H_3^+: A Tracer of the Cosmic Ray Ionization Rate in Diffuse Clouds

Ben McCall



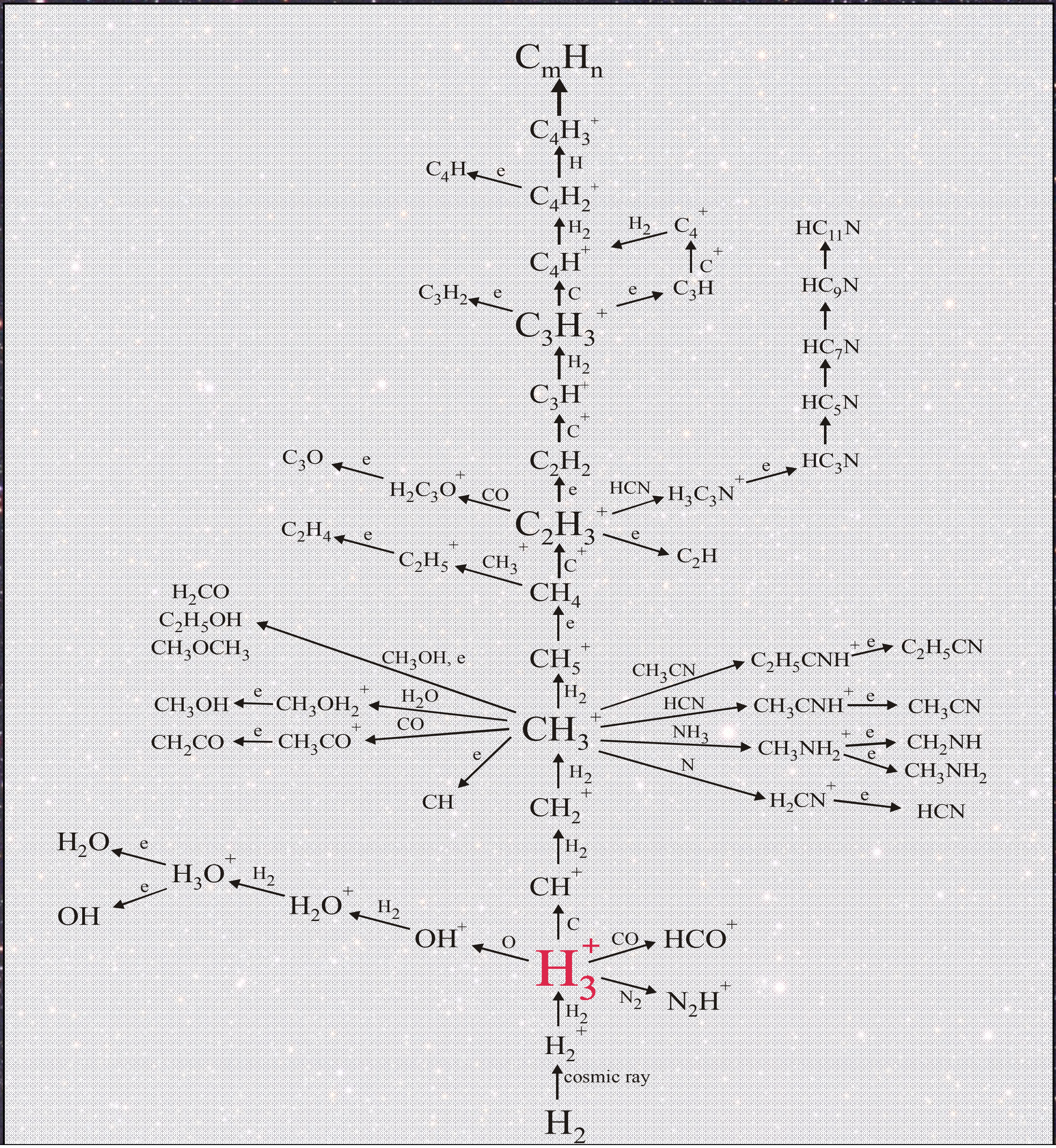
Department of Chemistry

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Department of Astronomy

Astronomer's Periodic Table

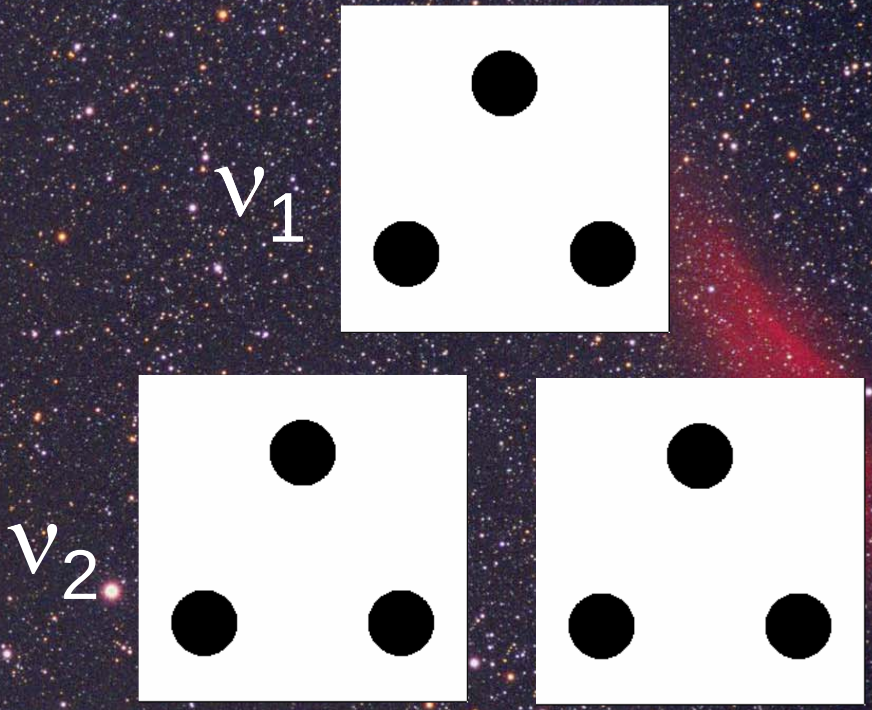
H_3^+: Cornerstone of Interstellar Chemistry



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:

