Dissociative Recombination of Cold H_3^+ and its Interstellar Implications

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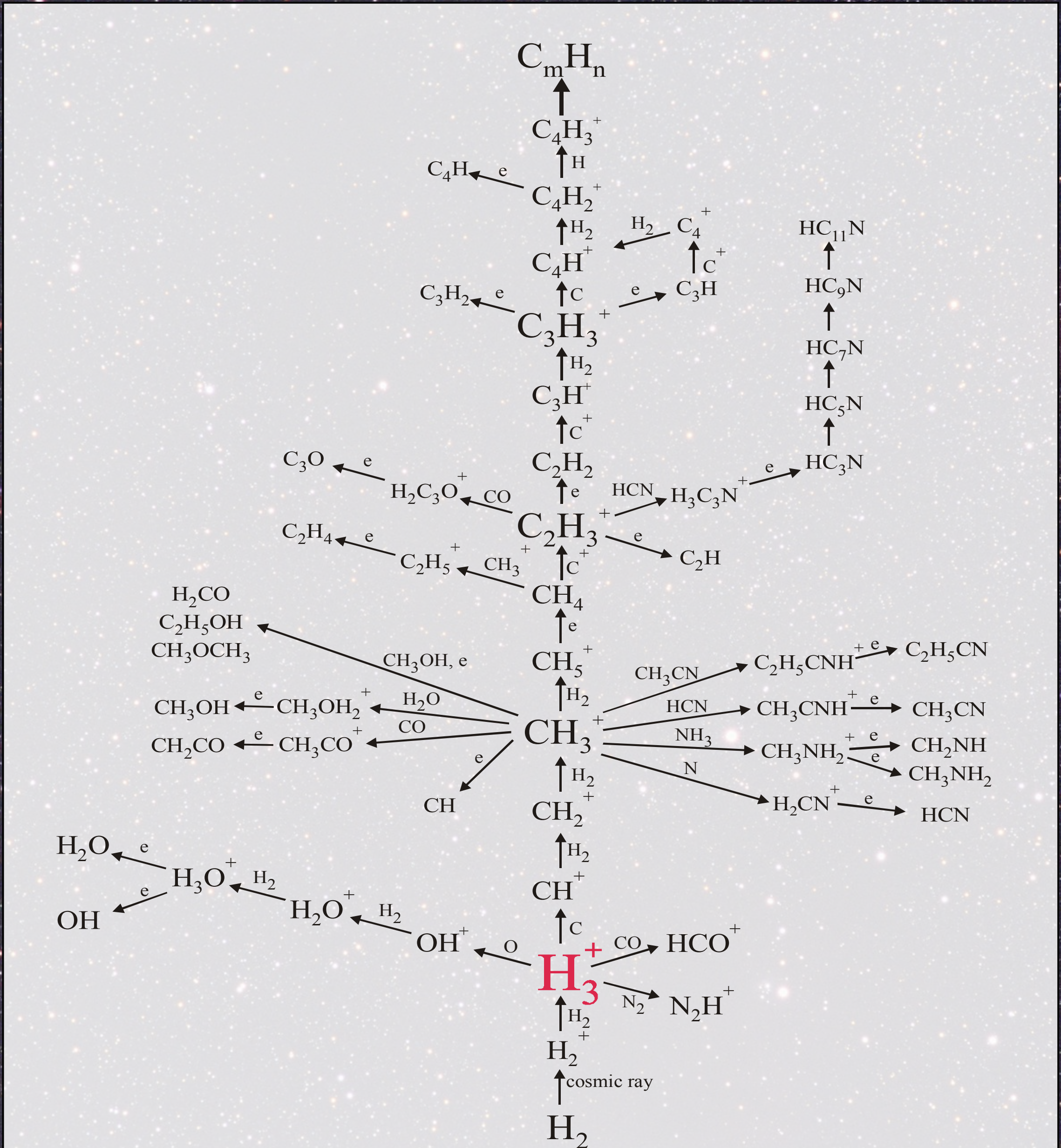
Astronomer's Periodic Table

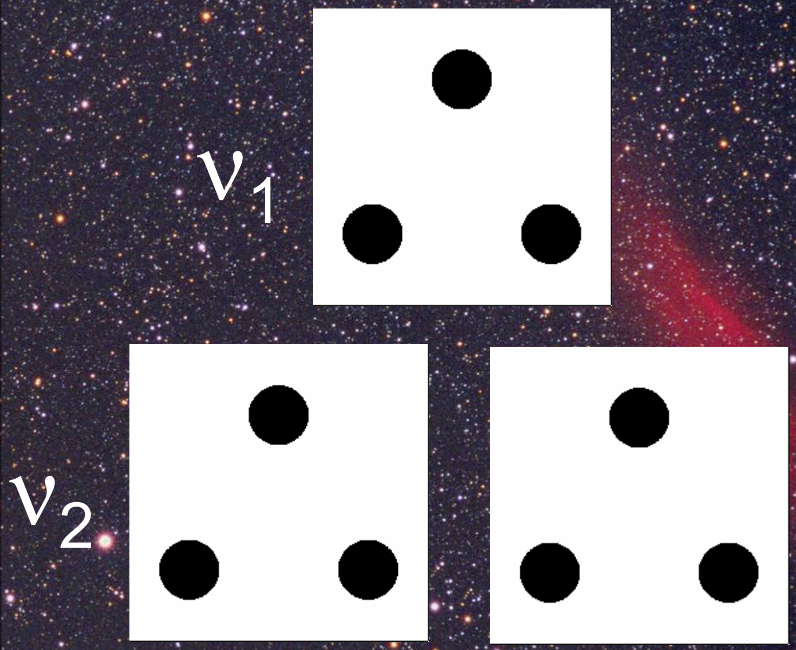
H_3^+: Cornerstone of Interstellar Chemistry



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}
  - [~10^{-18} atm]
- $T \sim 50$ K

