Dissociative Recombination of Cold H_3^+ (and its interstellar implications)

Ben McCall
Department of Chemistry
Department of Astronomy
University of Illinois at Urbana-Champaign

★ T. Oka (University of Chicago), T. R. Geballe (Gemini Observatory)
★ A. J. Huneycutt, R. J. Saykally (University of California at Berkeley)
★ N. Djuric, G. H. Dunn (University of Colorado & NIST)
★ J. Semaniak, O. Novotny (Świetokrzyska Academy, Poland)
★ A. Paal, F. Österdahl (Manne Siegbahn Laboratory)
★ A. Al-Khalili, A. Ehlerding, F. Hellberg, S. Kalhori, A. Neau, R. Thomas, M. Larsson (Stockholm University)

Astronomer's Periodic Table

H

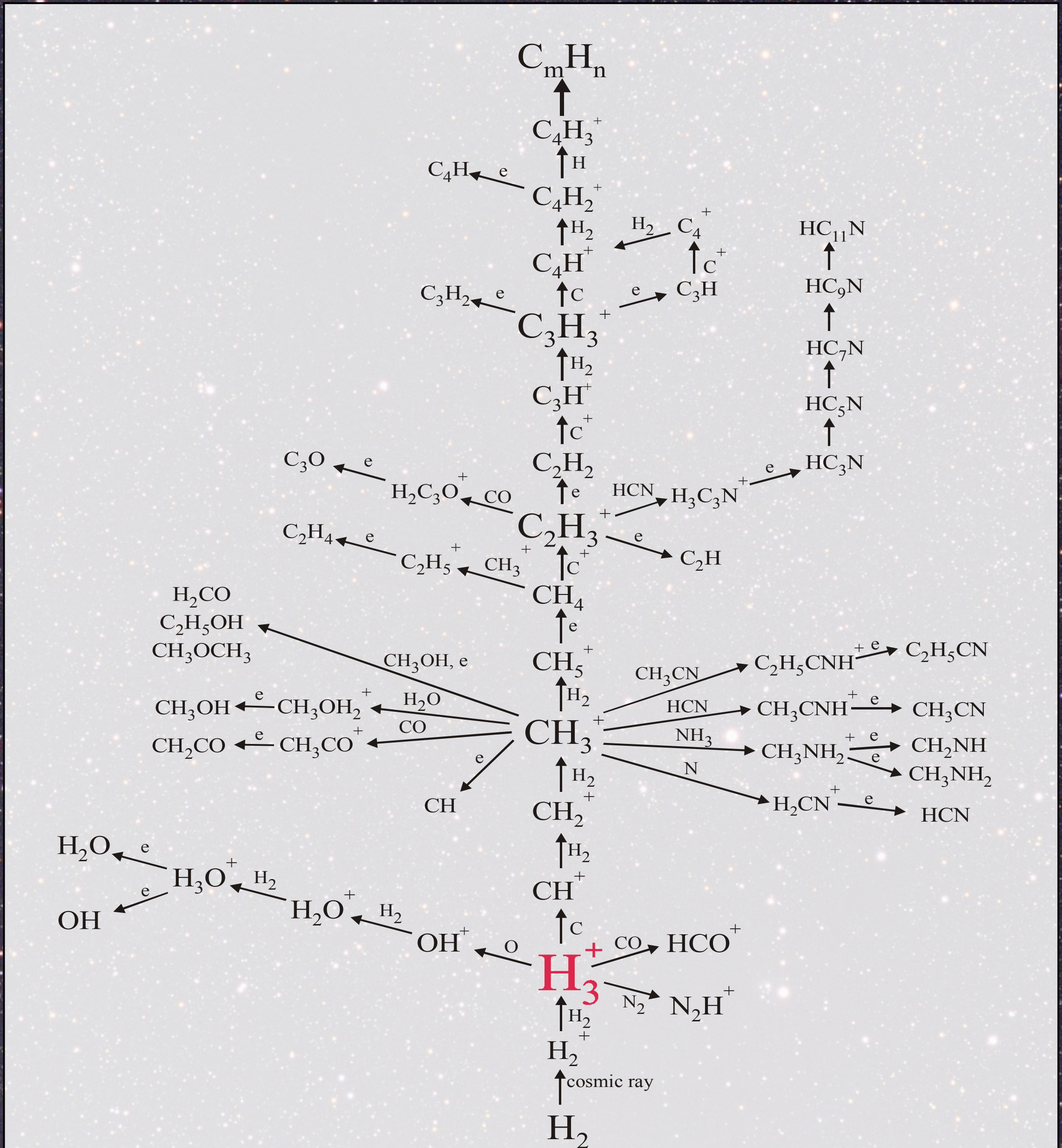
He

C N O Ne

Mg **Si** S Ar

Fe

H_3^+: Cornerstone of Interstellar Chemistry



$C_4H_3^+ \longrightarrow C_mH_n$

$C_4H_2^+ \xrightarrow{H} C_4H_3^+$

$C_4H_2^+ \xrightarrow{e} C_4H$

$C_4H^+ \xrightarrow{H_2} C_4H_2^+$

$C_4^+ \xrightarrow{H_2} C_4H^+$

$C_3H \xrightarrow{C^+} C_4^+$

$C_3H_3^+ \xrightarrow{C} C_4H^+$

$C_3H_3^+ \xrightarrow{e} C_3H_2$

$C_3H_3^+ \xrightarrow{e} C_3H$

$C_3H^+ \xrightarrow{H_2} C_3H_3^+$

$C_2H_2 \xrightarrow{C^+} C_3H^+$

$C_2H_3^+ \xrightarrow{e} C_2H_2$

$C_2H_3^+ \xrightarrow{CO} H_2C_3O^+ \xrightarrow{e} C_3O$

$C_2H_3^+ \xrightarrow{HCN} H_3C_3N^+ \xrightarrow{e} HC_3N \longrightarrow HC_5N \longrightarrow HC_7N \longrightarrow HC_9N \longrightarrow HC_{11}N$

$C_2H_3^+ \xrightarrow{e} C_2H$

$CH_4 \xrightarrow{C^+} C_2H_3^+$

$CH_4 \xrightarrow{CH_3^+} C_2H_5^+ \xrightarrow{e} C_2H_4$

$CH_5^+ \xrightarrow{e} CH_4$

$CH_3^+ \xrightarrow{H_2} CH_5^+$

$CH_3^+ \xrightarrow{CH_3OH,\ e} H_2CO,\ C_2H_5OH,\ CH_3OCH_3$

$CH_3^+ \xrightarrow{H_2O} CH_3OH_2^+ \xrightarrow{e} CH_3OH$

$CH_3^+ \xrightarrow{CO} CH_3CO^+ \xrightarrow{e} CH_2CO$

$CH_3^+ \xrightarrow{e} CH$

$CH_3^+ \xrightarrow{CH_3CN} C_2H_5CNH^+ \xrightarrow{e} C_2H_5CN$

$CH_3^+ \xrightarrow{HCN} CH_3CNH^+ \xrightarrow{e} CH_3CN$

$CH_3^+ \xrightarrow{NH_3} CH_3NH_2^+ \xrightarrow{e} CH_2NH$

$CH_3NH_2^+ \xrightarrow{e} CH_3NH_2$

$CH_3^+ \xrightarrow{N} H_2CN^+ \xrightarrow{e} HCN$

$CH_2^+ \xrightarrow{H_2} CH_3^+$

$CH^+ \xrightarrow{H_2} CH_2^+$

$H_3^+ \xrightarrow{C} CH^+$

$H_3^+ \xrightarrow{O} OH^+ \xrightarrow{H_2} H_2O^+ \xrightarrow{H_2} H_3O^+ \xrightarrow{e} H_2O$

$H_3O^+ \xrightarrow{e} OH$

$H_3^+ \xrightarrow{CO} HCO^+$

$H_3^+ \xrightarrow{N_2} N_2H^+$

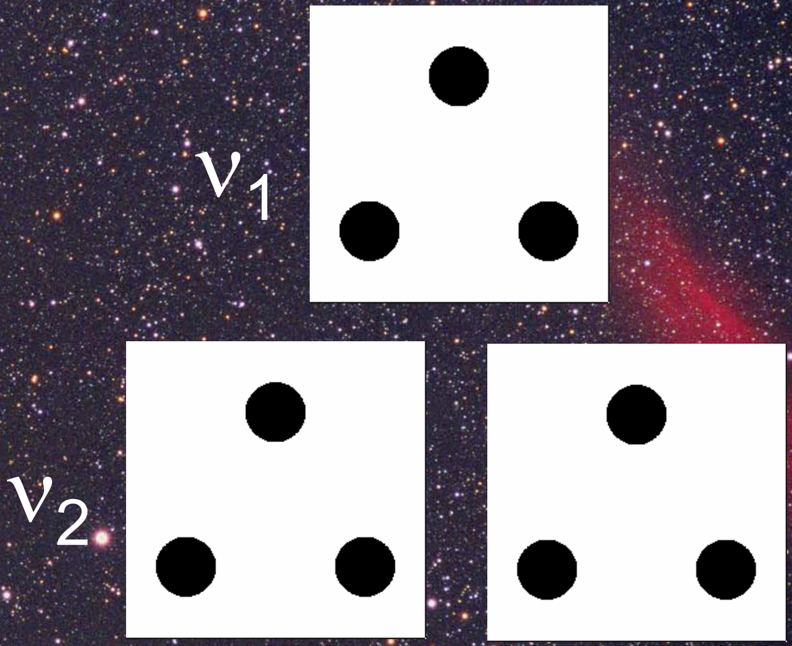
$H_2^+ \xrightarrow{H_2} H_3^+$

$H_2 \xrightarrow{\text{cosmic ray}} H_2^+$

Observing Interstellar H_3^+

- Equilateral triangle
- “No” rotational spectrum
- “No” electronic spectrum
- Vibrational spectrum is only probe

- Absorption spectroscopy against background or embedded star



Interstellar Cloud Classification*

Dense molecular clouds:

- $H \rightarrow H_2$
- $C \rightarrow CO$
- $n(H_2) \sim 10^4$–10^6 cm^{-3}
- $T \sim 20$ K

Barnard 68 (courtesy João Alves, ESO)

Diffuse clouds:

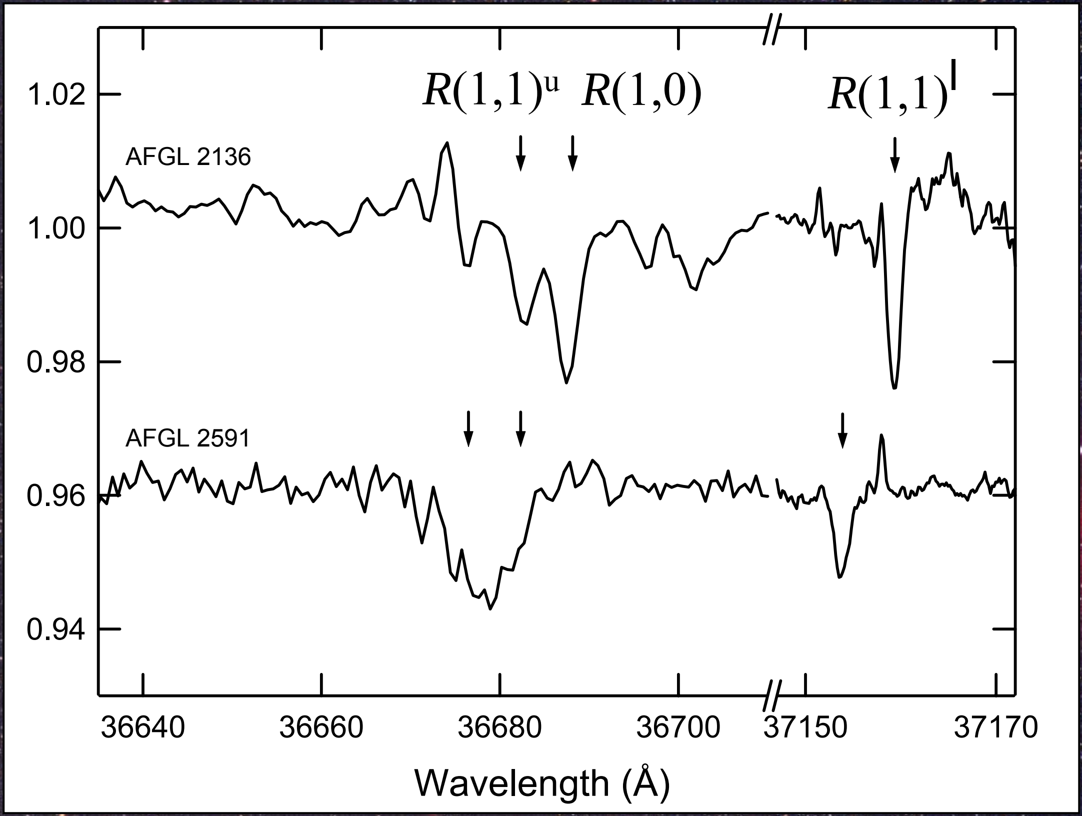
- $H \leftrightarrow H_2$
- $C \rightarrow C^+$
- $n(H_2) \sim 10^1$–10^3 cm^{-3}
  - [$\sim 10^{-18}$ atm]
- $T \sim 50$ K

- Diffuse atomic clouds
  - $H_2 \ll 10\%$
- Diffuse molecular clouds
  - $H_2 > 10\%$ (self-shielded)

* Snow & McCall, *ARAA*, 2006 (in press)

Photo: Jose Fernandez Garcia

H_3^+ in Dense Clouds



$N(H_3^+) = 1–5\times10^{14}\ \mathrm{cm}^{-2}$

McCall, Geballe, Hinkle, & Oka
ApJ 522, 338 (1999)

Dense Cloud H_3^+ Chemistry

Formation

$$H_2 \xrightarrow{\text{cosmic ray}} H_2^+ + e^- \qquad \text{Rate} = \zeta\,[H_2]$$

$$H_2 + H_2^+ \rightarrow H_3^+ + H \quad \text{(fast)}$$

Destruction

$$H_3^+ + CO \rightarrow HCO^+ + H_2 \qquad \text{Rate} = k\,[H_3^+]\,[CO]$$

Steady State

$$= \text{—}\;\;\text{———} = \frac{(3\times10^{-17}\ s^{-1})}{(2\times10^{-9}\ cm^3\ s^{-1})} \times (6700)$$

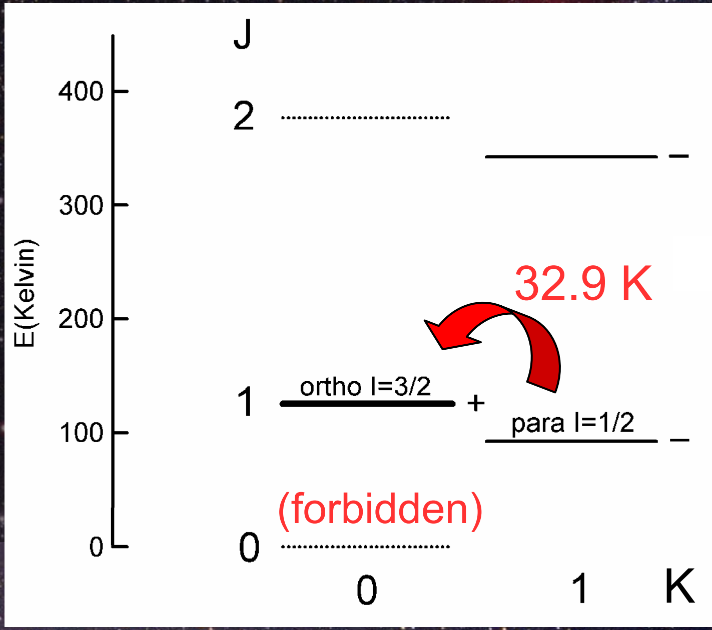
$$= 10^{-4}\ cm^{-3}$$

Density Independent!

