H_3^+ and the Cosmic Ray Flux

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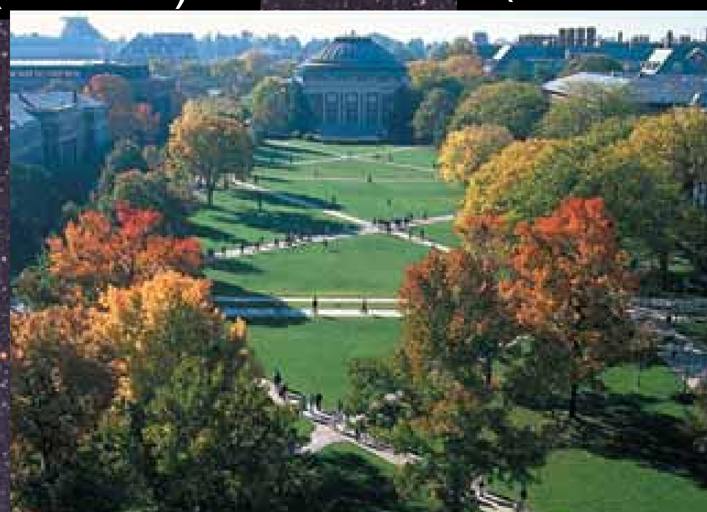

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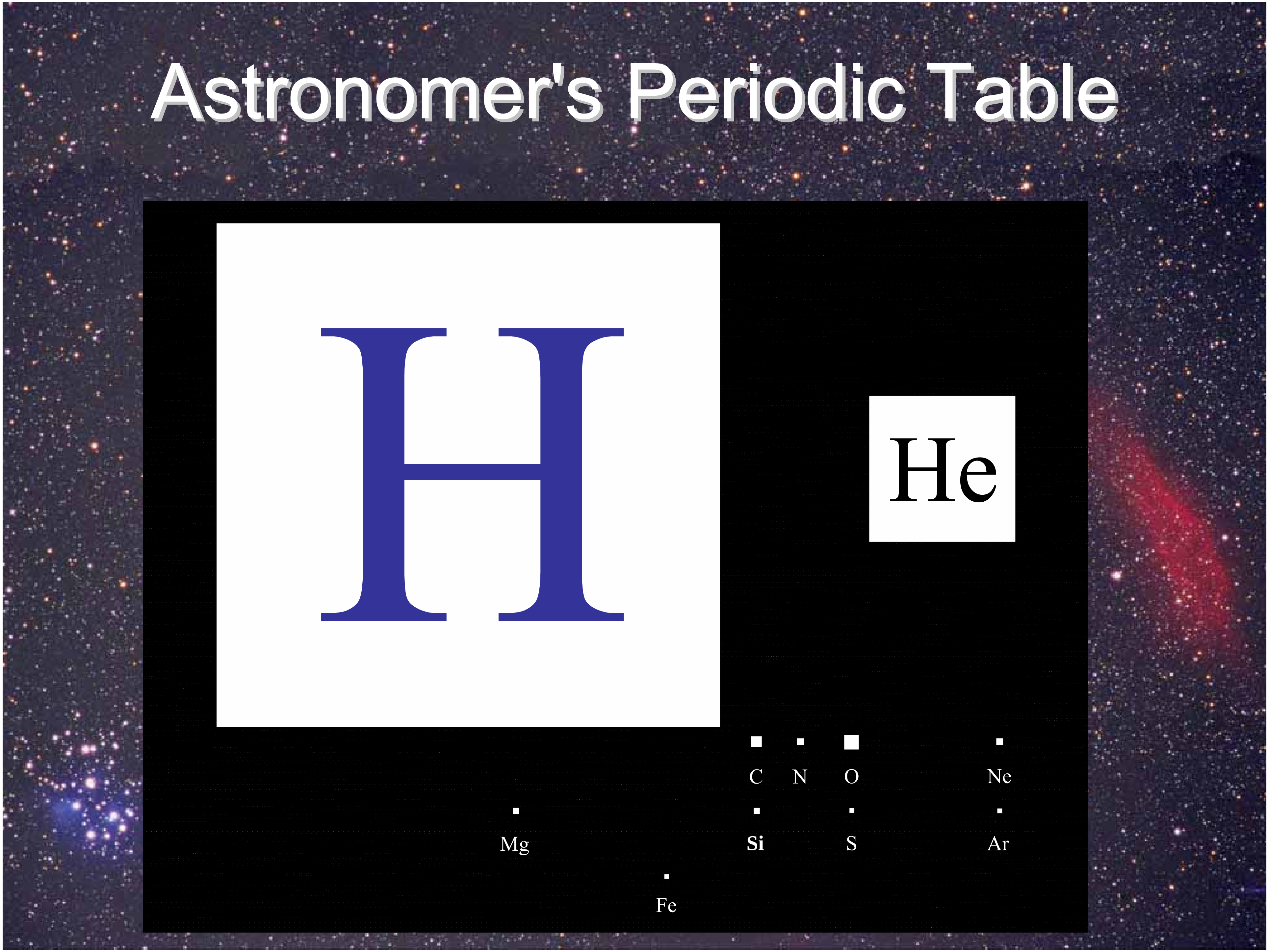
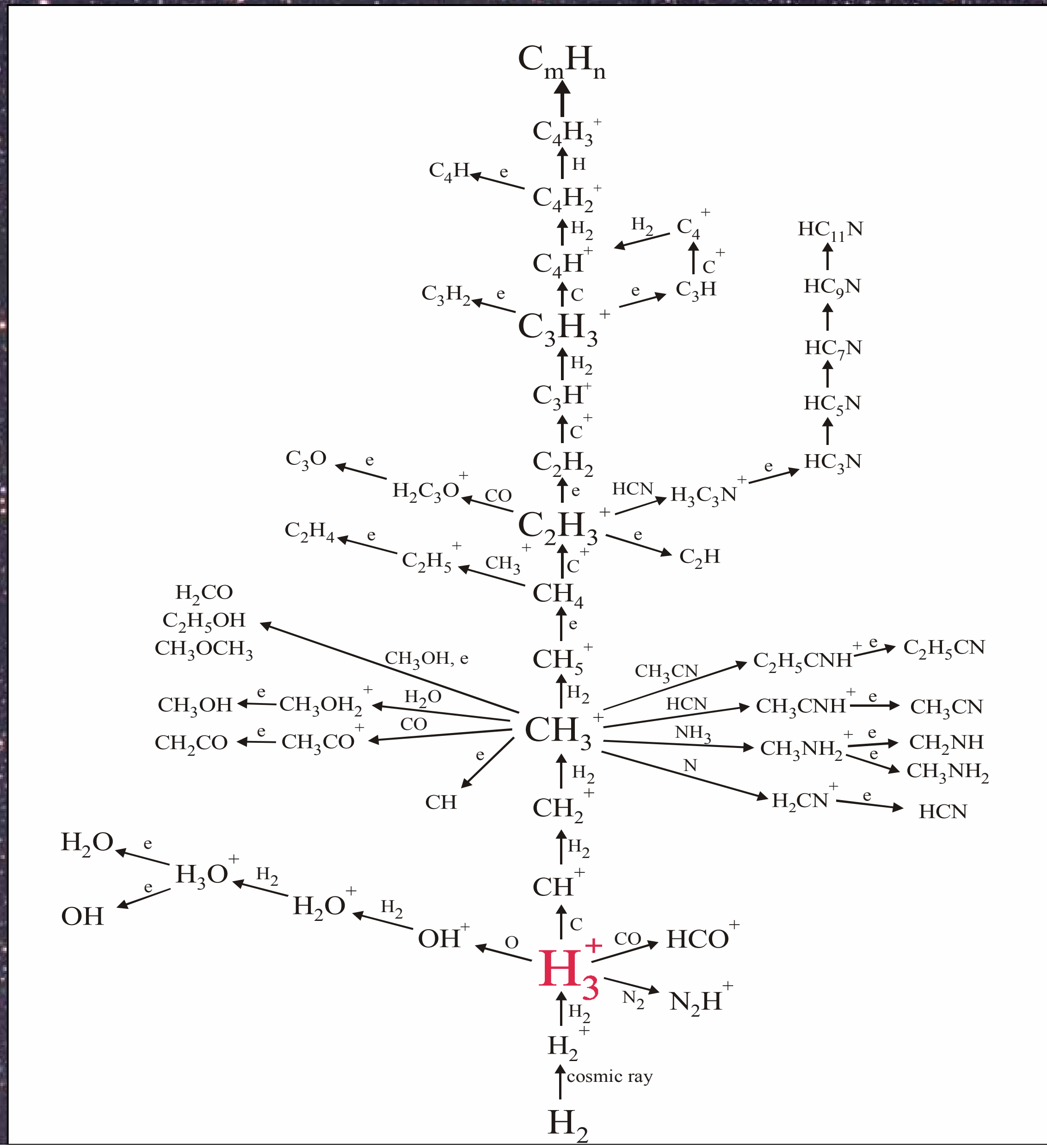

