Storage Ring Measurements of the DR Rate of Rotationally Cold H_3^+

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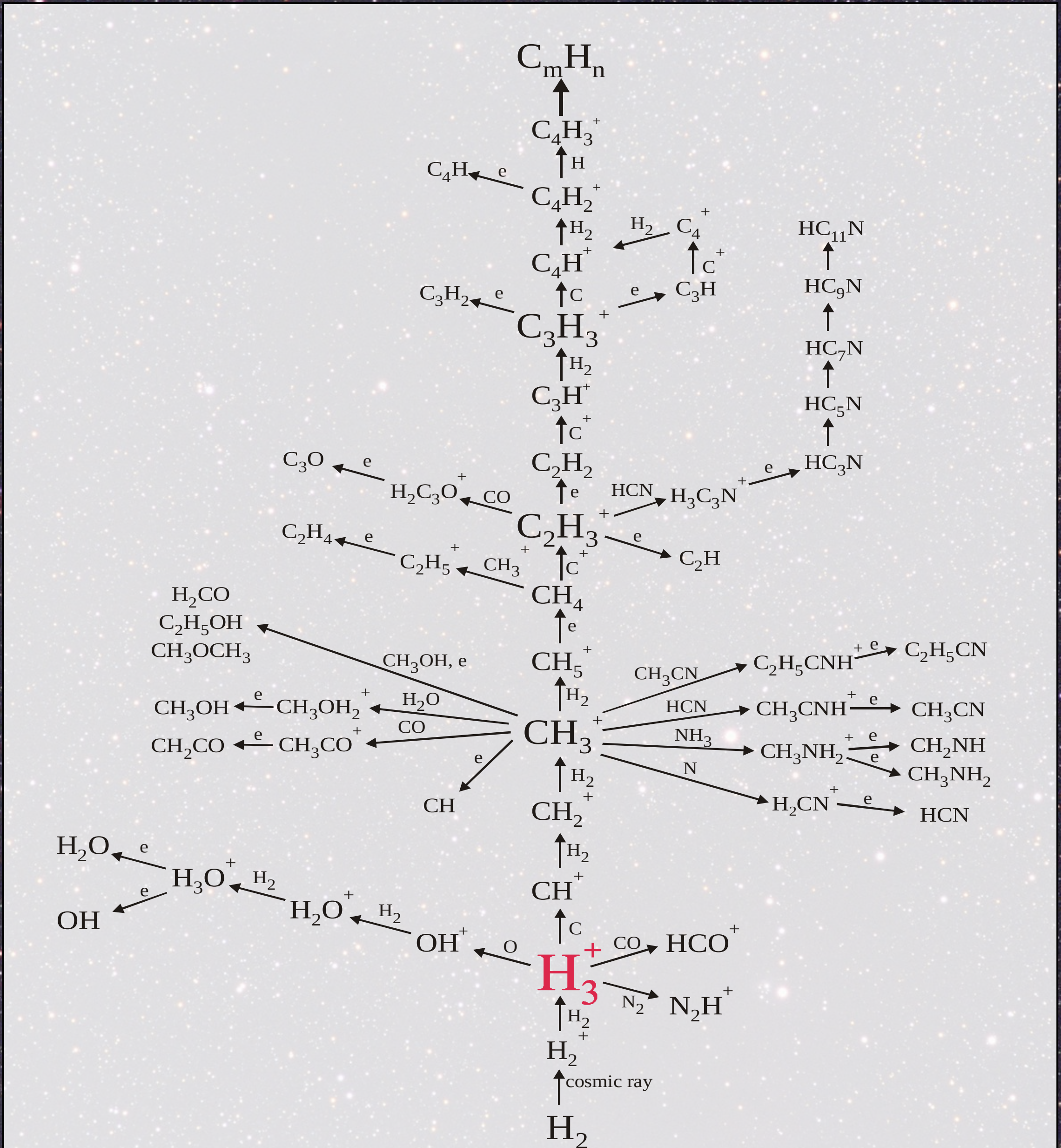
Why Am I Here?


They'll never get cold enough ions with a liquid nitrogen cooled source!
Why don't they just use a supersonic expansion source?

