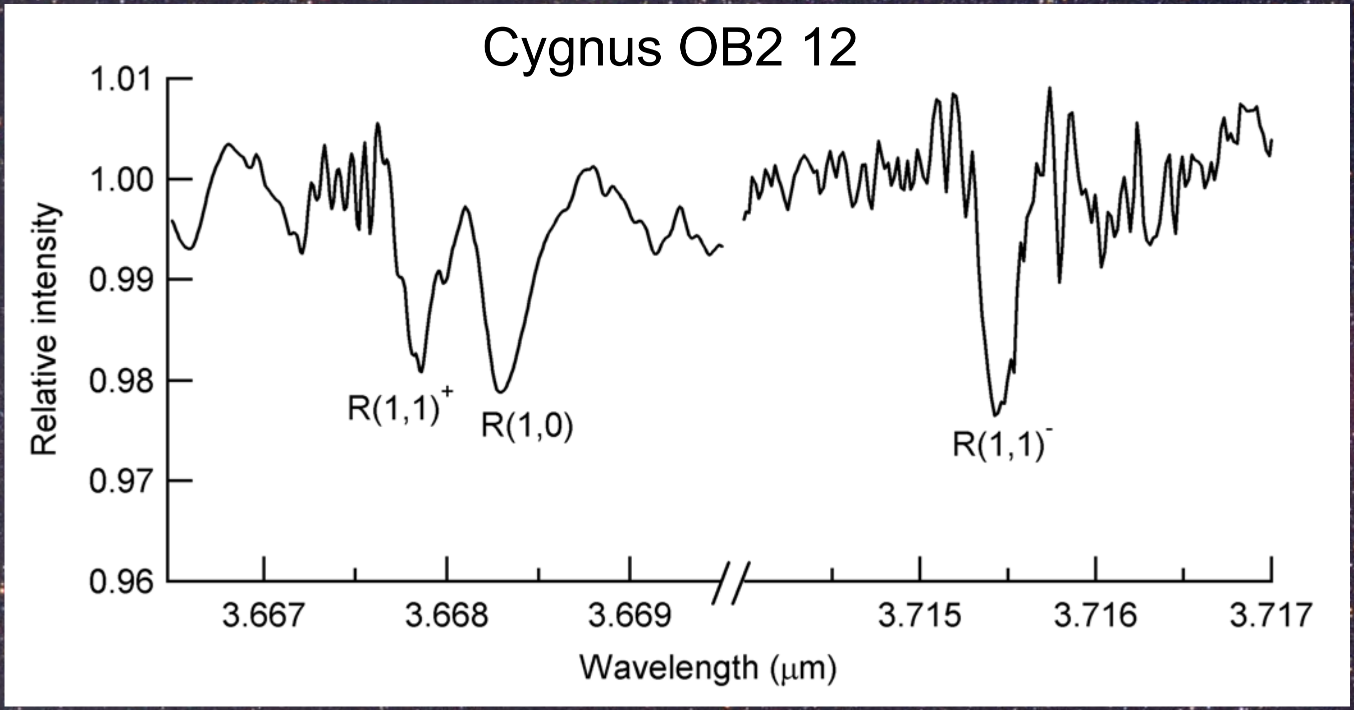
Enhanced cosmic-ray ionization toward ζ Persei inferred from storage ring measurement of dissociative recombination rate of rotationally cold H_3^+

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

Too Much H_3^+ in Diffuse Clouds



- Column density 3×10^{14} cm^{-2}, just like dense cloud!
- Chemical model → $n(H_3^+) \sim 10^{-7}$ cm^{-3}
- $N(H_3^+) / n(H_3^+)$ → path length is 1 kpc!?
- Implies $\langle n(H)\rangle \sim 20$ cm^{-3} (too low)

