H_3^+ AT THE INTERFACE OF ASTROCHEMISTRY AND ASTRO-PARTICLE PHYSICS

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Critical insights from interstellar H_3^+

✓The cosmic ray ionization rate is
$<\zeta>=3.5\times10^{-16}\ s^{-1}$
but with significant variations
(Indriolo & McCall 2012)

✓There is dilute (~100 cm^{-3}), warm (250 K)

molecular gas throughout the
Central Molecular Zone (inner 200 pc)
of the Galaxy (Oka et al.)

Cosmic rays of 10-100 MeV/nucleon
are most effective in ionizing hydrogen

Cosmic rays ≥GeV ⇒ hadronic interactions

$$p + p \rightarrow \pi^0 \rightarrow \gamma$$

the resulting γ-rays are observable as
diffuse emission from the interstellar medium

Fermi Gamma-ray Space Telescope has revealed

Diffuse γ-rays imply "dark" molecular gas

γ-ray sources associated with supernovae remnants

Can we find the sources of cosmic rays?
Can we test models of particle acceleration and propagation?

Hadronic Υ-ray emission spectra imply cosmic-ray ionization rates within the same emitting volumes...but with some extrapolation.

SN remnant	ζ/ζ_{gal} [1]	ζ/ζ_{gal} [2]	ζ/ζ_{gal} [3]
W 51C	0.026	0.69	3.5
W 44	0.75	23	139
W 28	0.25	8.4	25
IC 443	0.032	1.7	12
W 49B	1810	74000	450000
CTB 37A	0.039	1.4	8.4
3C 391	9.3	100	660
G8.7-0.1	1.1	64	400
G349.7+0.2	0.07	2.6	16

[1] cosmic-ray spectrum break at 1 GeV, slope at lower energies a=2.0
[2] break at 100 MeV, slope a=1.5
[3] break at 30 MeV, slope a=1.0

from Schuppan, Becker, Black, Casanova 2012 (arXiv:1201.4674)

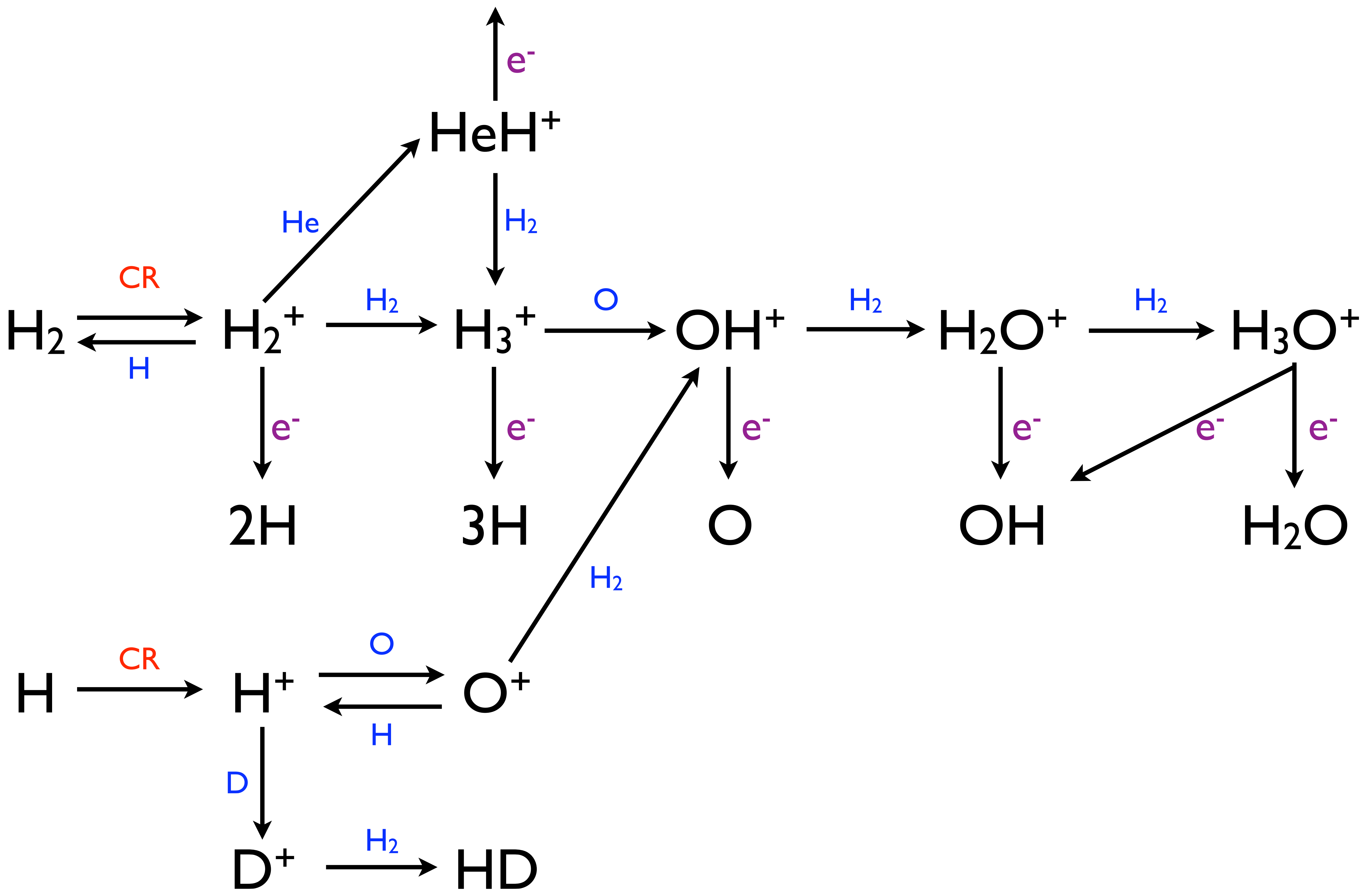
$$\zeta_{gal} = 2\times10^{-16}\ s^{-1}$$

What do cosmic rays do to interstellar matter?

FEEDBACK - in the Galactic cycle of star birth and star death

- ionize hydrogen and helium, produce e^-
- drive a rapid ion-neutral chemistry even at $T<10$ K
- heat (excess energy of secondary electrons)
- exert pressure, especially on magnetic field
- destroy or modify dust particles

Cosmic-ray-induced chemistry



Transient versus terminal ions

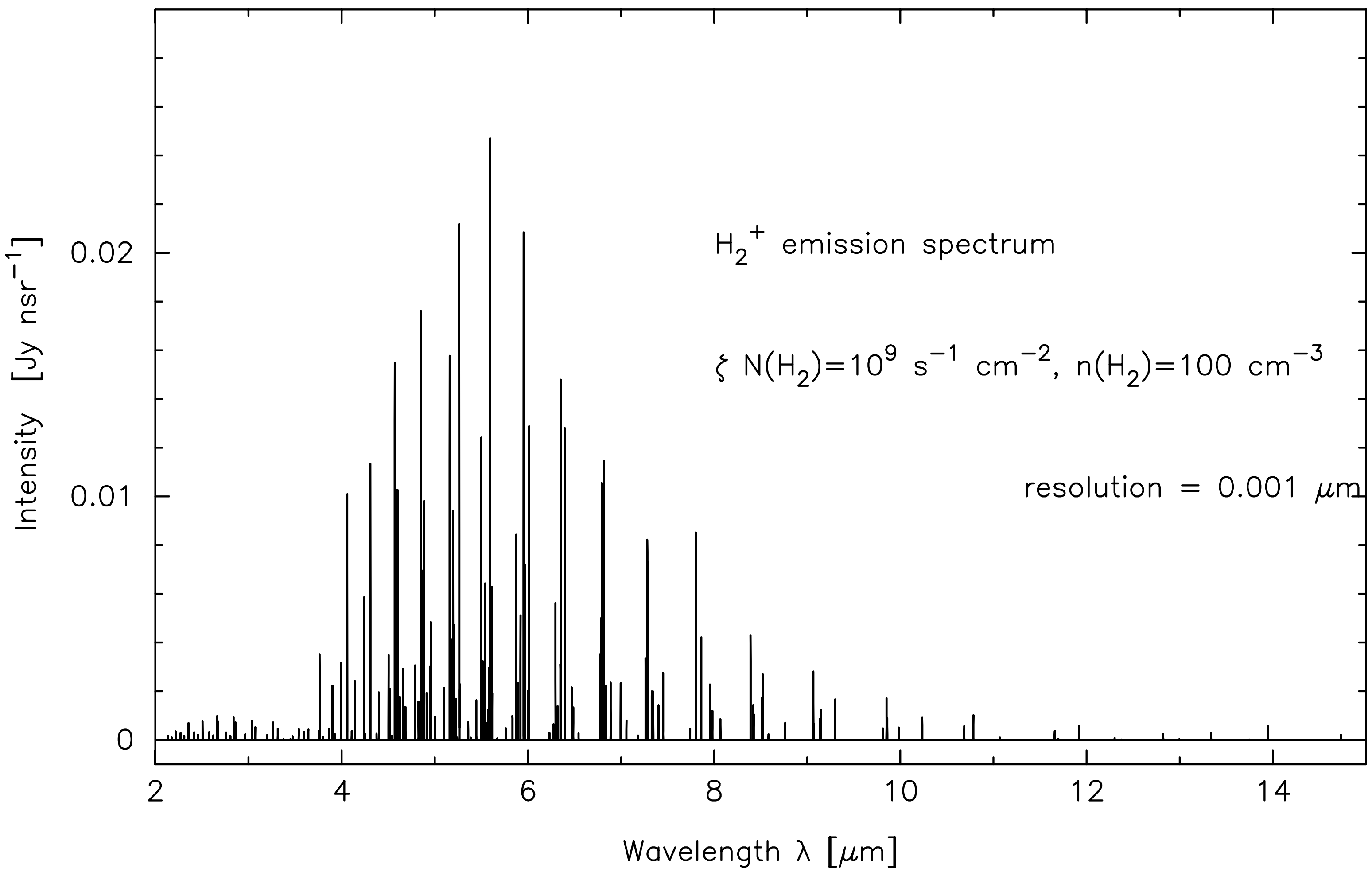
H_2^+, OH^+, H_2O^+, HeH^+ are transient: they react on nearly every collision with the most abundant neutrals, H_2 or H