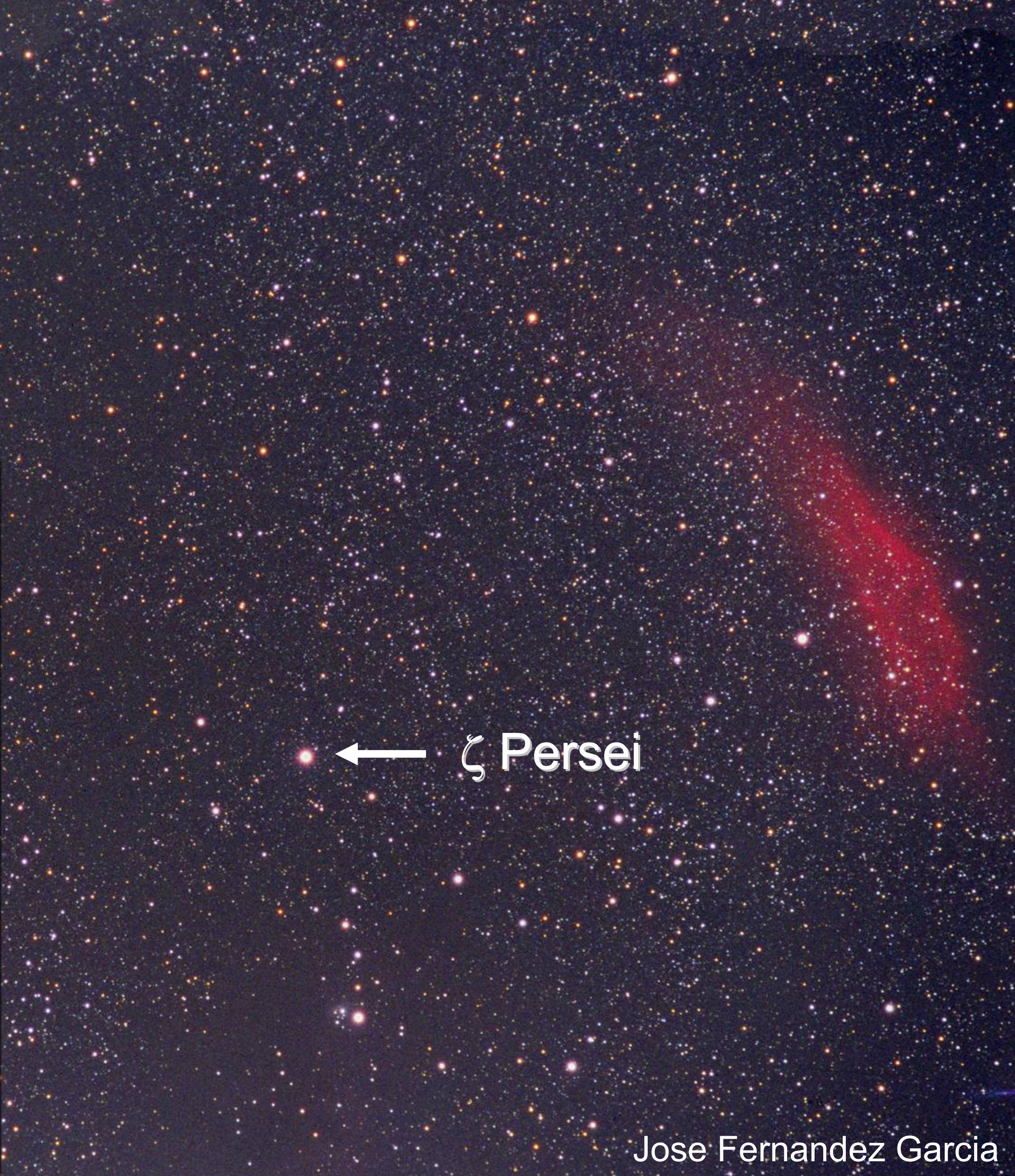
Astronomer's Periodic Table

Tree of Interstellar Chemistry



Diffuse Interstellar Clouds

- Translucent (vis, UV)
- Mixture of H & H_2
- $C \rightarrow C^{+} + e^{-}$
- DR limits chemistry
- $n(H_2) \sim 10^{1}–10^{3}\ cm^{-3}$
  - [~10^{-18} atm]
- $T \sim 50\ K$



Diffuse 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

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

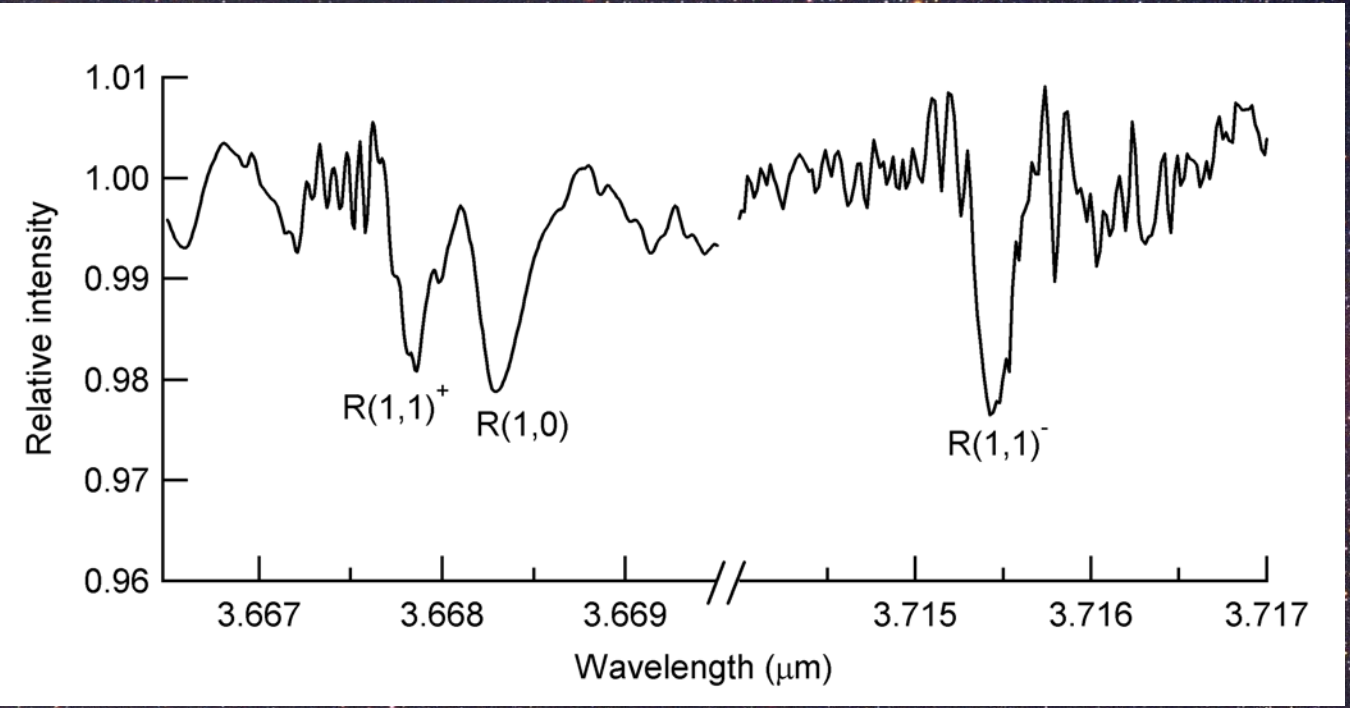
Steady State

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

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

Density Independent!
Small!