Astronomer's Periodic Table
H
He
C
N
O
Ne
Mg
Si
S
Ar
Fe

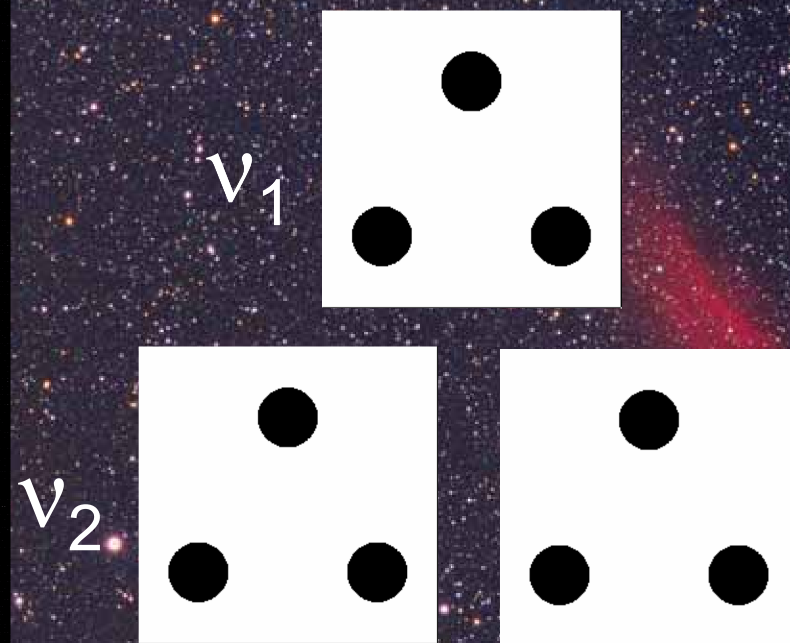
H_3^+: Cornerstone of Interstellar Chemistry



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

Diffuse clouds:

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

Barnard 68 (courtesy João Alves, ESO)