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

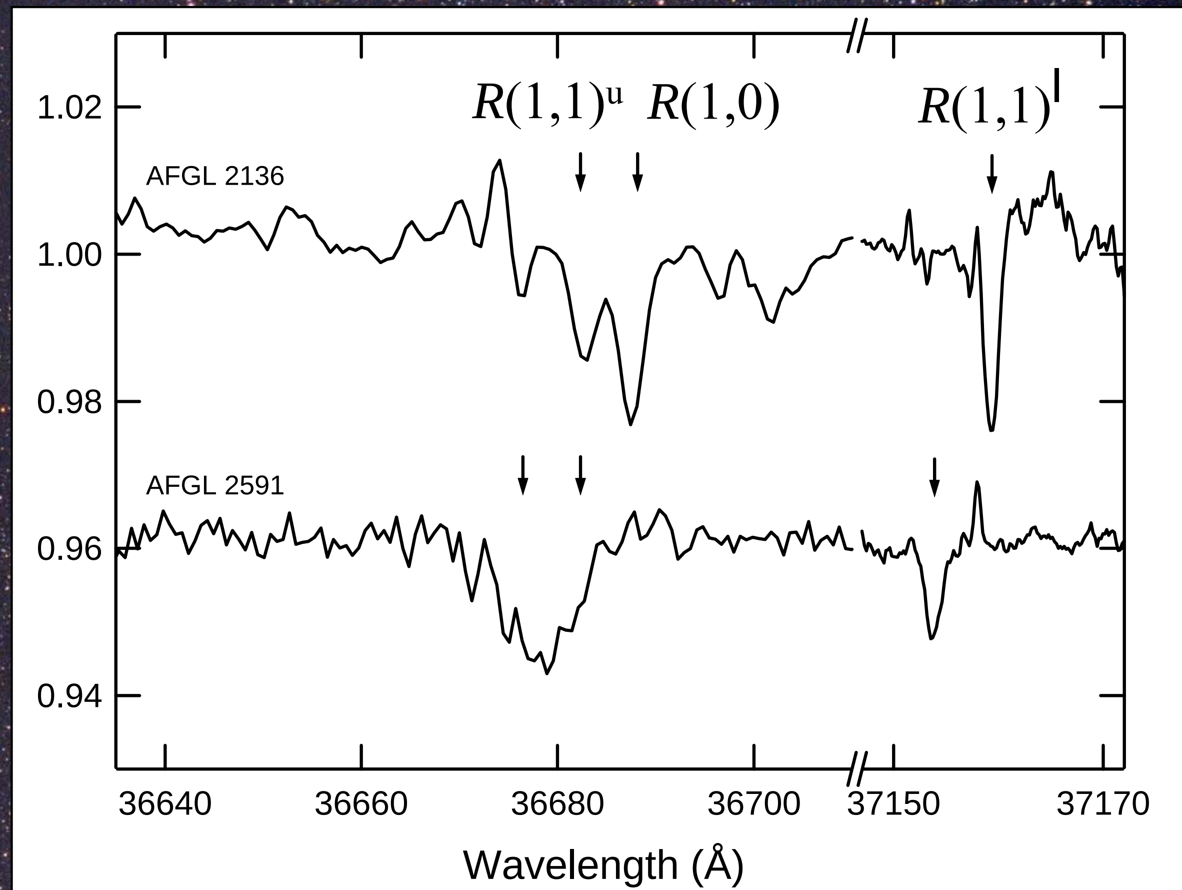
← ζ Persei

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

* Snow & McCall, *ARAA*, 44, 367 (2006)

Photo: Jose Fernandez Garcia

H_3^+ in Dense Clouds



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

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

Dense Cloud H_3^+ Chemistry

Formation

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

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

Rate = $\zeta\,[H_2]$

Destruction

$$H_3^+ + CO \rightarrow HCO^+ + H_2$$

Rate = $k\,[H_3^+]\,[CO]$

Steady State

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

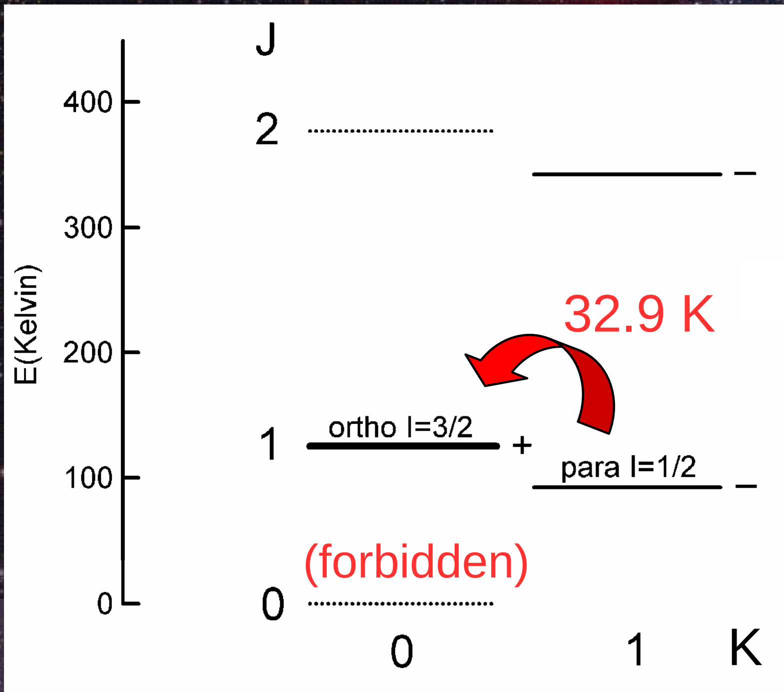
$$= 10^{-4}\ cm^{-3}$$

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

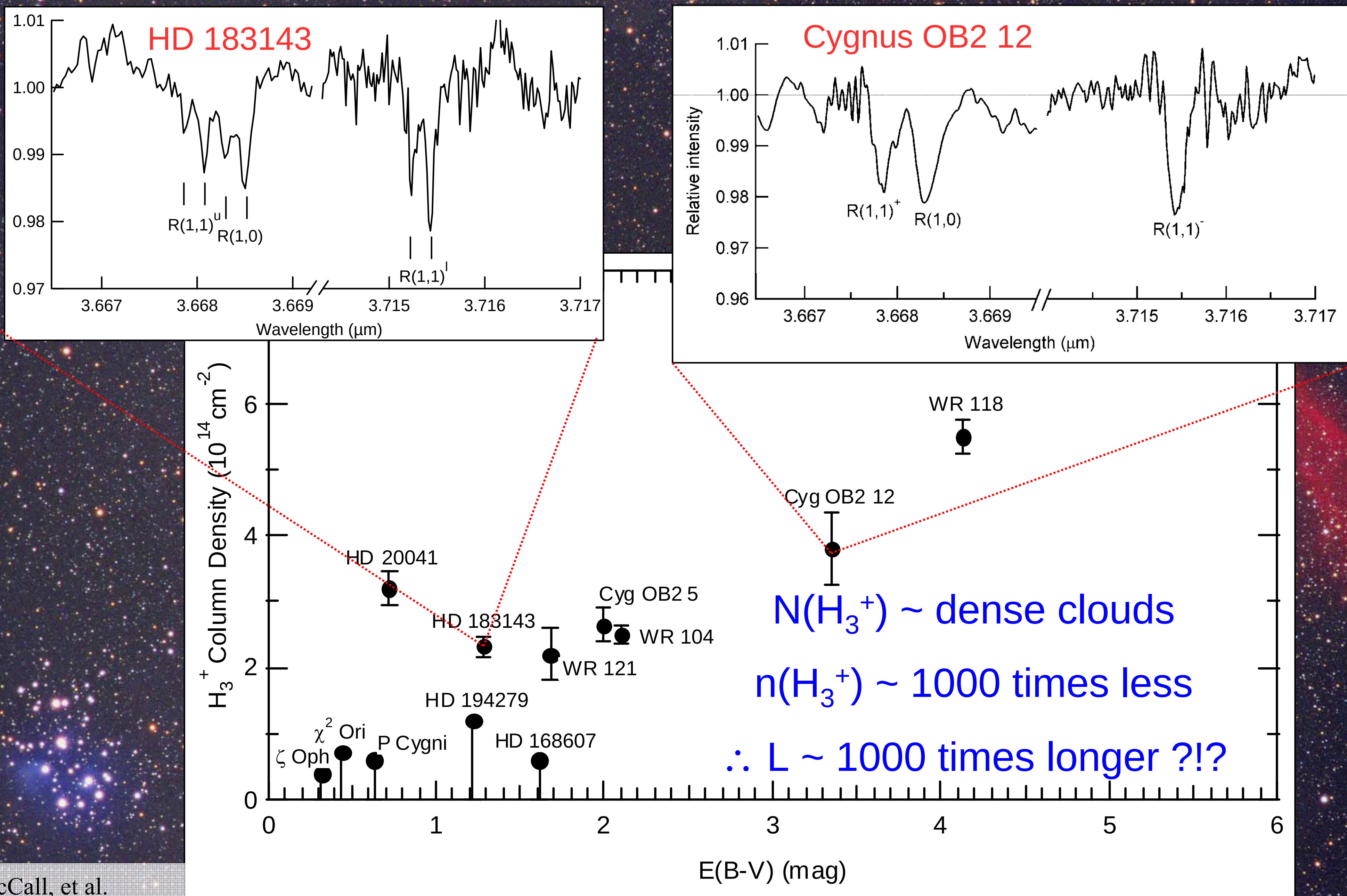
$$[H_3^+] = \frac{\zeta}{k_e}\,\frac{[H_2]}{[e^-]} = \frac{(3\times10^{-17}\ \text{s}^{-1})}{(5\times10^{-7}\ \text{cm}^3\ \text{s}^{-1})} \times (2400)$$