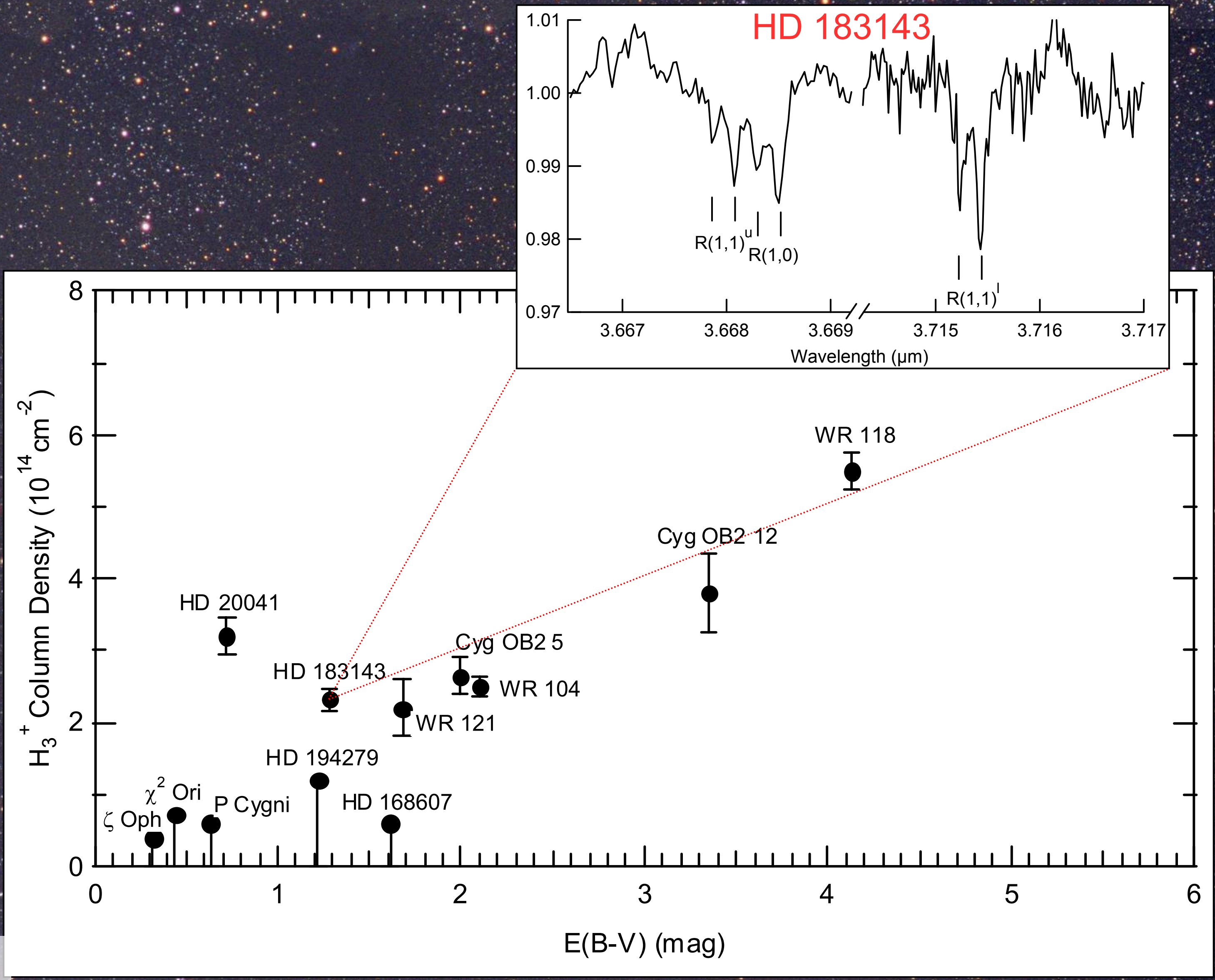
Cygnus OB2 12



- Surprising to detect H_3^+ in a diffuse cloud!
- Implies a path length of 1 kpc (3000 light-years)
- Implies average density ~ 20 cm^{-3} (too low)
- Peculiar sightline?

McCall, Geballe, Hinkle, & Oka
Science 279, 1910 (1998)

Other Diffuse Clouds, too!



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

Big Problem with the Chemistry!

★ 2-3 orders of magnitude!!

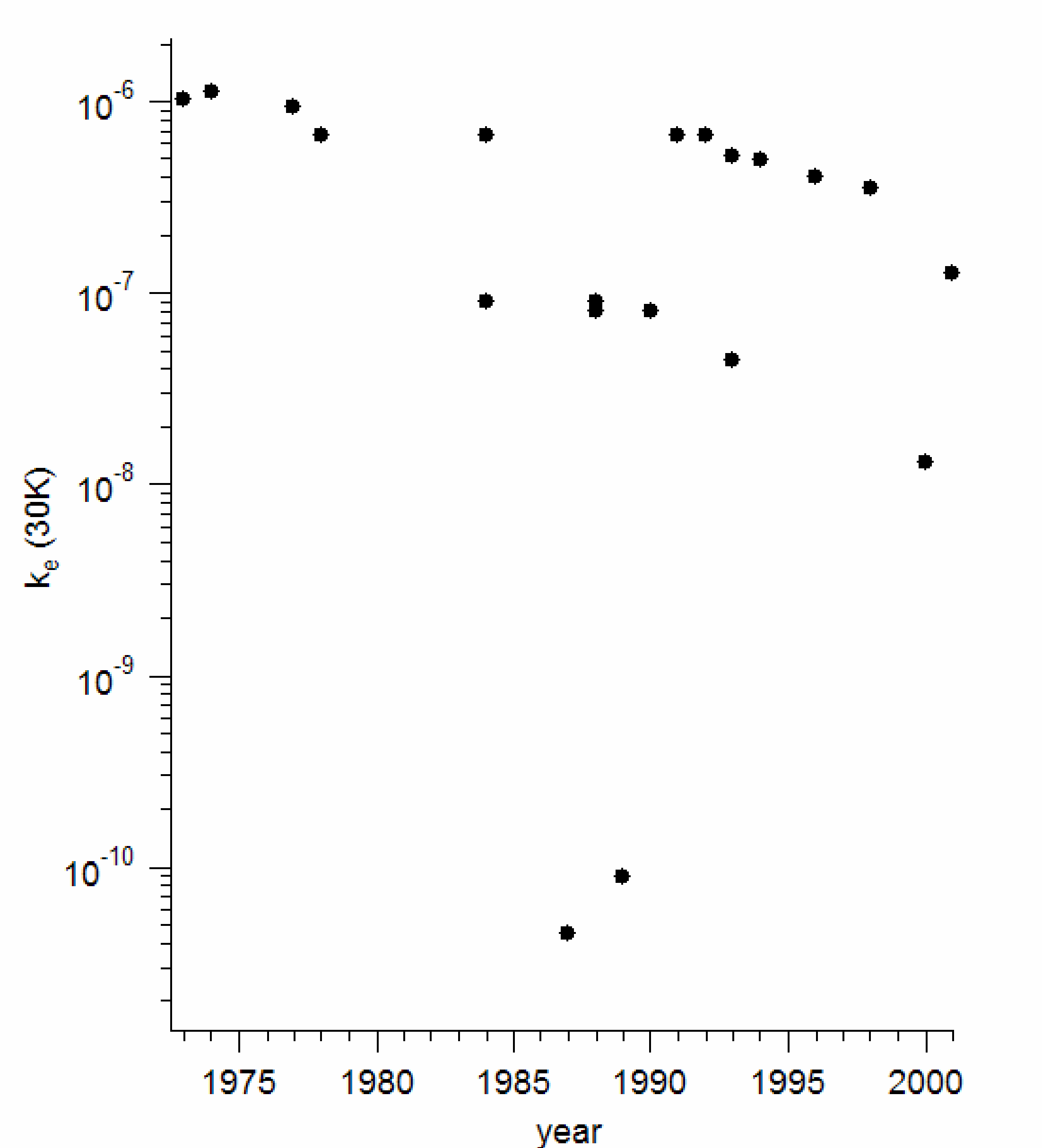
Steady State: $$[H_3^+] = \frac{\zeta}{k_e} \frac{[H_2]}{[e^-]}$$