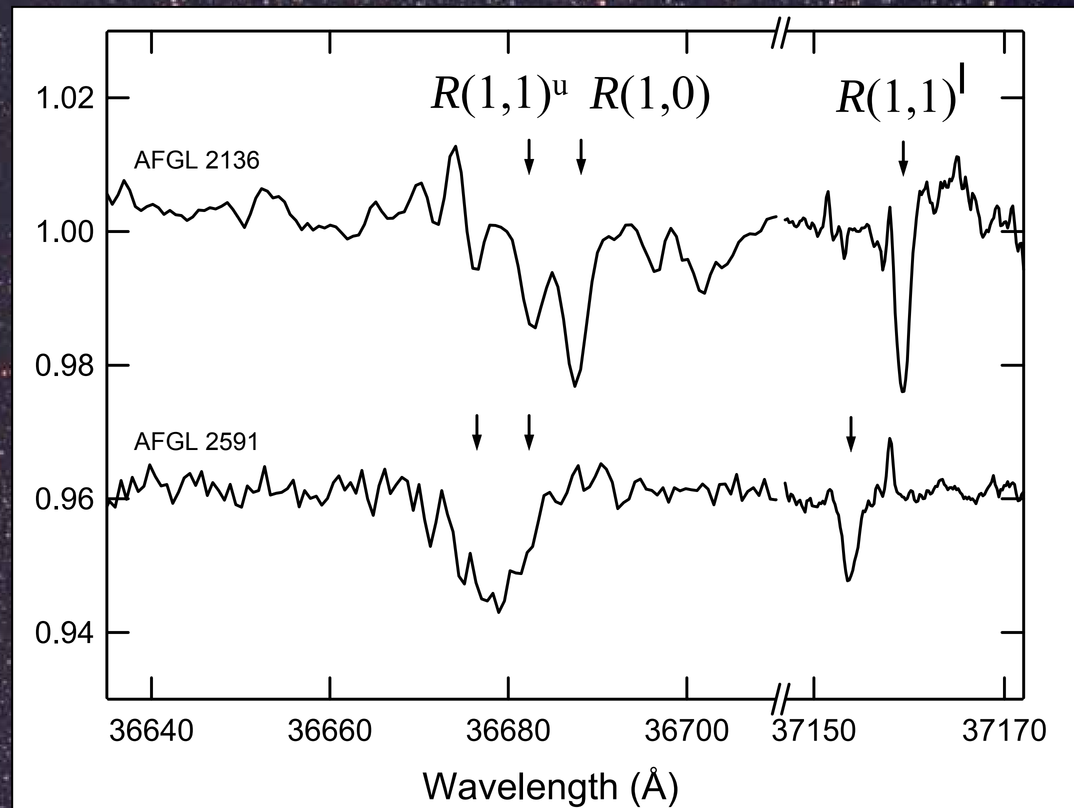
← ζ Persei

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

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

Photo: Jose Fernandez Garcia

H_3^+ in Dense Clouds



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

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

Dense Cloud H_3^+ Chemistry

Formation

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

$H_2 + H_2^+ \rightarrow H_3^+ + H$ (fast)

Destruction

$H_3^+ + CO \rightarrow HCO^+ + H_2$ Rate = $k\,[H_3^+]\,[CO]$

Steady State

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

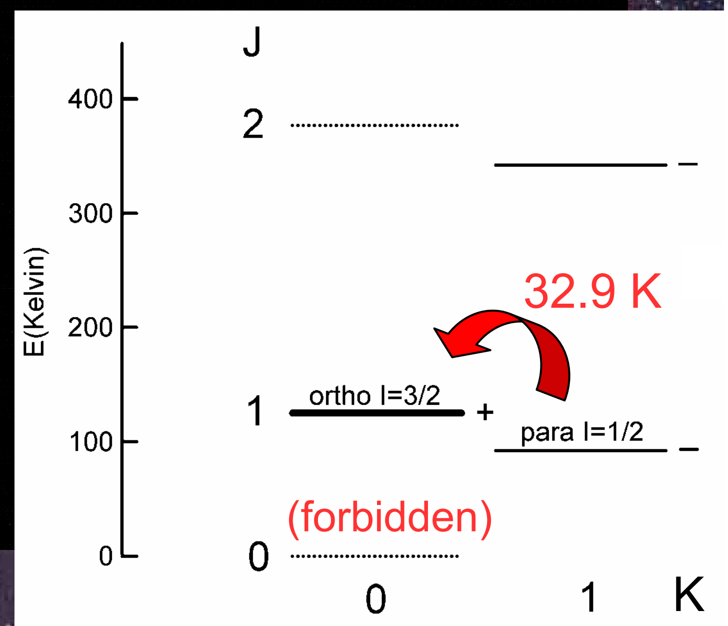
$$= 10^{-4}\ cm^{-3}$$

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 ~ 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