McCall, Geballe, Hinkle, & Oka
ApJ 522, 338 (1999)

H_3^+ as a Probe of Dense Clouds

- Given $n(H_3^+)$ from model, and $N(H_3^+)$ from infrared observations:
  - path length $L = N/n \sim 3\times10^{18}$ cm ~ 1 pc
  - density $\langle n(H_2)\rangle = N(H_2)/L \sim 6\times10^4\ \mathrm{cm}^{-3}$
  - temperature $T \sim 30$ K
- Unique probe of clouds
- Consistent with expectations
  - confirms dense cloud chemistry



Diffuse Molecular Cloud H_3^+ Chemistry

Formation

$$H_2 \xrightarrow{\text{cosmic ray}} H_2^+ + e^- \qquad \text{Rate} = \zeta\,[H_2]$$

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

Destruction

$$H_3^+ + e^- \rightarrow H + H_2 \text{ or } 3H \qquad \text{Rate} = k_e\,[H_3^+]\,[e^-]$$

Steady State

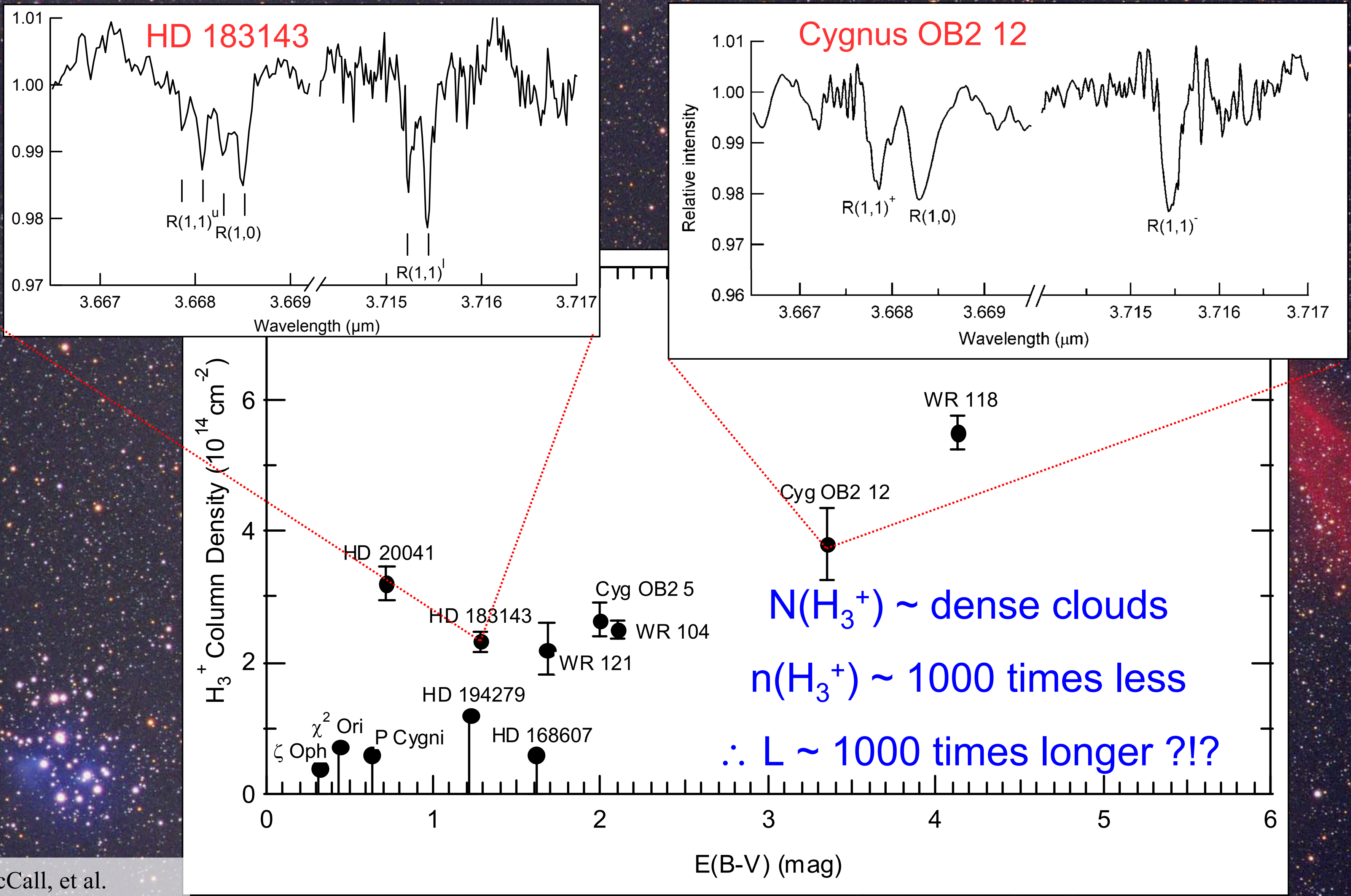
$$[H_3^+] = \frac{\zeta}{k_e}\,\frac{[H_2]}{[e^-]} = \frac{(3\times10^{-17}\ \text{s}^{-1})}{(5\times10^{-7}\ \text{cm}^3\ \text{s}^{-1})} \times (2400)$$

$$= 10^{-7}\ \text{cm}^{-3}$$

Density Independent!

10^3 times smaller than dense clouds!

Lots of H_3^+ in Diffuse Clouds!



$N(H_3^+)$ ~ dense clouds

$n(H_3^+)$ ~ 1000 times less

∴ L ~ 1000 times longer ?!?

McCall, et al.
ApJ 567, 391 (2002)

Big Problem with the Chemistry!

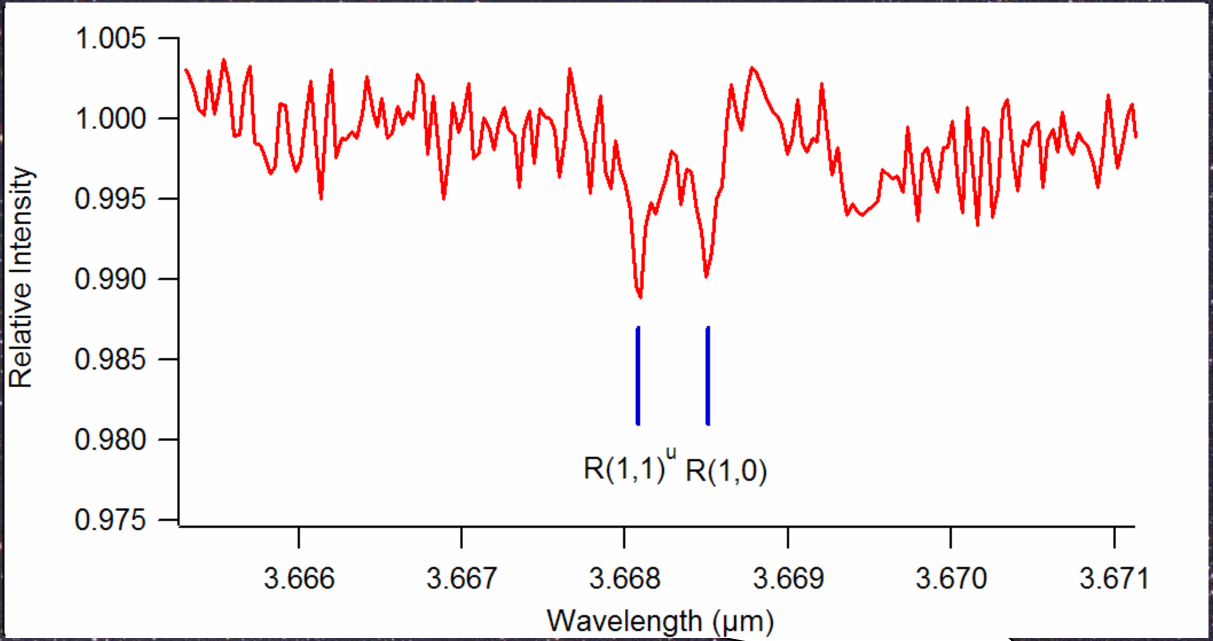
★ ~2 orders of magnitude!!

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

To increase the value of $[H_3^+]$, we need:

- Smaller electron fraction $[e^-]/[H_2]$
- Smaller recombination rate constant k_e
- Higher ionization rate ζ

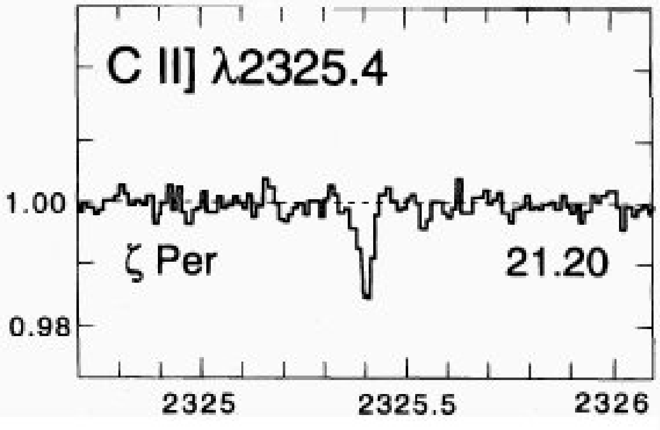
H_3^+ toward ζ Persei



McCall, et al. Nature 422, 500 (2003)

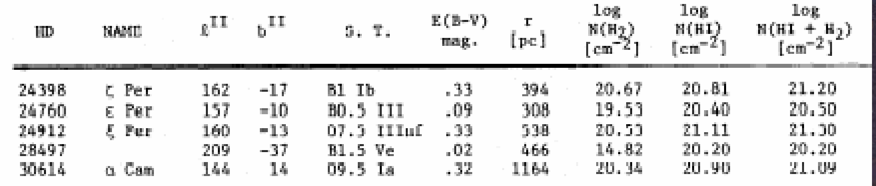
$[e^-]/[H_2]$
not to blame

N(C^+) from HST



Cardelli et al. ApJ 467, 334 (1996)

N(H_2) from Copernicus



HD	NAME	ℓ^{II}	b^{II}	S. T.	E(B-V) mag.	r [pc]	log N(H_2) [cm^{-2}]	log N(HI) [cm^{-2}]	log N(HI + H_2) [cm^{-2}]
24398	ζ Per	162	-17	B1 Ib	.33	394	20.67	20.81	21.20
24760	ε Per	157	-10	B0.5 III	.09	308	19.53	20.40	20.50
24912	ξ Per	160	-13	O7.5 IIInf	.33	538	20.53	21.11	21.30
28497		209	-37	B1.5 Ve	.02	466	14.82	20.20	20.20
30614	α Cam	144	14	O9.5 Ia	.32	1164	20.34	20.90	21.09

Savage et al. ApJ 216, 291 (1977)

Big Problem with the Chemistry!

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

To increase the value of $[H_3^+]$, we need:

- Smaller electron fraction $[e^-]/[H_2]$
- Smaller recombination rate constant k_e
- Higher ionization rate ζ