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

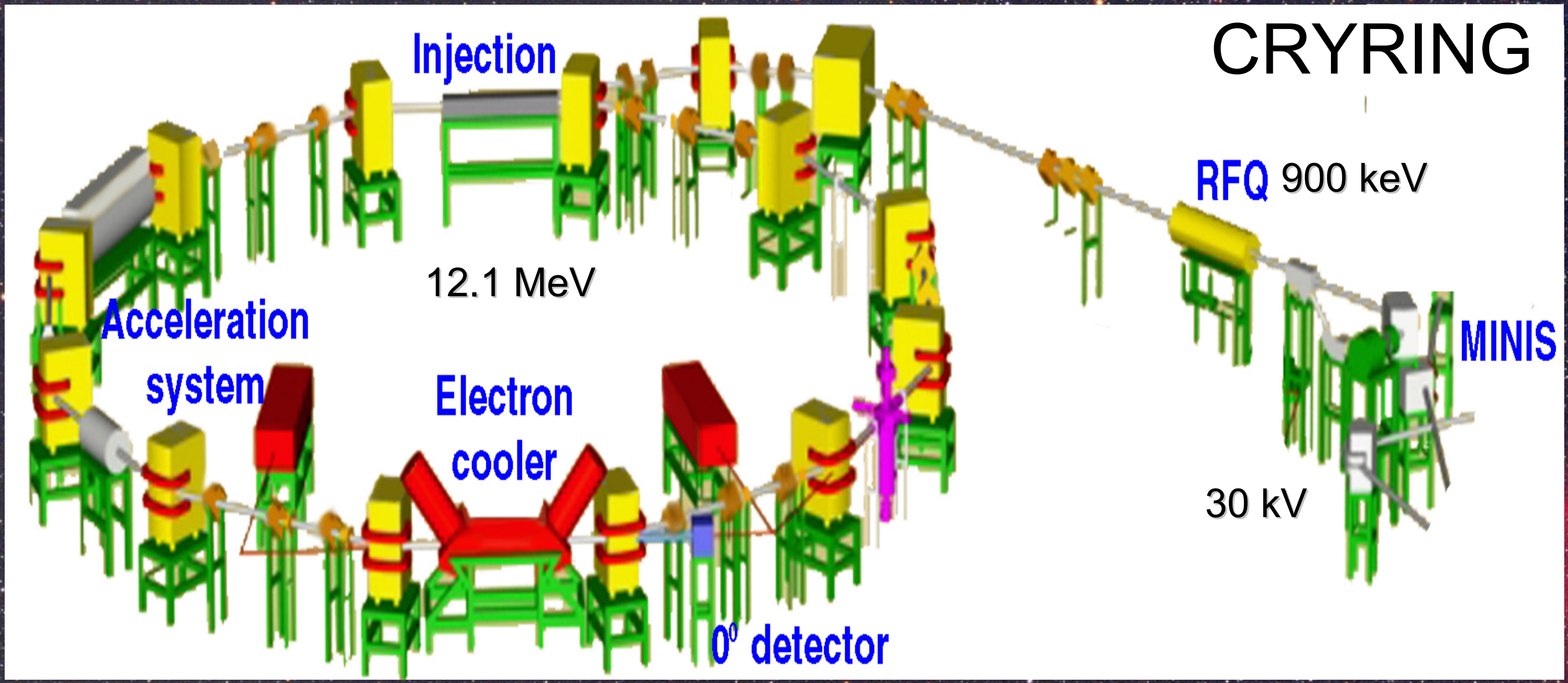
- Higher ionization rate ζ
- Smaller recombination rate constant k_e
- Smaller electron fraction $[e^-]/[H_2]$