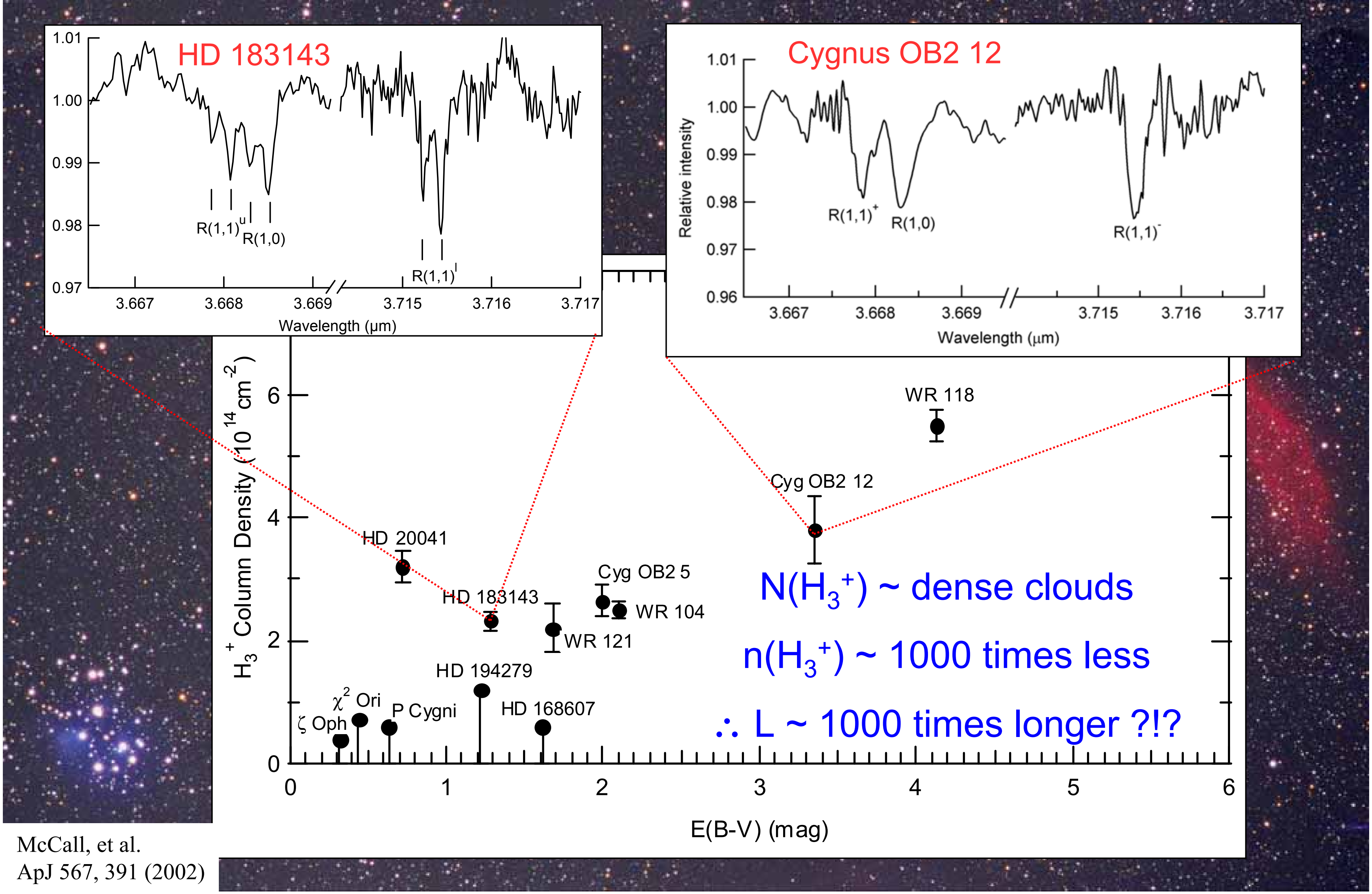
$$[H_3^+] = \frac{\zeta}{k_e}\,\frac{[H_2]}{[e^-]} = \frac{(3\times10^{-17}\ s^{-1})}{(5\times10^{-7}\ cm^3\ s^{-1})} \times (2400)$$

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

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!

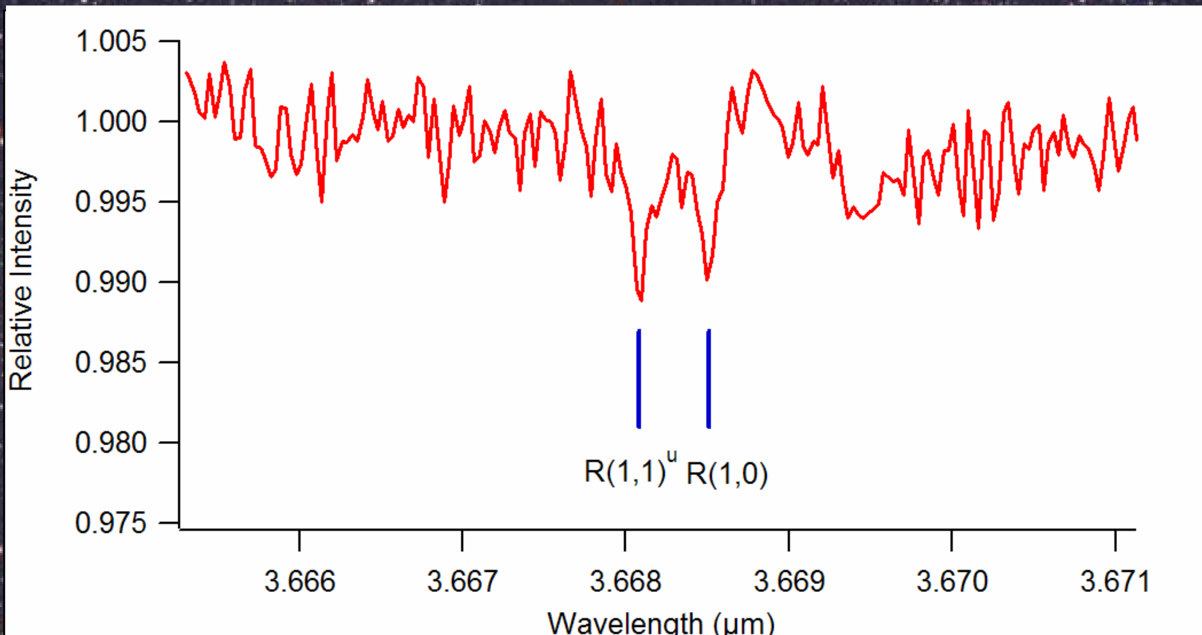
★ >1 order of magnitude!!

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

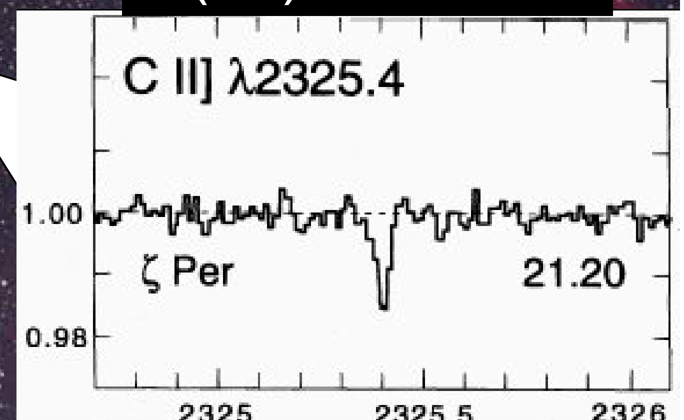
H_3^+ toward ζ Persei



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!