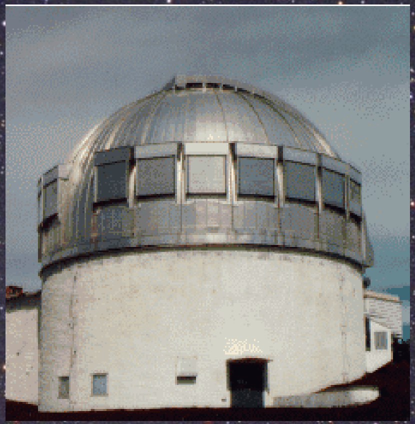
⟵ ζ Persei

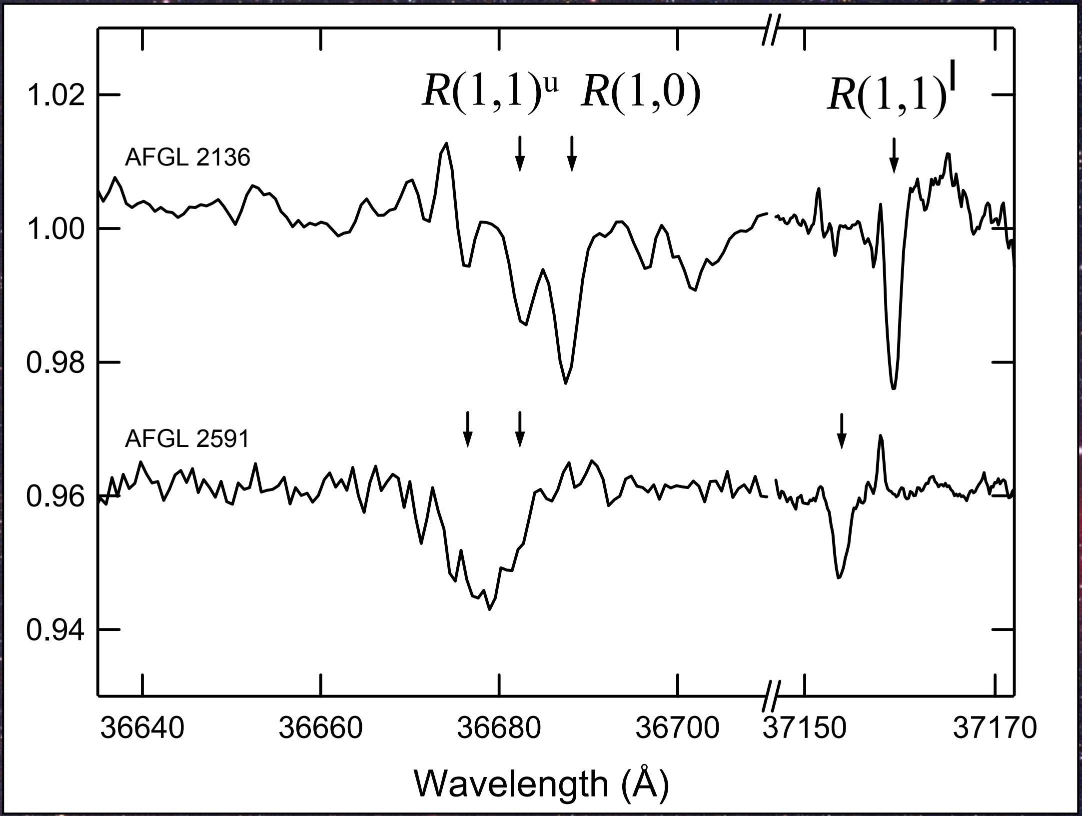
- Diffuse atomic clouds
  - H_2 << 10%
- Diffuse molecular clouds
  - H_2 > 10% (self-shielded)

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

Photo: Jose Fernandez Garcia

H_3^+ in Dense Clouds





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

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

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

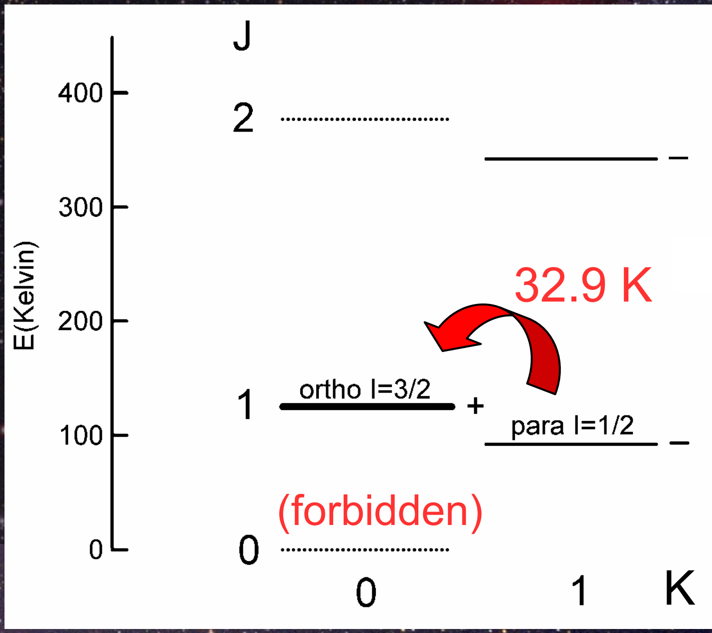
$$= 10^{-4}\ cm^{-3}$$

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 $\langle n(H_2)\rangle = N(H_2)/L \sim 6\times10^4\ cm^{-3}$
  - 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

