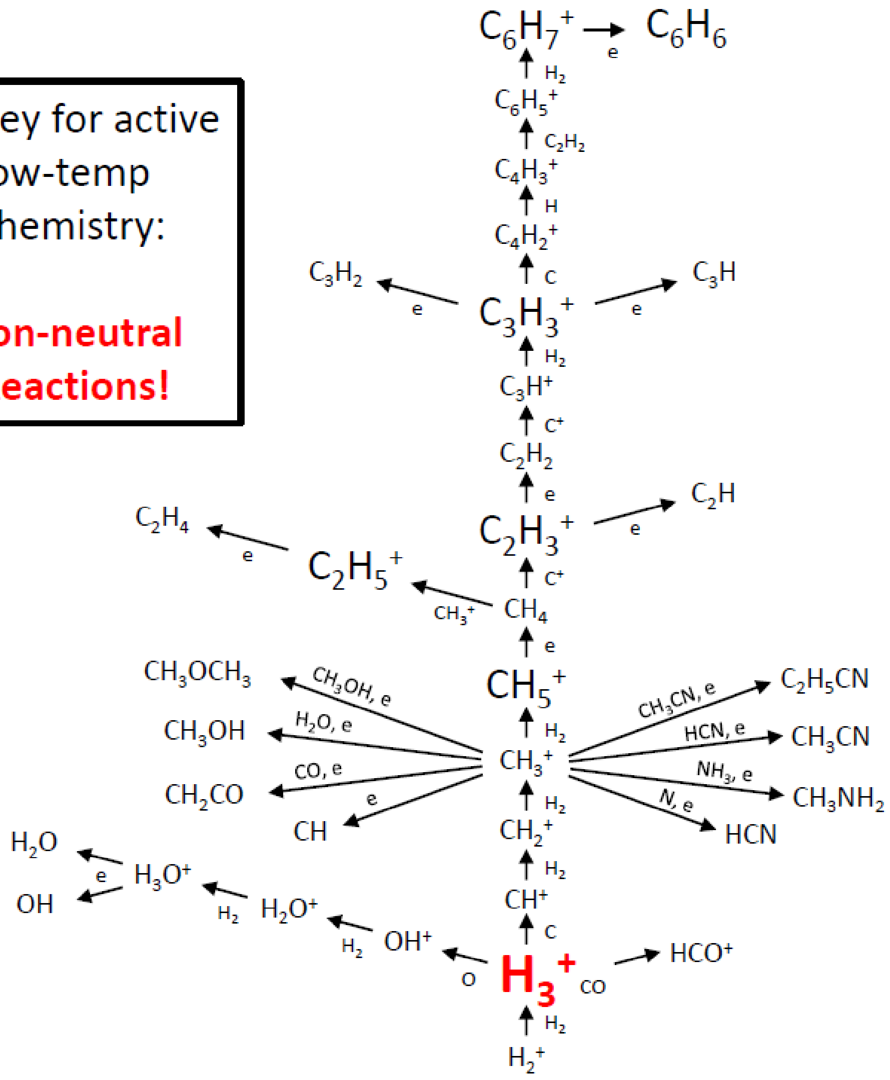
density: **10^2 - 10^4 cm^{-3}**

- No endothermic reactions
- No 3-body collisions
- No reactions with barriers

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$

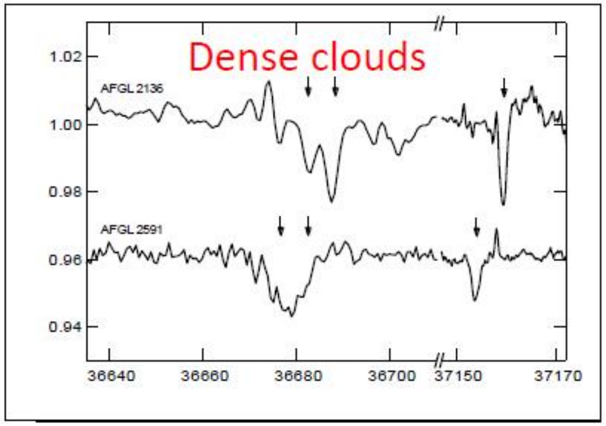
Key for active low-temp chemistry:

Ion-neutral Reactions!