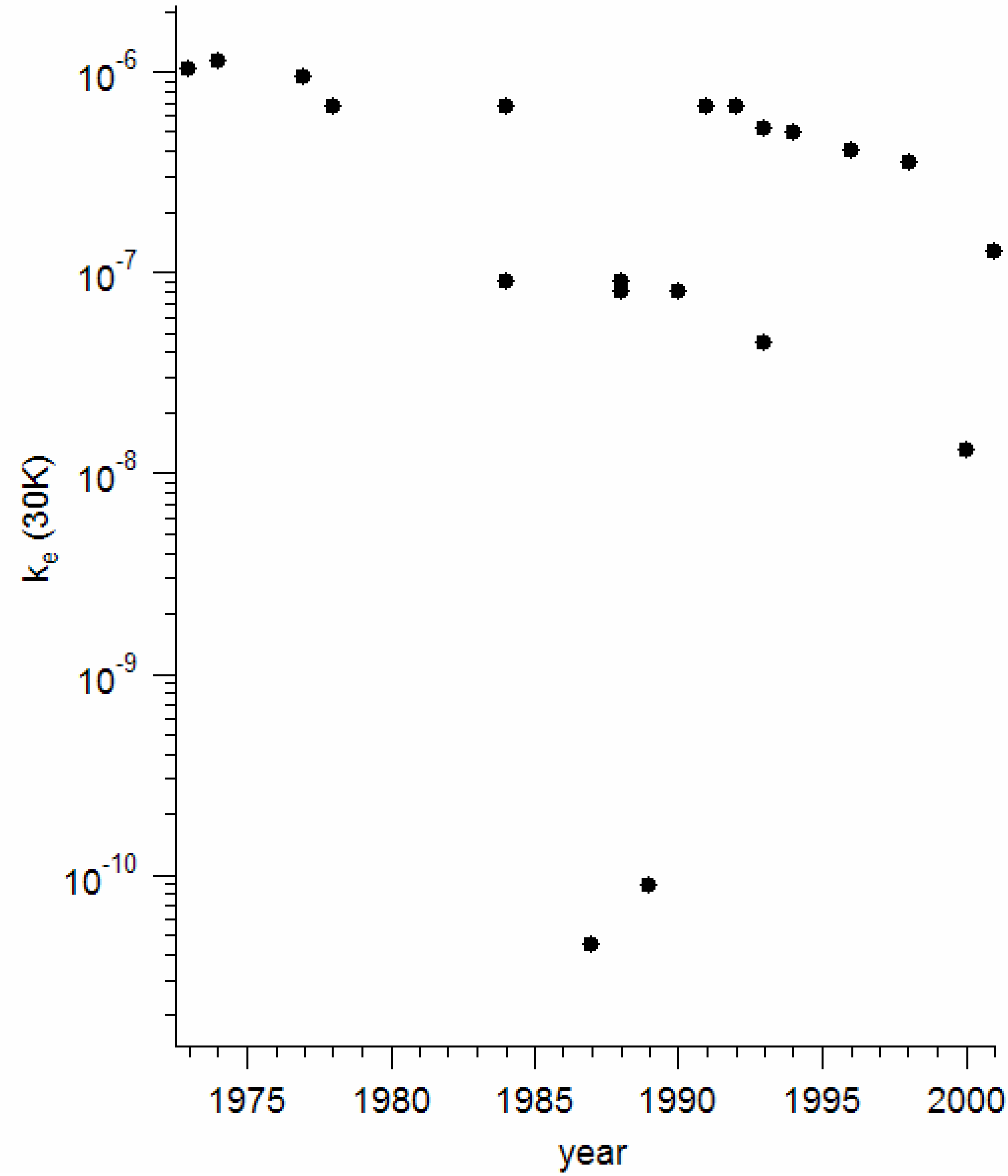
Steady State: $$[H_3^+] = \frac{\zeta}{k_e} \frac{[H_2]}{[e^-]}$$