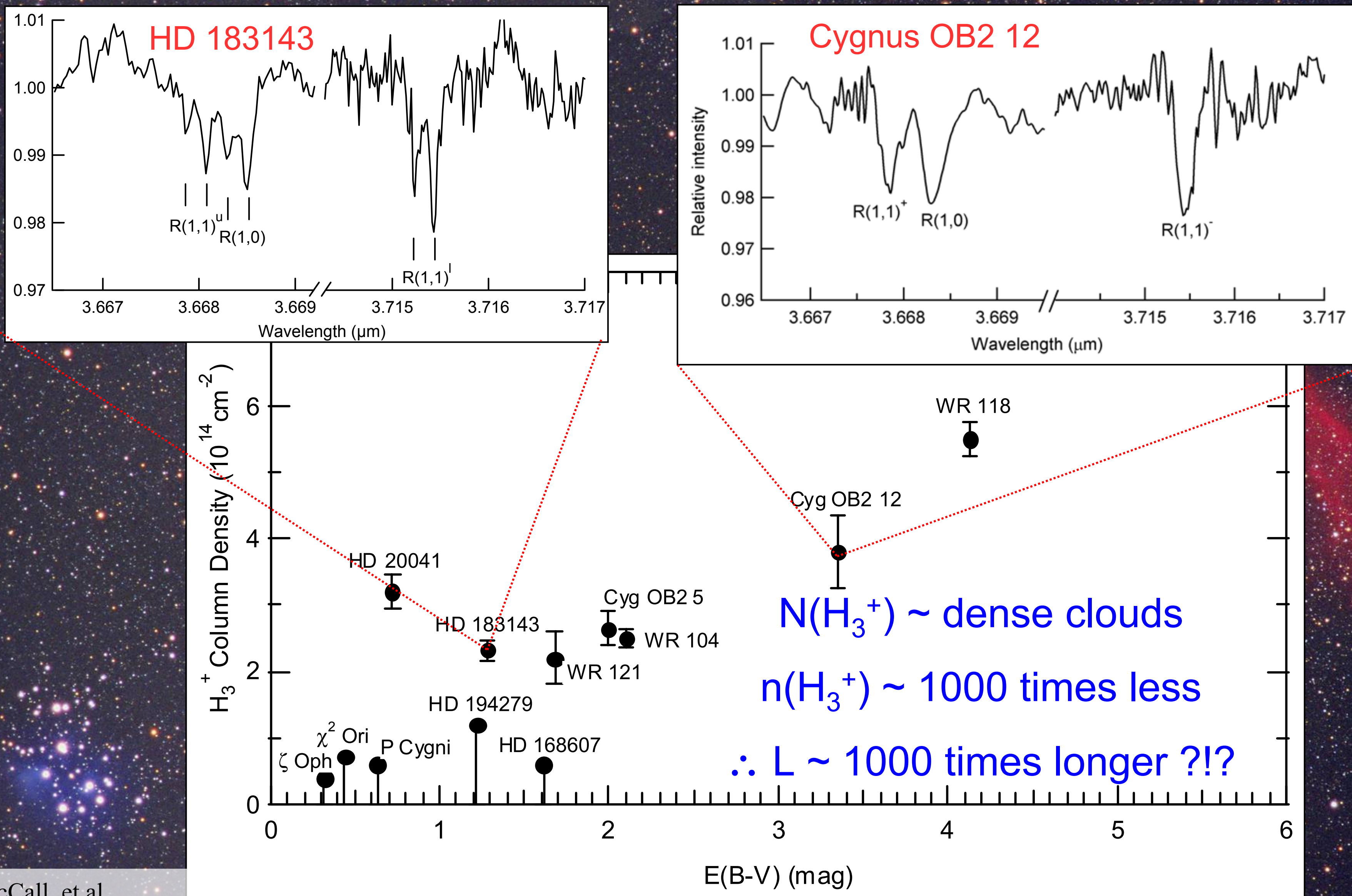
$$[H_3^+] = \frac{\zeta}{k_e}\,\frac{[H_2]}{[e^-]} = \frac{(3\times10^{-17}\ \text{s}^{-1})}{(5\times10^{-7}\ \text{cm}^3\ \text{s}^{-1})} \times (2400)$$

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

Density Independent!

10^3 times smaller than dense clouds!

Lots of H_3^+ in Diffuse Clouds!



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

Big Problem with the Chemistry!

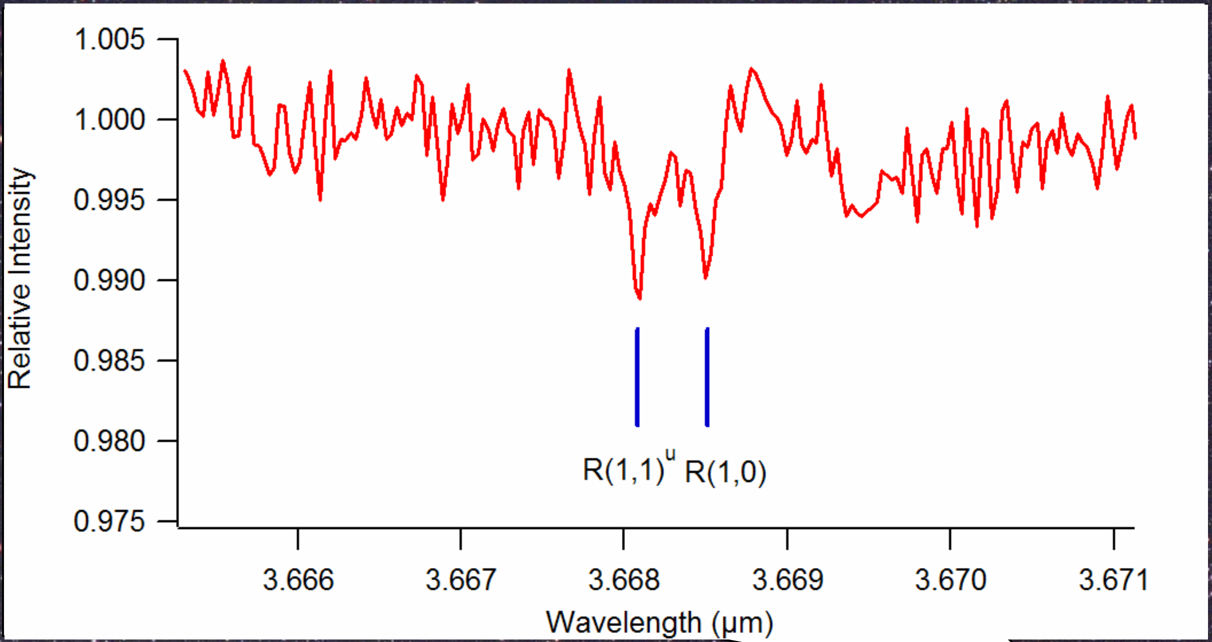
★ ~2 orders of magnitude!!