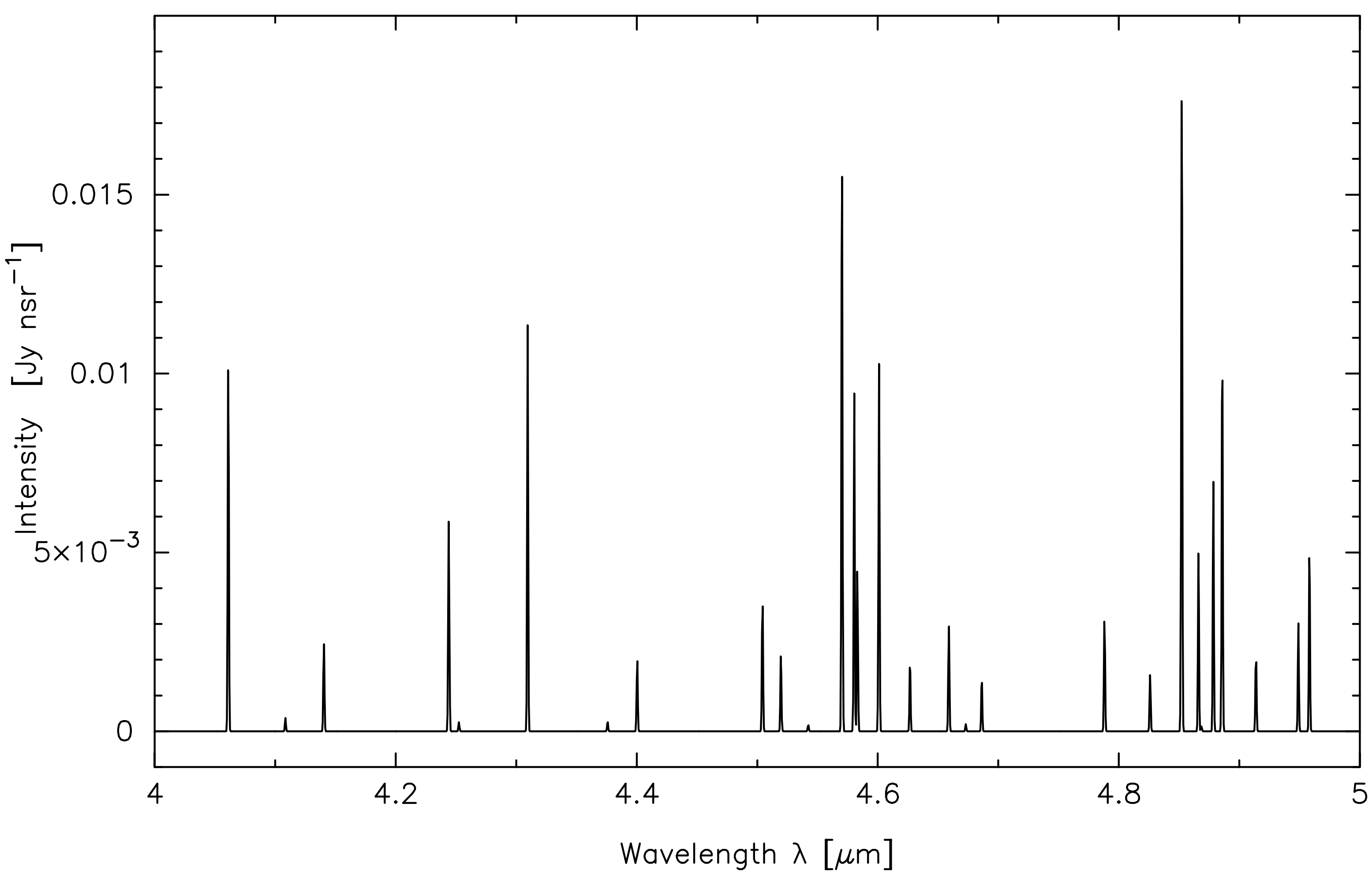
- transient ions cannot be thermalized
- population distributions over their quantum states governed by the energetic formation processes
- low steady-state abundances

H_3^+ and H_3O^+ wait around for less abundant reactants O, CO, e^-
and thus build up higher steady-state abundances

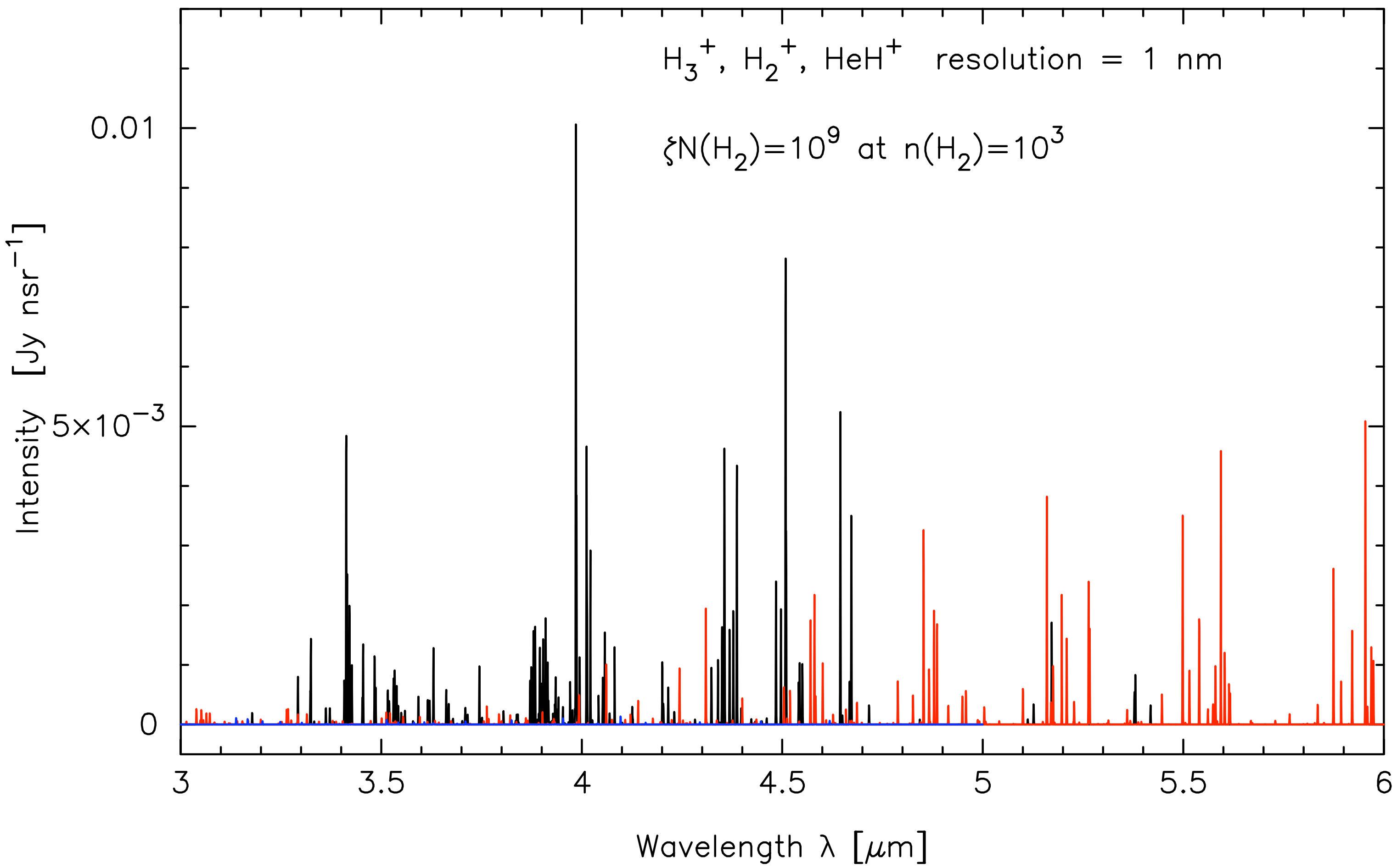
The fate of the transient ion H_2^+ is usually overlooked

- ionization of H_2 produces a broad distribution of highly excited H_2^+
- at interstellar densities the quadrupole vib-rot transitions are fast compared with collisions, lifetimes of the order of 10^6 s
- H_2^+ will produce an IR spectrum whose intensity depends upon the ion production rate, the cosmic-ray exposure: $\eta = \int n(H_2)\, \zeta\, dl$, where ζ is the ionizing frequency