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

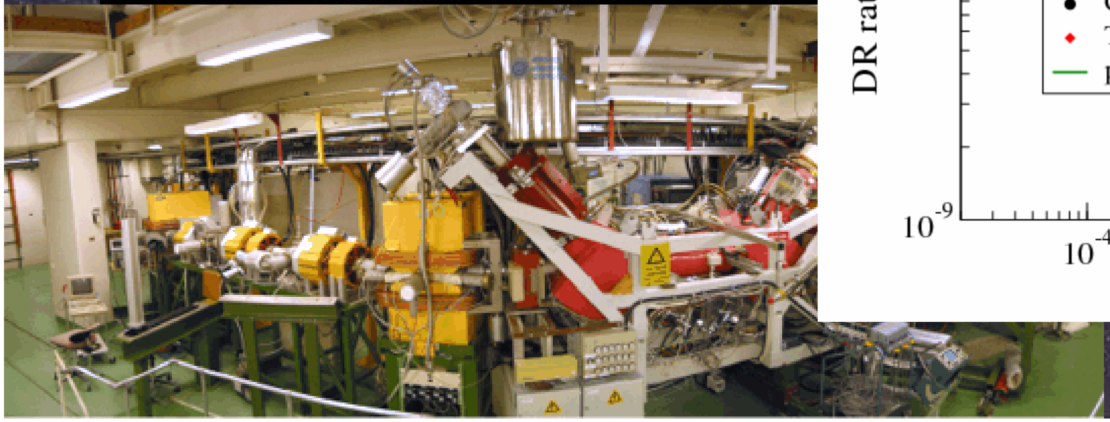
Enigma of H_3^+ Recombination

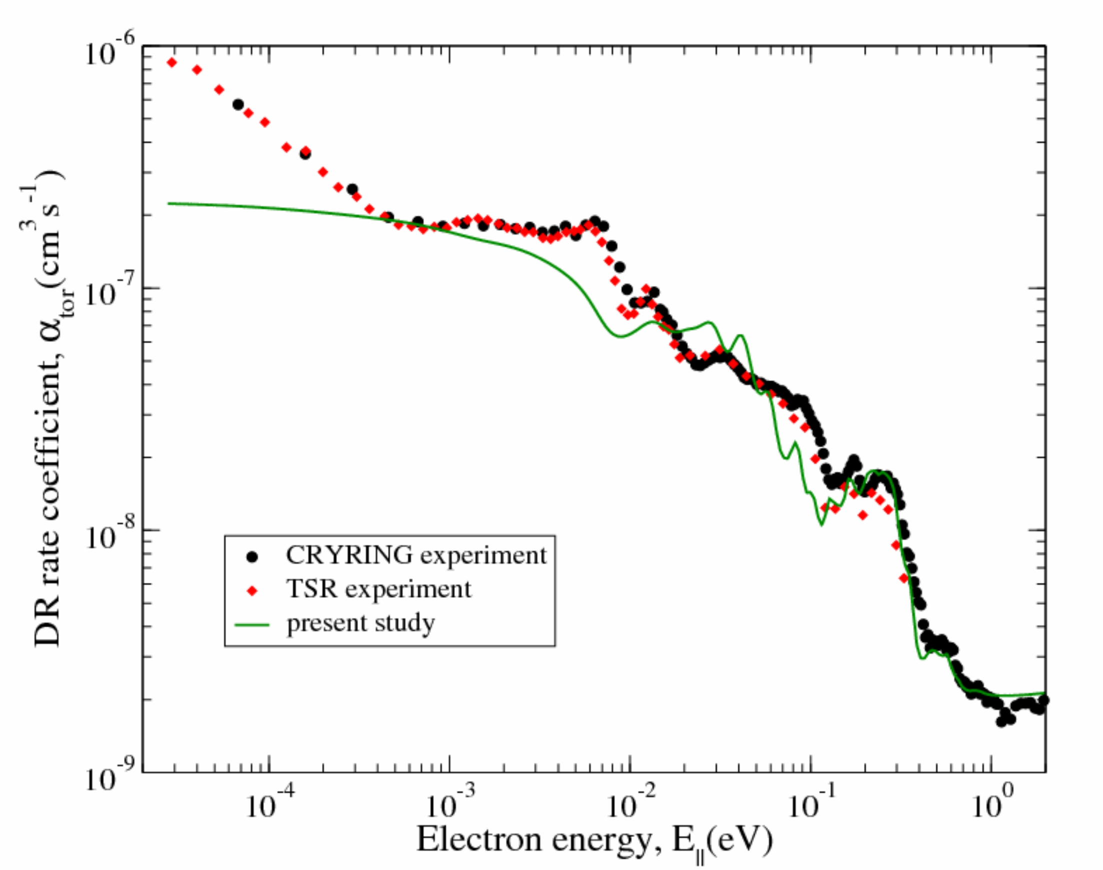
- Laboratory values of k_e have varied by 4 orders of magnitude!
- Problem: not measuring H_3^+ in ground states



Problem (mostly) Resolved

- Reasonable agreement between:
  - CRYRING
    - Supersonic expansion
  - TSR
    - 22-pole trap
  - Theory





S.F. dos Santos, V. Kokoouline and C. H. Greene, J. Chem. Phys 127 (2007) 124309

Big Problem with the Chemistry!

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

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

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

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

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

(dense cloud value)

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

$L = 60\ \mathrm{pc}$

$\langle n \rangle =$ [illegible] $\mathrm{cm^{-3}}$

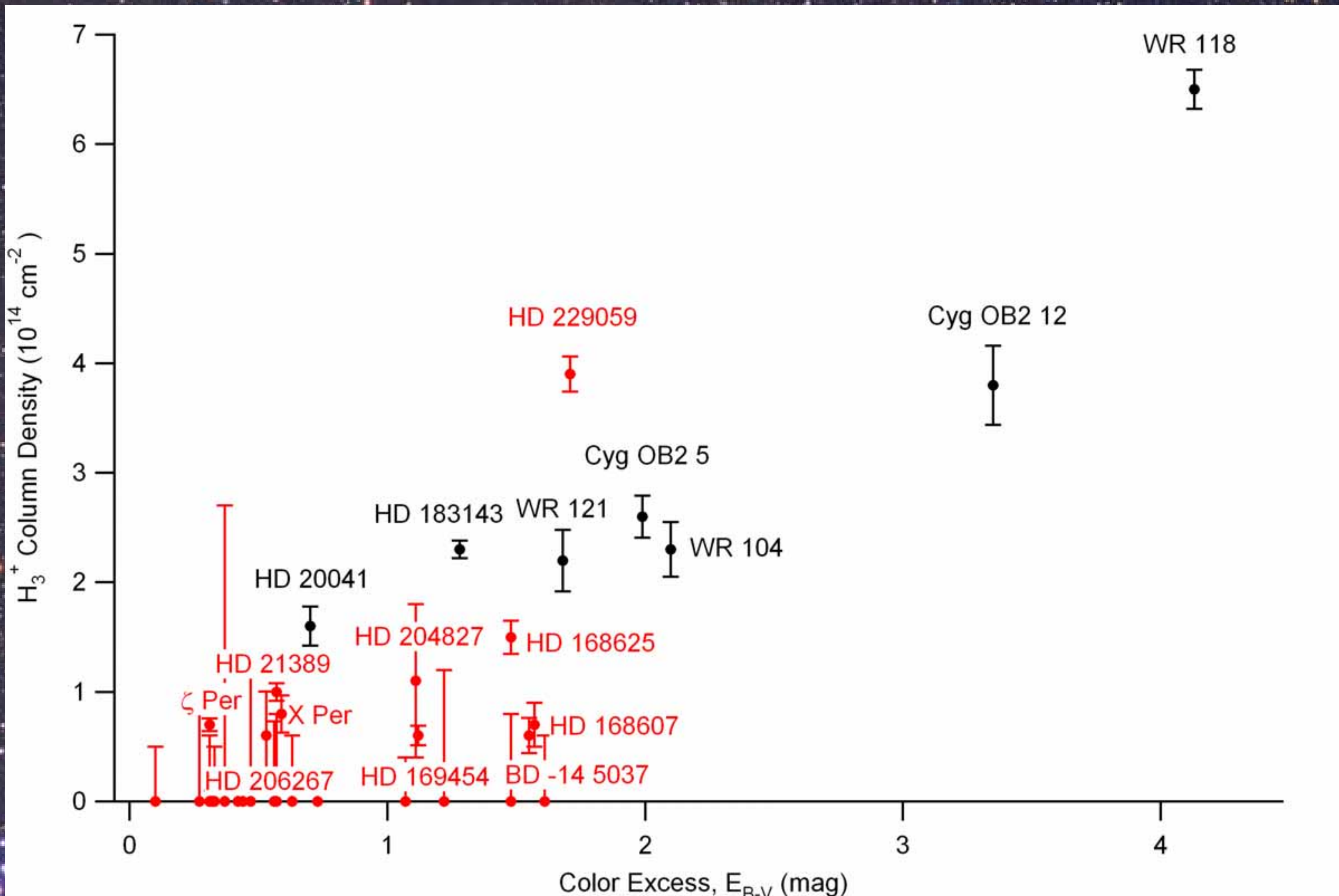
Adopt $\langle n \rangle = 215\ \mathrm{cm^{-3}}$