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

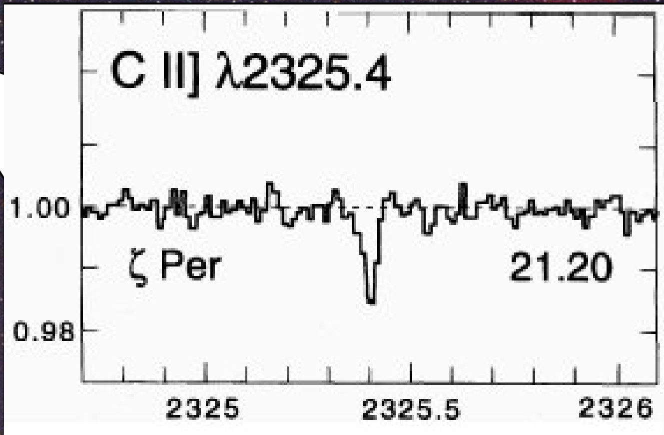
H_3^+ toward ζ Persei



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 IIIuf	.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!

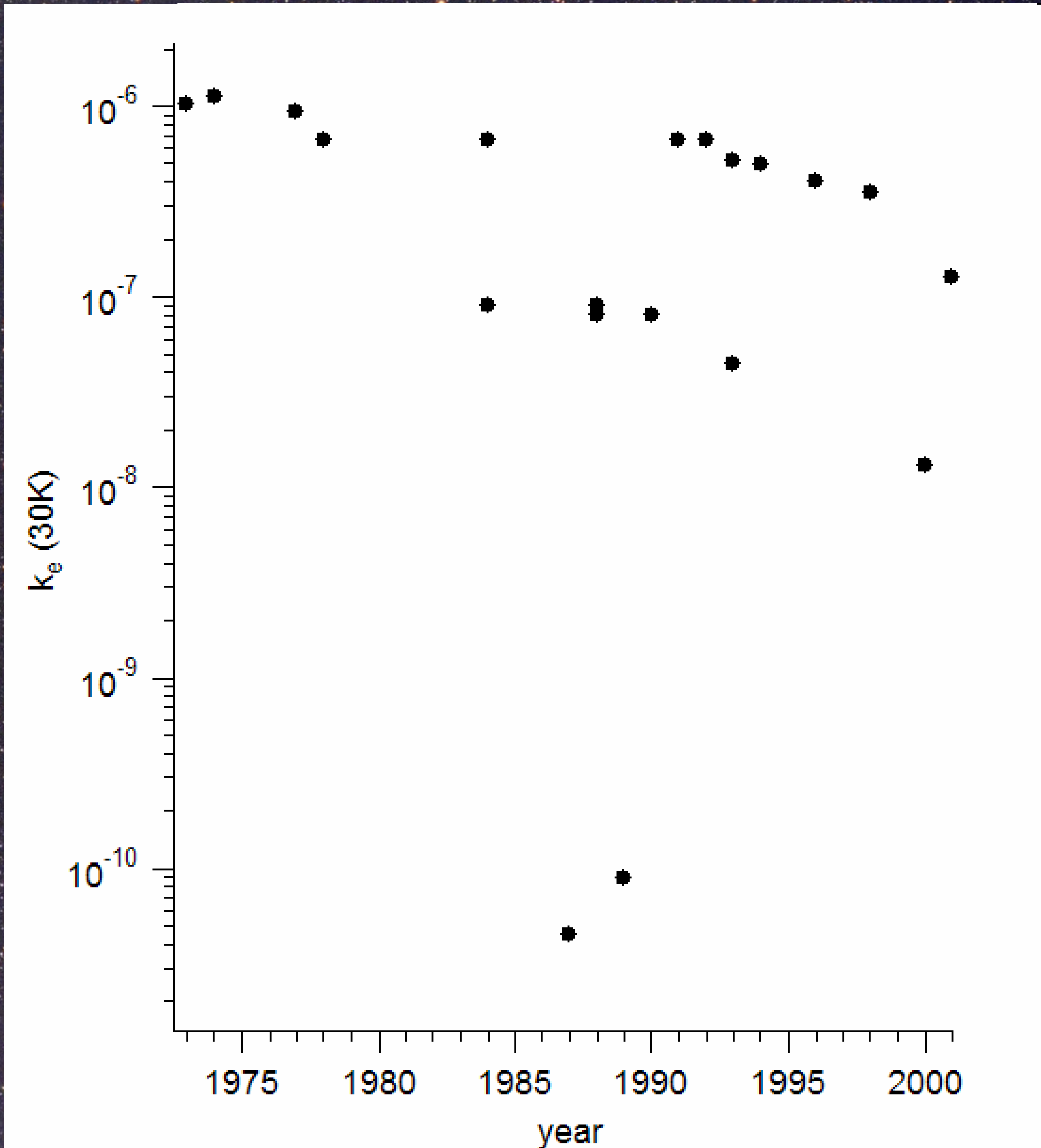
Steady State: $[H_3^+] = \frac{\zeta}{k_e} \frac{[H_2]}{[e^-]}$