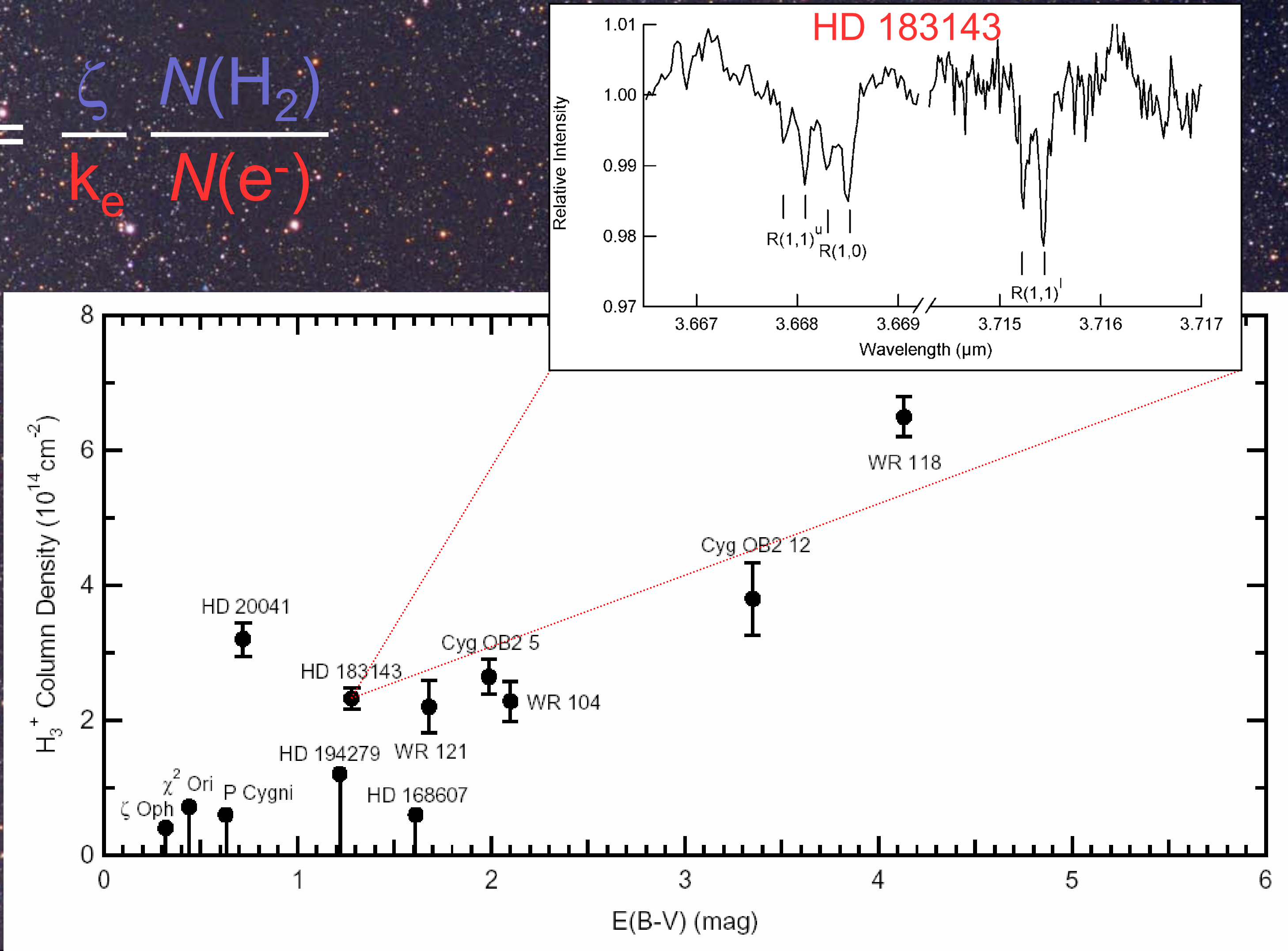
McCall, Geballe, Hinkle, & Oka
Science 279, 1910 (1998)

Other Diffuse Clouds, too!