H_3^+ Dissociative Recombination

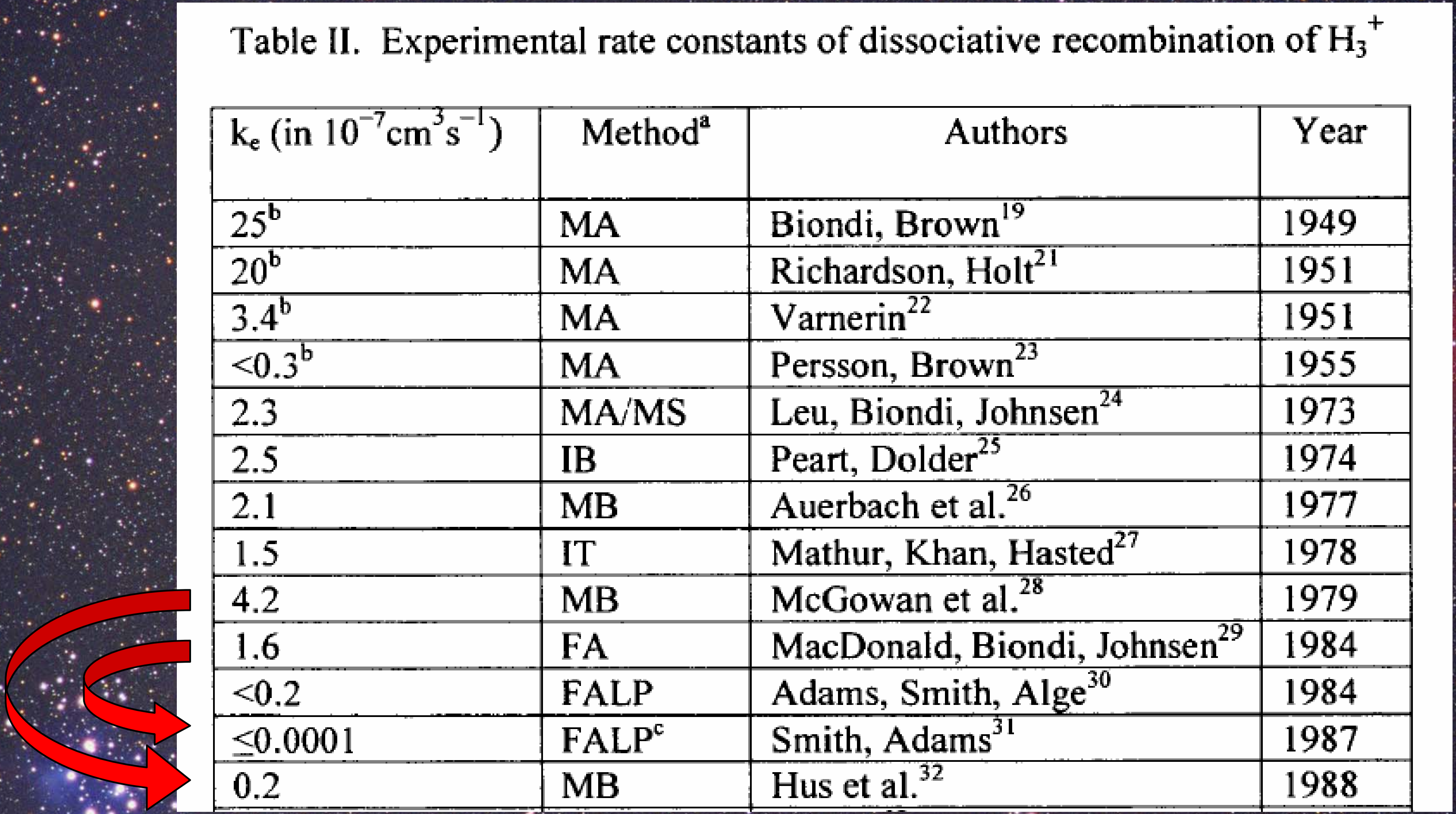


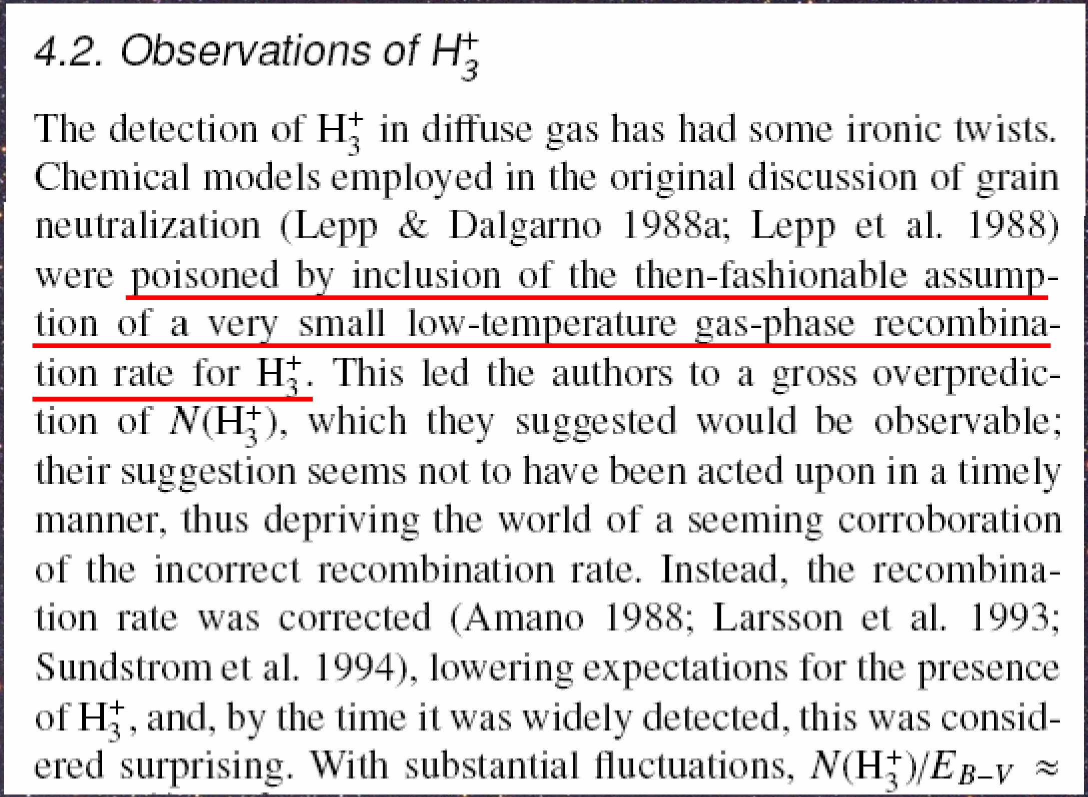
Table II. Experimental rate constants of dissociative recombination of H_3^+

k_e (in $10^{-7} cm^3 s^{-1}$)	Method[a]	Authors	Year
25[b]	MA	Biondi, Brown[19]	1949
20[b]	MA	Richardson, Holt[21]	1951
3.4[b]	MA	Varnerin[22]	1951
<0.3[b]	MA	Persson, Brown[23]	1955
2.3	MA/MS	Leu, Biondi, Johnsen[24]	1973
2.5	IB	Peart, Dolder[25]	1974
2.1	MB	Auerbach et al.[26]	1977
1.5	IT	Mathur, Khan, Hasted[27]	1978
4.2	MB	McGowan et al.[28]	1979
1.6	FA	MacDonald, Biondi, Johnsen[29]	1984
<0.2	FALP	Adams, Smith, Alge[30]	1984
≤0.0001	FALP[c]	Smith, Adams[31]	1987
0.2	MB	Hus et al.[32]	1988

Oka (2003)

Low rate widely believed

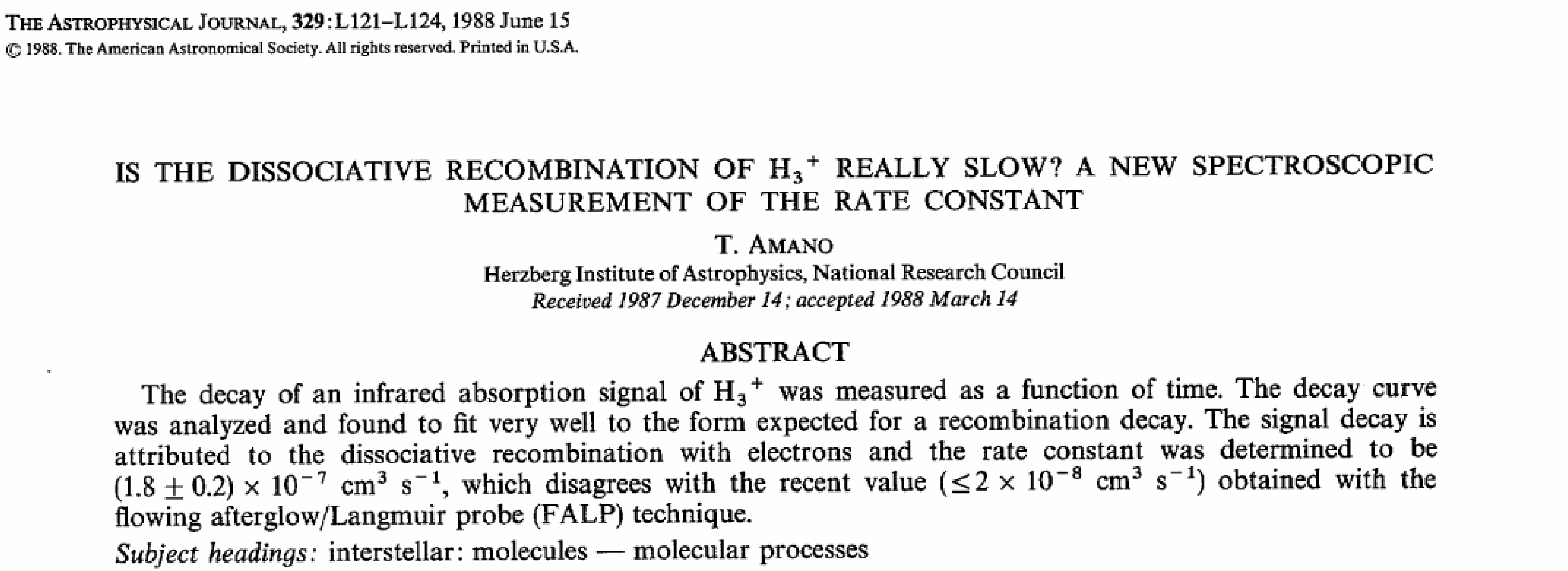
- Chemical models (van Dishoeck & Black)
- Grain neutralization models



4.2. Observations of H_3^+

The detection of H_3^+ in diffuse gas has had some ironic twists. Chemical models employed in the original discussion of grain neutralization (Lepp & Dalgarno 1988a; Lepp et al. 1988) were poisoned by inclusion of the then-fashionable assumption of a very small low-temperature gas-phase recombination rate for H_3^+. This led the authors to a gross overprediction of $N(H_3^+)$, which they suggested would be observable; their suggestion seems not to have been acted upon in a timely manner, thus depriving the world of a seeming corroboration of the incorrect recombination rate. Instead, the recombination rate was corrected (Amano 1988; Larsson et al. 1993; Sundstrom et al. 1994), lowering expectations for the presence of H_3^+, and, by the time it was widely detected, this was considered surprising. With substantial fluctuations, $N(H_3^+)/E_{B-V} \approx$

Liszt (2003)



THE ASTROPHYSICAL JOURNAL, **329**: L121–L124, 1988 June 15

IS THE DISSOCIATIVE RECOMBINATION OF H_3^+ REALLY SLOW? A NEW SPECTROSCOPIC MEASUREMENT OF THE RATE CONSTANT

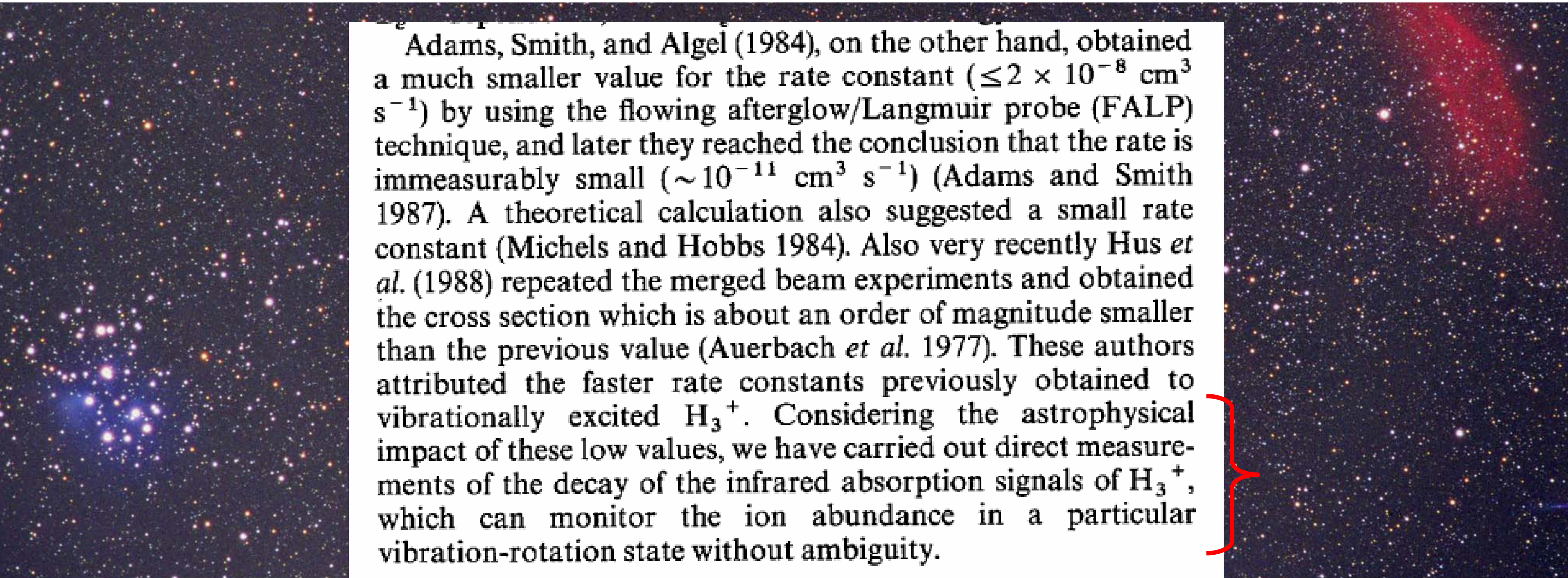
T. AMANO
Herzberg Institute of Astrophysics, National Research Council

Received 1987 December 14; accepted 1988 March 14

ABSTRACT

The decay of an infrared absorption signal of H_3^+ was measured as a function of time. The decay curve was analyzed and found to fit very well to the form expected for a recombination decay. The signal decay is attributed to the dissociative recombination with electrons and the rate constant was determined to be $(1.8 \pm 0.2) \times 10^{-7}$ cm^3 s^{-1}, which disagrees with the recent value ($\leq 2 \times 10^{-8}$ cm^3 s^{-1}) obtained with the flowing afterglow/Langmuir probe (FALP) technique.

Subject headings: interstellar: molecules — molecular processes



Adams, Smith, and Algel (1984), on the other hand, obtained a much smaller value for the rate constant ($\leq 2 \times 10^{-8}$ cm^3 s^{-1}) by using the flowing afterglow/Langmuir probe (FALP) technique, and later they reached the conclusion that the rate is immeasurably small ($\sim 10^{-11}$ cm^3 s^{-1}) (Adams and Smith 1987). A theoretical calculation also suggested a small rate constant (Michels and Hobbs 1984). Also very recently Hus *et al.* (1988) repeated the merged beam experiments and obtained the cross section which is about an order of magnitude smaller than the previous value (Auerbach *et al.* 1977). These authors attributed the faster rate constants previously obtained to vibrationally excited H_3^+. Considering the astrophysical impact of these low values, we have carried out direct measurements of the decay of the infrared absorption signals of H_3^+, which can monitor the ion abundance in a particular vibration-rotation state without ambiguity.