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

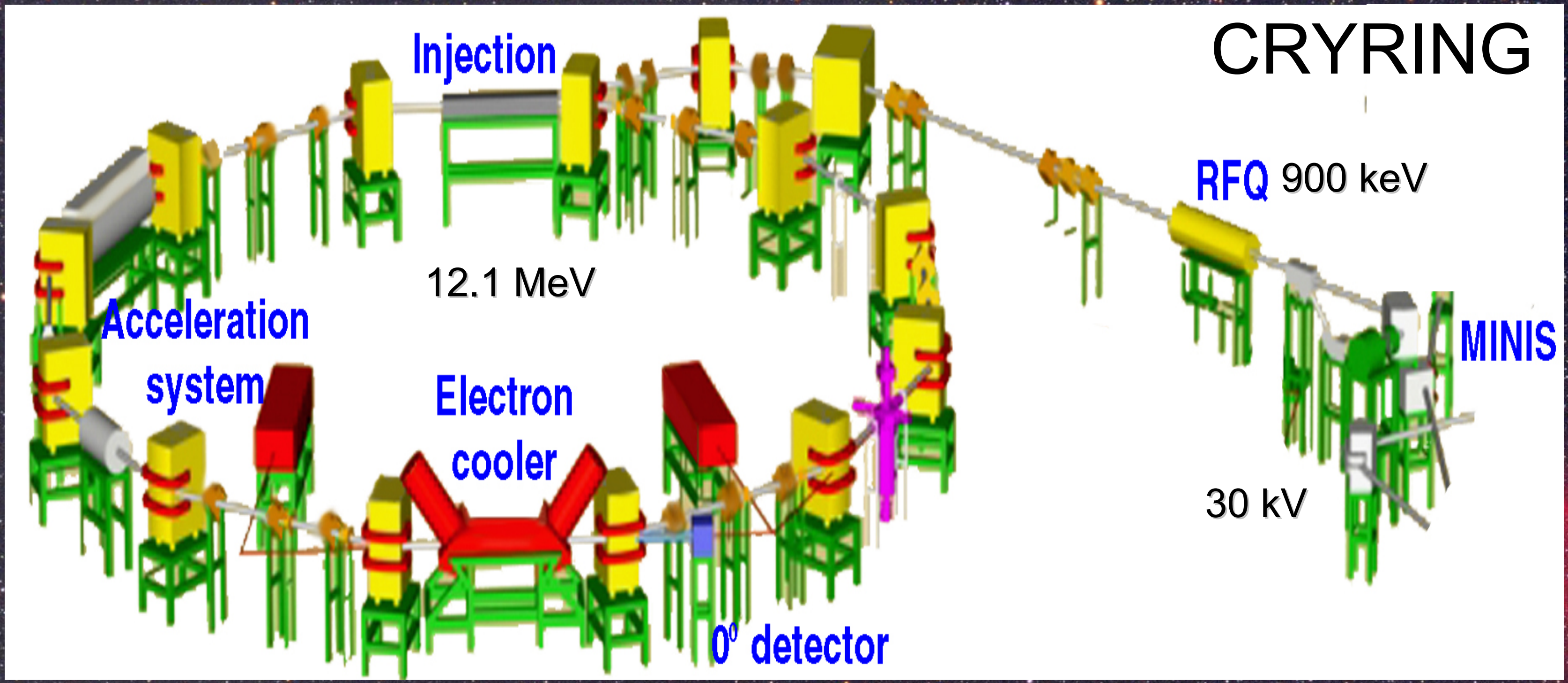
- Smaller electron fraction $[e^-]/[H_2]$
- Smaller recombination rate constant k_e
- Higher ionization rate ζ

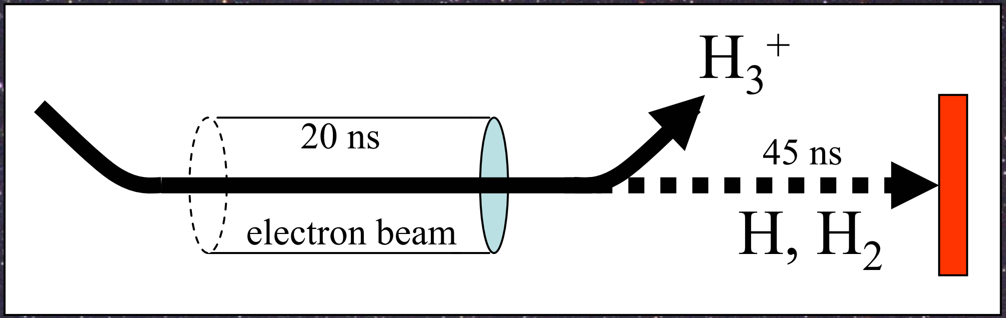
H_3^+ Dissociative Recombination

- Laboratory values of k_e have varied by 4 orders of magnitude!
- Theory unreliable (until recently)...
- Problem (?): not measuring H_3^+ in ground states