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

Density Independent!

10^3 times smaller than dense clouds!

Lots of H_3^+ in Diffuse Clouds!



$N(H_3^+)$ ~ dense clouds

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

∴ L ~ 1000 times longer ?!?

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

Big Problem with the Chemistry!

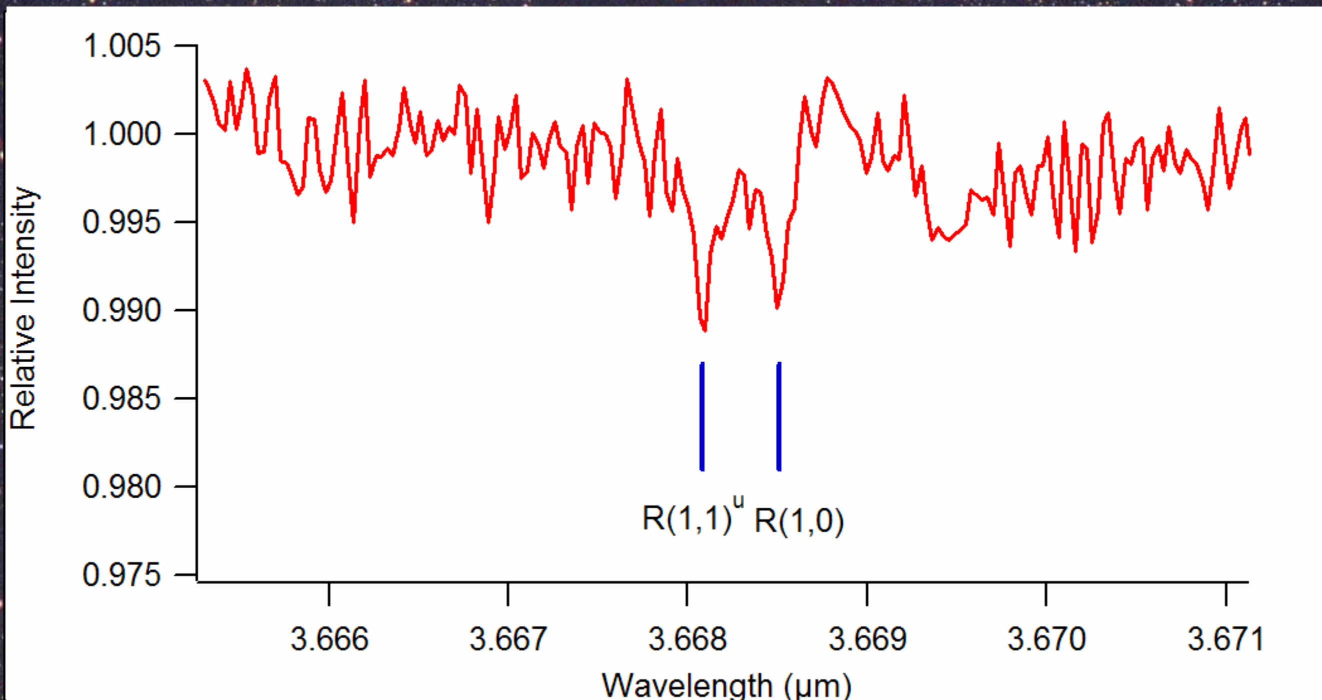
★ >1 order of magnitude!!

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

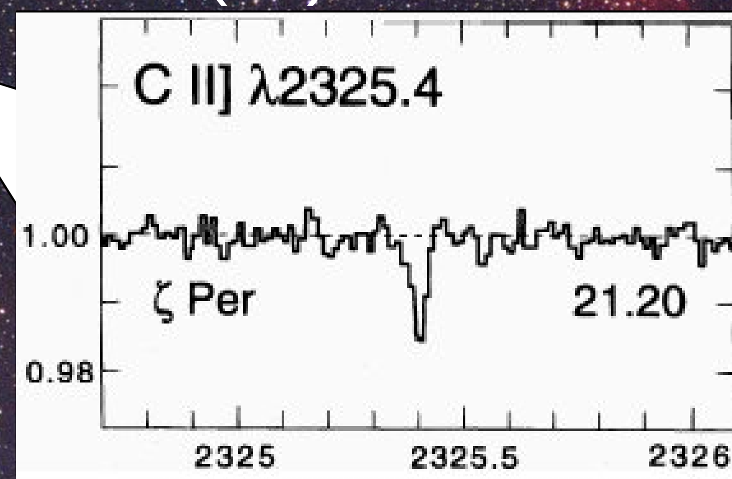
H_3^+ toward ζ Persei



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

NAME	ℓ^{II}	b^{II}	S. T.	E(B−V) mag.	r [pc]	log N(H_2) [cm^{-2}]	log N(HI) [cm^{-2}]
ζ Per	162	-17	B1 Ib	.33	394	20.67	20.81

Savage et al. ApJ 216, 291 (1977)

Big Problem with the Chemistry!