- General problem with model:

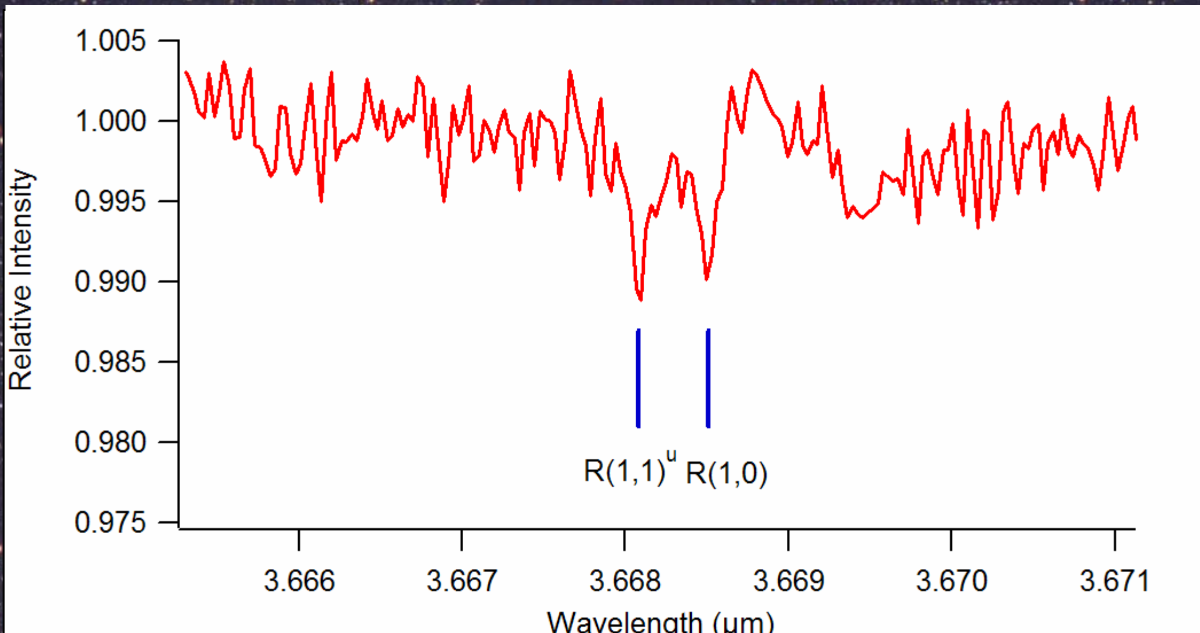
$$[H_3^+] = \frac{\zeta}{k_e} \frac{N(H_2)}{N(e^-)}$$

- ζ
- k_e
- $[H_2]/[e^-]$



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

H_3^+ toward ζ Persei

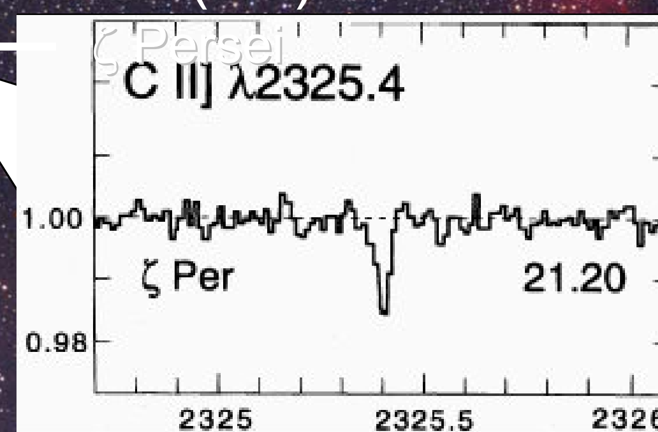


McCall, et al. Nature 422, 500 (2003)

Rules out $[e^-]/[H_2]$

N(C+) from HST

ζ Persei



Cardelli et al. ApJ 467, 334 (1996)