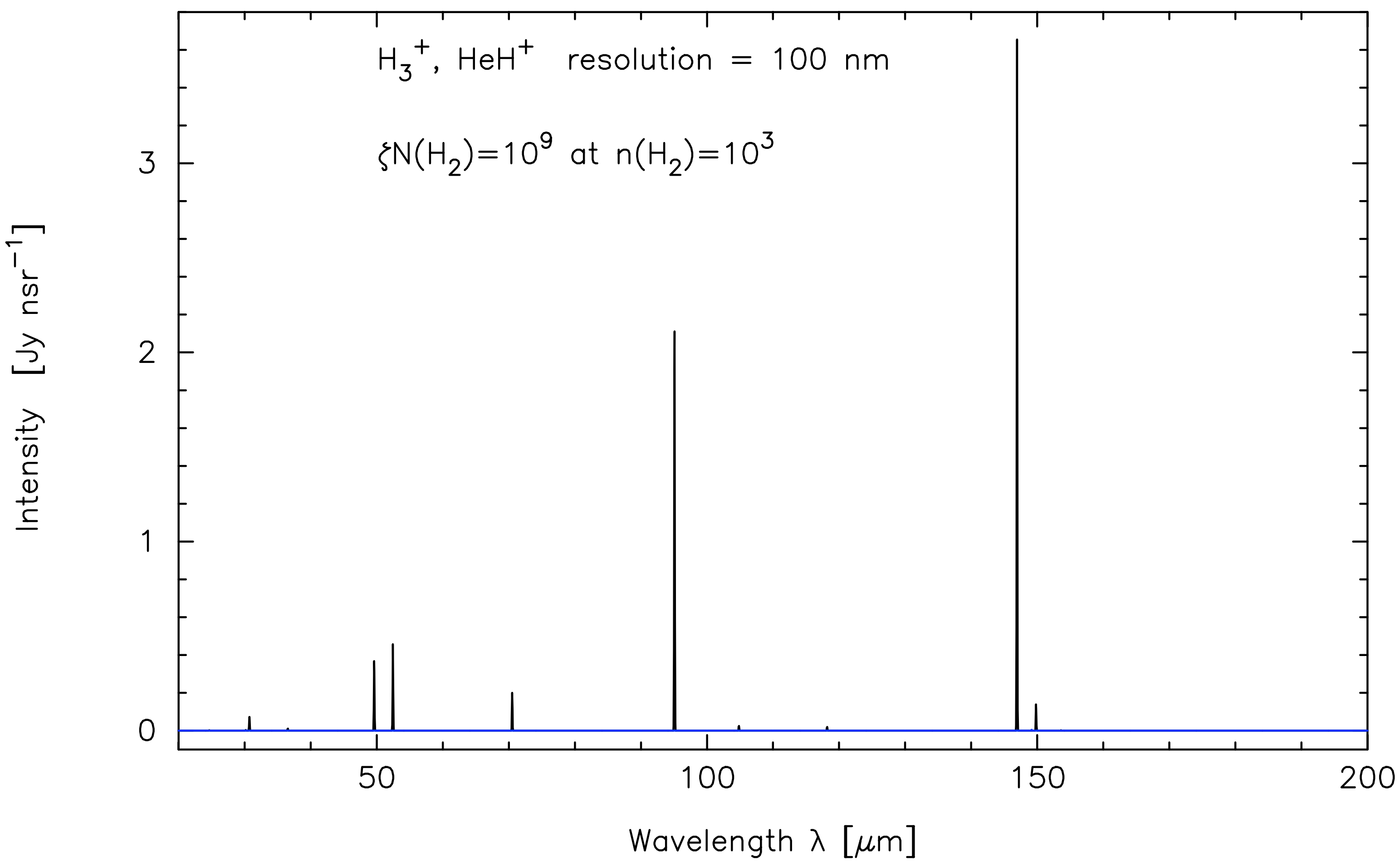




J.K. Becker,
J.H. Black,
M. Safarzadeh,
F. Schuppan
2011
ApJ, 739, L43



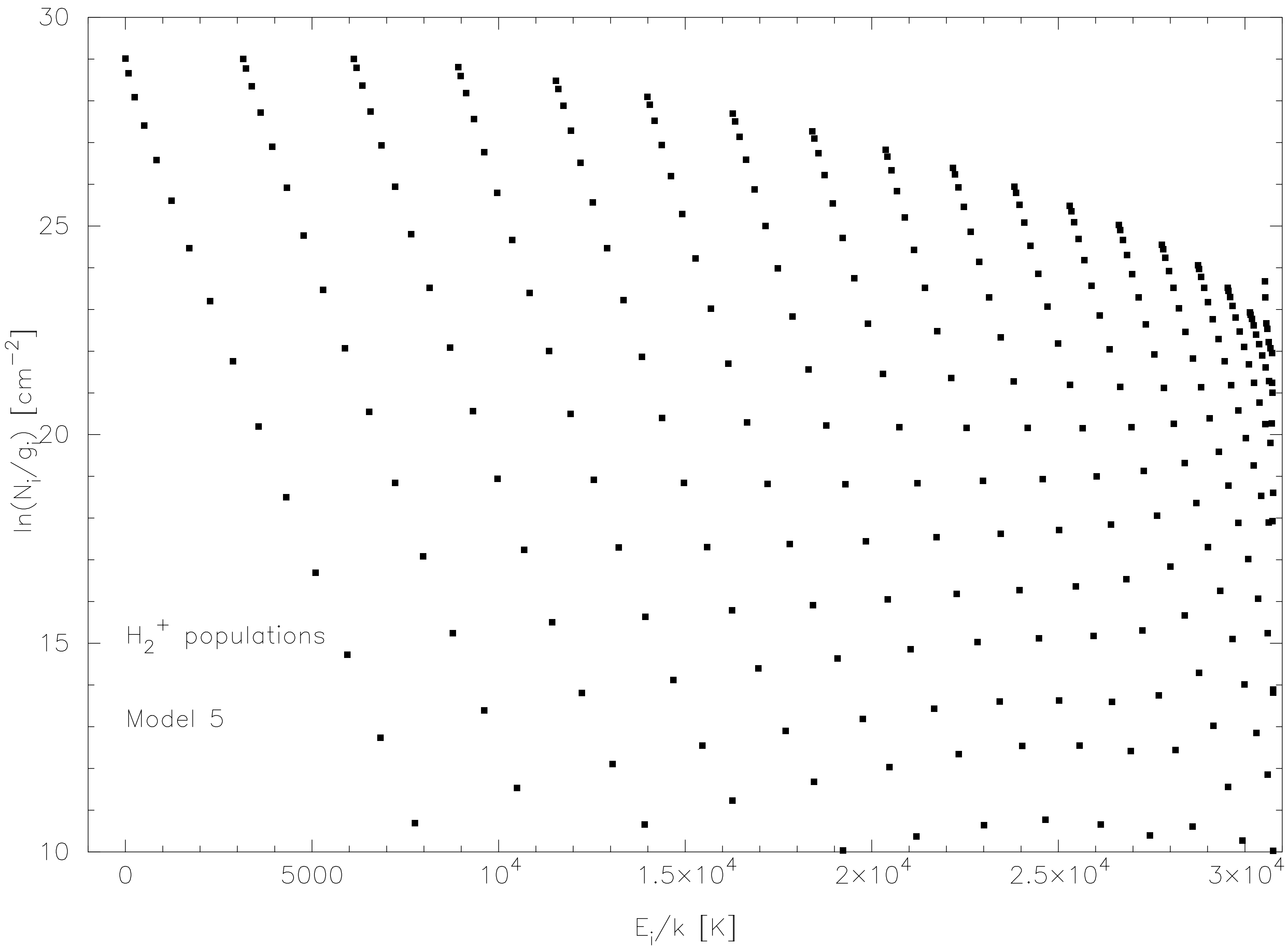
Combined model: H_2, H_2^+, H_3^+, HeH^+



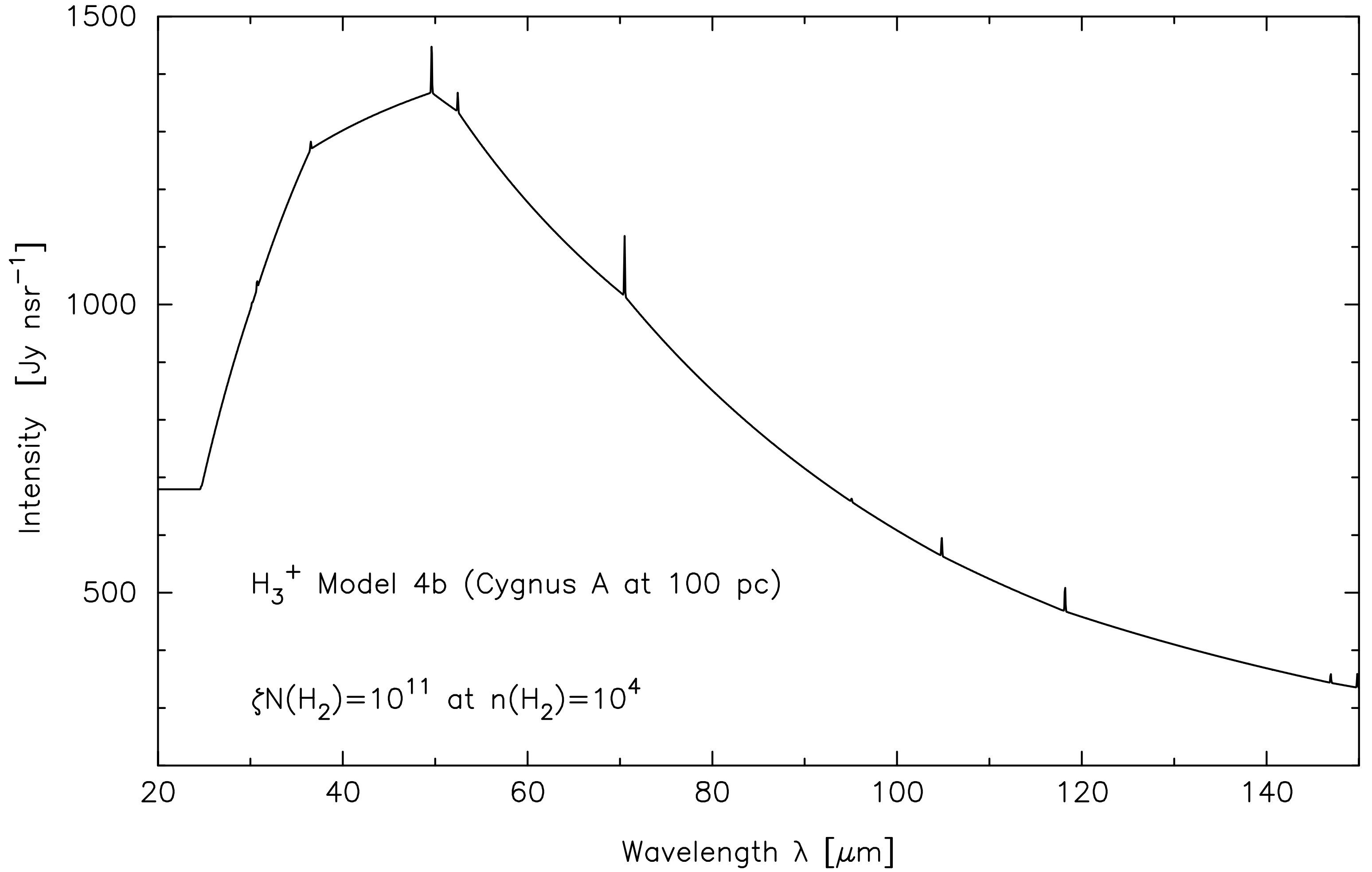
with such a large cosmic-ray exposure the H_3^+ rotational line (4,4)-(3,1) at 217.8 GHz will have a detectable intensity, T_B=10 mK

Model: $n(H_2)=10^3$ cm^{-3}, T=150 K, $\zeta=10^{-13}$ s^{-1}

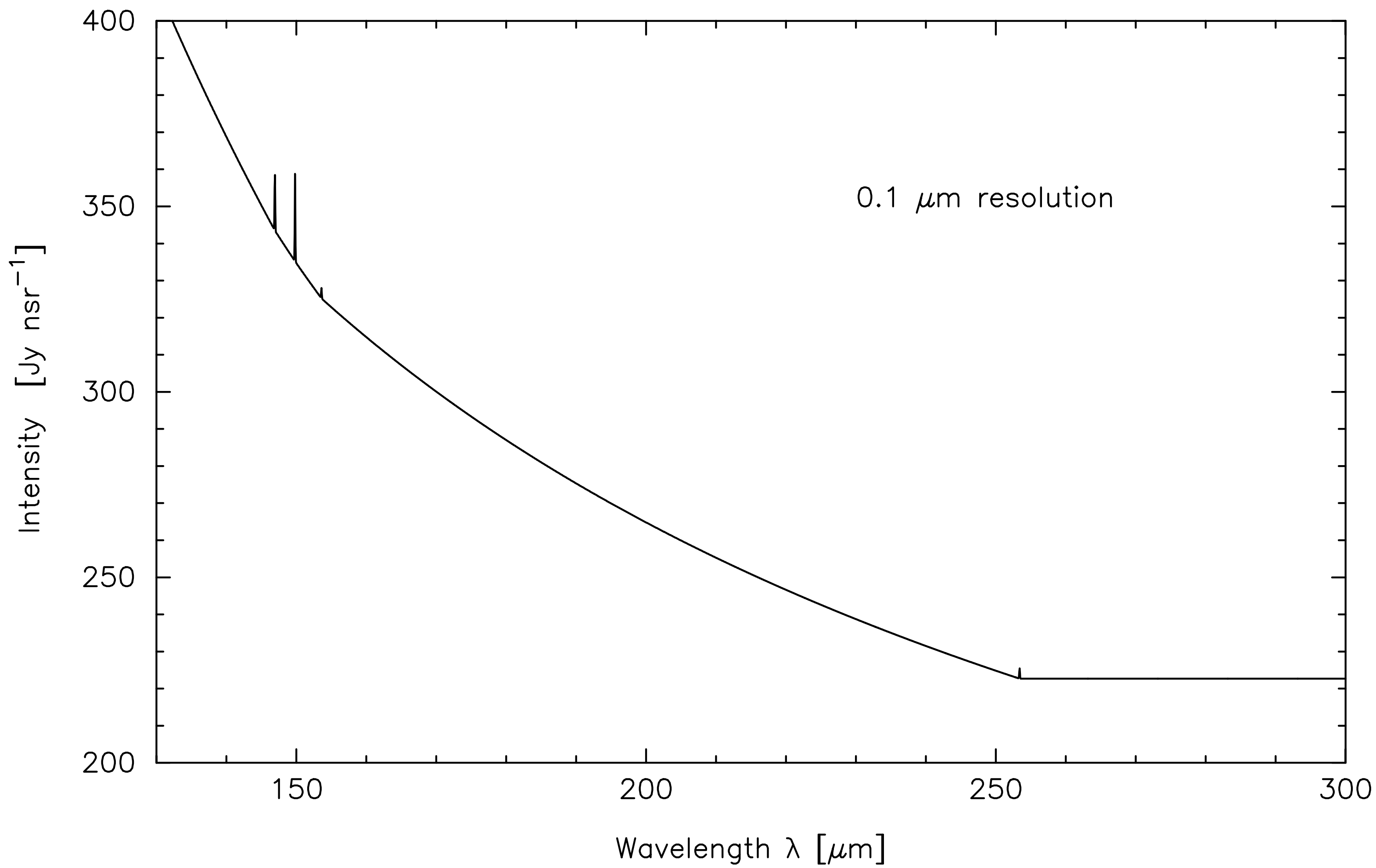
Species	Column Density	Destr. rate
	cm^{-2}	s^{-1}
H_2	1×10^{22}	10^{-13}
H_2^+	4.6×10^{14}	2×10^{-6}
H_3^+	3.2×10^{17}	3.2×10^{-9}
HeH^+	6.0×10^{12}	1.5×10^{-6}