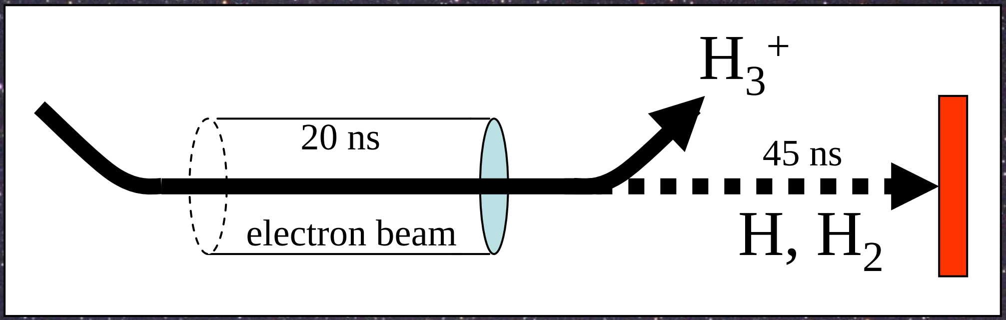
H_3^+ Dissociative Recombination

- 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

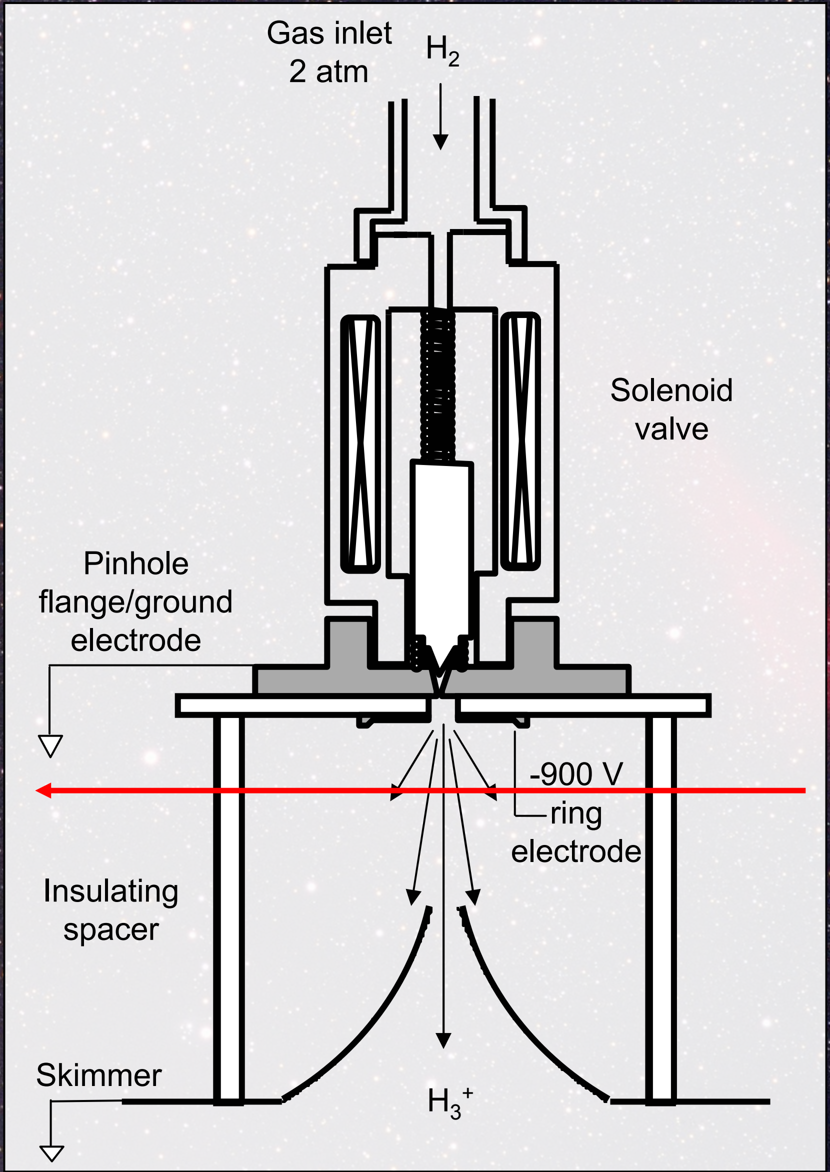


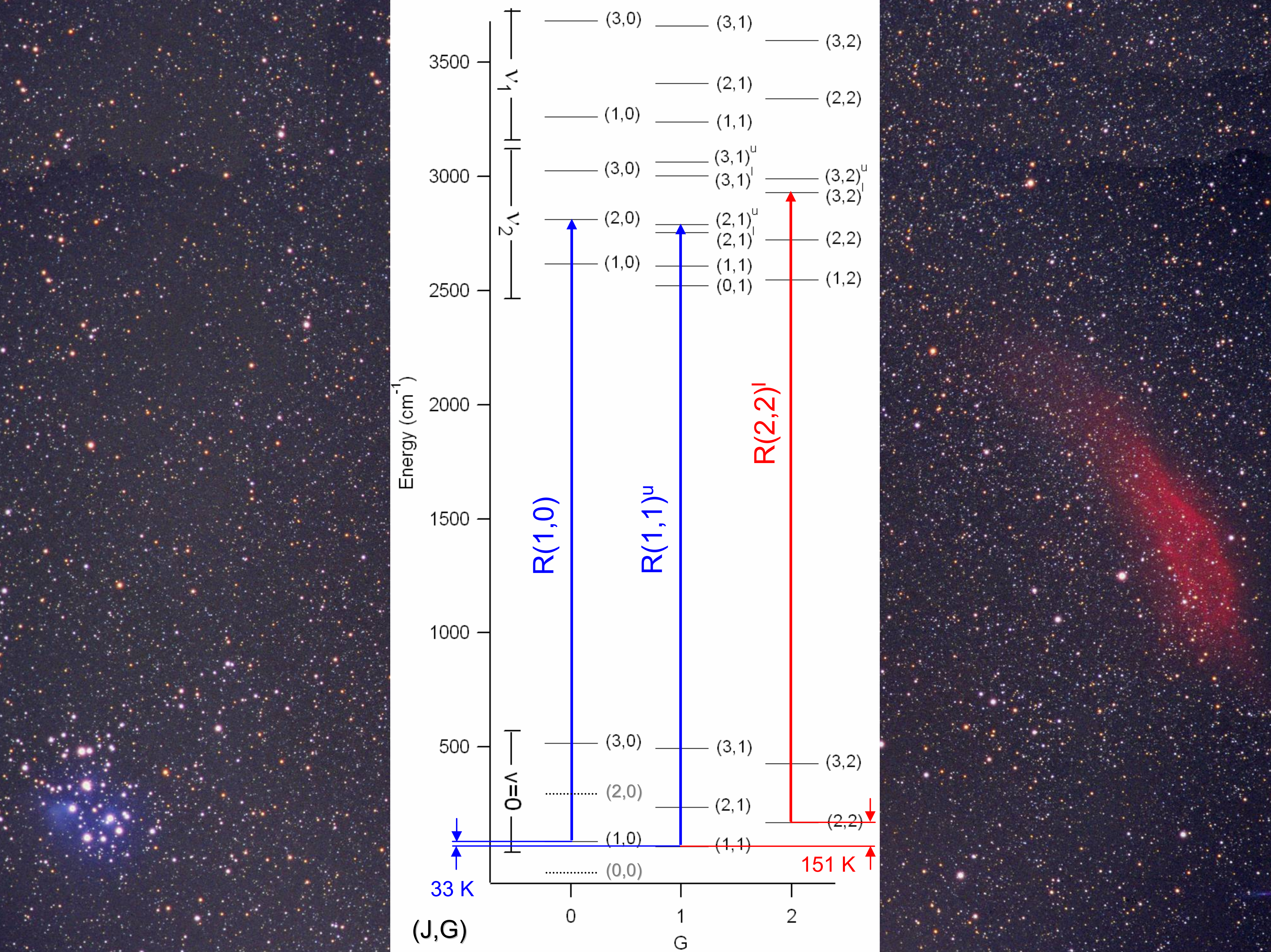


- \+ Very simple experiment
- \+ Complete vibrational relaxation
- \+ Control H_3^+ – e^- impact energy
- \- Rotationally hot ions produced
- \- No rotational cooling in ring

Berkeley Supersonic Ion Source

- Similar to sources for laboratory spectroscopy in Saykally group
- 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