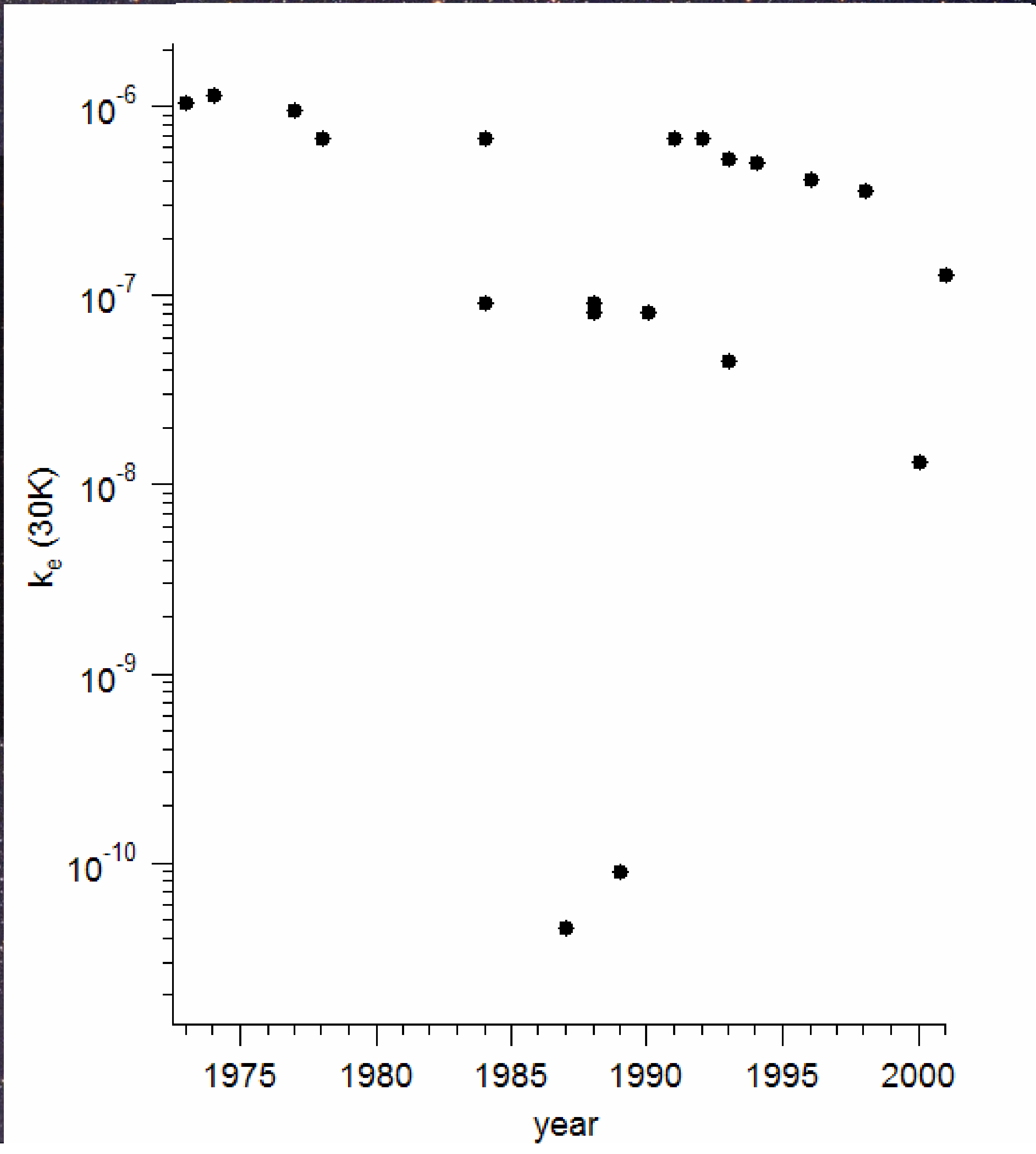
Steady State: $[H_3^+] = \frac{\zeta}{k_e} \frac{[H_2]}{[e^-]}$

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

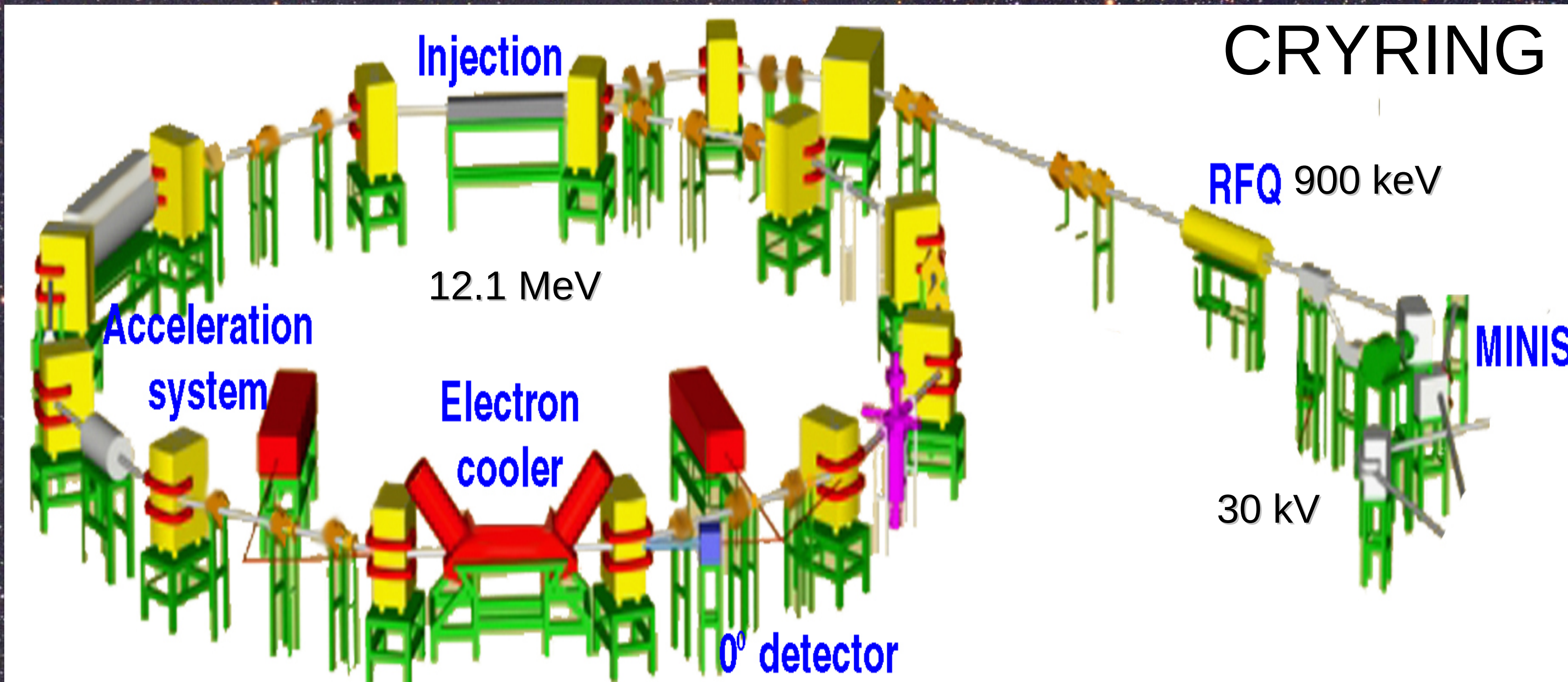
- ~~Smaller electron fraction $[e^-]/[H_2]$~~
- Smaller recombination rate constant k_e
- Higher ionization rate ζ