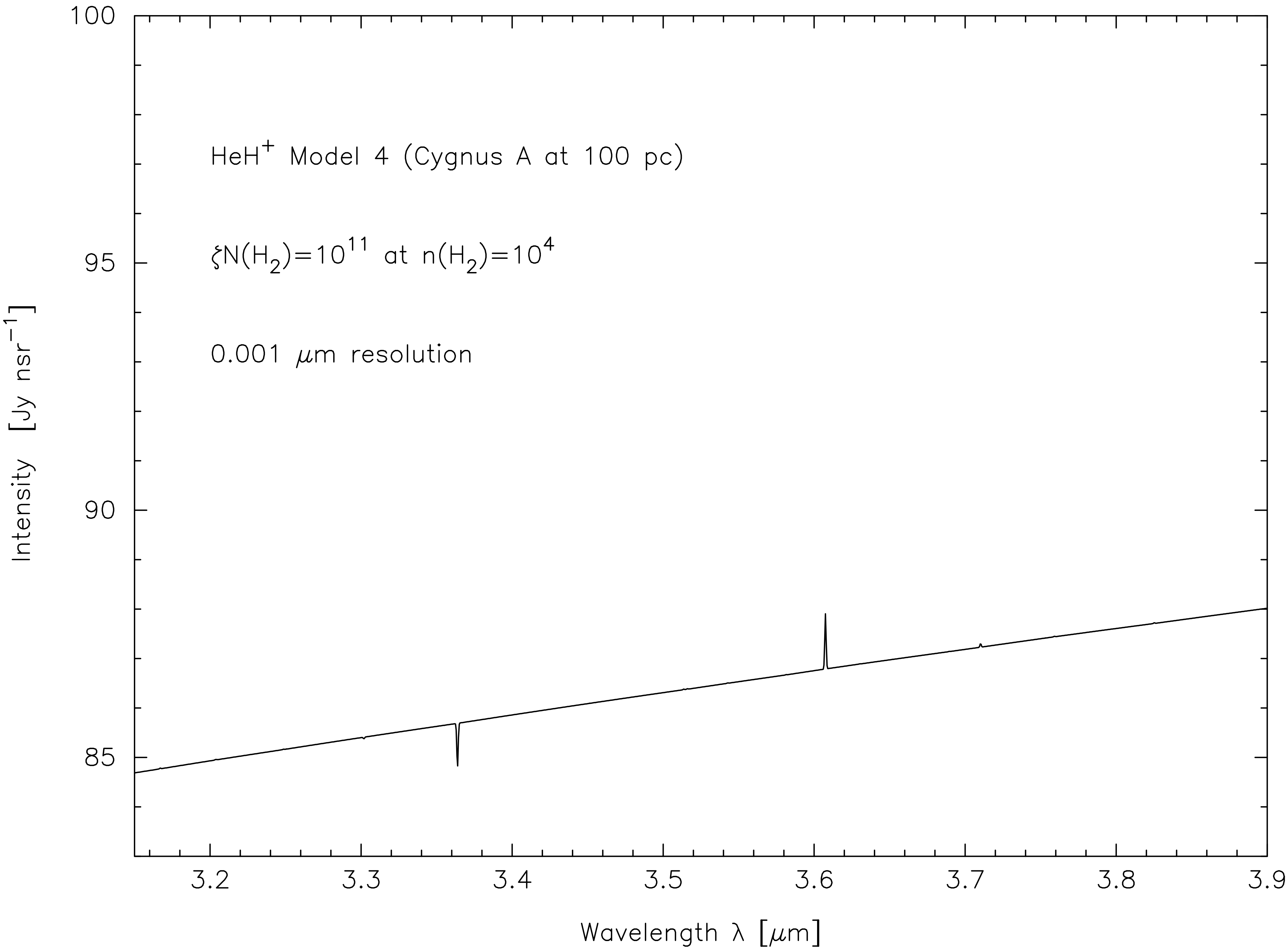
H2+ populations
Model 5
ln(Ni/gi) [cm−2]
Ei/k [K]
30
25
20
15
10
0
5000
10^4
1.5×10^4
2×10^4
2.5×10^4
3×10^4



1500
1000
500
Intensity [Jy nsr^{-1}]
H_3^+ Model 4b (Cygnus A at 100 pc)
$\zeta N(H_2)=10^{11}$ at $n(H_2)=10^4$
20
40
60
80
100
120
140
Wavelength λ [μm]



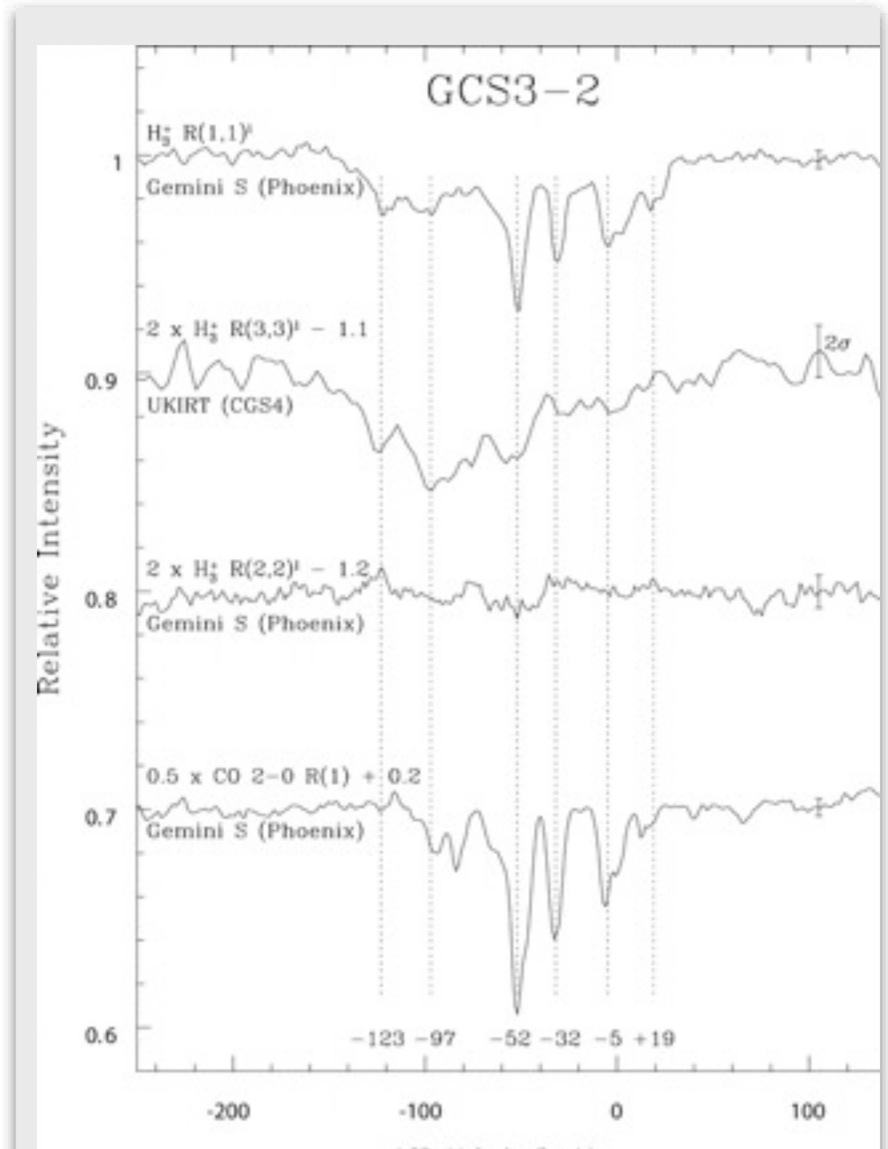
400
350
300
250
200
Intensity [Jy nsr^{-1}]
0.1 μm resolution
150
200
250
300
Wavelength λ [μm]



HeH+ Model 4 (Cygnus A at 100 pc)
ζN(H2)=10^11 at n(H2)=10^4
0.001 μm resolution
Intensity [Jy nsr−1]
100
95
90
85
3.2
3.3
3.4
3.5
3.6
3.7
3.8
3.9
Wavelength λ [μm]

H_3^+ toward the Galactic Center

- Goto et al. (2002), Oka et al. (2005)
- abundant metastable (J,K)=(3,3)
- negligible (J,K)=(2,2)
- implies hot (250 K), dilute (<200 cm^{-3}) gas?