Storage Ring Measurements

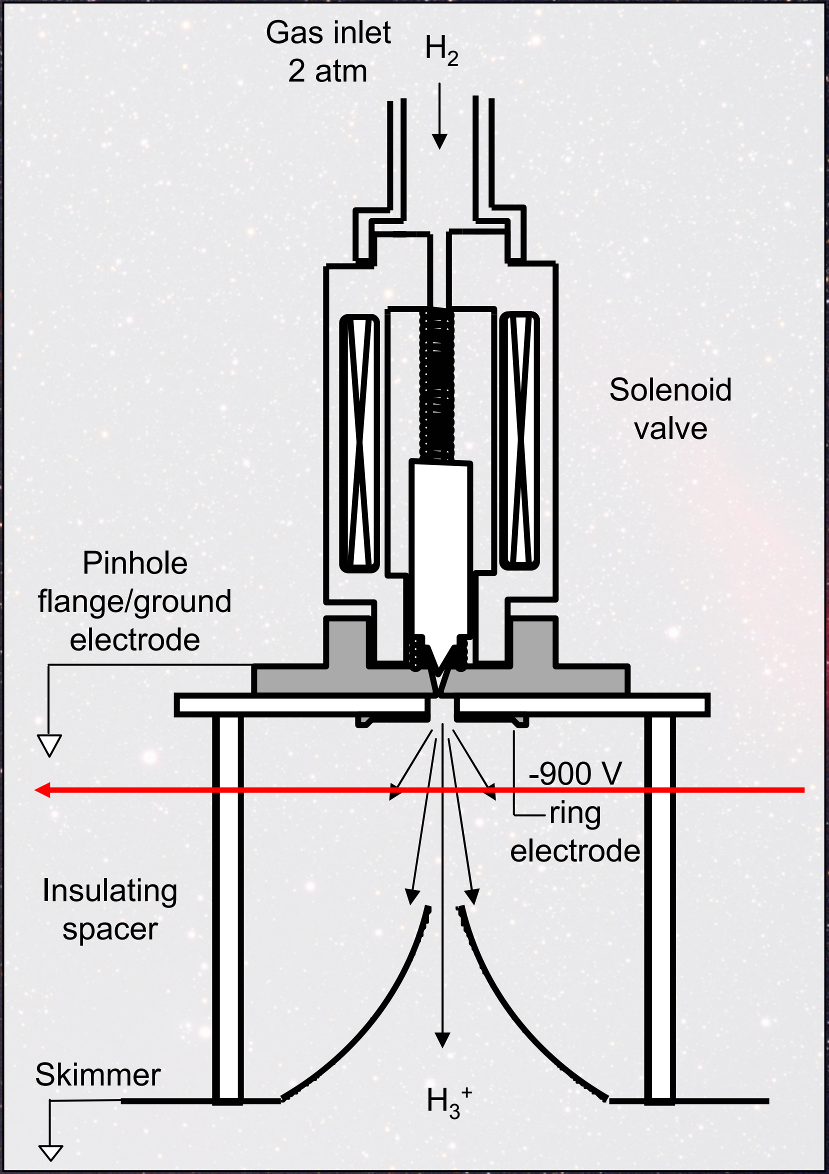




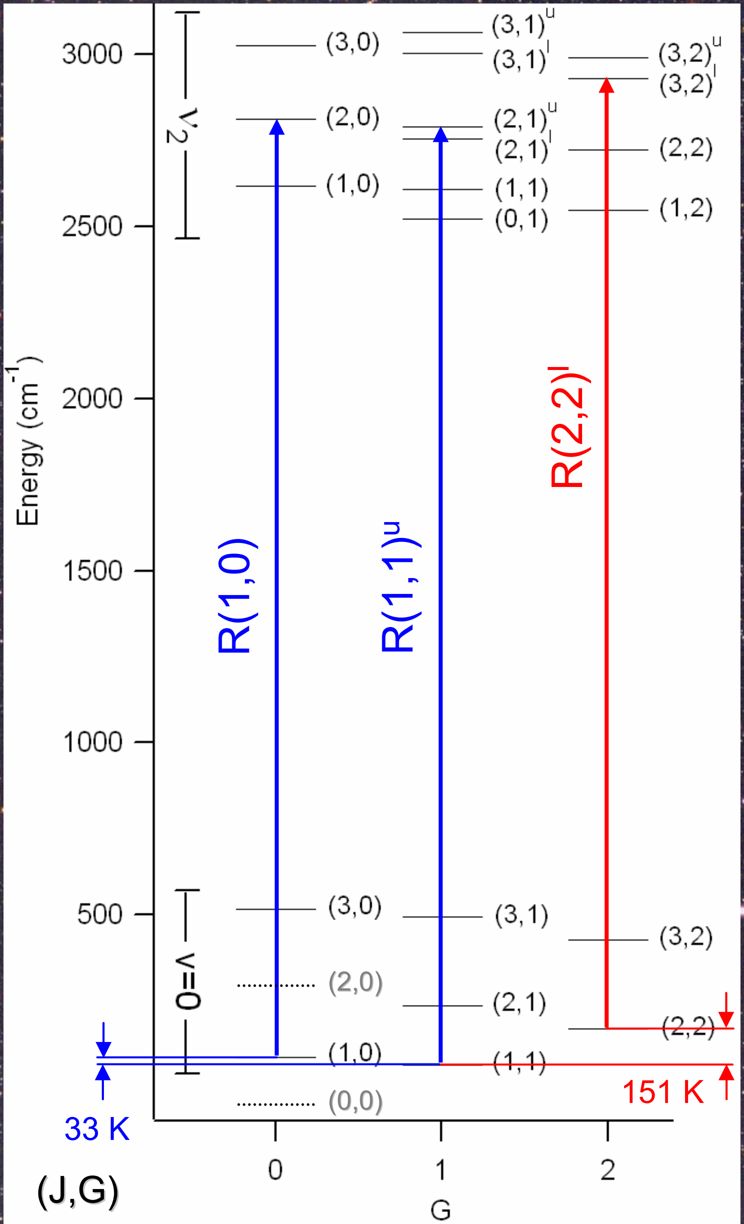
- \+ Very simple experiment
- \+ Complete vibrational relaxation
- \+ Control H_3^+ – e^- impact energy
- \- Rotationally hot ions produced
- \- "No" rotational cooling in ring