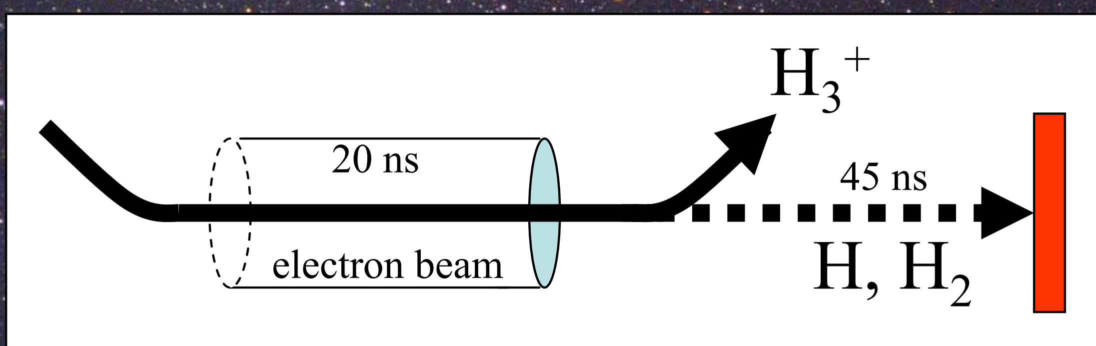
H_3^+ Dissociative Recombination

- Laboratory values of k_e have varied by 4 orders of magnitude!
- Problem: not measuring H_3^+ in ground states



Storage Ring Measurements

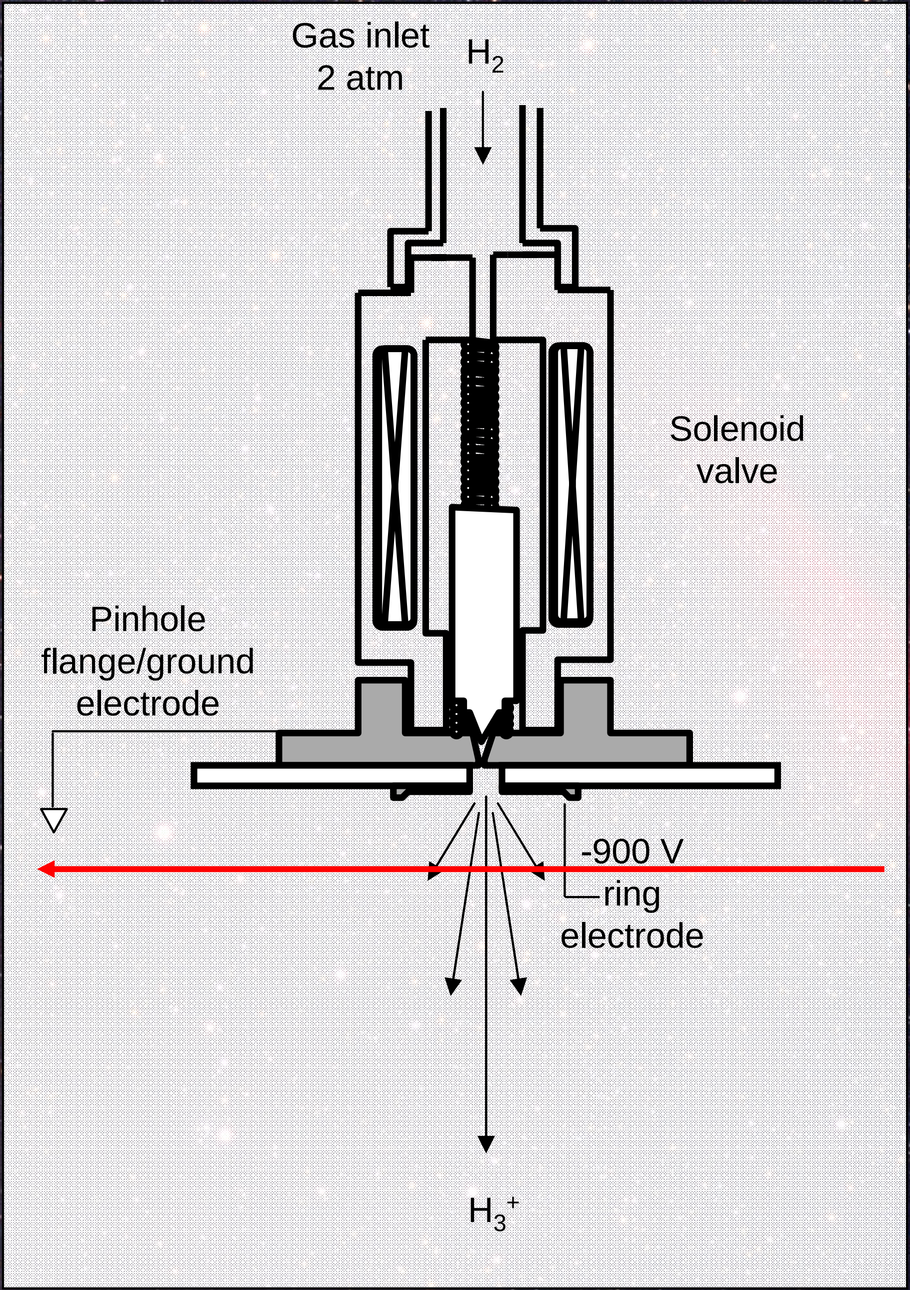




- \+ Very simple experiment
- \+ Complete vibrational relaxation
- \+ Control H_3^+ – e^- impact energy
- \- Rotationally hot ions produced
- \- "No" rotational cooling in ring