H_3^+ energy levels (J,K)

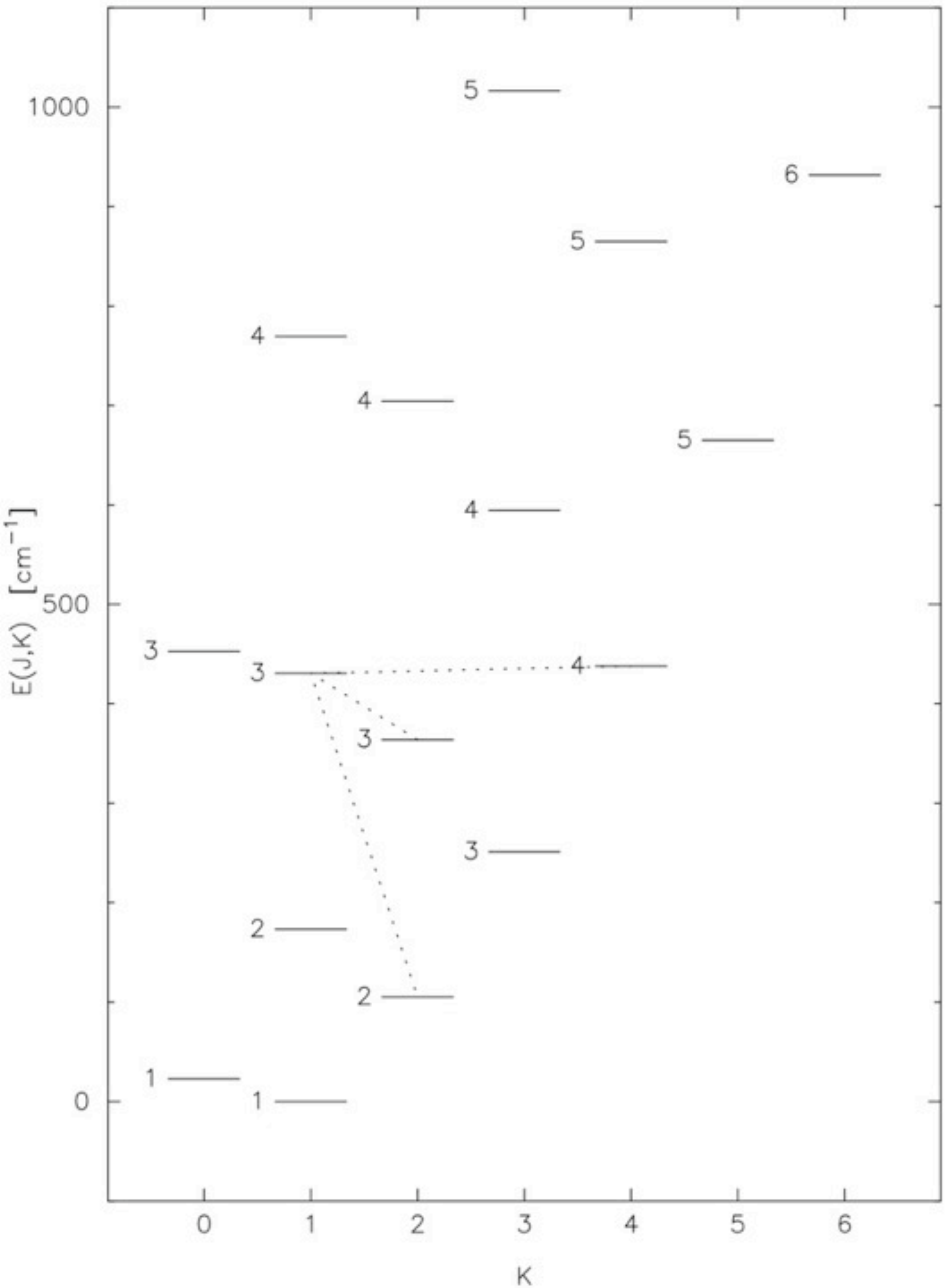
- (1,0), (3,3), (5,5), and (6,6) levels are highly metastable (no spontaneous emission)

- (4,4) is quasi-metastable with a slow ($A=3\times10^{-9}$ s^{-1}) transition to (3,1) at 218 GHz, a possible maser (Black 1998)

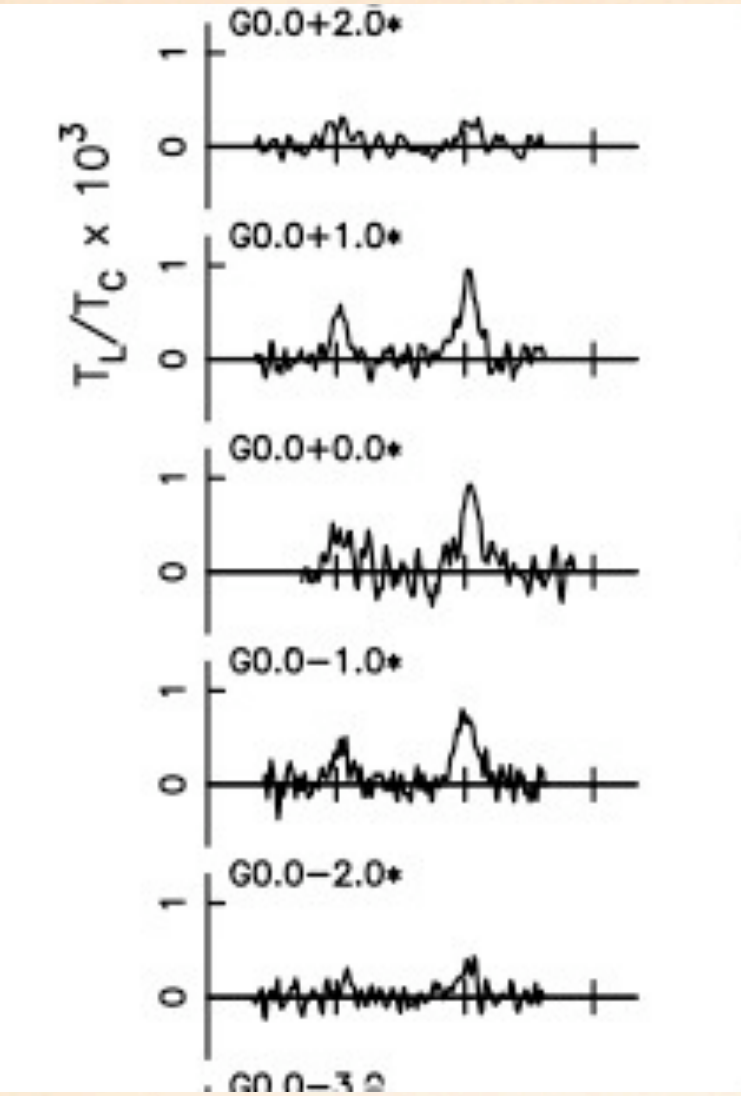
- all levels can be re-shuffled by reactive collisions with H2 (cf. Oka & Epp 2004, ApJ, 613, 349)

- the formation process may be important in populating the highly excited states

- in some environments, radiative pumping through the vibration-rotation transitions may be important



Kantharia & Anantharamaiah 2001



H I & C I
327 MHz, n=270-273
(Roshi & Anantharamaiah 2001)

Carbon Recombination Lines 57

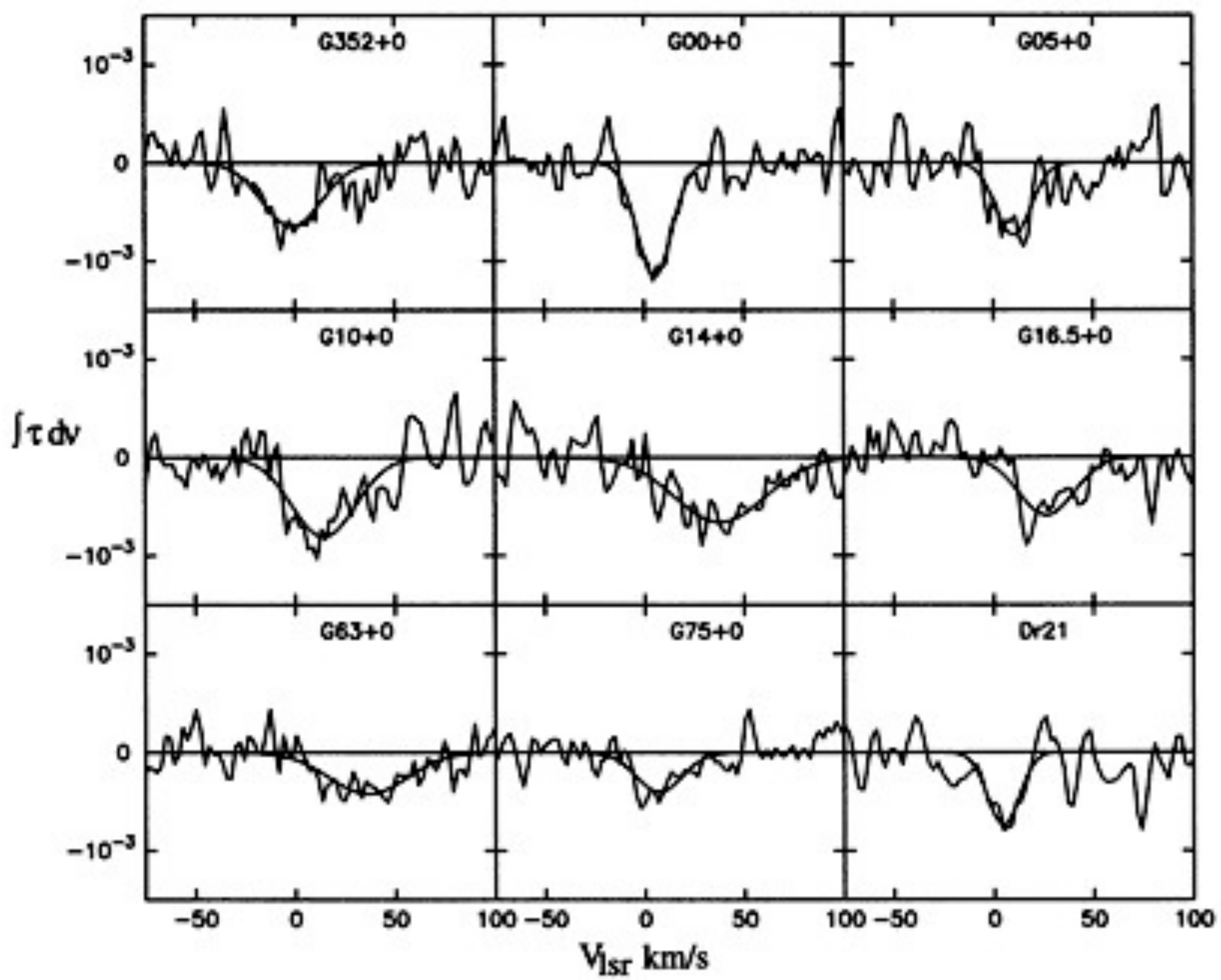


Figure 1. Carbon recombination lines detected near 34.5 MHz ($n \sim 575$). The smooth curve superposed on the observed spectrum is the Gaussian fit to the line profile.

high-n recombination lines of C I toward Galactic Center show a dilute component of weakly ionized gas

Largest atoms in space: C in Rydberg states up to n=1009

RRLs from the largest bound atoms in space 853

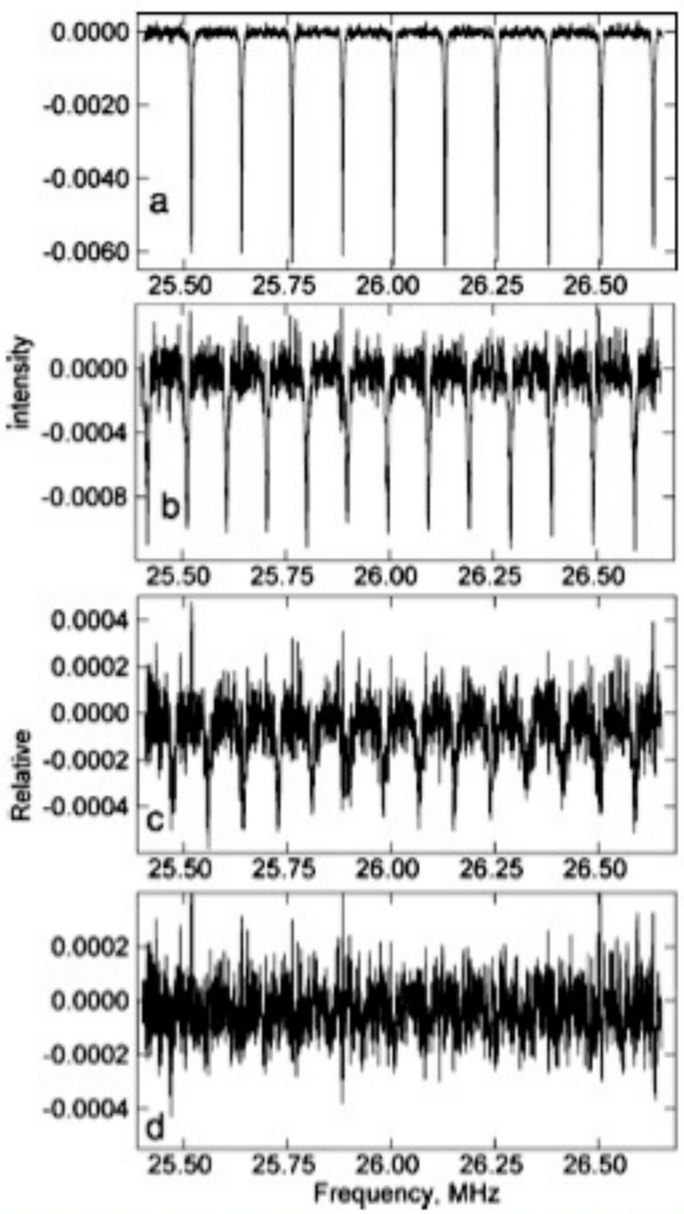


Figure 2. The series of α, β, γ and δ RRLs observed around 26 MHz in the direction of Cas A. Panel (a) shows α series C627. . .C636, panel (b) shows β series C790. . .C802, panel (c) shows γ series C904. . .C917, and panel (d) shows δ series C994. . .C1009.