Amano’s Results

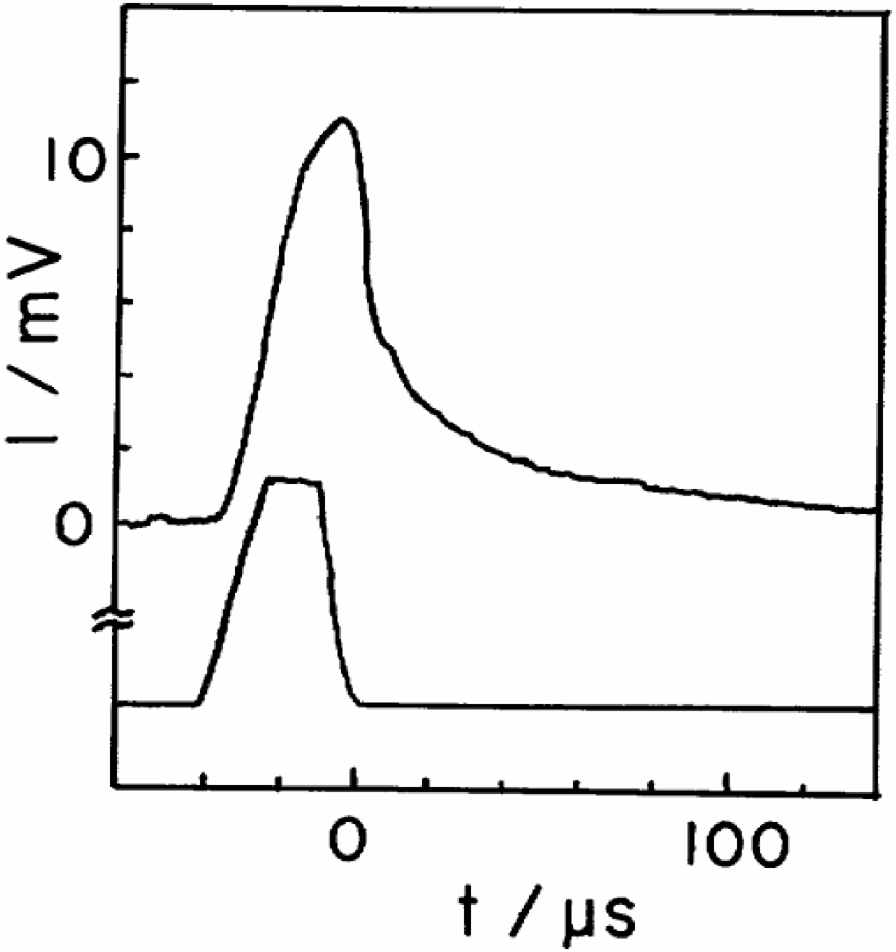


FIG. 2.—The transient absorption signal of the $R_3(3)$ line of H_3^+ (*top trace*) and the discharge current (*bottom trace*). The hydrogen pressure was 500 mtorr.

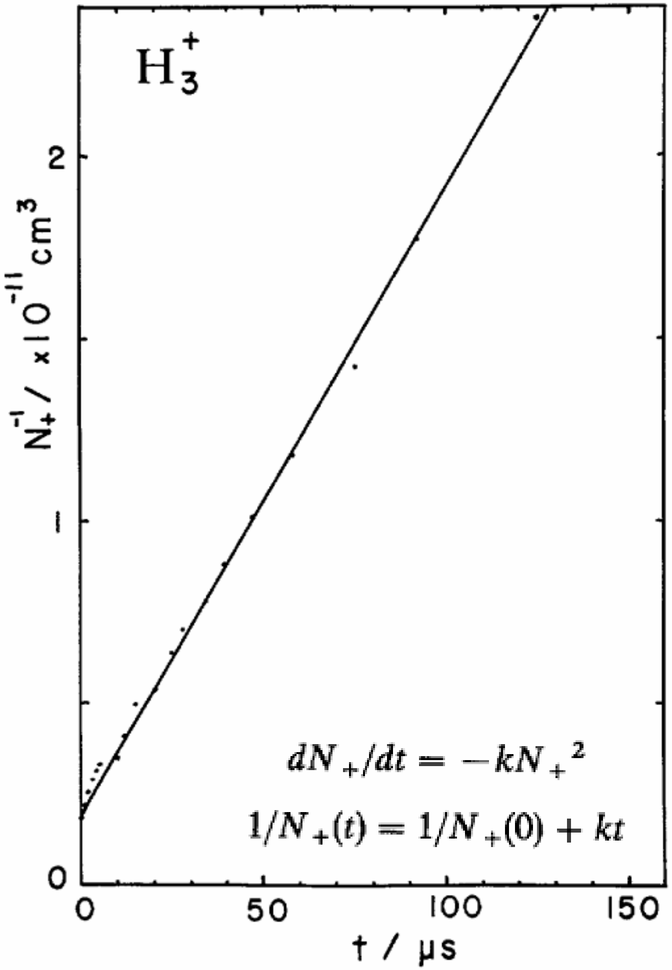
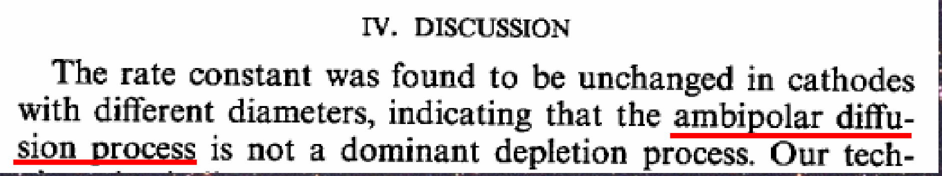


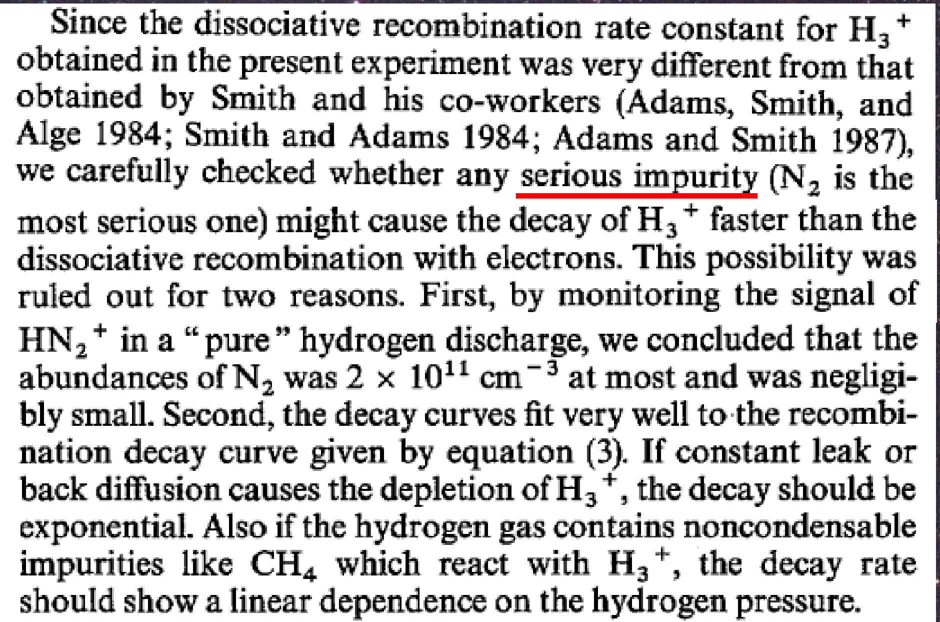
FIG. 3.—The $1/N_+(t)$ vs. t plot of a decay signal of H_3^+. The origin of the time is taken at the point where the current falls to zero completely, as shown in Fig. 2. The ion concentration at $t = 0$ is measured to be $3 \times 10^{12}\ cm^{-3}$ in this example. The peak concentration is larger than that at $t = 0$ by about 30%, as seen from Fig. 2.

Amano's Analysis

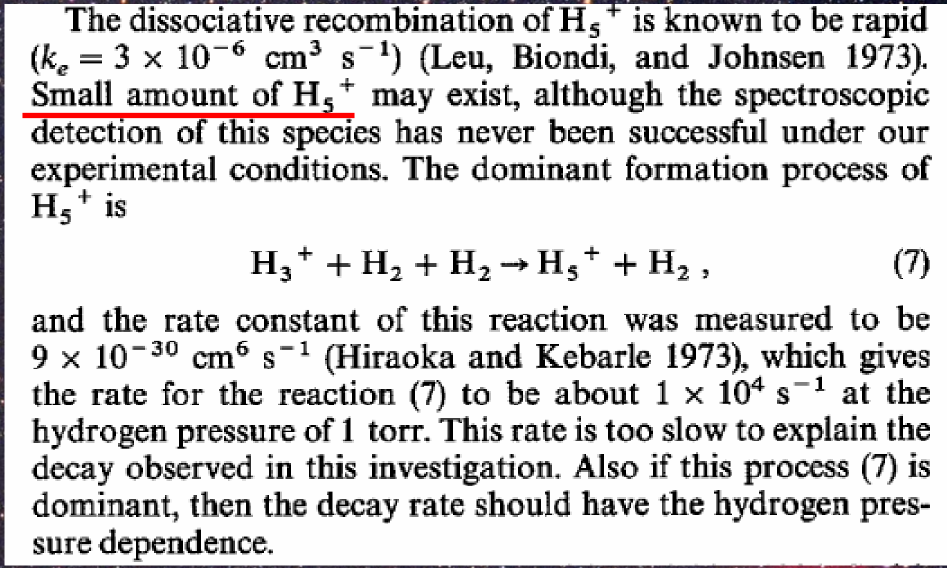


IV. DISCUSSION

The rate constant was found to be unchanged in cathodes with different diameters, indicating that the ambipolar diffusion process is not a dominant depletion process. Our tech-



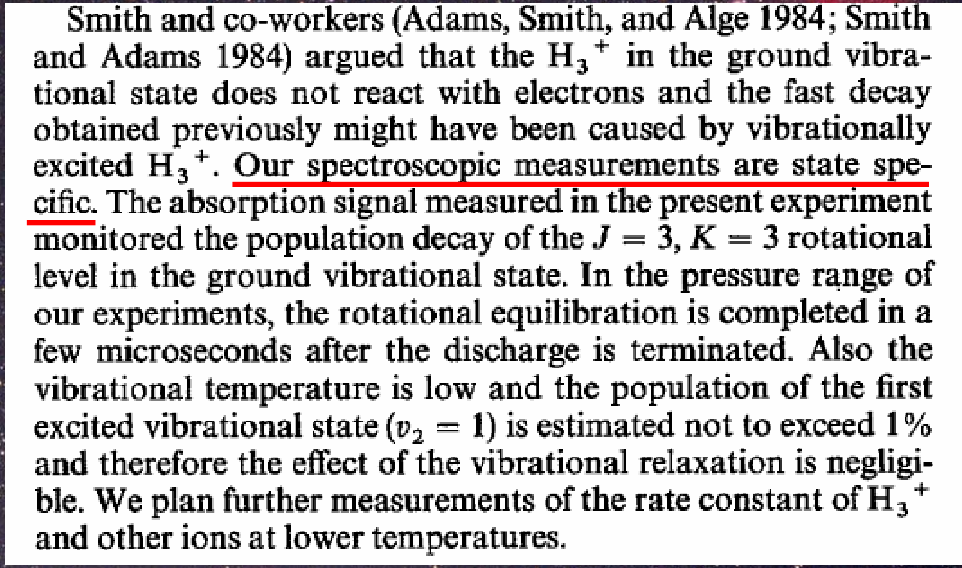
Since the dissociative recombination rate constant for H_3^+ obtained in the present experiment was very different from that obtained by Smith and his co-workers (Adams, Smith, and Alge 1984; Smith and Adams 1984; Adams and Smith 1987), we carefully checked whether any serious impurity (N_2 is the most serious one) might cause the decay of H_3^+ faster than the dissociative recombination with electrons. This possibility was ruled out for two reasons. First, by monitoring the signal of HN_2^+ in a "pure" hydrogen discharge, we concluded that the abundances of N_2 was 2×10^{11} cm^{-3} at most and was negligibly small. Second, the decay curves fit very well to the recombination decay curve given by equation (3). If constant leak or back diffusion causes the depletion of H_3^+, the decay should be exponential. Also if the hydrogen gas contains noncondensable impurities like CH_4 which react with H_3^+, the decay rate should show a linear dependence on the hydrogen pressure.



The dissociative recombination of H_5^+ is known to be rapid ($k_e = 3 \times 10^{-6}$ cm^3 s^{-1}) (Leu, Biondi, and Johnsen 1973). Small amount of H_5^+ may exist, although the spectroscopic detection of this species has never been successful under our experimental conditions. The dominant formation process of H_5^+ is

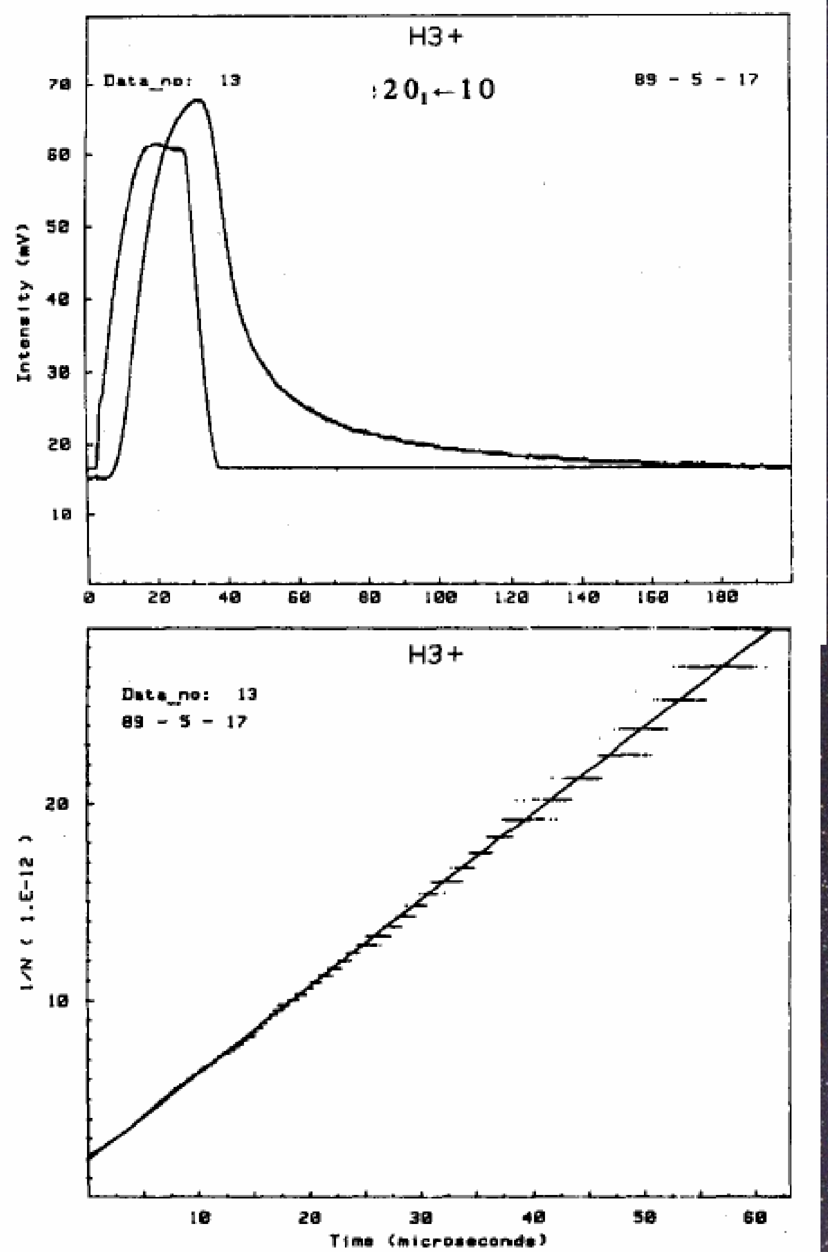
$$H_3^+ + H_2 + H_2 \rightarrow H_5^+ + H_2 \,, \tag{7}$$

and the rate constant of this reaction was measured to be 9×10^{-30} cm^6 s^{-1} (Hiraoka and Kebarle 1973), which gives the rate for the reaction (7) to be about 1×10^4 s^{-1} at the hydrogen pressure of 1 torr. This rate is too slow to explain the decay observed in this investigation. Also if this process (7) is dominant, then the decay rate should have the hydrogen pressure dependence.