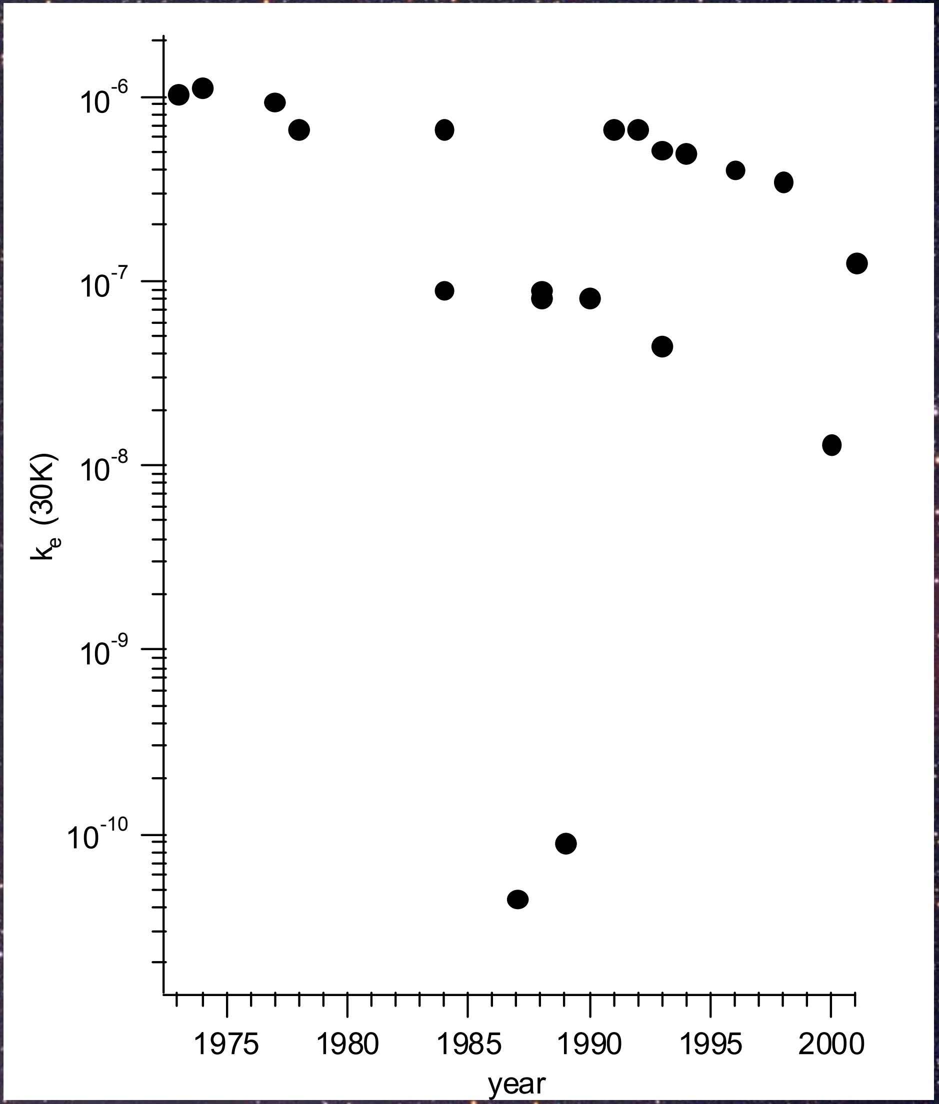
$N(H_2)$ from Copernicus

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	07.5 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	09.5 Ia	.32	1164	20.34	20.90	21.09