Size ≈ $n^2 a_o$

≈ 54 μm

Stepkin et al.
2007, MNRAS, **374**, 852

854 *S. V. Stepkin et al.*

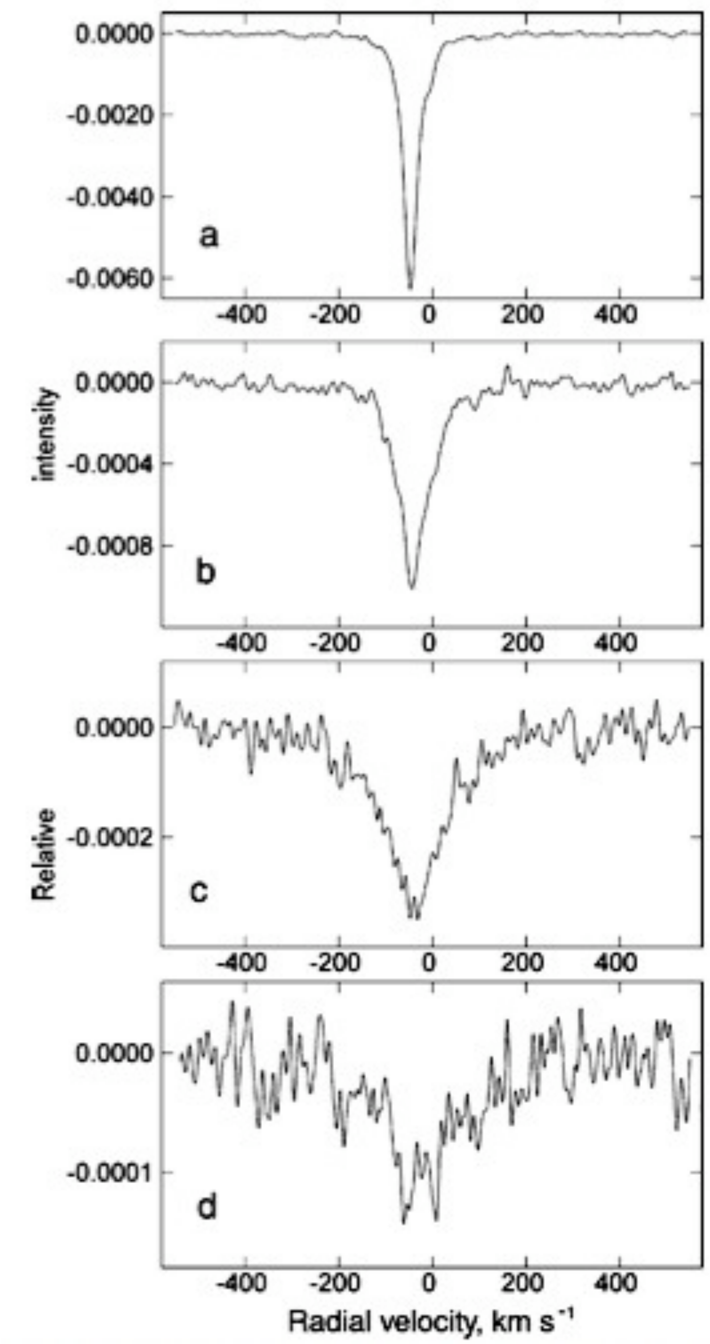
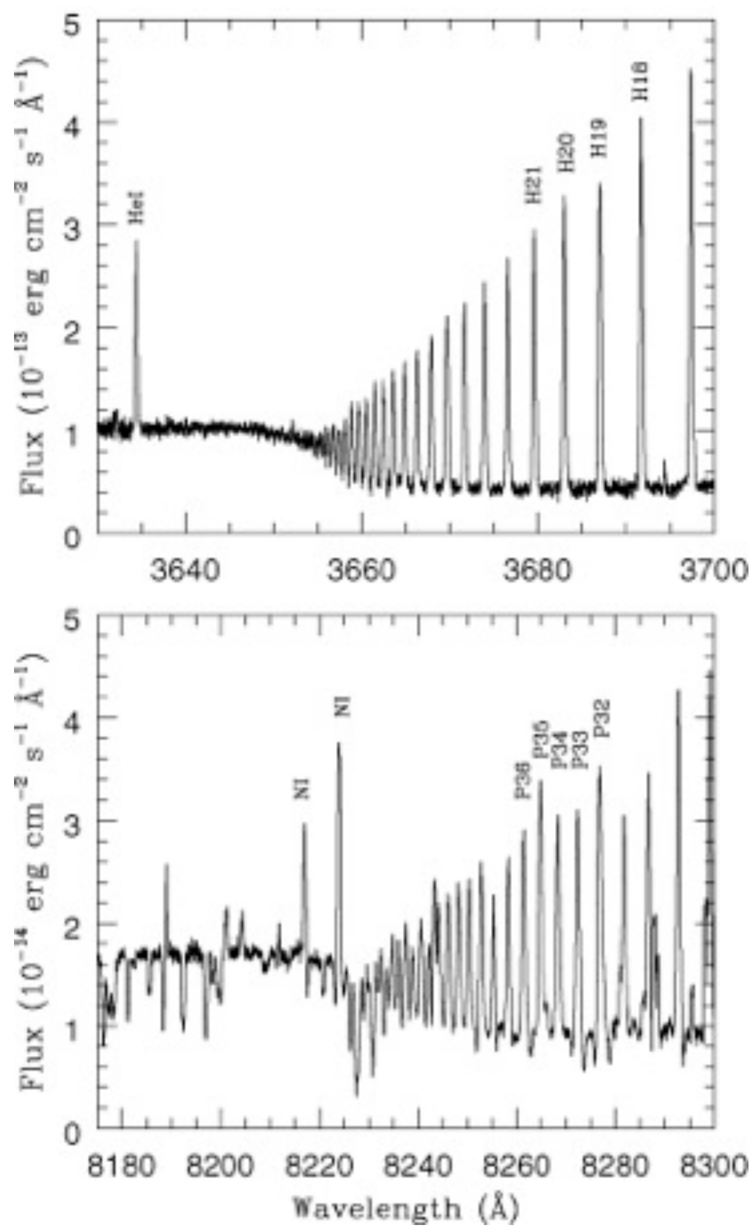


Figure 3. The averaged α, β, γ and δ transitions. Panel (a) shows folded α transitions C627. . .C636, panel (b) shows folded β transitions C790. . .C802, panel (c) shows folded γ transitions C904. . .C917, and panel (d) shows folded δ transitions C994. . .C1009.

A reappraisal of the chemical composition of the Orion nebula based on Very Large Telescope echelle spectrophotometry

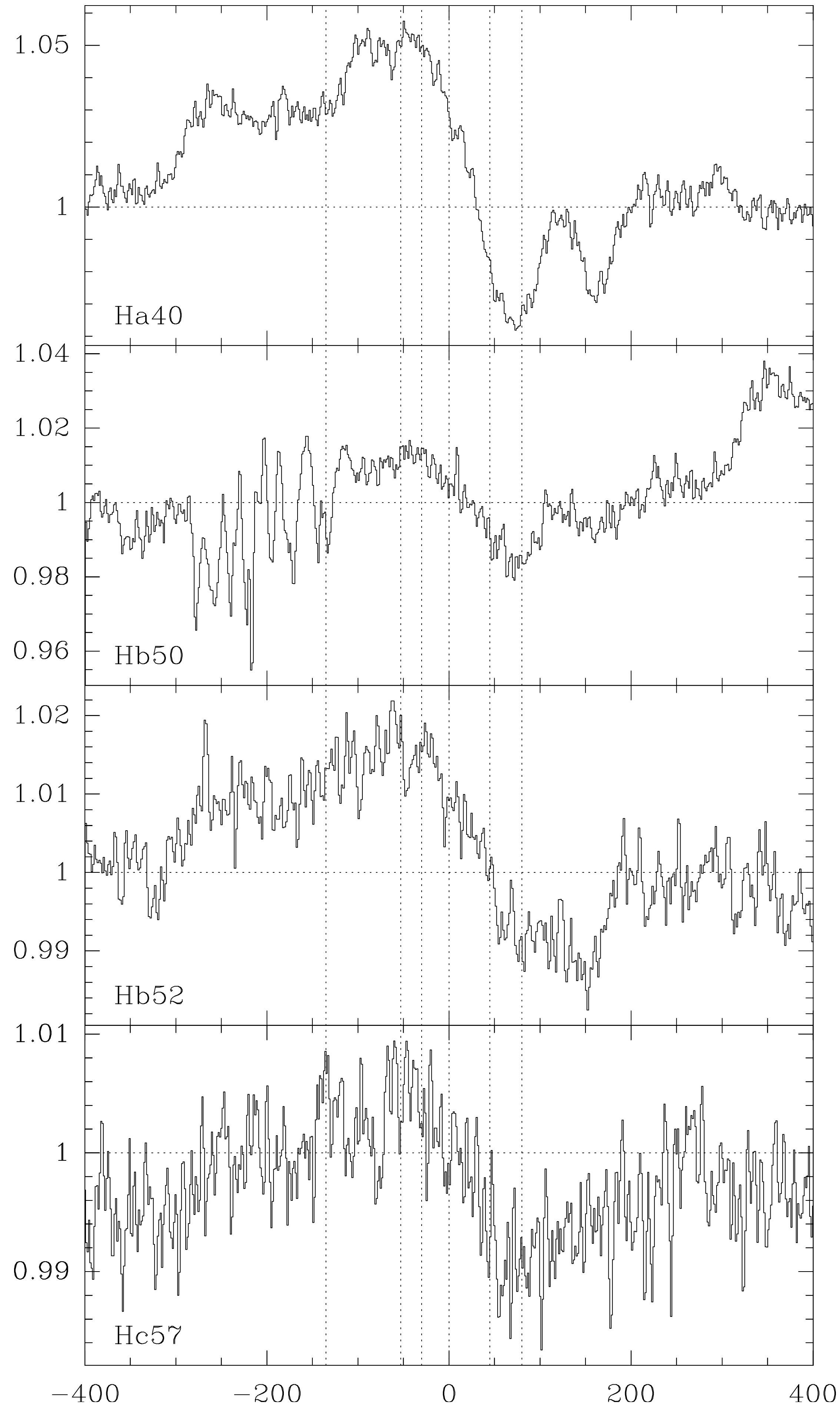


Esteban et al. 2004

Monthly Notices of the Royal Astronomical Society

Volume 355, Issue 1, pages 229-247, 17 SEP 2004 DOI: 10.1111/j.1365-2966.2004.08313.x

http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2966.2004.08313.x/full#f3