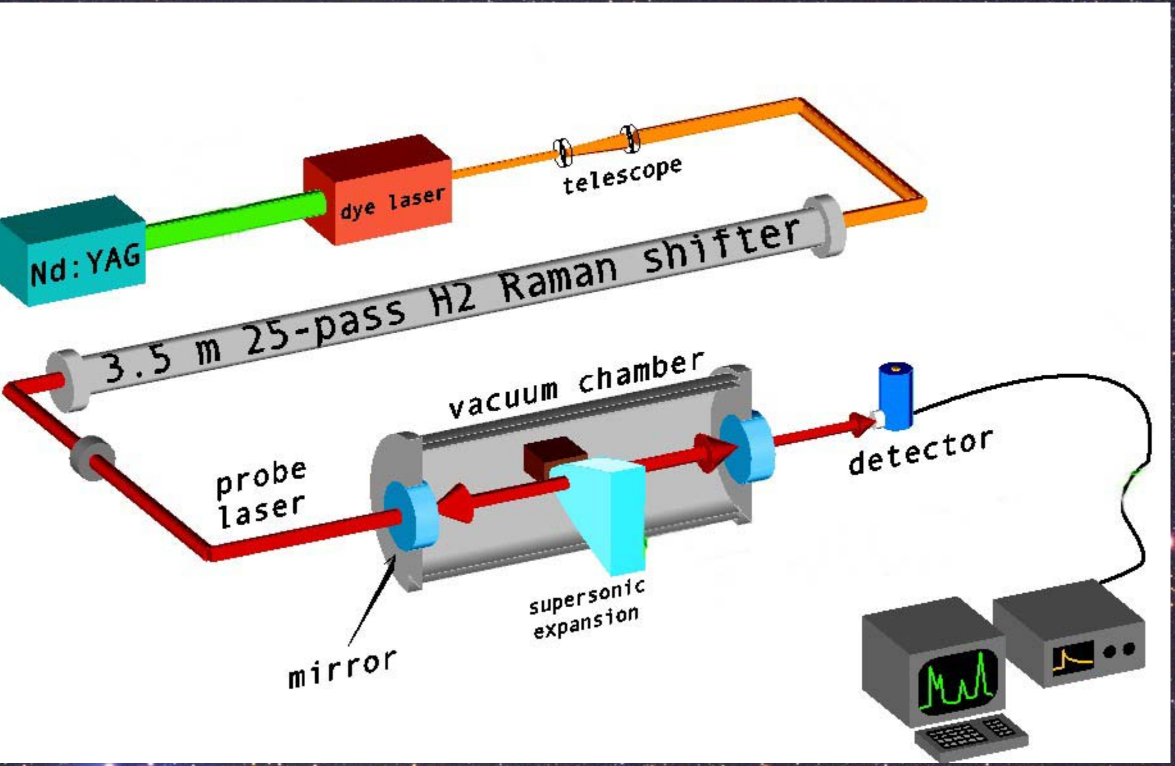




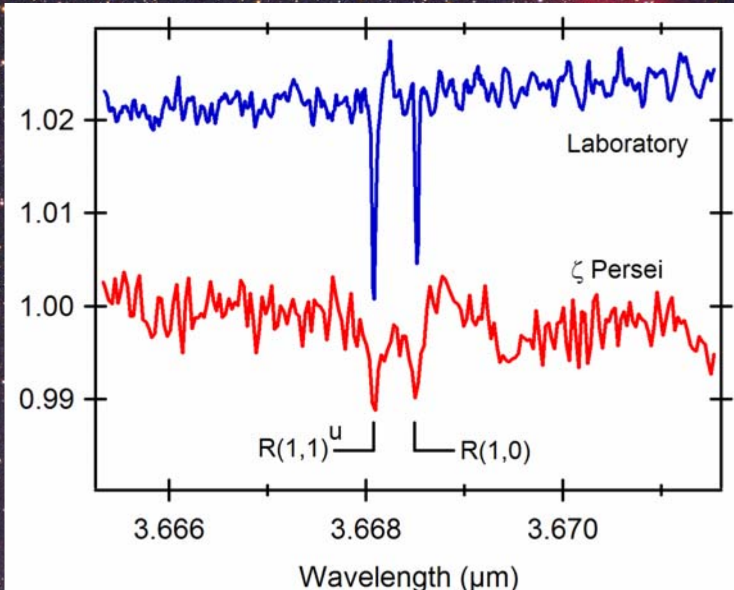
Energy (cm^{-1})
3500
3000
2500
2000
1500
1000
500
ν_1
ν_2
v=0
(3,0)
(1,0)
(3,0)
(2,0)
(1,0)
(3,0)
(2,0)
(1,0)
(0,0)
(3,1)
(2,1)
(1,1)
(3,1)^u
(3,1)^l
(2,1)^u
(2,1)^l
(1,1)
(0,1)
(3,1)
(2,1)
(1,1)
(3,2)
(2,2)
(3,2)^u
(3,2)^l
(2,2)
(1,2)
(3,2)
(2,2)
R(1,0)
R(1,1)^u
R(2,2)^l
33 K
151 K
(J,G)
0
1
2
G