$\rightarrow L = 2.4\ \mathrm{pc}$

$\zeta = 7.4\times10^{-16}\ \mathrm{s^{-1}}$

(25x higher!)

Recent Astronomical Results



- Range of ζ from $1.1\text{-}7.3 \times 10^{-16}$ s^{-1}
- Biggest uncertainty is in adopted $\langle n \rangle$

N. Indriolo, T. R. Geballe, T. Oka, & B. J. McCall, ApJ 671, 1736 (2007)

Surprise → Conventional Wisdom

- Higher ζ in diffuse (vs. dense) clouds initially greeted with "skepticism"
- Incorporated into models without incident

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]

The Astrophysical Journal, 675:405–412, 2008 March 1

ON THE ENHANCED COSMIC-RAY IONIZATION RATE IN THE DIFFUSE CLOUD TOWARD ζ PERSEI

Gargi Shaw,[1] G. J. Ferland,[1] R. Srianand,[2] N. P. Abel,[1] P. A. M. van Hoof,[3] and P. C. Stancil[4]
Received 2007 July 19; accepted 2007 October 30

- Now generally accepted (but not understood!)

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

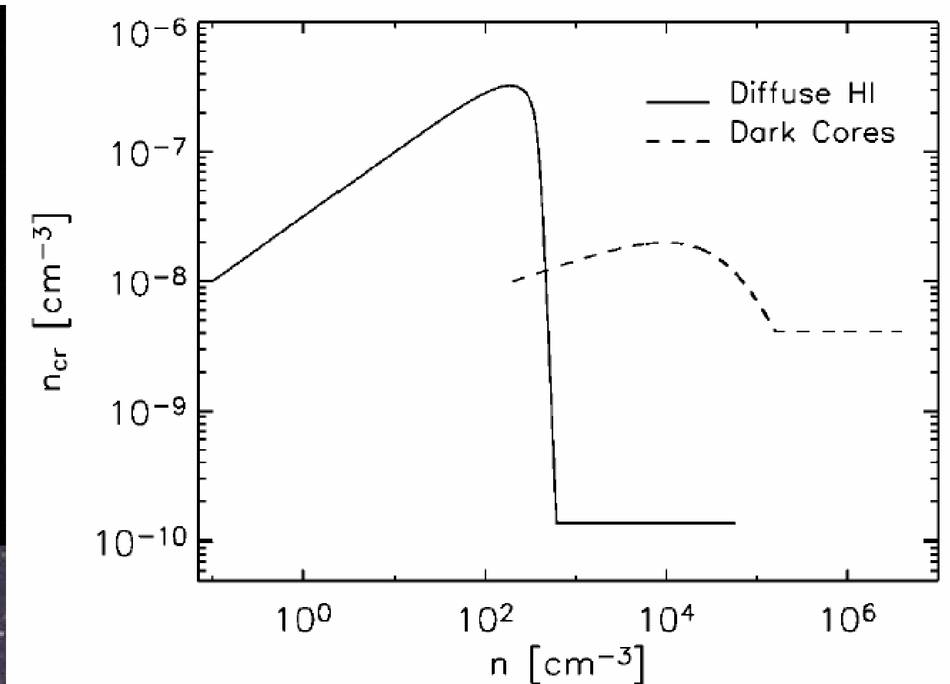
CONFINEMENT-DRIVEN SPATIAL VARIATIONS IN THE COSMIC-RAY FLUX

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.