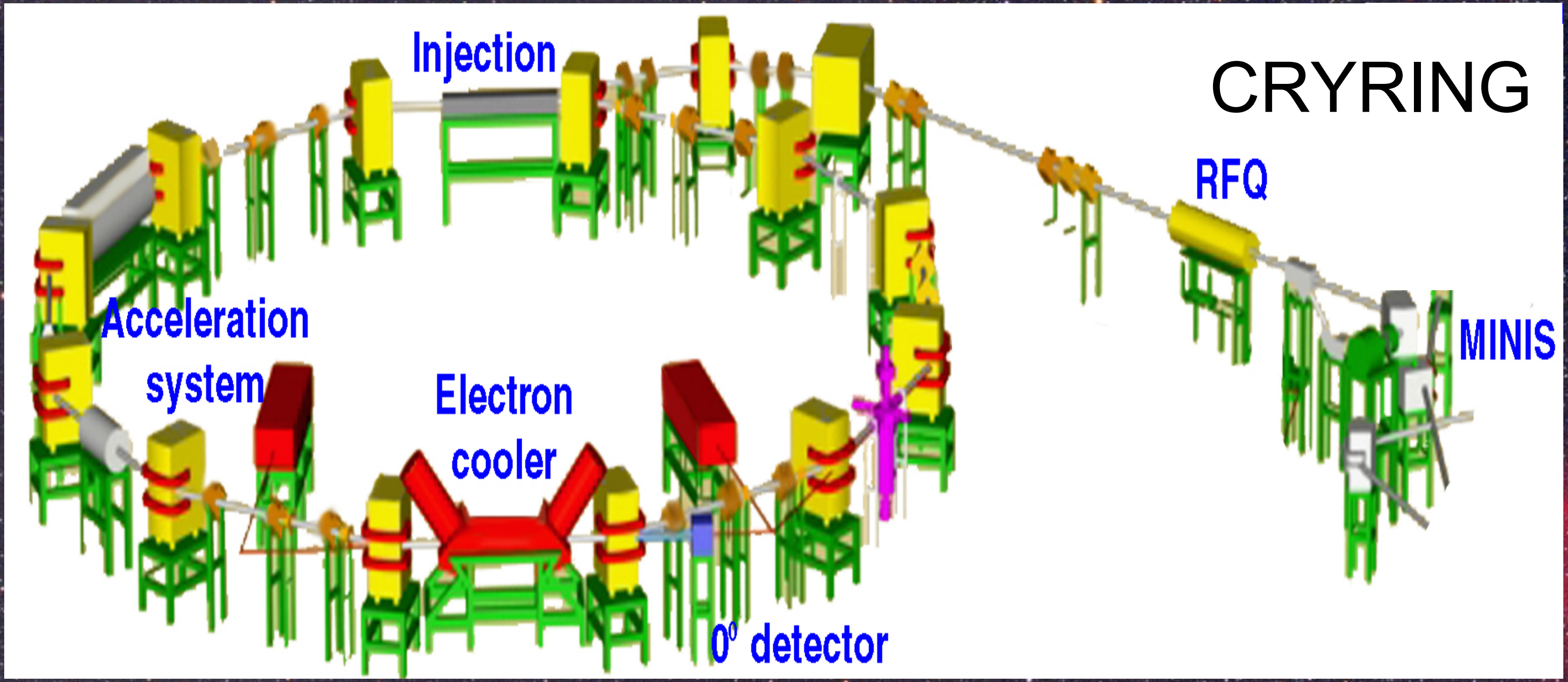
Savage et al. ApJ 216, 291 (1977)

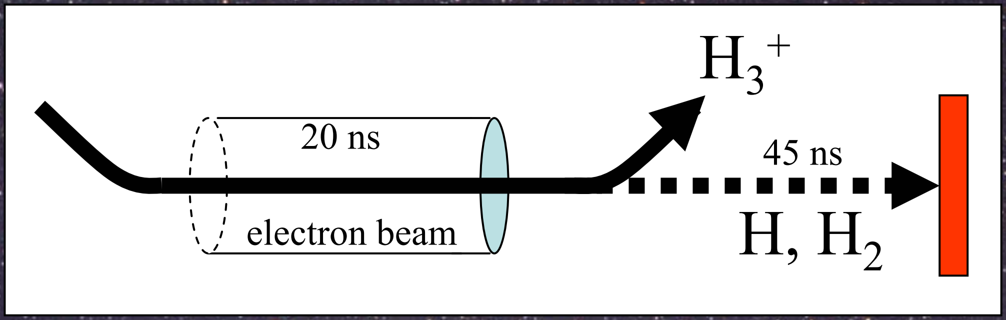
H_3^+ Dissociative Recombination

- Laboratory values of k_e varied by 4 orders of magnitude!
- Even worse: theory in infancy, way off...
- Big problem: not measuring H_3^+ in ground states