Spectroscopy of H_3^+ Source

Infrared Cavity Ringdown Laser Absorption Spectroscopy

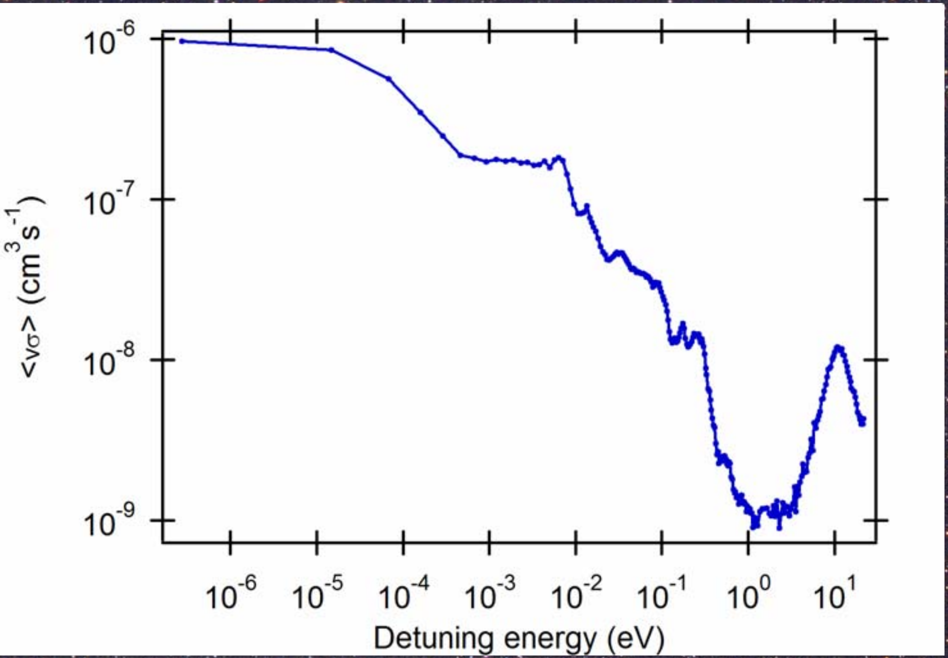


- Confirmed that H_3^+ produced is rotationally cold, as in interstellar medium

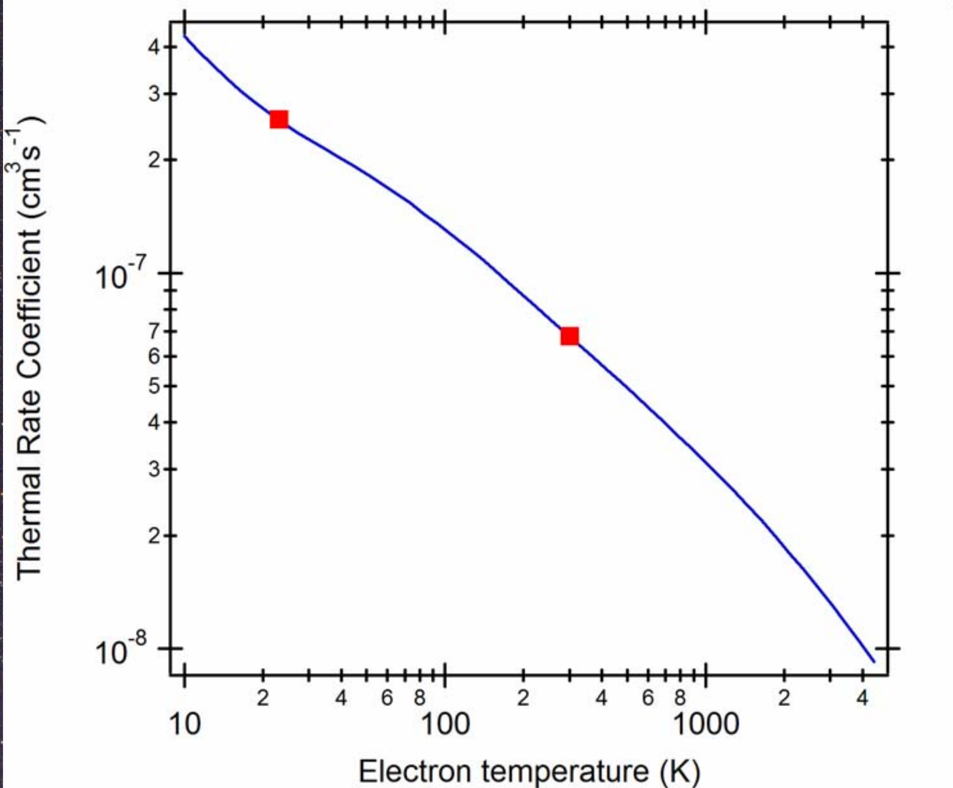


McCall, et al.
Nature 422, 500 (2003)

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



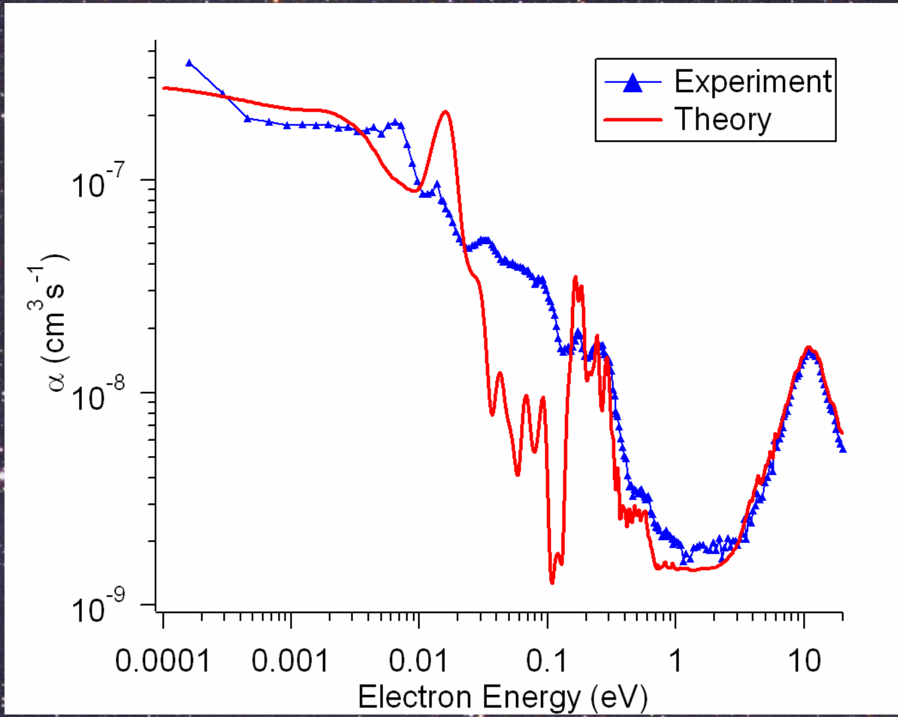
McCall, et al.
Nature 422, 500 (2003)

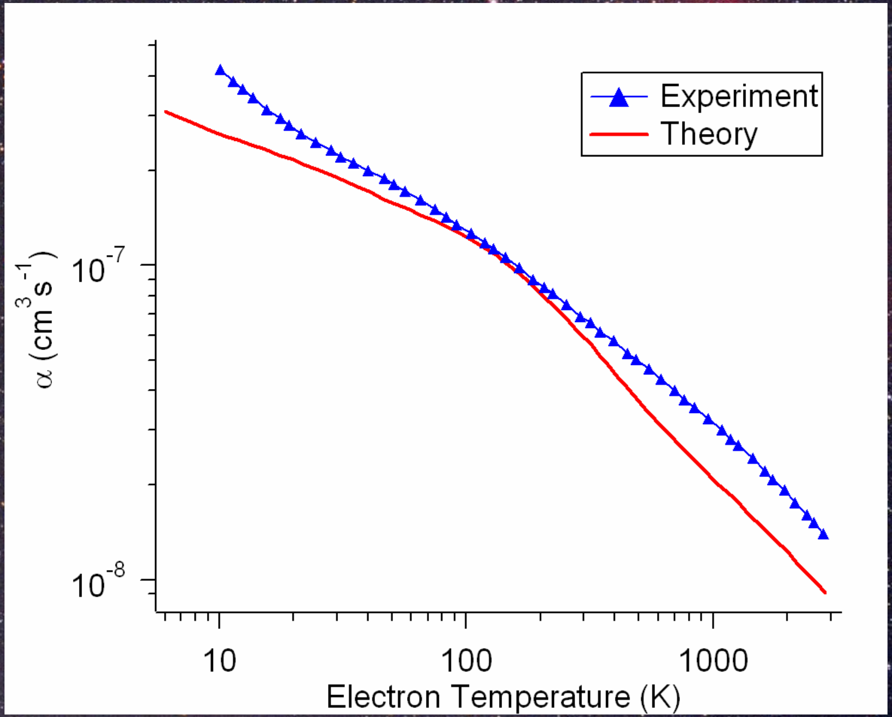
Recent Theoretical Work

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)





Lingering Questions

- (Minor) discrepancies with theory
  - theory is wrong?
  - experiment is “wrong”?
    - high magnetic fields (~300 Gauss)
    - high electron density (~10^7 cm^{-3})
    - perhaps ions don't stay cold?
- Major discrepancies with other experiments
  - new stationary afterglow measurements
  - some flowing afterglow measurements
- Present storage-ring results are “preferred”
  - more control over ion preparation
  - conditions closest to interstellar medium
  - rough agreement with theory