Smith and co-workers (Adams, Smith, and Alge 1984; Smith and Adams 1984) argued that the H_3^+ in the ground vibrational state does not react with electrons and the fast decay obtained previously might have been caused by vibrationally excited H_3^+. Our spectroscopic measurements are state specific. The absorption signal measured in the present experiment monitored the population decay of the $J = 3, K = 3$ rotational level in the ground vibrational state. In the pressure range of our experiments, the rotational equilibration is completed in a few microseconds after the discharge is terminated. Also the vibrational temperature is low and the population of the first excited vibrational state ($v_2 = 1$) is estimated not to exceed 1% and therefore the effect of the vibrational relaxation is negligible. We plan further measurements of the rate constant of H_3^+ and other ions at lower temperatures.

Amano 1990



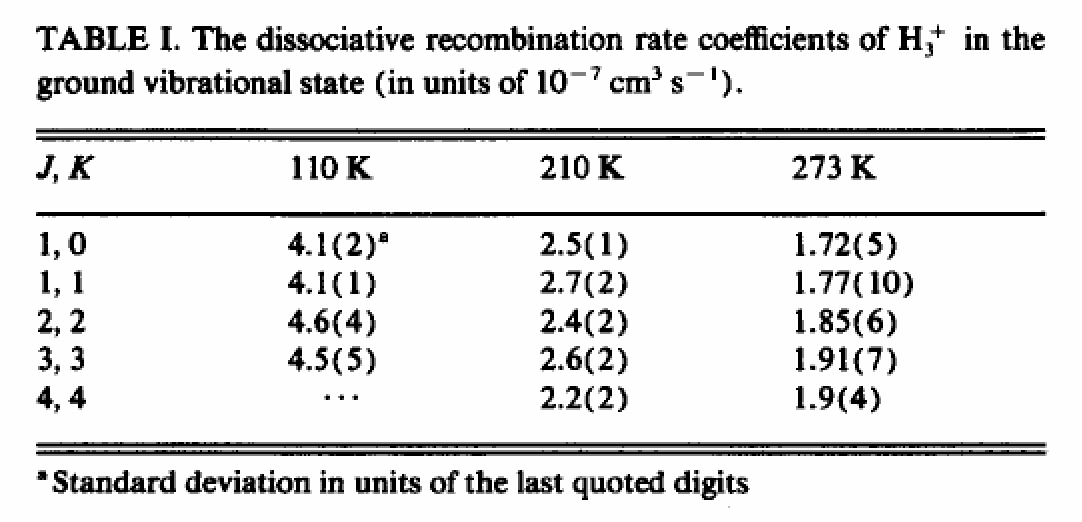
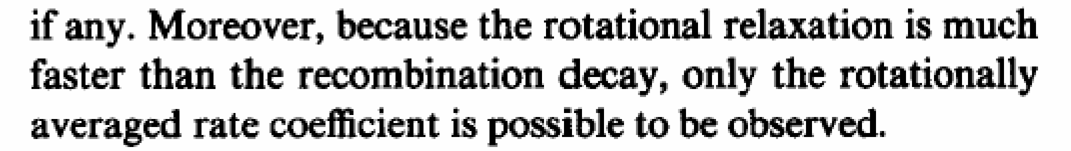


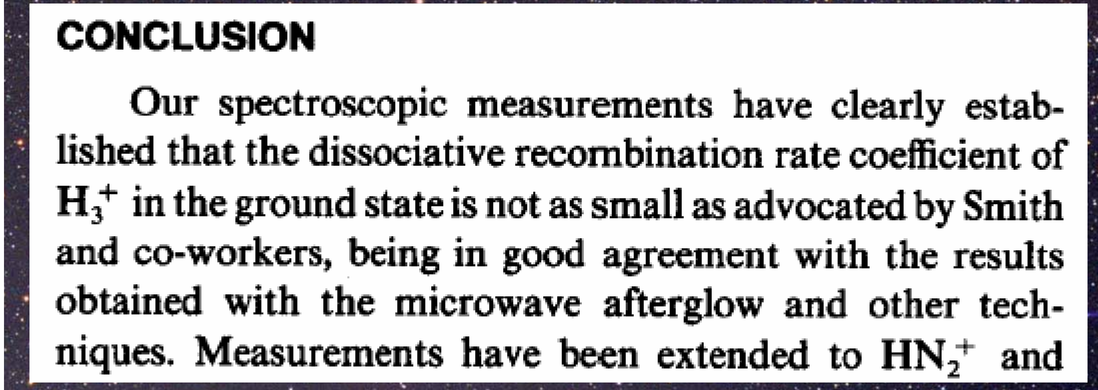
TABLE I. The dissociative recombination rate coefficients of H_3^+ in the ground vibrational state (in units of 10^{-7} cm^3 s^{-1}).

J, K	110 K	210 K	273 K
1, 0	4.1(2)[a]	2.5(1)	1.72(5)
1, 1	4.1(1)	2.7(2)	1.77(10)
2, 2	4.6(4)	2.4(2)	1.85(6)
3, 3	4.5(5)	2.6(2)	1.91(7)
4, 4	···	2.2(2)	1.9(4)

[a] Standard deviation in units of the last quoted digits



if any. Moreover, because the rotational relaxation is much faster than the recombination decay, only the rotationally averaged rate coefficient is possible to be observed.



CONCLUSION

Our spectroscopic measurements have clearly established that the dissociative recombination rate coefficient of H_3^+ in the ground state is not as small as advocated by Smith and co-workers, being in good agreement with the results obtained with the microwave afterglow and other techniques. Measurements have been extended to HN_2^+ and

H_3^+ Dissociative Recombination

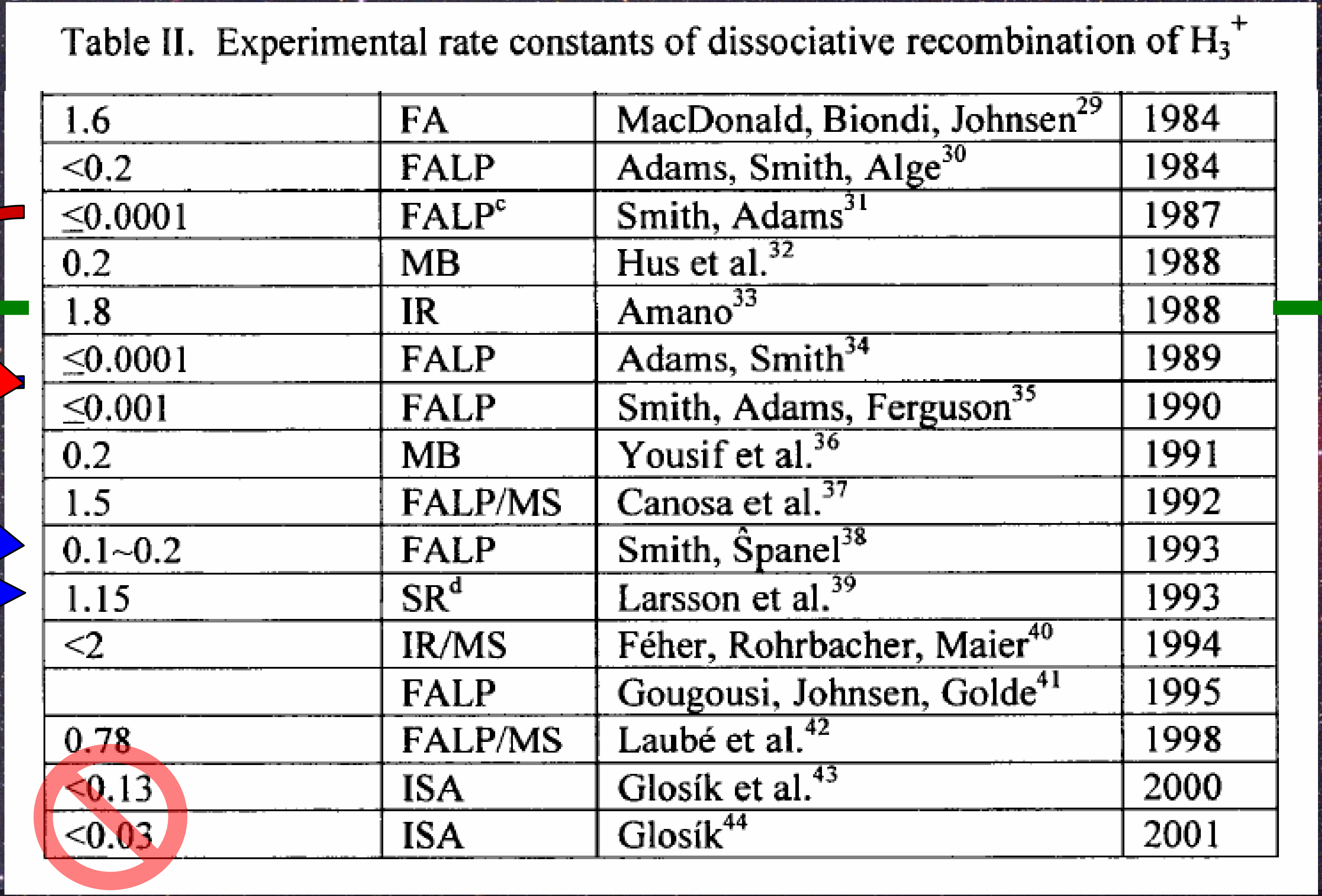


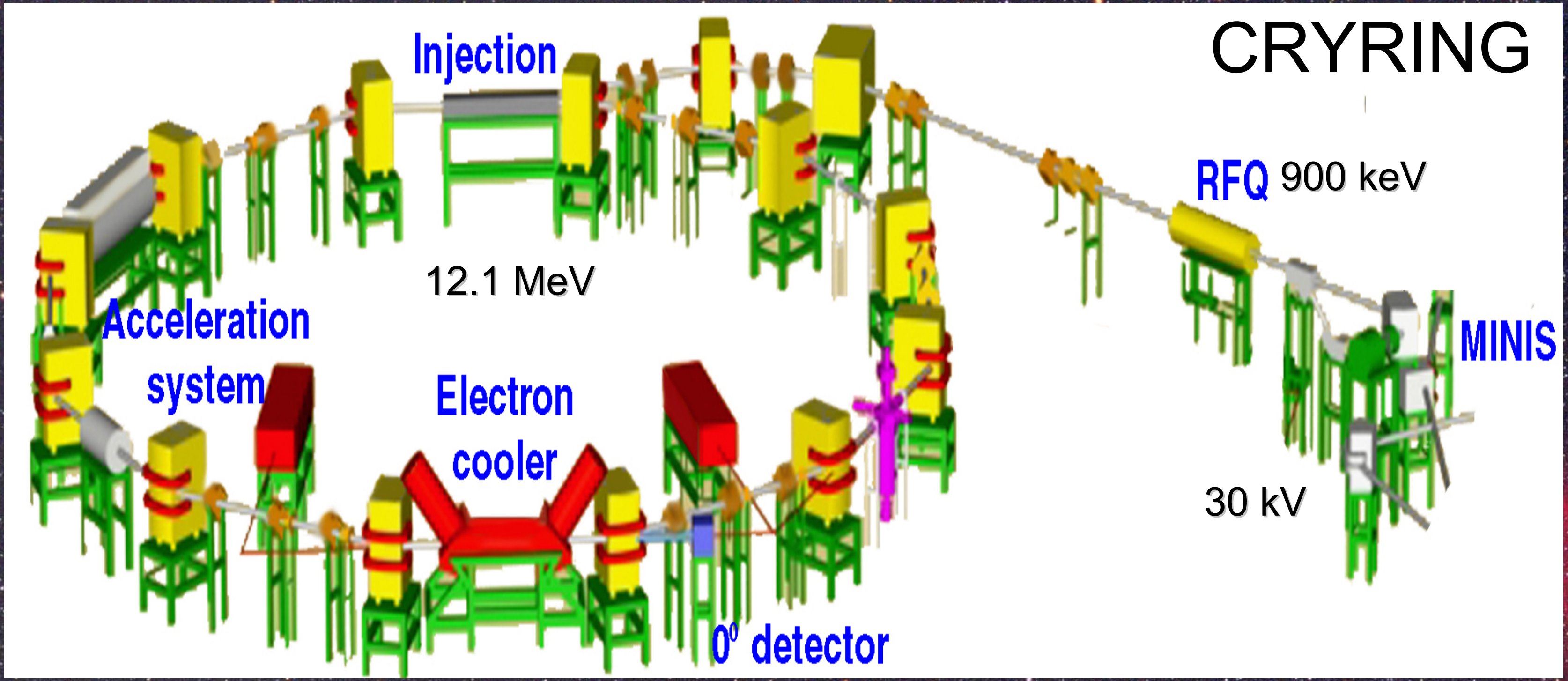
Table II. Experimental rate constants of dissociative recombination of H_3^+