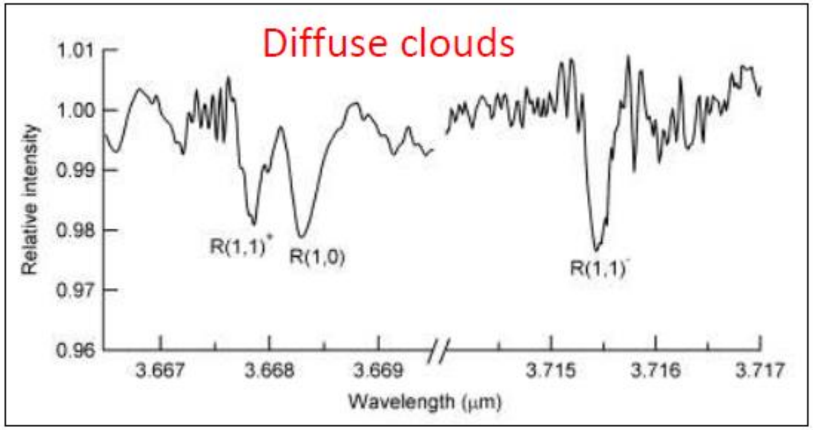


McCall, PhD thesis, Chicago 2001

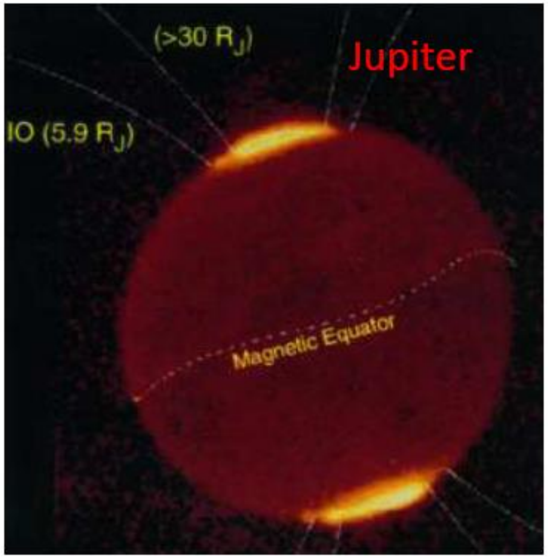
Extraterrestrial H_3^+



Geballe & Oka, Nature 384, 334 (1996)



McCall et al., Science 279, 1910 (1998)



Connerney et al., Science 262 , 1035 (1993)

Plus:

- detection in the atmosphere of Uranus
- detection in Saturn's atmosphere
- high abundance towards the galactic center
- extragalactic detection in IRAS 08572+3915NW

The enigma related to interstellar H_3^+

Dense clouds: formation $H_2 + \text{c.r.} \longrightarrow H_2^+$

$H_2^+ + H_2 \longrightarrow H_3^+ + H$

destruction $H_3^+ + CO \longrightarrow HCO^+ + H_2$

observed column density: $6 \times 10^{14}\ \text{cm}^{-2}$ ✓

Diffuse clouds: formation $H_2 + \text{c.r.} \longrightarrow H_2^+$

$H_2^+ + H_2 \longrightarrow H_3^+ + H$

destruction $H_3^+ + e^- \longrightarrow H_2 + H \;/\; H + H + H$

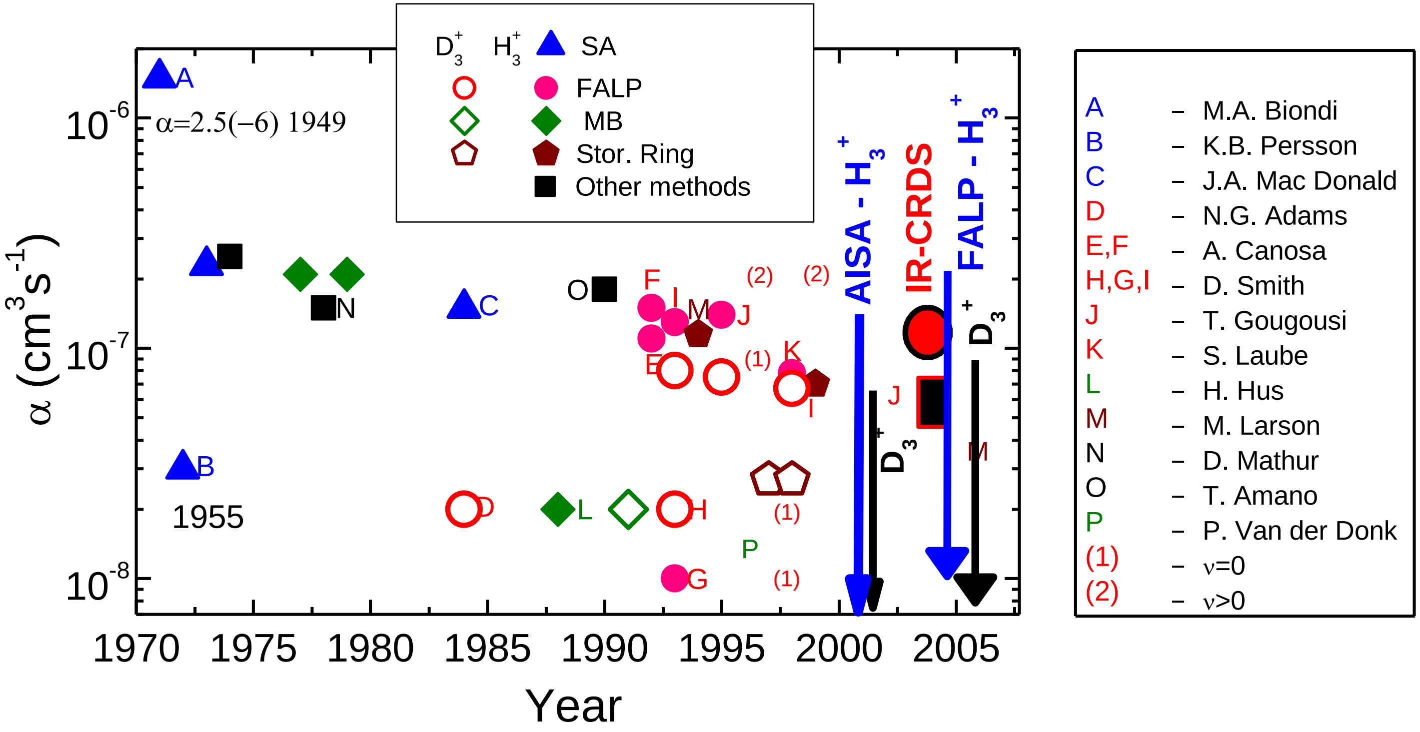
observed column density: $4 \times 10^{14}\ \text{cm}^{-2}$