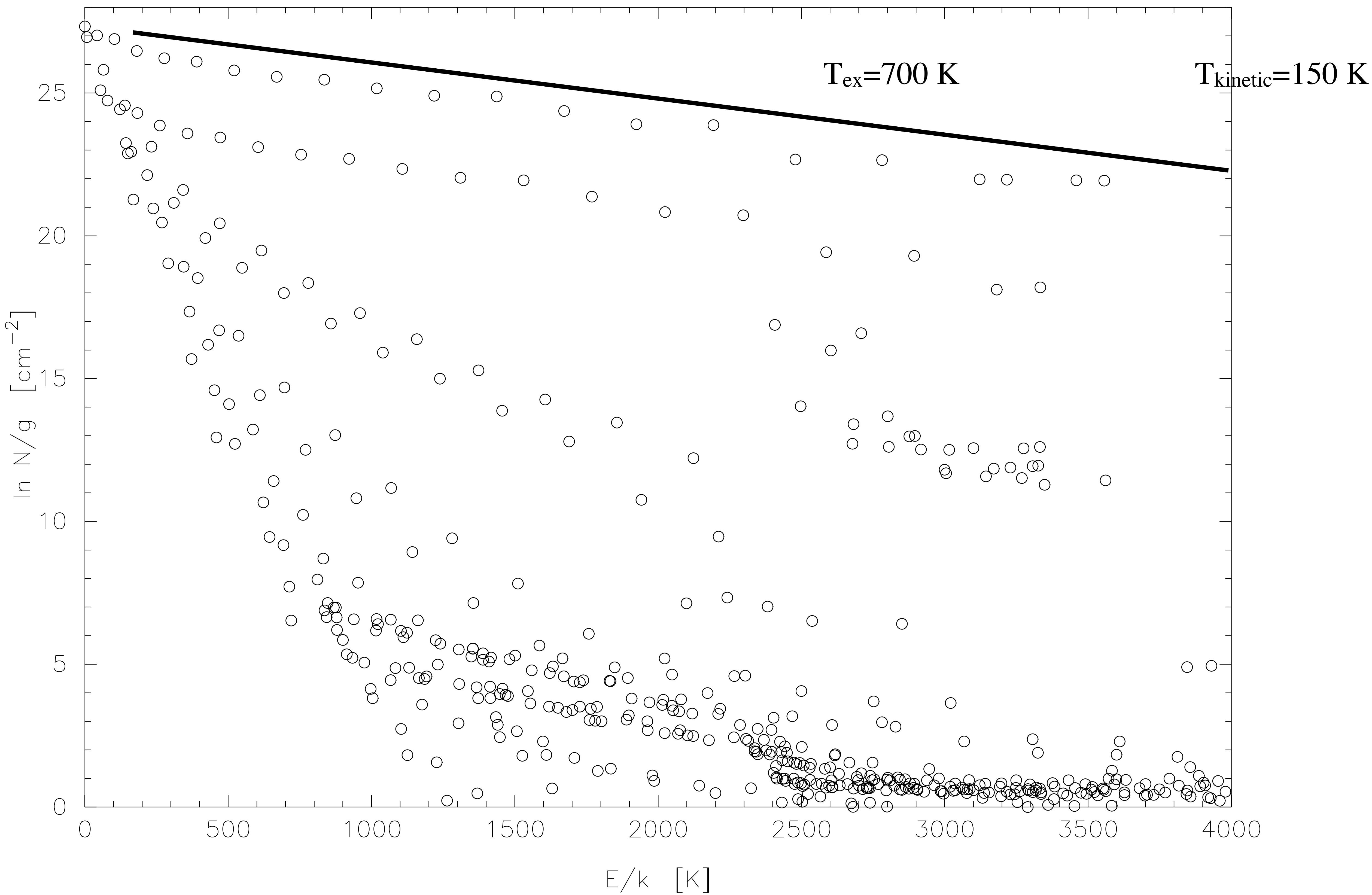
ALMA band 3 commissioning data showing 3 mm-wave recombination lines in absorption toward Sgr A*

H_3 in space?

Although dissociative recombination of H_3^+ is the dominant electron capture process and Rydberg states of H_3 are known to dissociate with lifetimes ~10 ps, there must be some

radiative recombination into highly excited Rydberg states of H_3, some of which will produce radio line emission.

H_3O^+ population distribution with formation-pumping



Alice: "There's no use trying, one can't believe impossible things"

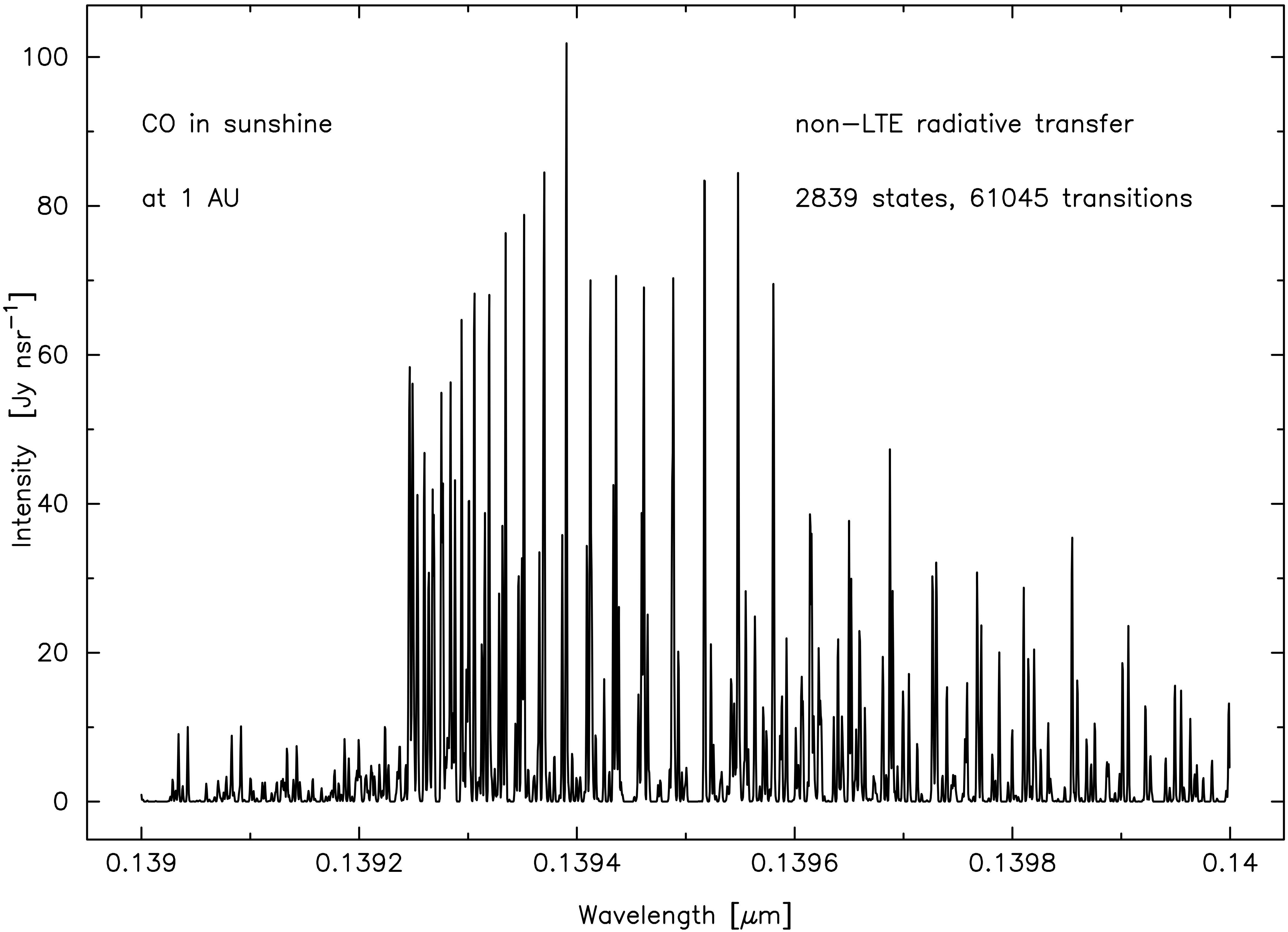
to which the White Queen replied:
"I daresay you haven't had much practice...
why sometimes I've believed as many as
six impossible things before breakfast."

---Lewis Carroll, *Through the Looking-glass*

What is a molecular cloud?

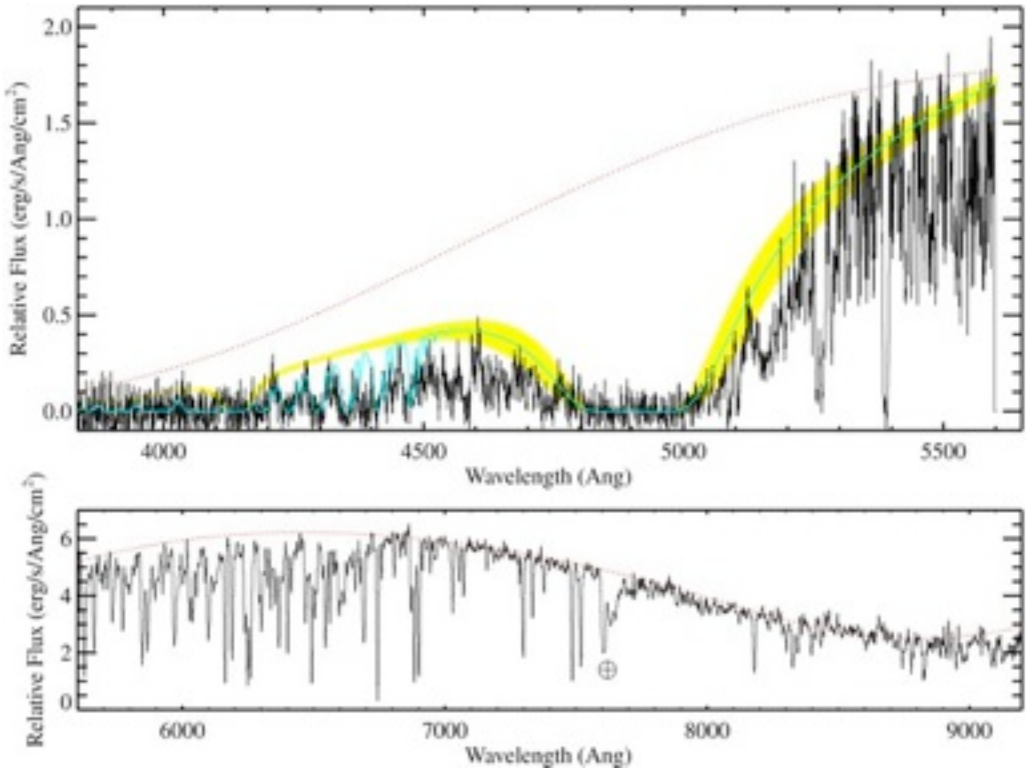
- concentration of gas & dust
- isolated in projection on the sky and in Doppler velocity
- hierarchical structure, turbulence
- weakly ionized: $e/H_2 = 10^{-9}$ to 10^{-4}
- magnetic field coupled to gas via charged particles only
- physical & chemical state far from equilibrium