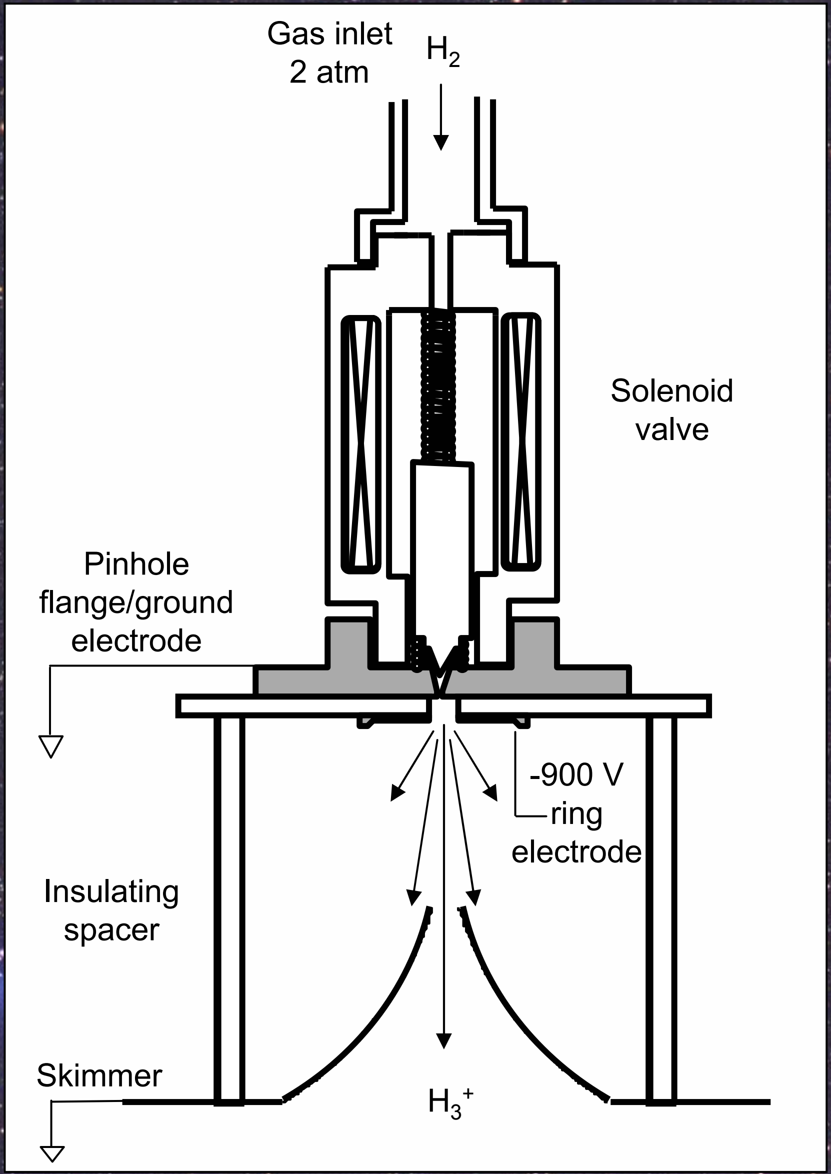
Storage Ring Measurements

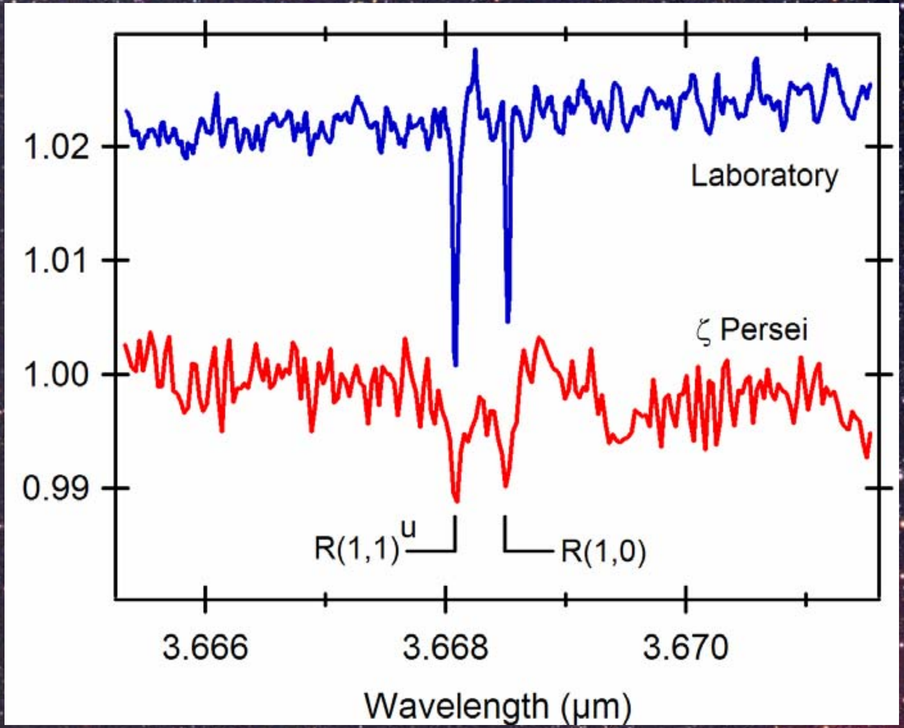




- \+ Complete vibrational relaxation
- \+ Very simple experiment
- \+ Control H_3^+ – e^- impact energy
- \- Rotationally hot ions produced
- \- No rotational cooling in ring