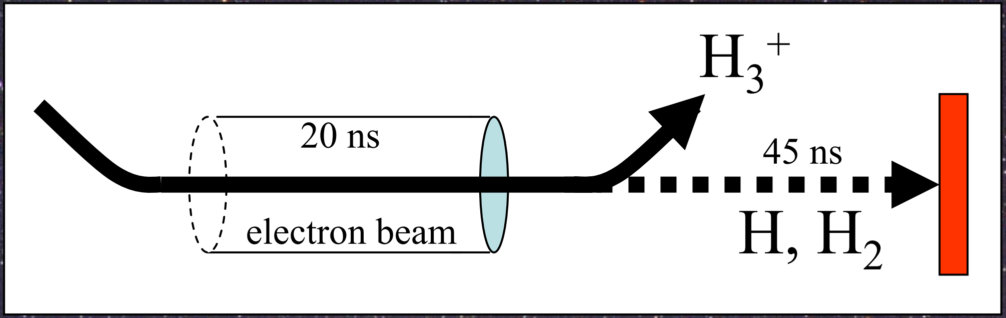
1.6	FA	MacDonald, Biondi, Johnsen[29]	1984
<0.2	FALP	Adams, Smith, Alge[30]	1984
≤0.0001	FALP[c]	Smith, Adams[31]	1987
0.2	MB	Hus et al.[32]	1988
1.8	IR	Amano[33]	1988
≤0.0001	FALP	Adams, Smith[34]	1989
≤0.001	FALP	Smith, Adams, Ferguson[35]	1990
0.2	MB	Yousif et al.[36]	1991
1.5	FALP/MS	Canosa et al.[37]	1992
0.1~0.2	FALP	Smith, Španel[38]	1993
1.15	SR[d]	Larsson et al.[39]	1993
<2	IR/MS	Féher, Rohrbacher, Maier[40]	1994
	FALP	Gougousi, Johnsen, Golde[41]	1995
0.78	FALP/MS	Laubé et al.[42]	1998
<0.13	ISA	Glosík et al.[43]	2000
<0.03	ISA	Glosík[44]	2001

Oka (2003)

- Theory unreliable (until recently)...
- Still not measuring H_3^+ in ground rotational states

Storage Ring Measurements

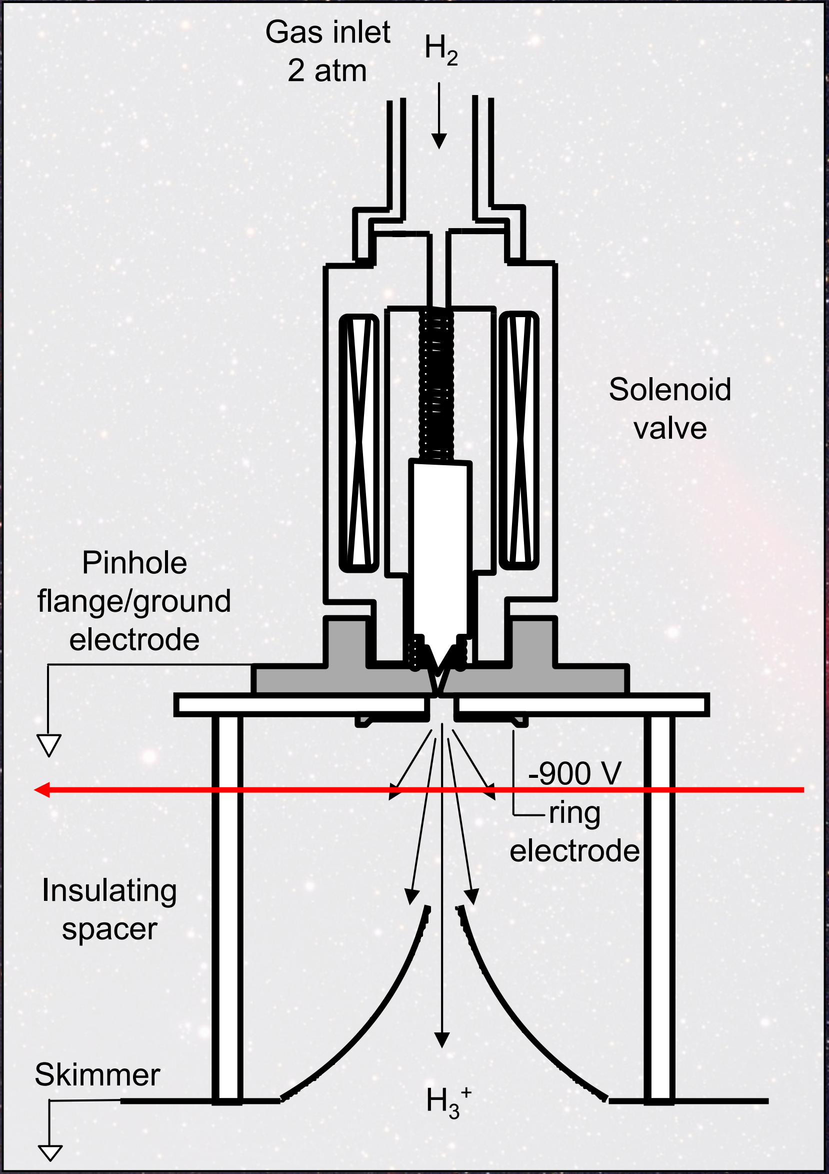




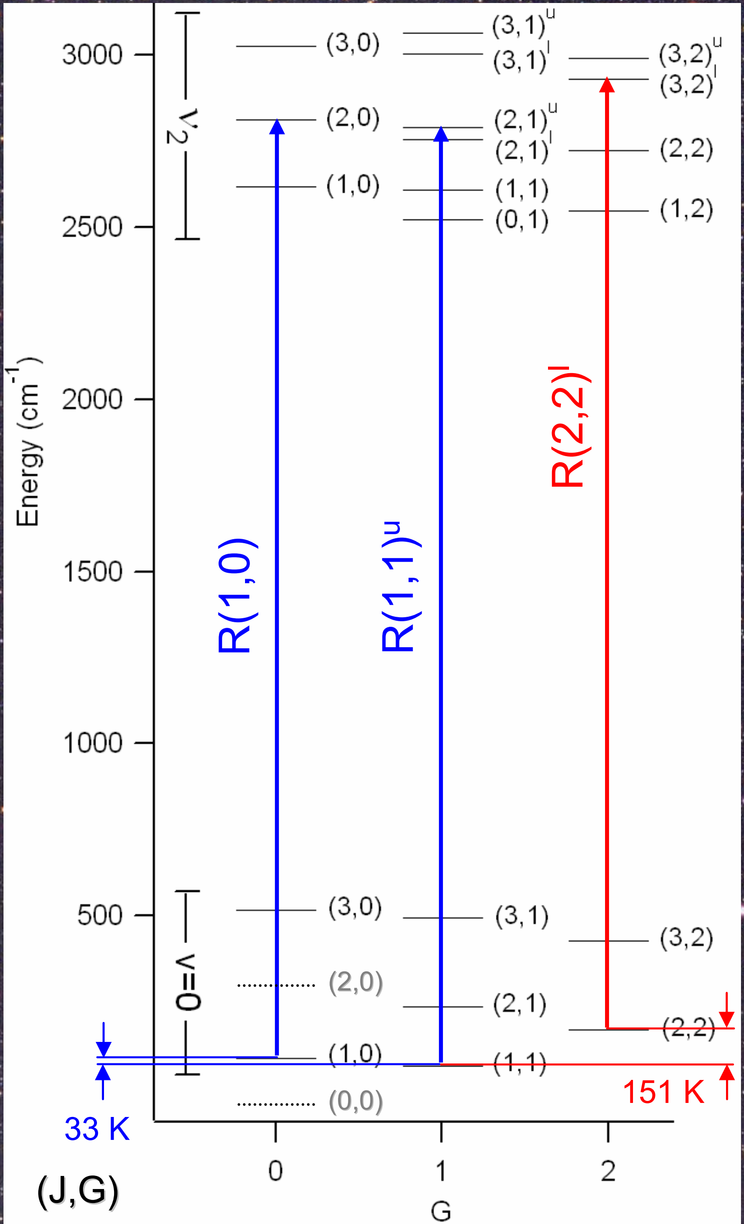
- \+ Very simple experiment
- \+ Complete vibrational relaxation
- \+ Control H_3^+ – e^- impact energy
- \- Rotationally hot ions produced
- \- “No” rotational cooling in ring

Supersonic Expansion Ion Source

- Similar to sources for laboratory spectroscopy in many groups
- Pulsed nozzle design
- Supersonic expansion leads to rapid cooling
- Discharge from ring electrode downstream
- Spectroscopy used to characterize ions
- Skimmer employed to minimize arcing to ring