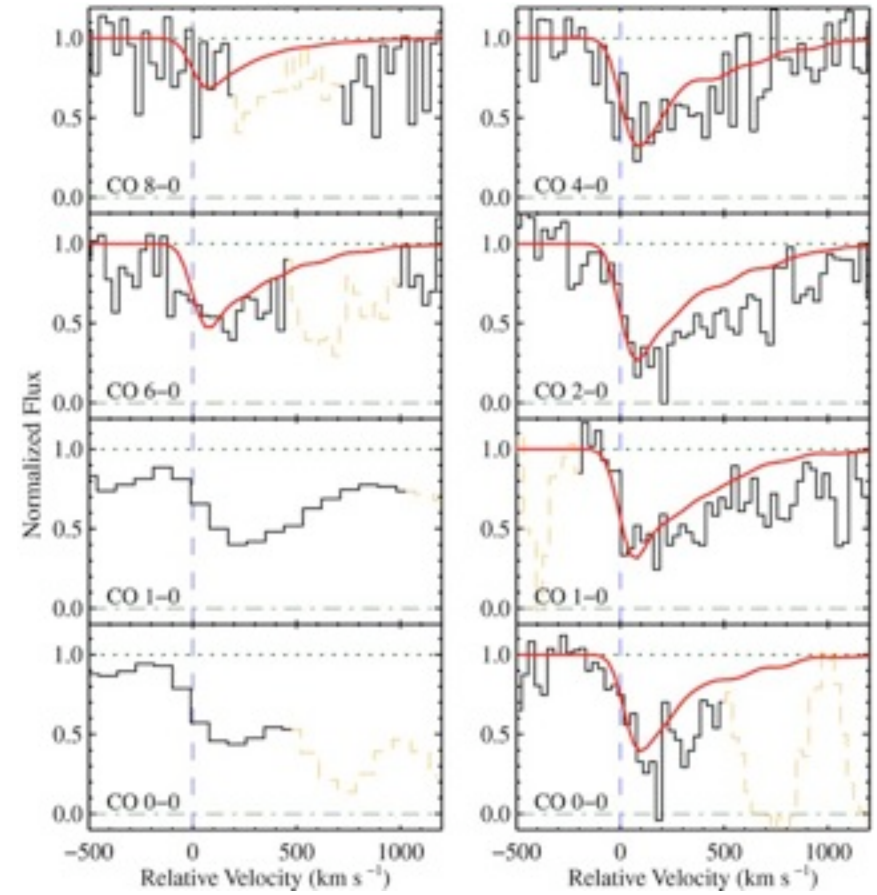
Example: UV-pumped CO in sunlight



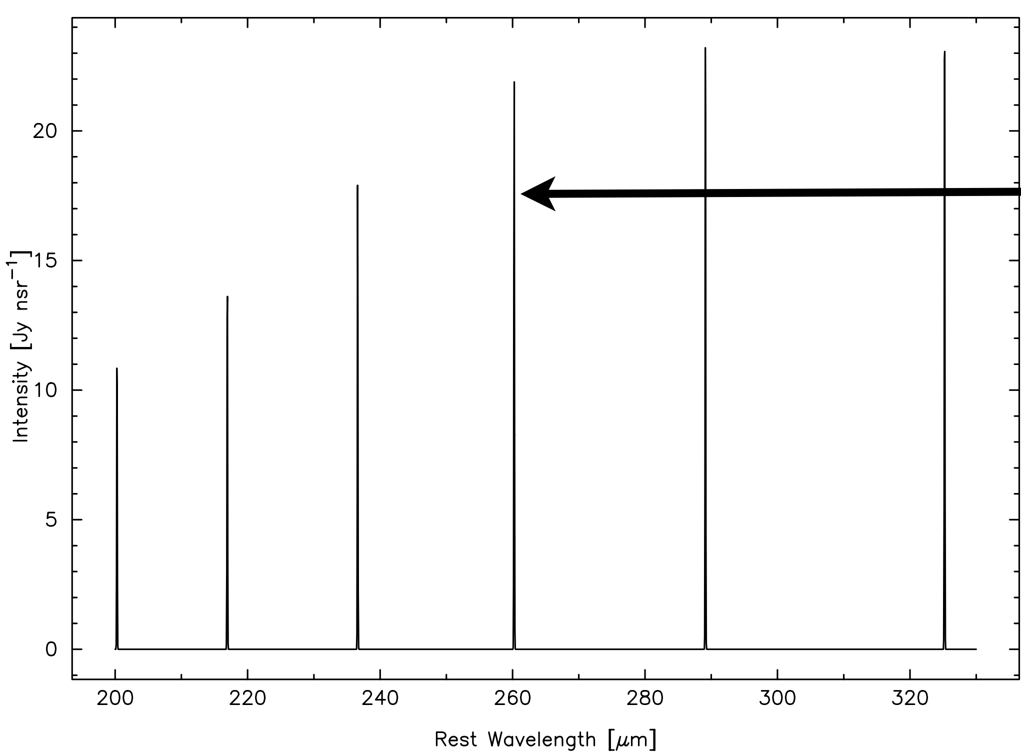
J.H. Black & J. L. Fox (in preparation)

GRB080607: H_2 and CO at z=3.0363

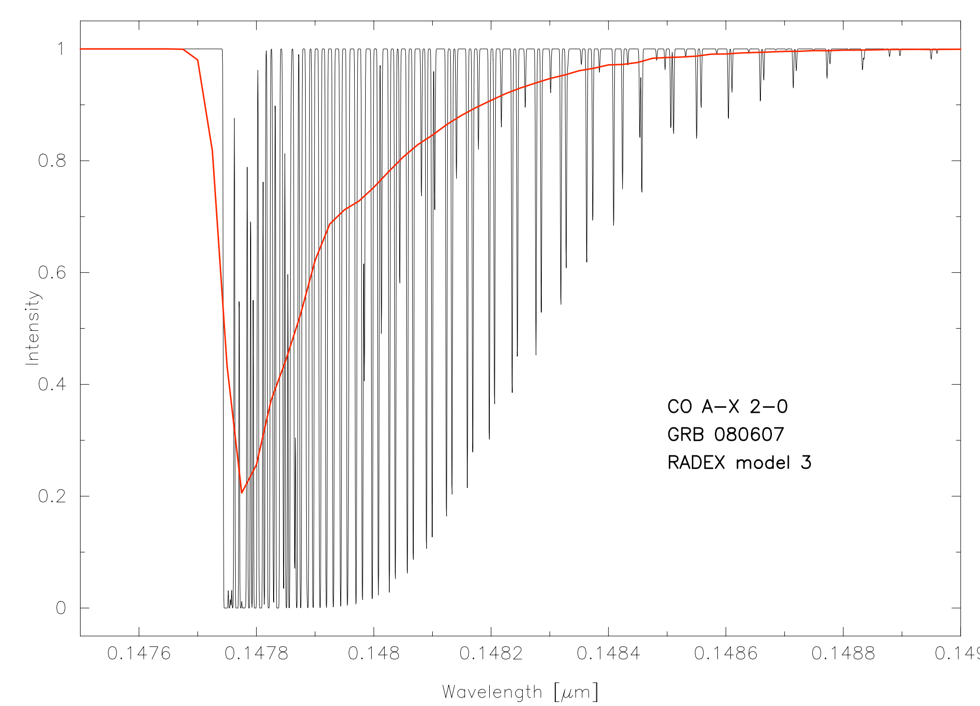




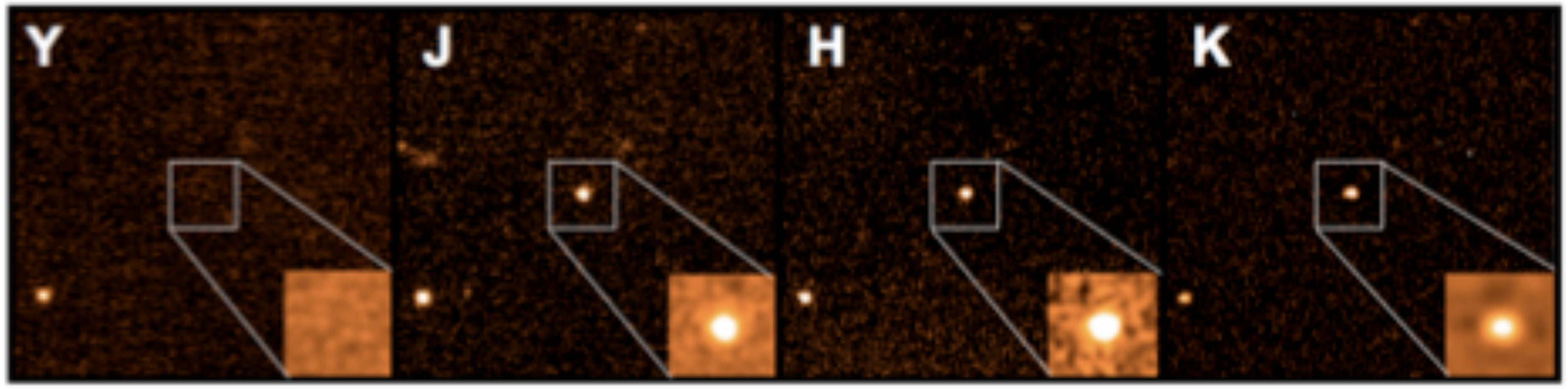
Prochaska et al. (2009, ApJ, 691, L27), Sheffer et al. (2009, ApJ, 701, L63) show that H2 is pumped by the UV afterglow ↑
Black (2009, in prep.) predicts the UV pumping in CO, which produces submm-wave emission, too ↓



CO J=12-11
1.38 THz (rest)
red-shifted to
342.4 GHz
at z=3.0363



Afterglows of γ-ray Bursts at High Redshift



UKIRT discovery images from Tanvir et al. astro-ph:0906.1577

GRB090423 is the most distant known source in the Universe at z=8.26

mm/submm-wave afterglow?

Castro-Tirado et al. report a λ=3 mm source at the burst position with flux density 0.2 mJy (GCN Circular 9273, 09-04-28) consistent with Bock et al. upper limit of 0.7 mJy at CARMA

⇒Prospects for ALMA to probe high-z galaxies