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

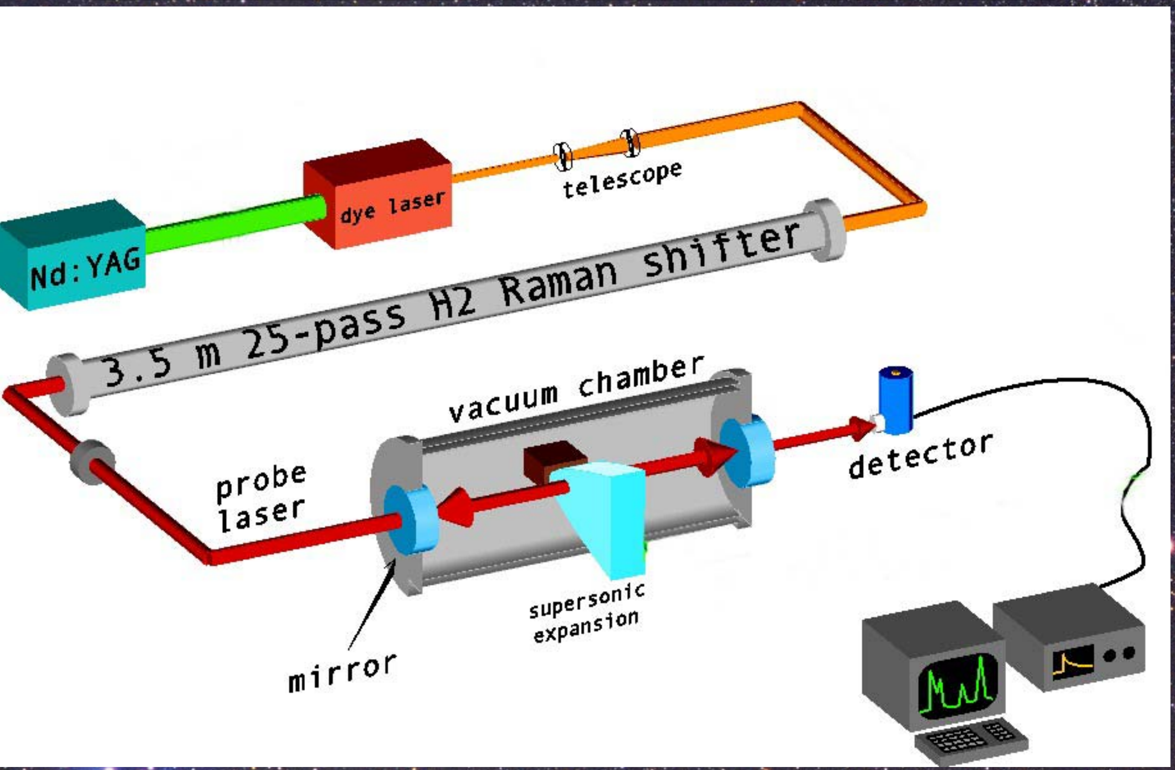


probe of temperature

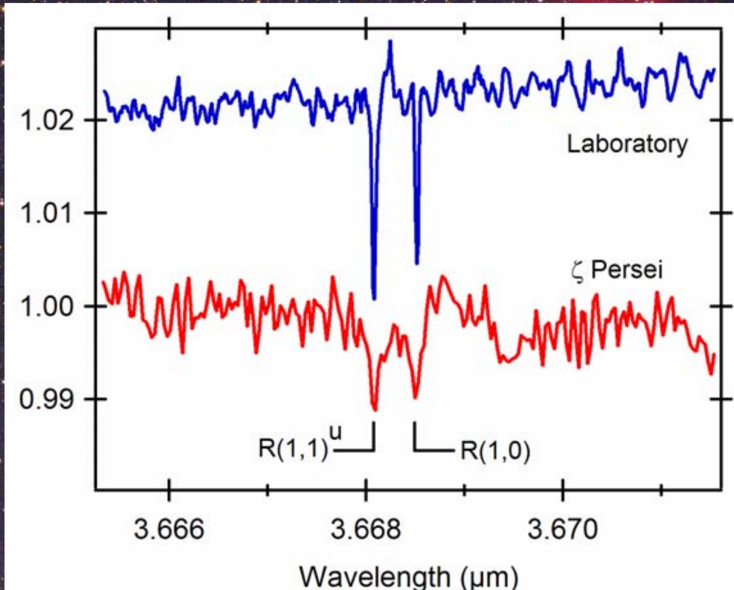
not detected

Spectroscopy of H_3^+ Source

Infrared Cavity Ringdown Laser Absorption Spectroscopy

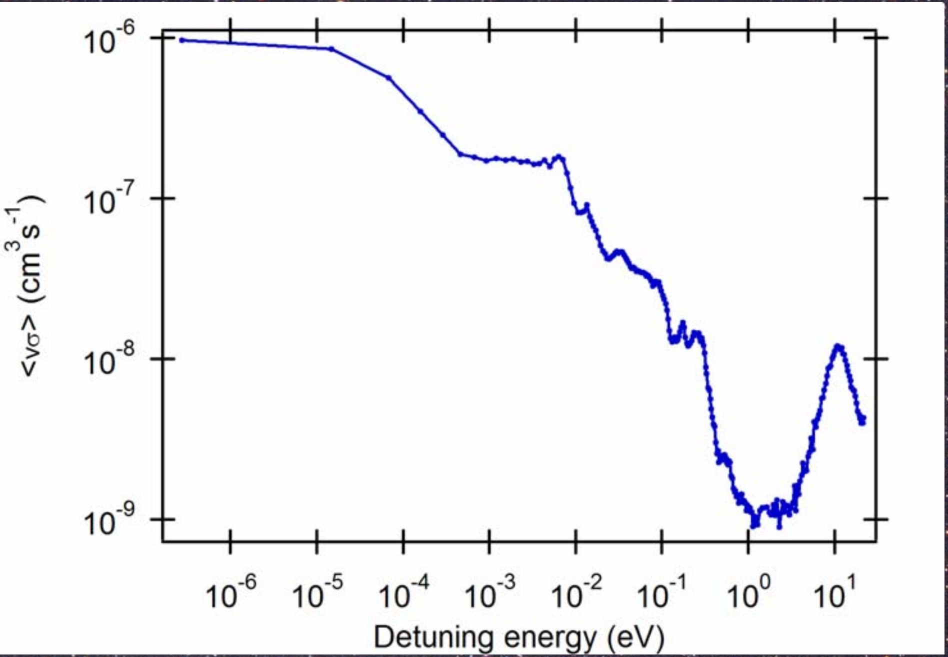


- Confirmed that H_3^+ produced is rotationally cold, as in interstellar medium



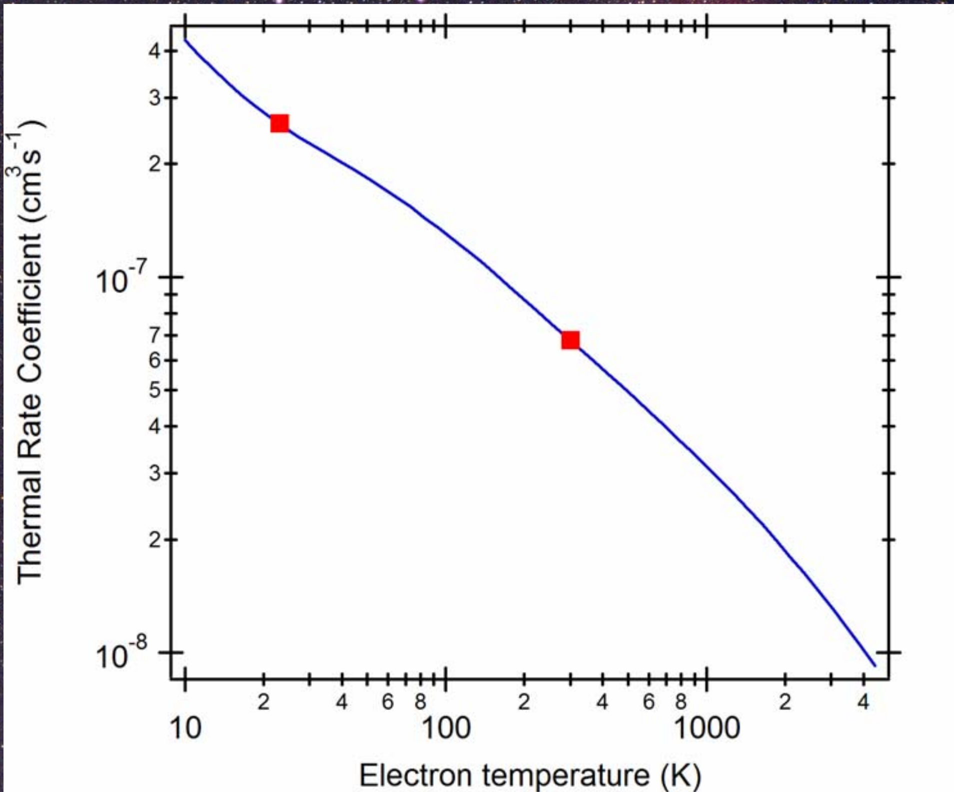
McCall, et al.
Nature 422, 500 (2003)

CRYRING Results



- Chris Greene: new theory
- Andreas Wolf: TSR 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)

Back to the Interstellar Clouds!

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

Implications for ζ Persei

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

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