H_3^+ Energy Level Structure

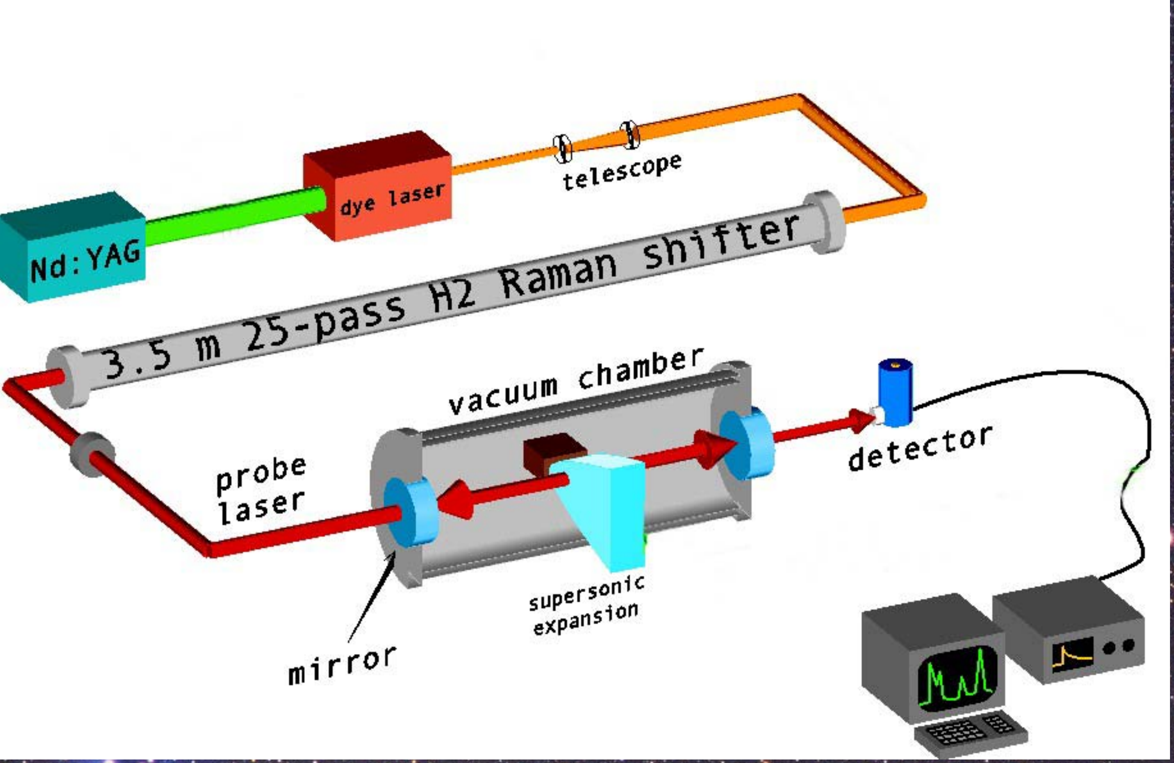


probe of temperature

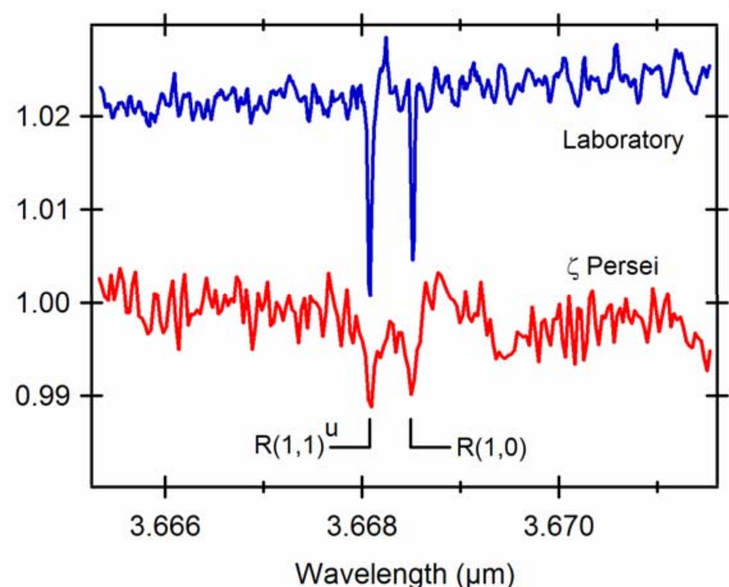
not detected

Spectroscopy of H_3^+ Source

Infrared Cavity Ringdown Laser Absorption Spectroscopy

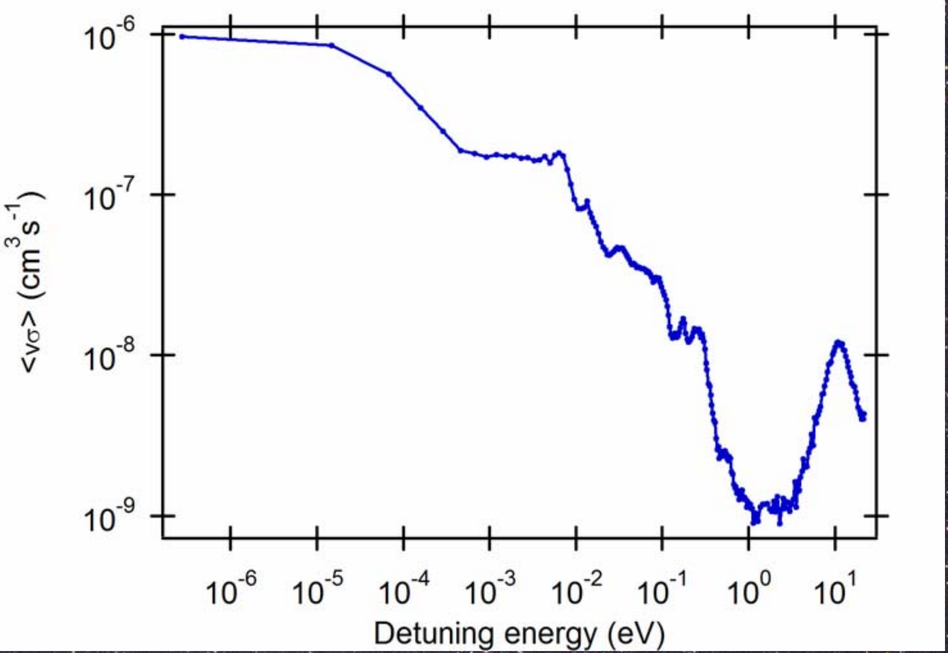


- Confirmed that H_3^+ produced is rotationally cold, as in interstellar medium



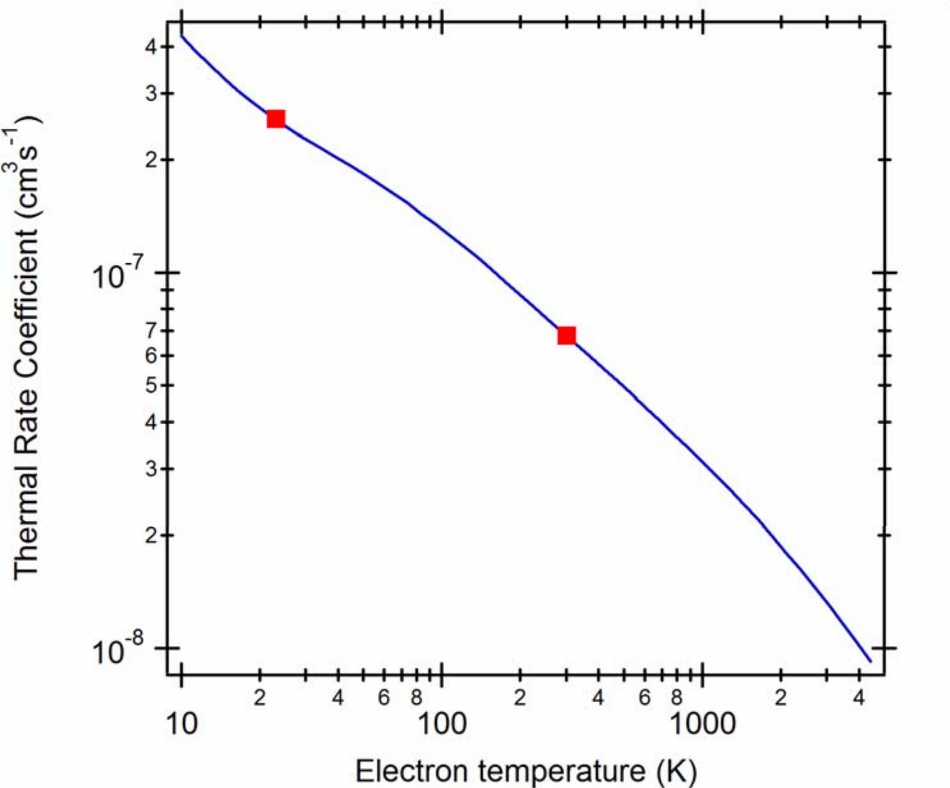
McCall, et al.
Nature 422, 500 (2003)

CRYRING Results

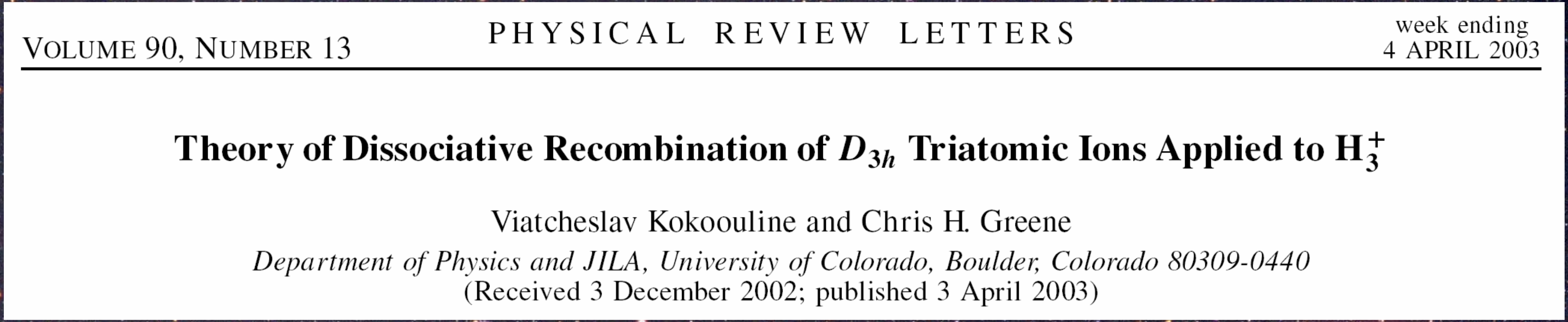


- Considerable amount of structure (resonances) in the cross-section
- $k_e = 2.6 \times 10^{-7}$ cm^3 s^{-1}
- Factor of two smaller

McCall, et al.
Phys. Rev. A 70, 052716 (2004)



Recent Theoretical Work

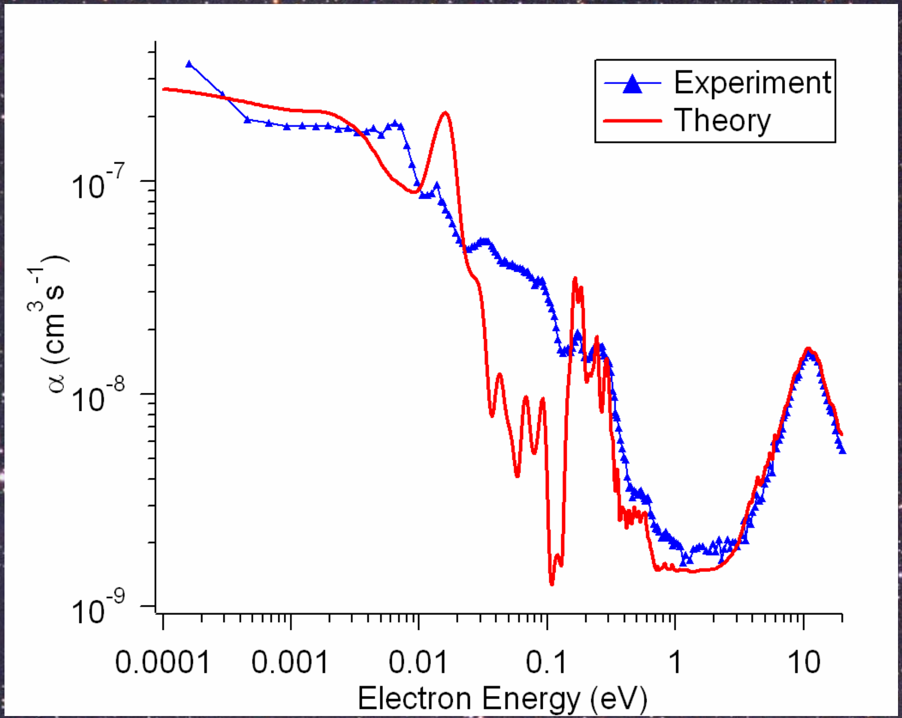


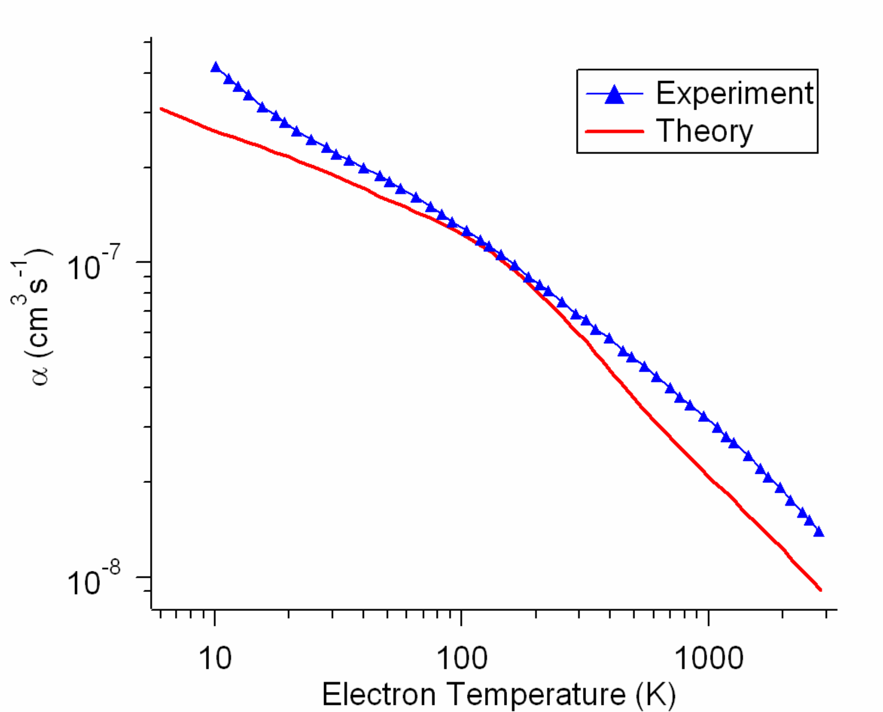
VOLUME 90, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 4 APRIL 2003

Theory of Dissociative Recombination of D_{3h} Triatomic Ions Applied to H_3^+

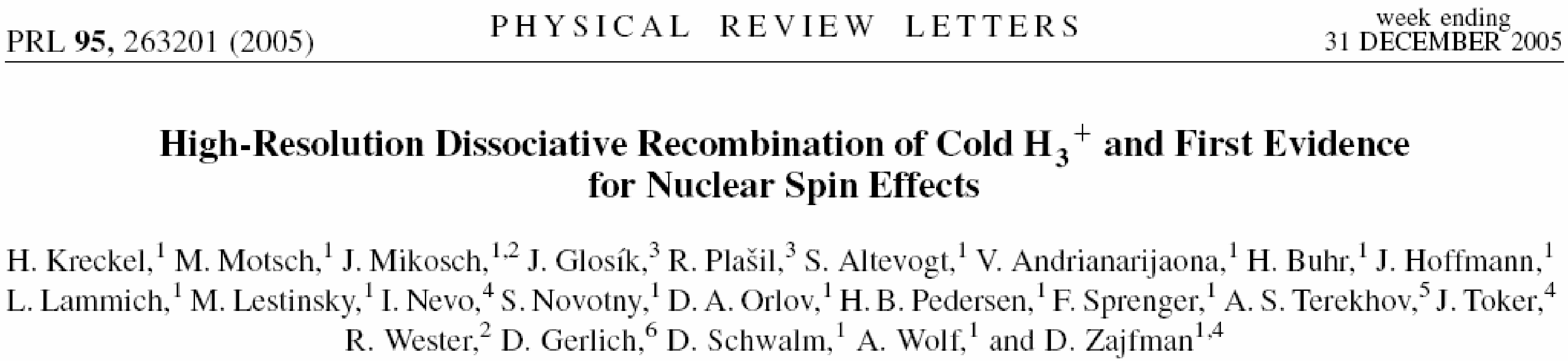
Viatcheslav Kokoouline and Chris H. Greene
Department of Physics and JILA, University of Colorado, Boulder, Colorado 80309-0440

(Received 3 December 2002; published 3 April 2003)





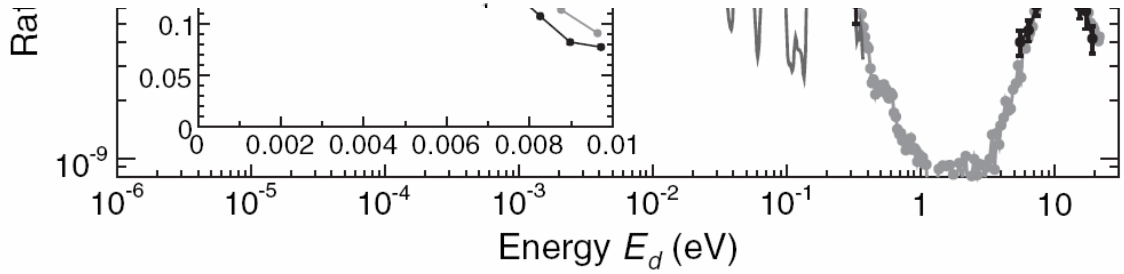
Recent TSR Results



PRL **95,** 263201 (2005) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2005

High-Resolution Dissociative Recombination of Cold H_3^+ and First Evidence for Nuclear Spin Effects

H. Kreckel,[1] M. Motsch,[1] J. Mikosch,[1,2] J. Glosík,[3] R. Plašil,[3] S. Altevogt,[1] V. Andrianarijaona,[1] H. Buhr,[1] J. Hoffmann,[1] L. Lammich,[1] M. Lestinsky,[1] I. Nevo,[4] S. Novotny,[1] D. A. Orlov,[1] H. B. Pedersen,[1] F. Sprenger,[1] A. S. Terekhov,[5] J. Toker,[4] R. Wester,[2] D. Gerlich,[6] D. Schwalm,[1] A. Wolf,[1] and D. Zajfman[1,4]



	CRYRING	TSR
	Supersonic expansion	RF 22-pole ion trap @ 13 K
Electron target	$kT_\perp$~ 2 meV n_e~6.3×10^6 cm^{-3}	$kT_\perp$~ 500 μeV n_e~4.5×10^5 cm^{-3}
Electron cooler	(same as target)	$kT_\perp$~ 10.5 meV n_e~1.6×10^7 cm^{-3}
Beam energy	12.1 MeV	5.25 MeV

H. Kreckel, et al.
Phys. Rev. Lett. 95, 263201 (2005)

Back to the Interstellar Clouds!