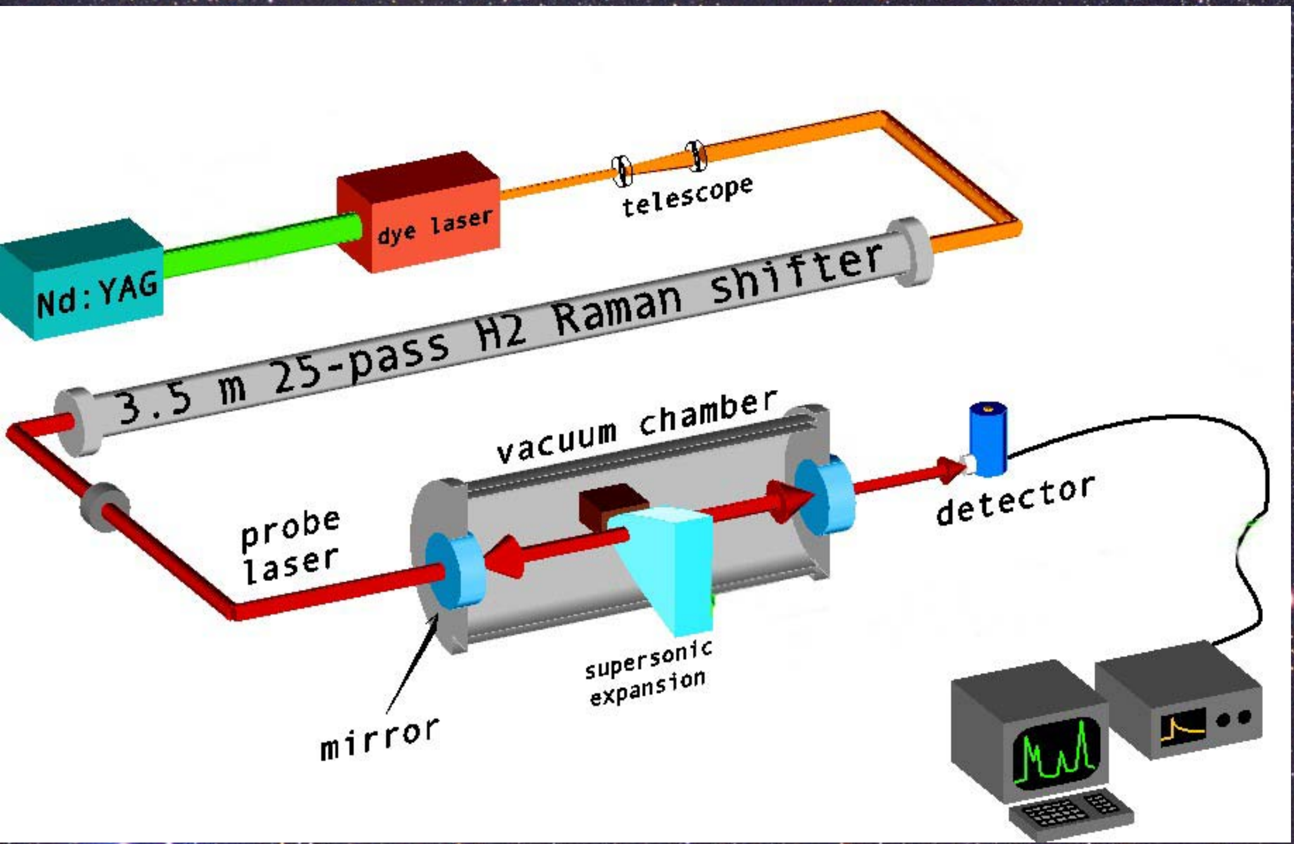
Supersonic Expansion Ion Source

- Similar to sources used for laboratory spectroscopy
- Pulsed nozzle design
- Supersonic expansion leads to rapid cooling
- Discharge from ring electrode downstream
- Spectroscopy used to characterize ions