Dissociative Recombination DR

⚡

2-3 orders of magnitude too much H_3^+ in diffuse clouds !

Rekombinace iontů H_3^+ s elektrony



Není to jednoduchý problém

$$H_3^+ + e^- \rightarrow H + H + H$$

$$\rightarrow H_2 + H$$

The Enigma of H_3^+ in Diffuse Clouds

Cosmic ray ionization rate

(10^{-17} s^{-1})

Steady State: $$[H_3^+] = \frac{\zeta}{k_e}\frac{[H_2]}{[e^-]}$$

Fast DR rate coefficient

(10^{-7} cm^3 s^{-1})

Inverse ionization fraction

($1/10^{-4}$)

→ $N(H_3^+) = 10^{-6}$ cm^{-3}

With the canonical value for the Cosmic Ray Ionization Rate

Of $\zeta \approx 10^{-17}$ s^{-1} and a fast DR process,

H_3^+ should not be observable in the diffuse ISM!

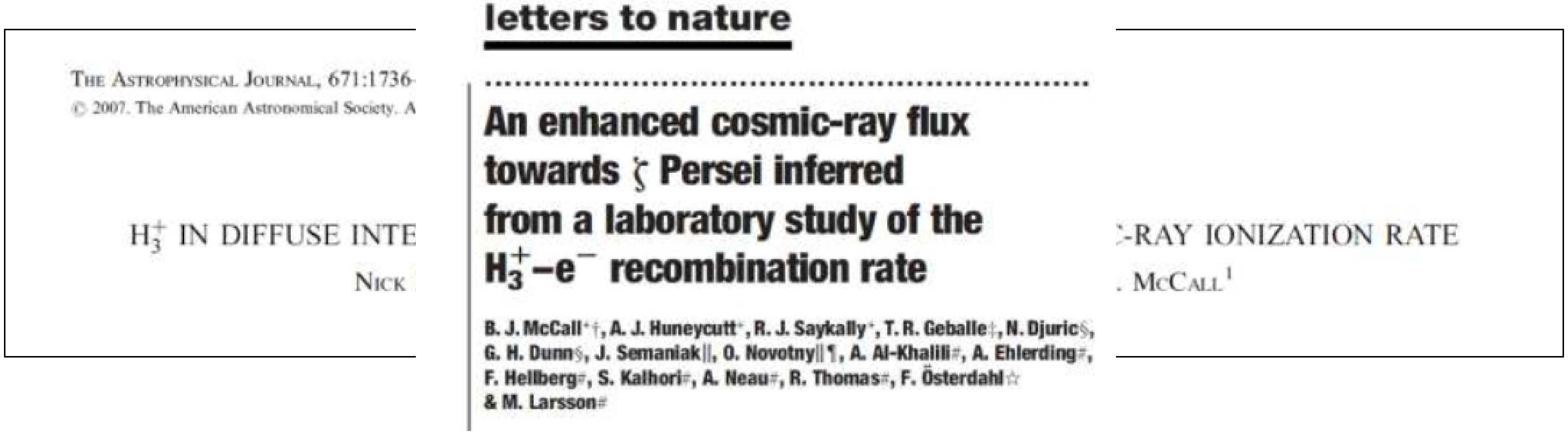
H_3^+ Laboratory Astrophysics Research leads to a revised Cosmic ray ionization rate in the Diffuse ISM

High Cosmic ray ionization rate

High observed H_3^+ column densities

Steady State: $$[H_3^+] = \frac{\zeta}{k_e}\frac{[H_2]}{[e^-]}$$

Fast DR rate coefficient



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H_3^+ IN DIFFUSE INTE

NICK

-RAY IONIZATION RATE

. MCCALL[1]

letters to nature

An enhanced cosmic-ray flux towards ζ Persei inferred from a laboratory study of the H_3^+–e^- recombination rate

B. J. McCall*†, A. J. Huneycutt*, R. J. Saykally*, T. R. Geballe‡, N. Djuric§, G. H. Dunn§, J. Semaniak||, O. Novotny||¶, A. Al-Khalili#, A. Ehlerding#, F. Hellberg#, S. Kalhori#, A. Neau#, R. Thomas#, F. Österdahl☆ & M. Larsson#

Děkuji vám za pozornost