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

To increase the value of $[H_3^+]$, we need:

- ~~Smaller electron fraction $[e^-]/[H_2]$~~
- ~~Smaller recombination rate constant k_e~~
- Higher ionization rate ζ

Implications for ζ Persei

$$\frac{N(\mathrm{H_3^+})}{L} = [\mathrm{H_3^+}] = \frac{\zeta}{\mathrm{k_e}}\,\frac{N(\mathrm{H_2})}{N(\mathrm{e^-})}$$

$$\zeta\, L = \mathrm{k_e}\; N(\mathrm{H_3^+})\; \frac{N(\mathrm{e^-})}{N(\mathrm{H_2})}$$

$$(2.6\times10^{-7}\ \mathrm{cm^3\ s^{-1}})\quad (8\times10^{13}\ \mathrm{cm^{-2}})\quad (3.8\times10^{-4})$$

$$\zeta\, L = 8000\ \mathrm{cm\ s^{-1}}$$ (solid)

Adopt
$\zeta = 3\times10^{-17}\ \mathrm{s^{-1}}$

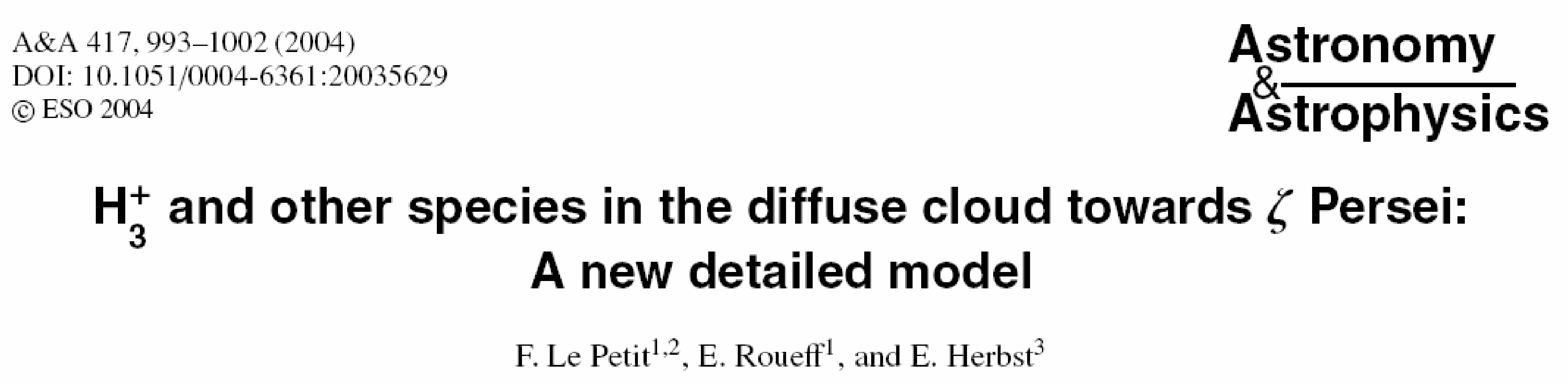
~~$L = 85$ pc~~
~~$\langle n\rangle = 6\ \mathrm{cm^{-3}}$~~

Adopt
$L = 2.1$ pc

$\zeta = 1.2\times10^{-15}\ \mathrm{s^{-1}}$
(40x higher!)

What Does This Mean?

- Enhanced ionization rate in ζ Persei
- Widespread H_3^+ in diffuse clouds
  - perhaps widespread ionization enhancement?
- Dense cloud H_3^+ is "normal"
  - enhanced ionization rate only in diffuse clouds
  - low energy cosmic-ray flux?
  - cosmic-ray self-confinement?
  - no constraints, aside from chemistry!!
- New chemical models necessary
  - Harvey Liszt
  - Franck Le Petit



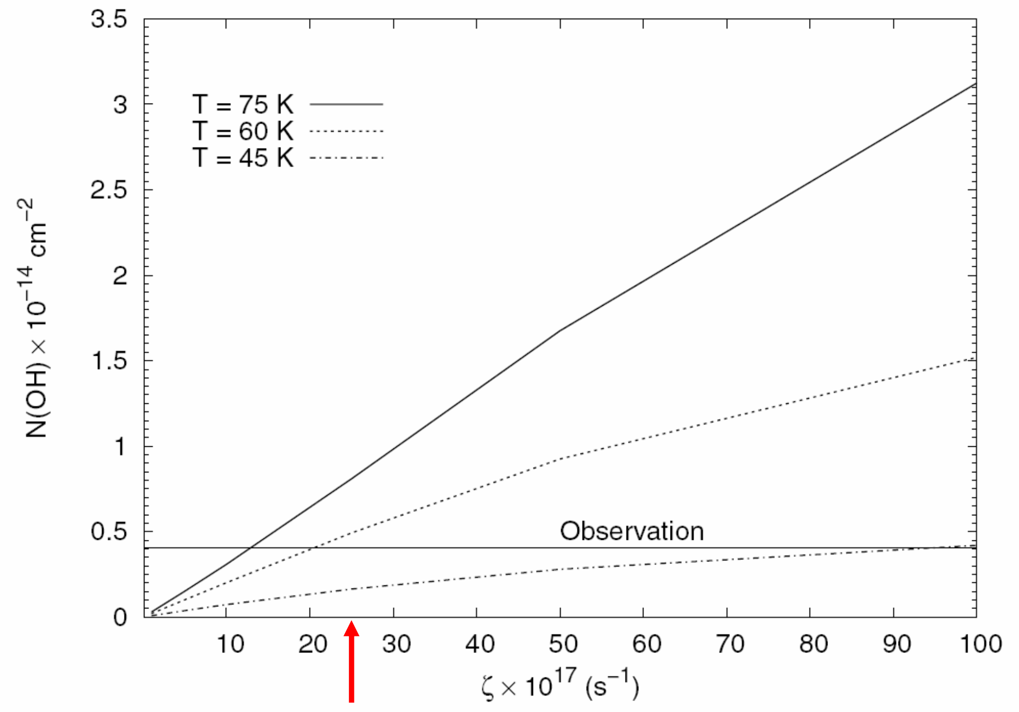
A&A 417, 993–1002 (2004)
DOI: 10.1051/0004-6361:20035629
© ESO 2004

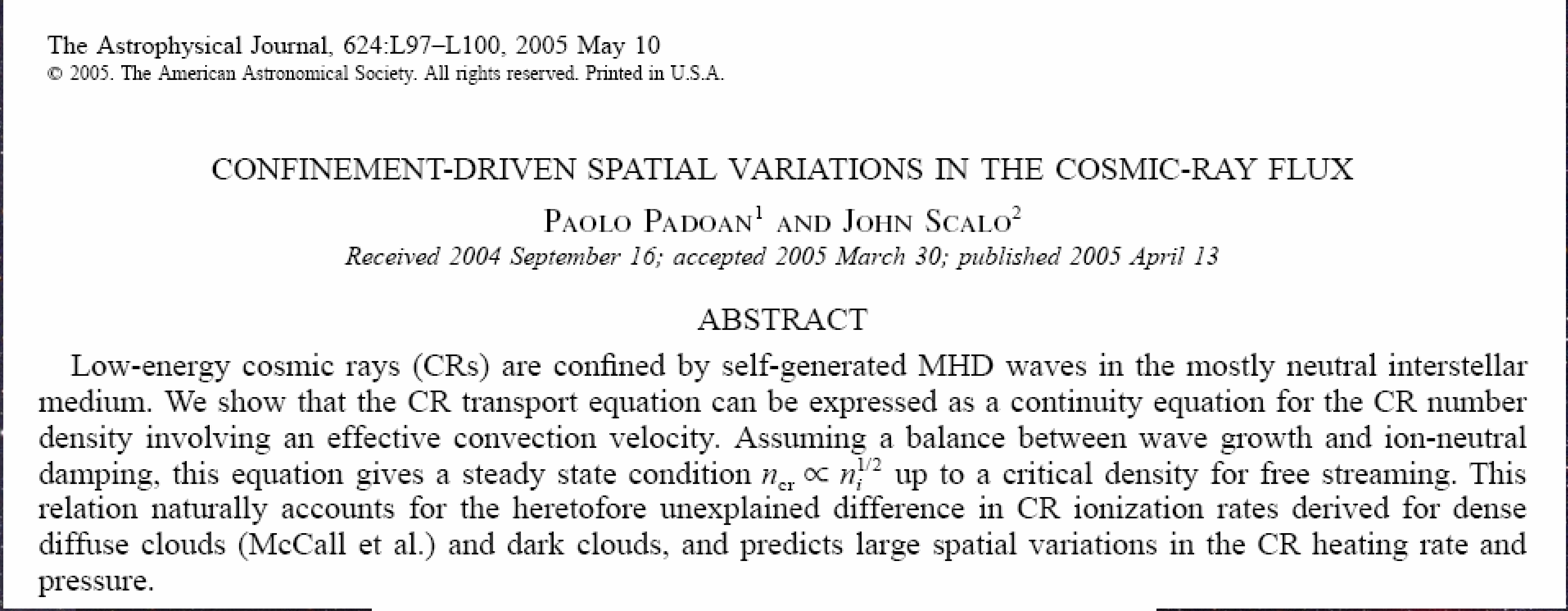
Astronomy & Astrophysics

H_3^+ and other species in the diffuse cloud towards ζ Persei: A new detailed model

F. Le Petit[1,2], E. Roueff[1], and E. Herbst[3]

- Parameters: n=100 cm^{-3}, L=4.2 pc, T=60 K
- Matches all observations within a factor of 3
- $\zeta = 2.5 \times 10^{-16}\ s^{-1}$
  - 10× canonical value
- OH not a problem
  - $H^+ + O \rightarrow O^+ + H$ endothermic by 227 K
  - OH lowered: T→60 K
- Still underpredicts H_3^+
  - "Proof of concept"





The Astrophysical Journal, 624:L97–L100, 2005 May 10

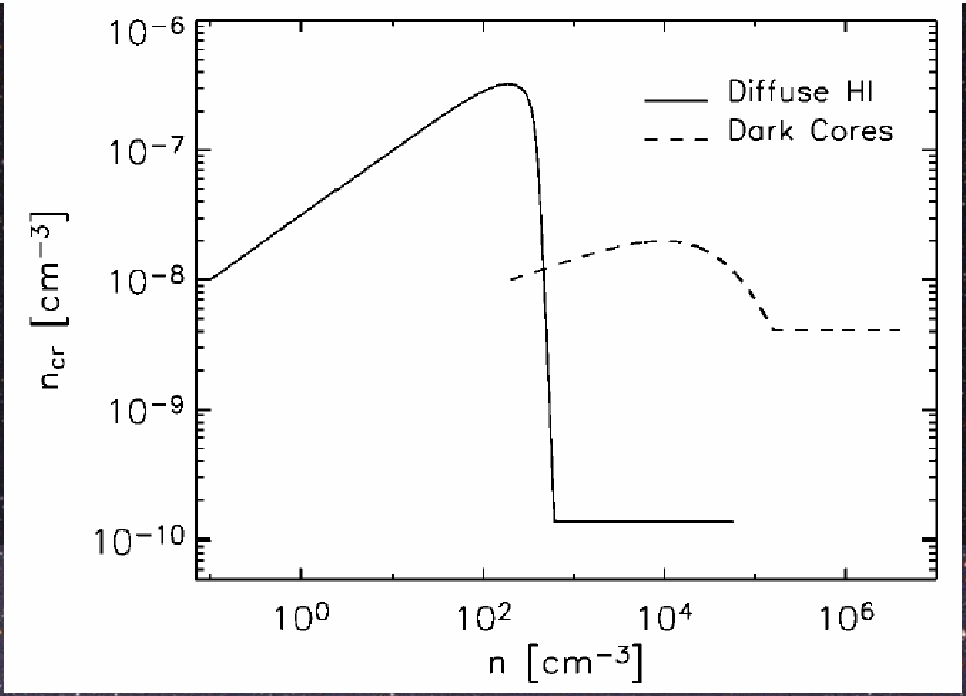
CONFINEMENT-DRIVEN SPATIAL VARIATIONS IN THE COSMIC-RAY FLUX

Paolo Padoan[1] and John Scalo[2]

Received 2004 September 16; accepted 2005 March 30; published 2005 April 13

ABSTRACT

Low-energy cosmic rays (CRs) are confined by self-generated MHD waves in the mostly neutral interstellar medium. We show that the CR transport equation can be expressed as a continuity equation for the CR number density involving an effective convection velocity. Assuming a balance between wave growth and ion-neutral damping, this equation gives a steady state condition $n_{\rm cr} \propto n_i^{1/2}$ up to a critical density for free streaming. This relation naturally accounts for the heretofore unexplained difference in CR ionization rates derived for dense diffuse clouds (McCall et al.) and dark clouds, and predicts large spatial variations in the CR heating rate and pressure.



Future Work

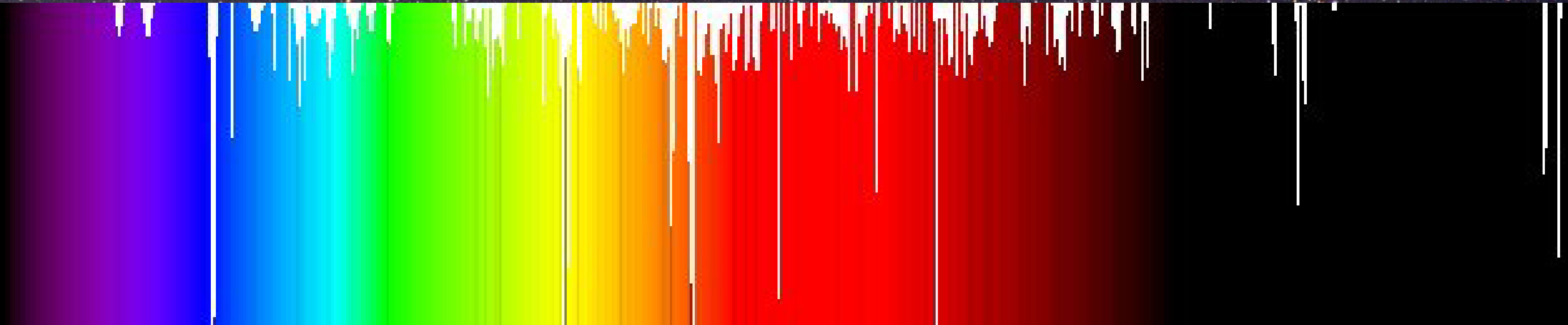
- More experiments!
  - – Improved spectroscopy of ion source
    - Higher resolution & higher sensitivity
    - Better characterization of ro-vib distribution
  - – Testing of new (piezo) ion source
  - – Single quantum-state CRYRING measurements
    - produce pure para-H_3^+ using para-H_2

- More observational data!
  - – Search for H_3^+ in more diffuse cloud sightlines
    - Confirm generality of result in classical diffuse clouds
  - – Observations of H_3^+ in "translucent" sightlines
    - $C^+ \rightarrow C \rightarrow CO$

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Rich Diffuse Cloud Chemistry

- From 1930s through the mid-1990s, only diatomic molecules thought to be abundant in diffuse clouds
- Recently, many polyatomics observed:
  - H_3^+ in infrared
  - HCO^+, C_2H, C_3H_2, etc. in radio (Lucas & Liszt)
  - C_3 in near-UV (Maier, et al.)
- Diffuse Interstellar Bands!



Acknowledgements


- Takeshi Oka (U. Chicago)
- Tom Geballe (Gemini)
- Staff of UKIRT (Mauna Kea)
  - United Kingdom InfraRed Telescope
- Staff of CRYRING (Stockholm)
- Chris Greene (Boulder)
- Eric Herbst (Ohio State)
- Mike Lindsay (Eglin AFB)
- Funding:
  - Berkeley: NSF, AFOSR
  - Illinois: NSF, NASA, ACS, Dreyfus