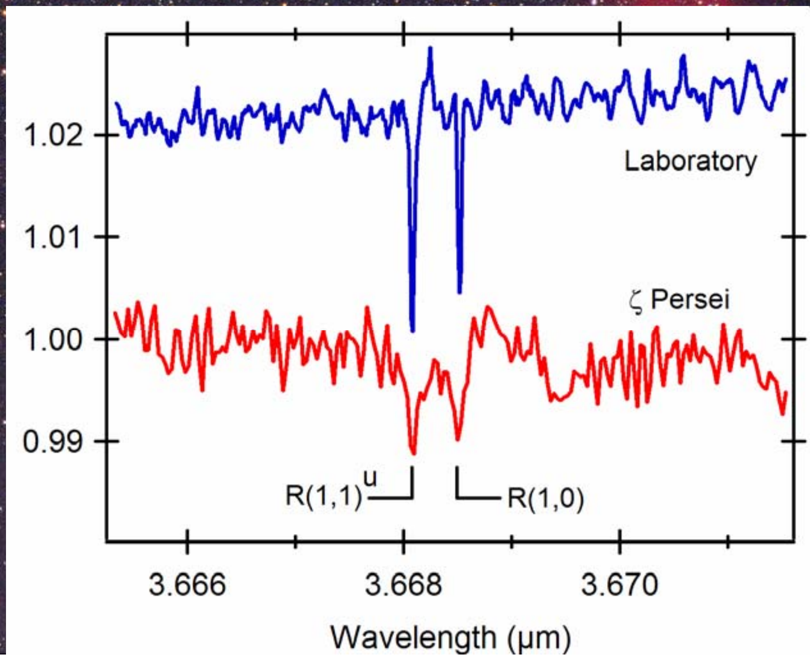


Spectroscopy of H_3^+ Source

Infrared Cavity Ringdown Laser Absorption Spectroscopy

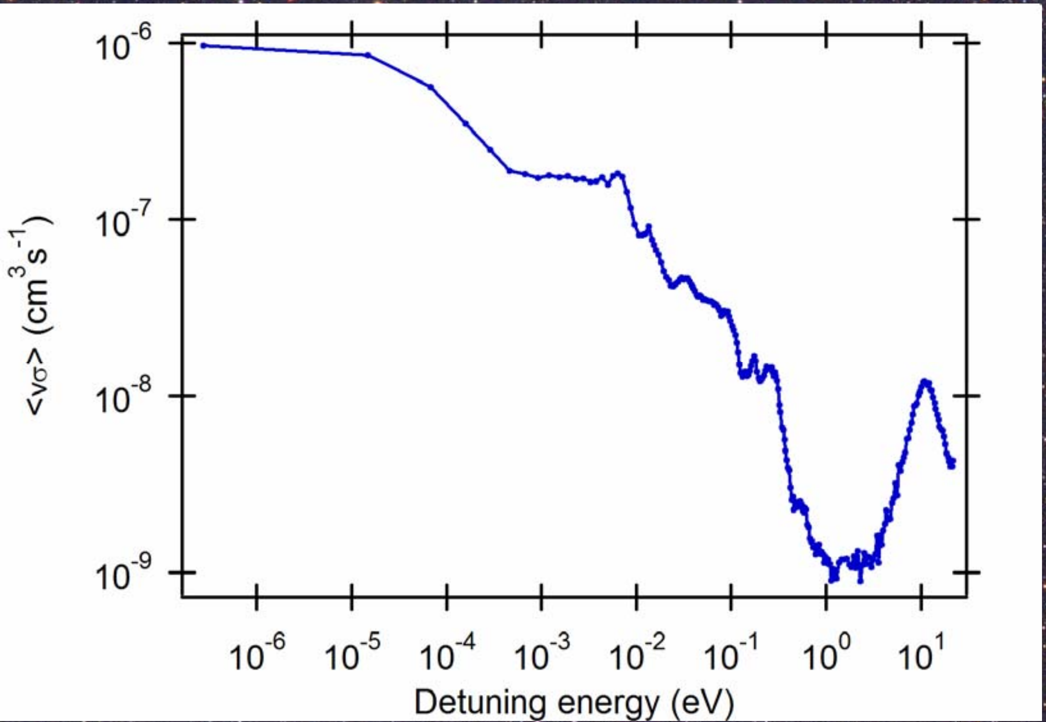


- Confirmed that H_3^+ produced is rotationally cold, as in interstellar medium

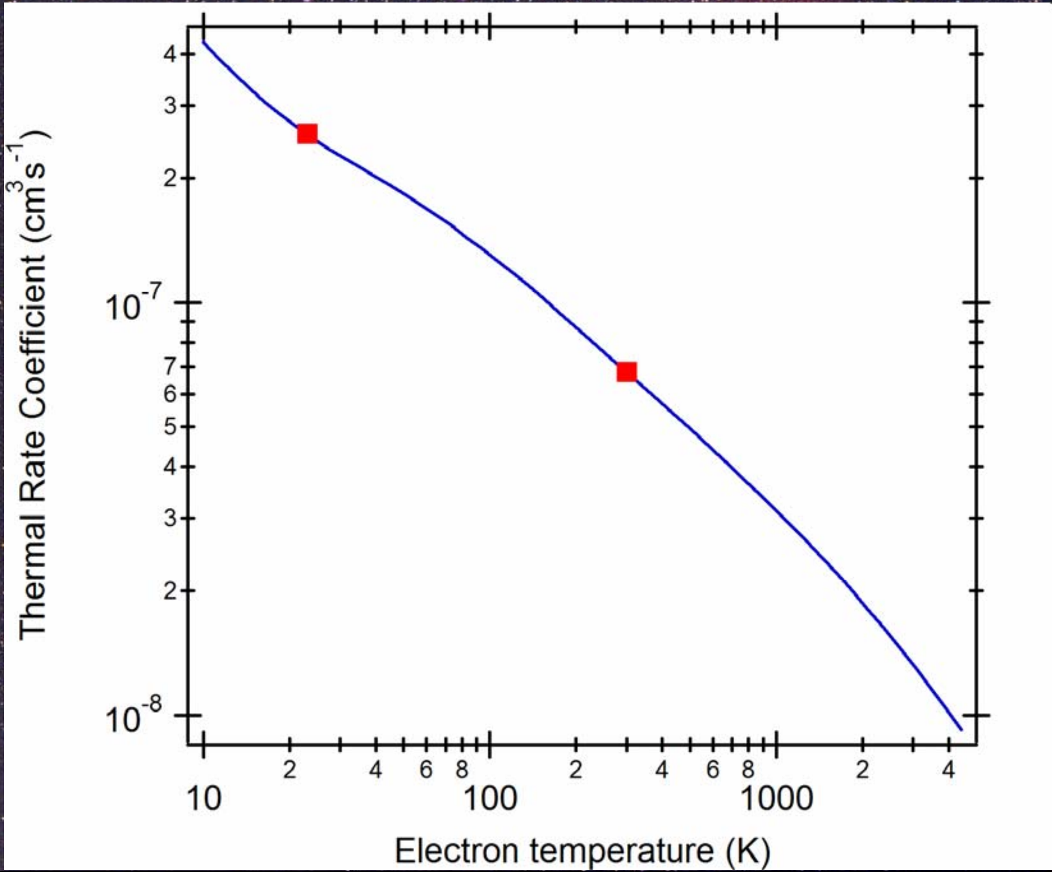


McCall, et al.
Nature 422, 500 (2003)

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)

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

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

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

$(1.6\times10^{-7}\ \mathrm{cm^3\ s^{-1}})$ $(7\times10^{13}\ \mathrm{cm^{-2}})$ (4.7×10^{-4})

$\zeta L = 5300\ \mathrm{cm\ s^{-1}}$ (firm)

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

$L = 60$ pc
$\langle n\rangle = 9\ \mathrm{cm^{-3}}$

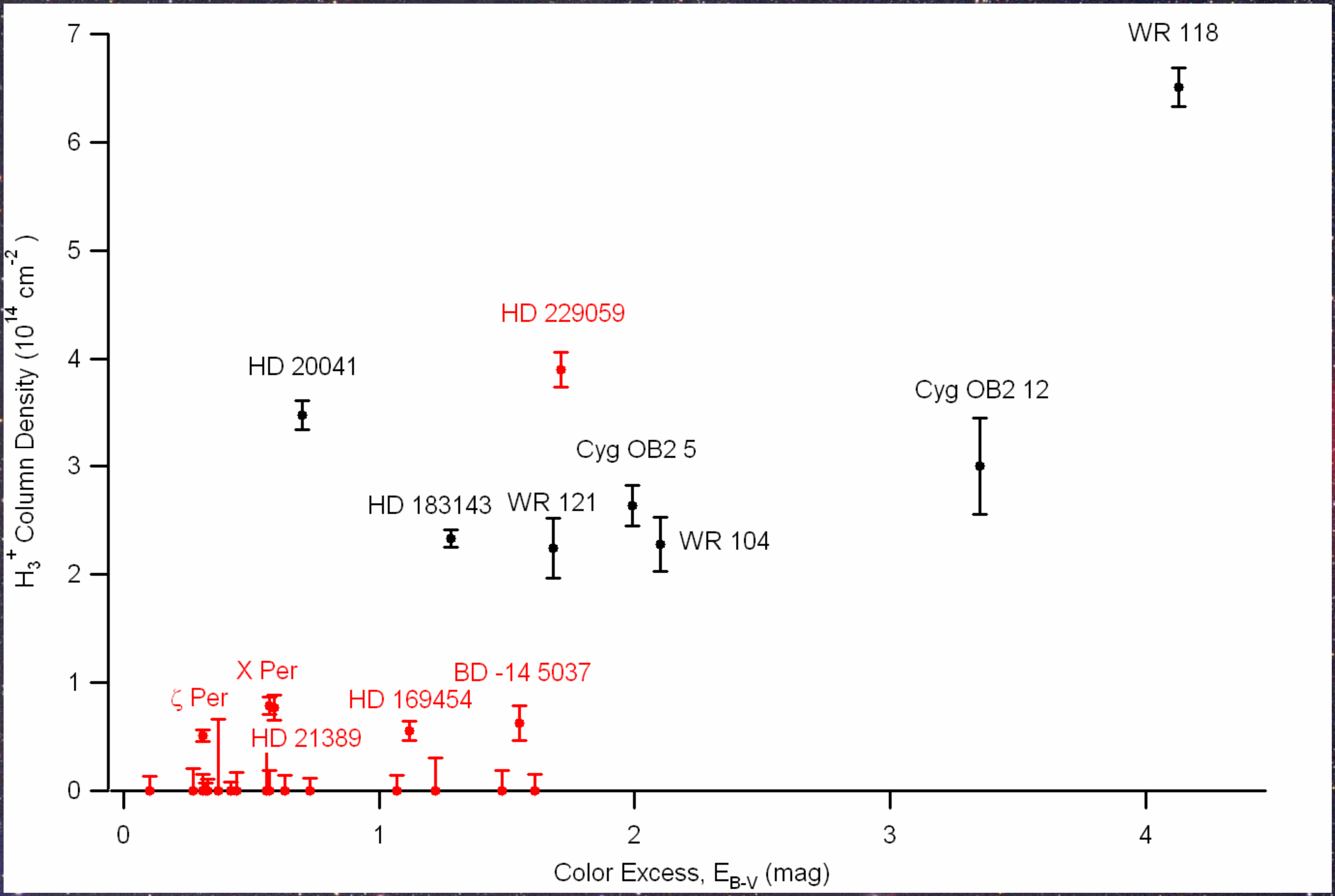
Adopt $\langle n\rangle = 215\ \mathrm{cm^{-3}}$
$\rightarrow L=2.4$ pc