$(2.6\times10^{-7}\ cm^3\ s^{-1})$ $(8\times10^{13}\ cm^{-2})$ (3.8×10^{-4})

ζL = 8000 cm s^{-1} (solid)

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

Adopt L=2.1 pc

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

$\zeta = 1.2\times10^{-15}\ s^{-1}$
(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

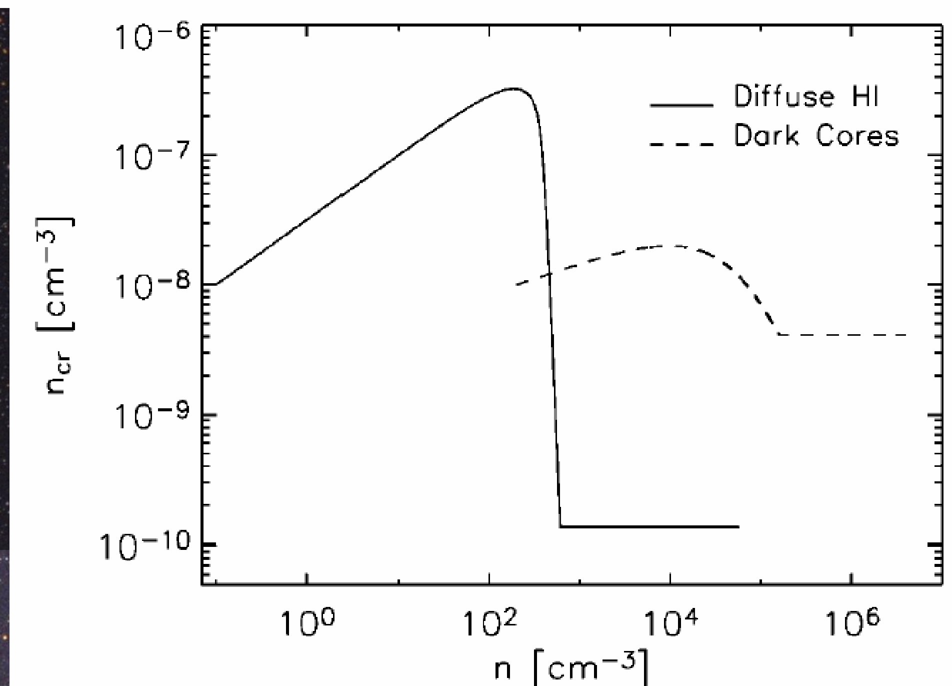
The Astrophysical Journal, 624:L97–L100, 2005 May 10

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 $n_{cr} \propto n_i^{1/2}$ 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
    - $C^+ \rightarrow C \rightarrow CO$

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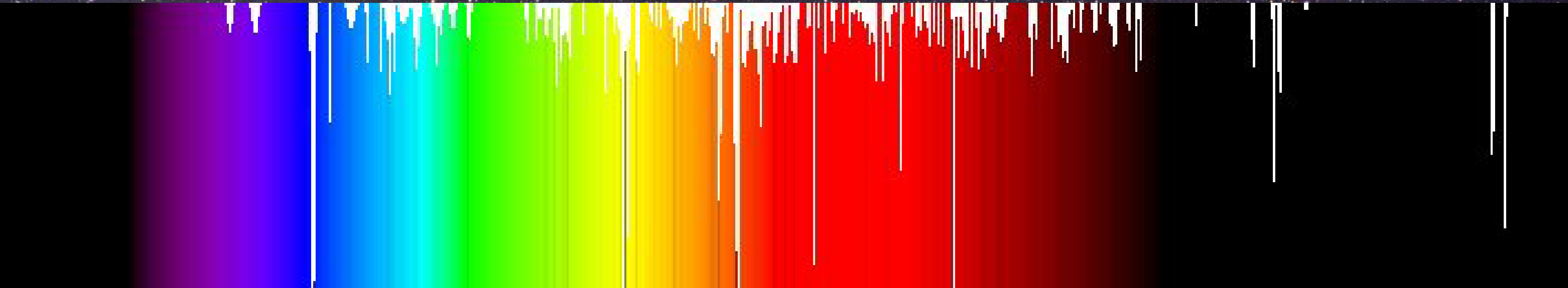
Rich Diffuse Cloud Chemistry

- 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!



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