Berkeley Supersonic Ion Source

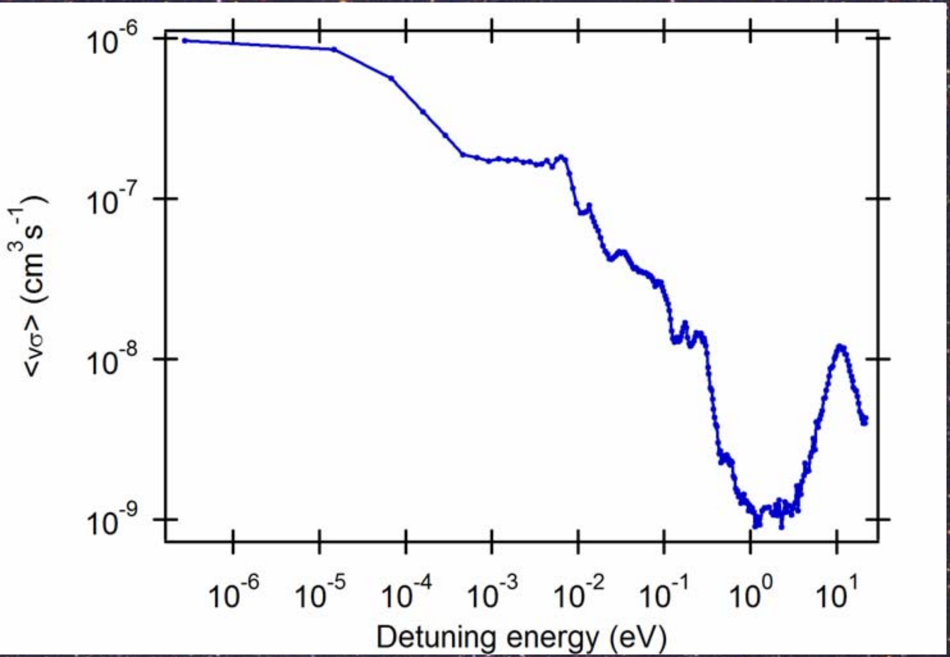




- H_3^+ produced is rotationally cold, as in interstellar medium

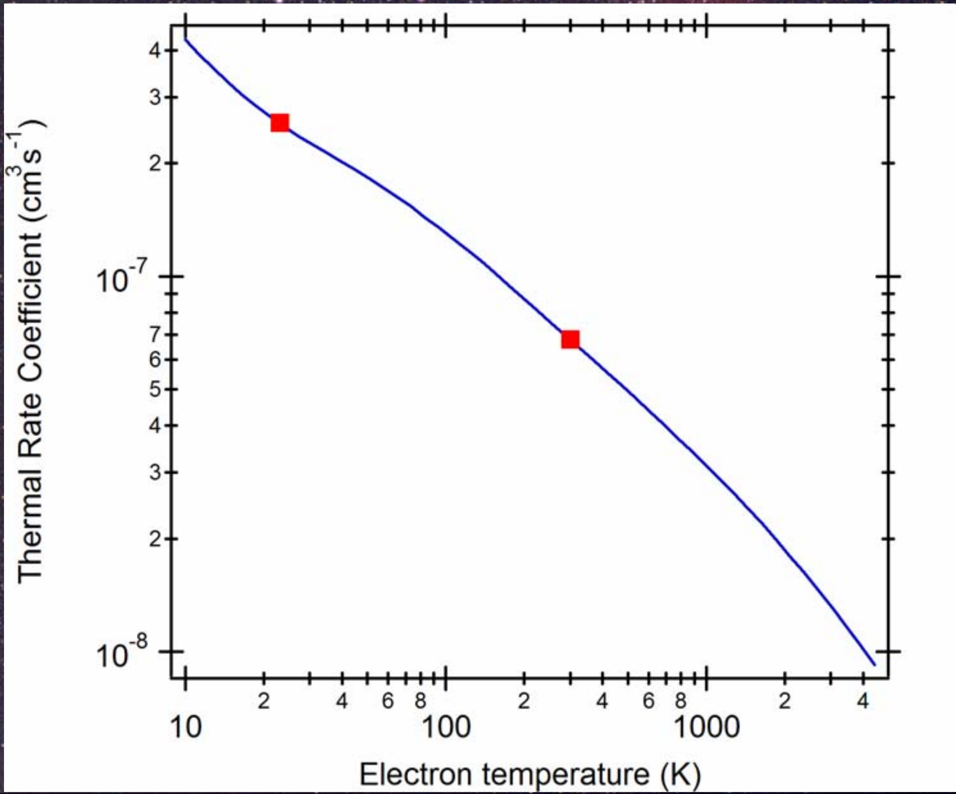
McCall, et al.
Nature 422, 500 (2003)

CRYRING Results



Rules out k_e

- Structure (resonances) in the cross-section
- $k_e = 2.6 \times 10^{-7}\ cm^3\ s^{-1}$
- Chris Greene's theory



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

Implications for ζ Persei

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

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

k_e $(2.6\times10^{-7}\ \mathrm{cm^3\ s^{-1}})$, $N(H_3^+)$ $(8\times10^{13}\ \mathrm{cm^{-2}})$, $\frac{N(e^-)}{N(H_2)}$ (3.8×10^{-4})

$$\zeta L = 8000\ \mathrm{cm\ s^{-1}}$$

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 cosmic-ray flux in ζ Persei
- Widespread H_3^+ in diffuse clouds
  - perhaps widespread cosmic-ray enhancement?
- Dense cloud H_3^+ is "normal"
  - enhanced cosmic-ray flux only in diffuse clouds
  - low energy component?
  - no constraints, aside from chemistry!!
- Substantial impact on diffuse cloud chemistry
  - more frequent ion-neutral reactions
  - enhanced oxygen chemistry ($H^+ + O \rightarrow O^+ + H$)

Future Work

- Search for H_3^+ in more UV-accessible sightlines
  - "Direct" probe of cosmic-ray flux
  - [Non-detections in o Persei, ζ Ophiuchi ?]
- Observations of H_3^+ in heavily reddened sources
  - Fall-off in cosmic-ray flux
  - Transition of $C^+ \rightarrow CO$
- Comprehensive study of ζ Persei
  - Review all constraints on density, path length
  - Model cloud structure, inhomogeneities

Rich Diffuse Cloud Chemistry

- From 1930s through the mid-1990s, only diatomic molecules thought to be abundant in diffuse clouds
- Since 1998, many polyatomics observed:
  - H_3^+ in infrared
  - HCO^+, C_2H, C_3H_2 in radio (Lucas & Liszt)
  - C_3 in near-UV (Maier, et al.)
- Diffuse Interstellar Bands!