$\zeta=7.4\times10^{-16}\ \mathrm{s^{-1}}$
(25x 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!!
- Substantial impact on diffuse cloud chemistry

New Astronomical Results



- Range of ζ from ~1-7 × 10^{-16} s^{-1}
- Biggest uncertainty is in adopted ⟨n⟩

N. Indriolo, T. R. Geballe, T. Oka, & B. J. McCall, in preparation

Coming Soon…

- More observations!
  - June 2007: revisit marginal detections, reduce limits
  - Jan 2008?: revisit Perseus OB2 association
- New electron recombination measurements
  - Improved spectroscopy of ion source
    - Higher resolution & higher sensitivity
      - "cw cavity ringdown spectroscopy"
      - difference frequency laser
    - Better characterization of ro-vib distribution
  - Use of pure para-H_2 to produce para-H_3^+
  - Single quantum-state CRYRING measurements

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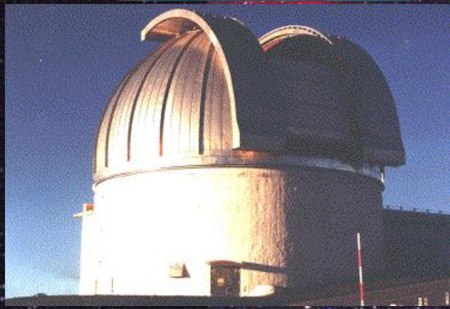

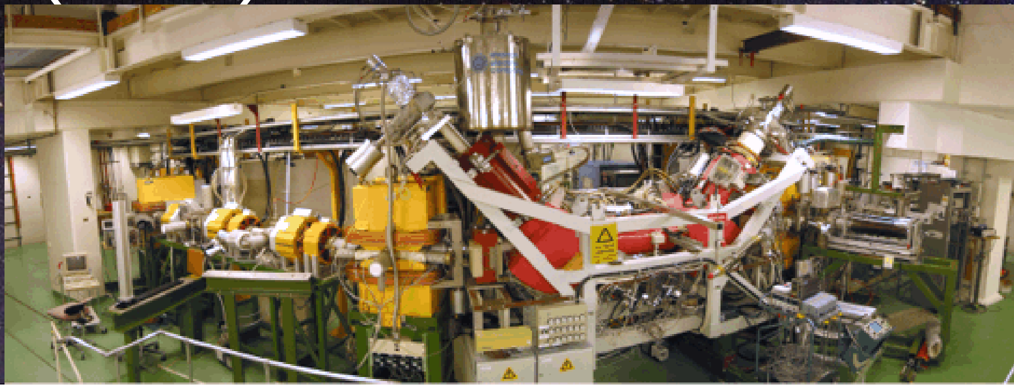

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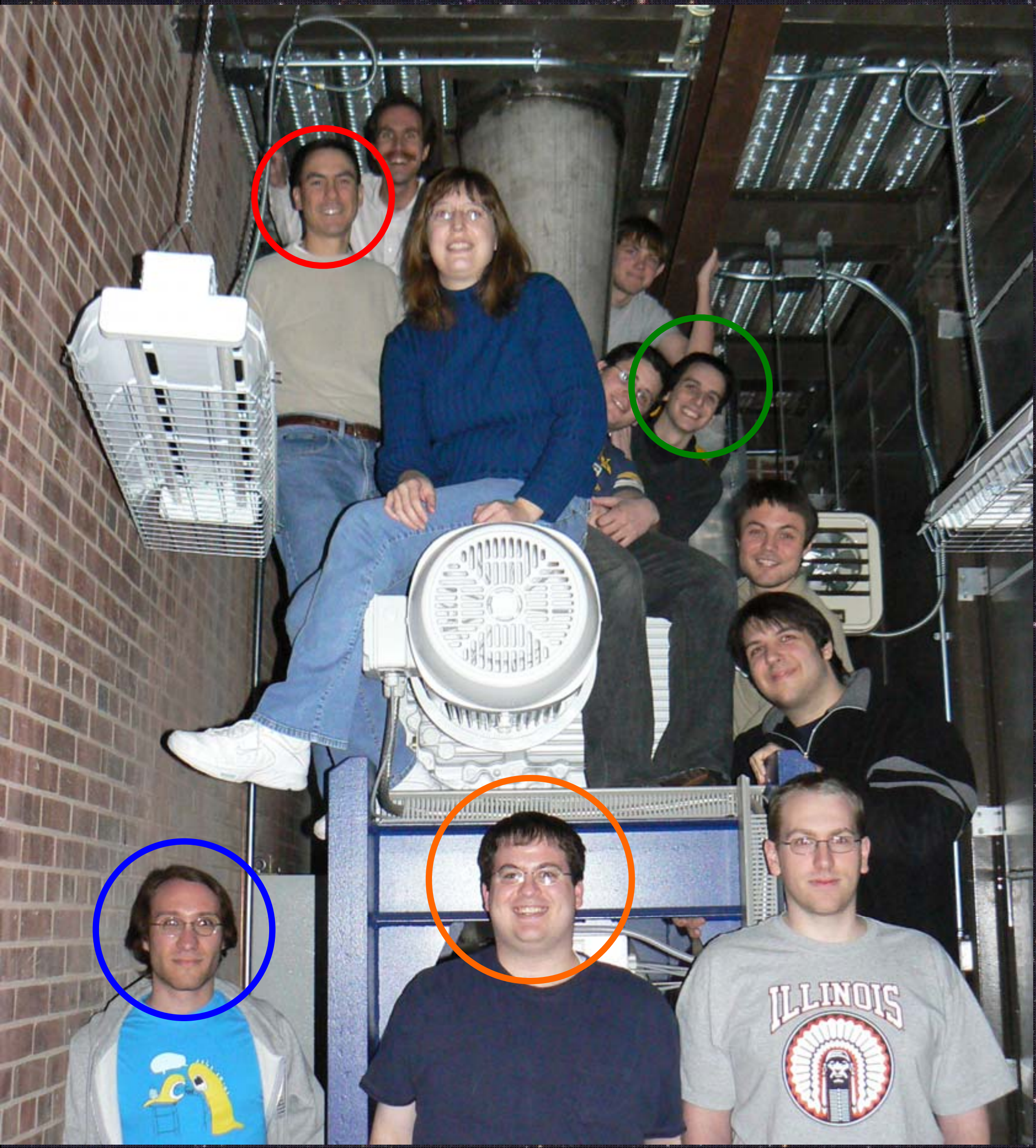

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http://astrochemistry.uiuc.edu