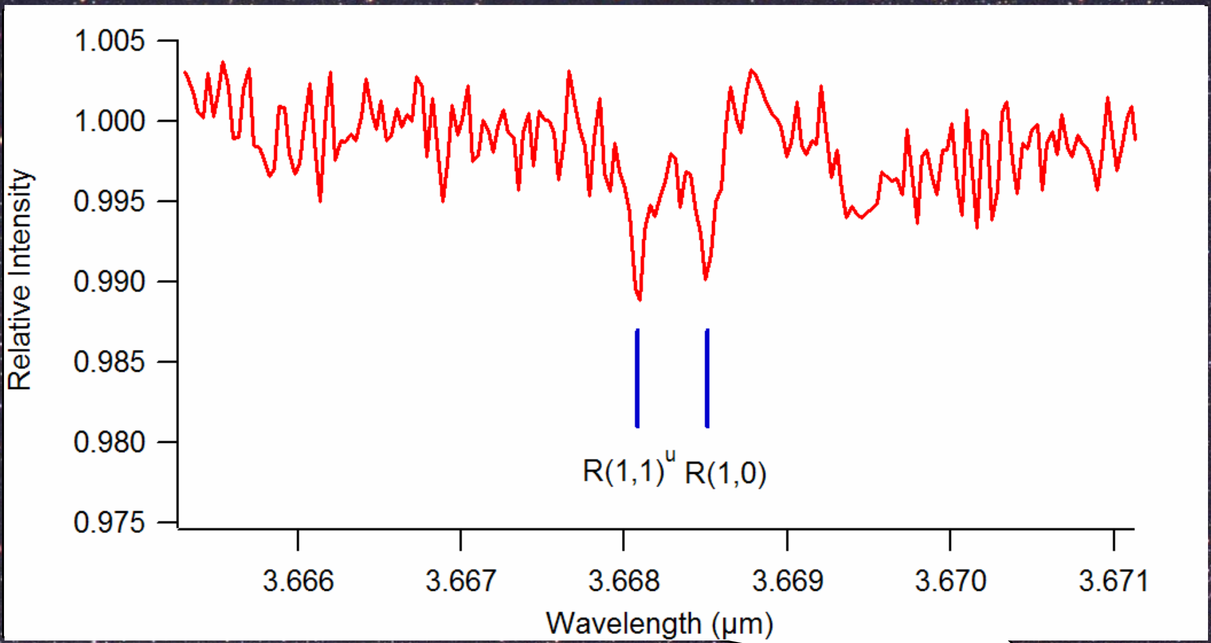
Back to the Interstellar Clouds!

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

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

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

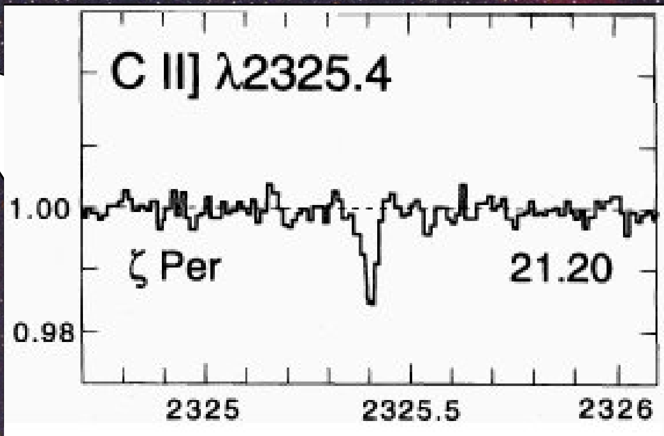
H_3^+ toward ζ Persei



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

[e$^-$]/[H_2] determined

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)

Back to the Interstellar Clouds!

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

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

Implications for ζ Persei

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

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

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

ζL = 8000 cm s^{-1} (solid)

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

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

Adopt L=2.1 pc

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

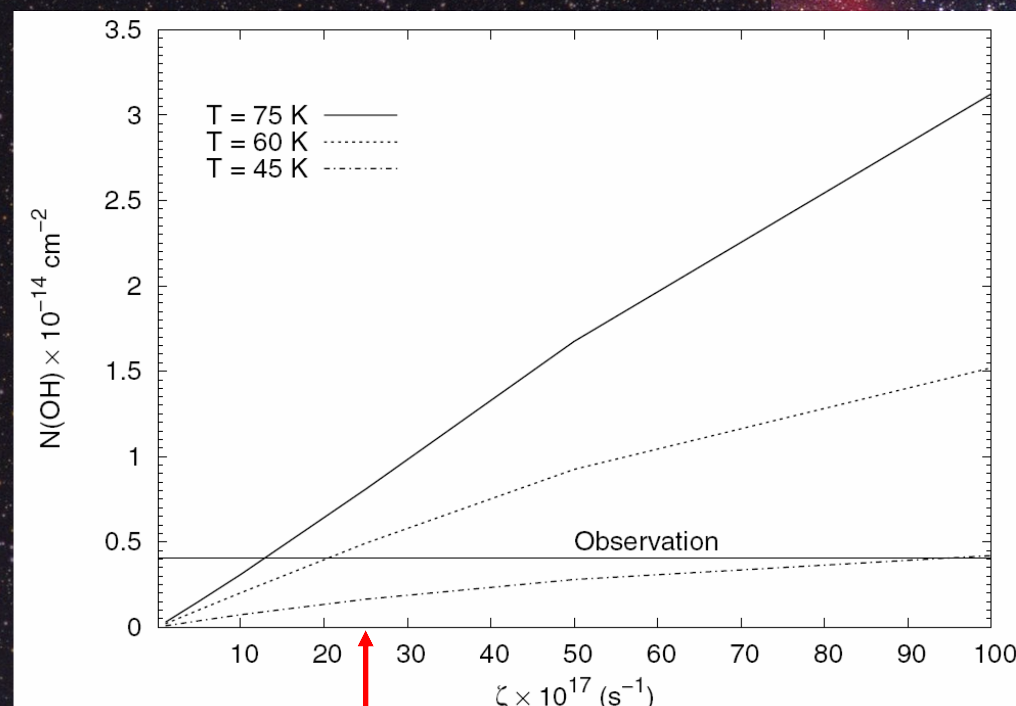
A&A 417, 993–1002 (2004)
DOI: 10.1051/0004-6361:20035629

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"



Future Work

- Better experiments!
  - Improved spectroscopy of ion source
    - Higher resolution & higher sensitivity
    - Better characterization of ro-vib distribution
  - Spectroscopy of extracted ions?
- More observations!
  - Search for H_3^+ in more sightlines
    - "Direct" probe of ionization rate
  - Better observations of ζ Persei cloud
    - Probes of cosmic-ray flux: C IV, He* ?
    - Other atomic & molecular species (C I, CO)

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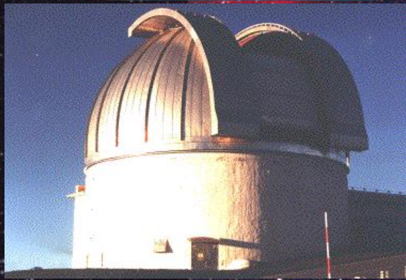
Acknowledgements



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