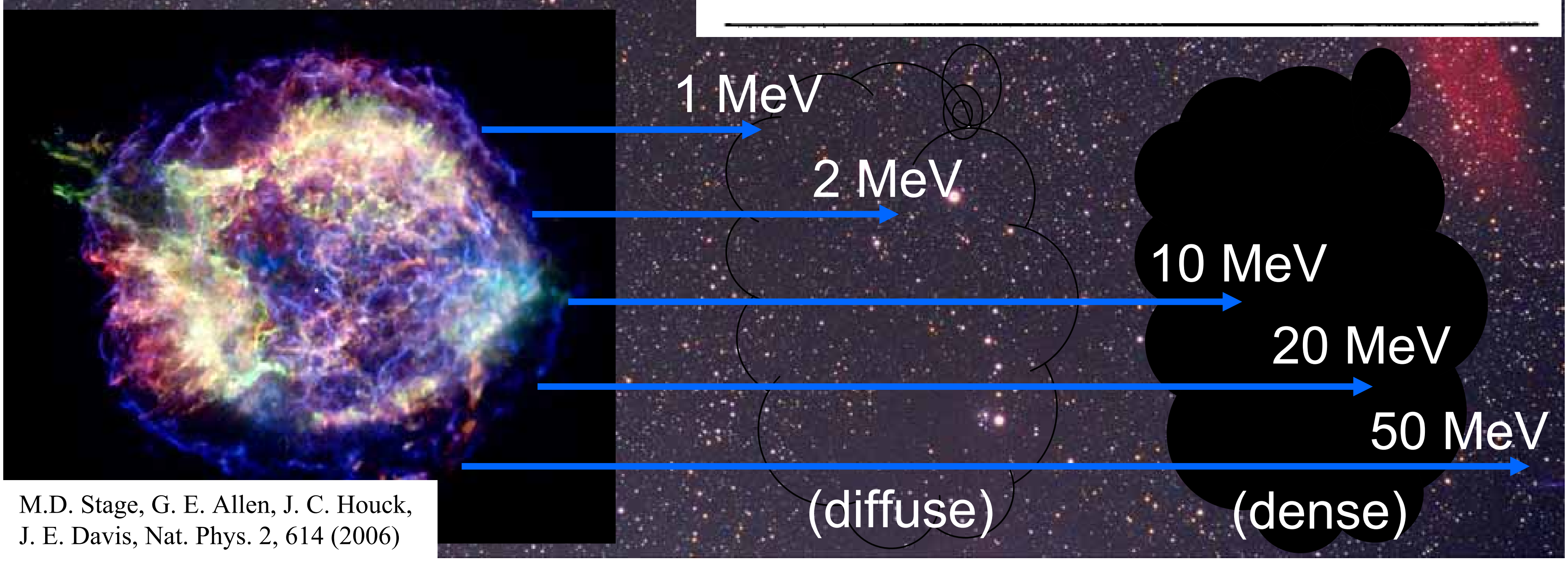
Low Energy CRs?

- Could there be a large flux of low energy cosmic rays?

T. E. Cravens & A. Dalgarno, ApJ 219, 750 (1978)

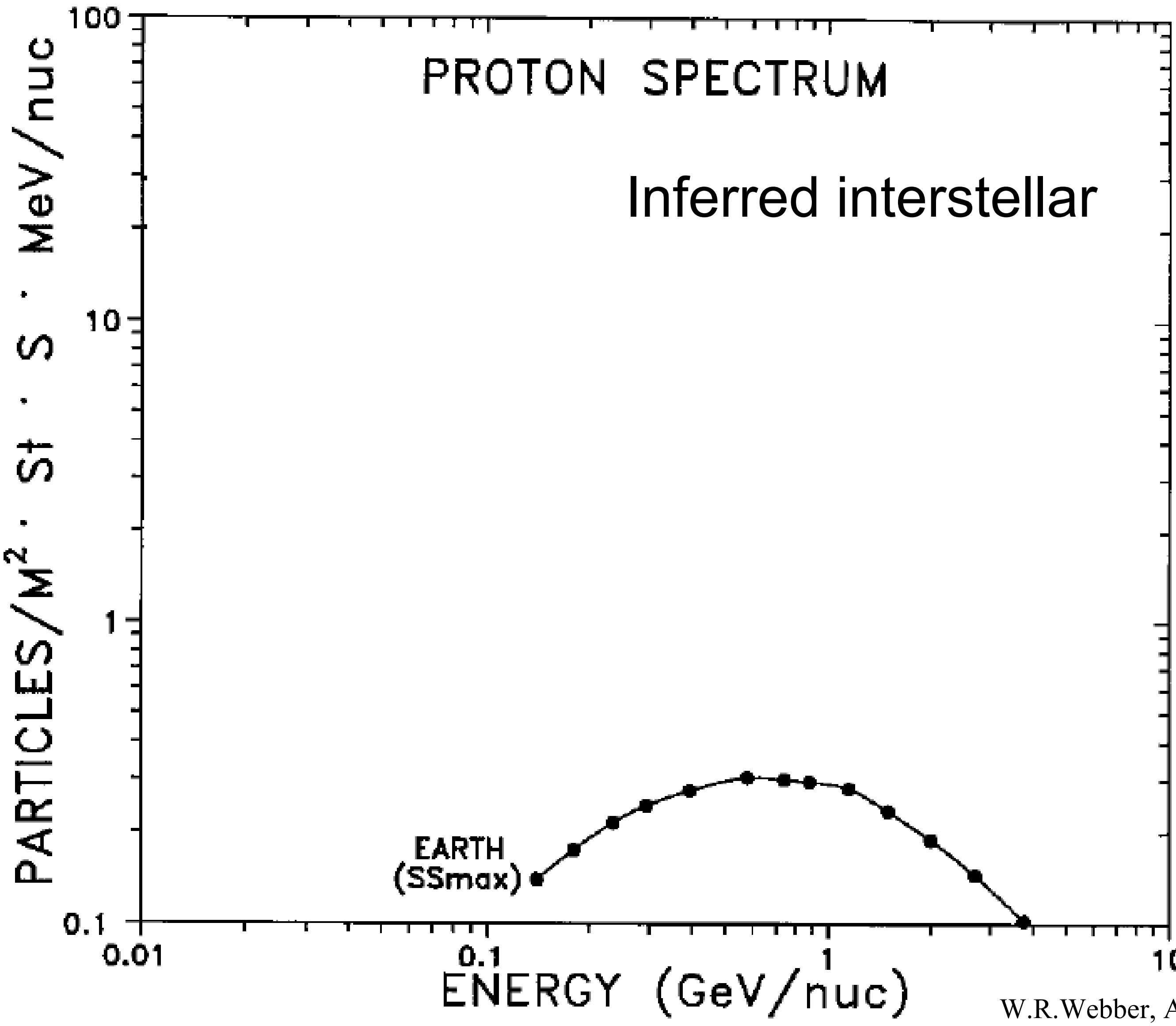
RANGES OF ENERGETIC PROTONS EXPRESSED AS THE PRODUCT OF Rn IN cm^{-2}

E (MeV)	Measured Rn	A_V	Calculated Rn
1..........	2.5×10^{20}	.13	2.6×10^{20}
2..........	8.8×10^{20}	.44	9.2×10^{20}
10.........	1.6×10^{22}	8	1.6×10^{22}
20.........	5.9×10^{22}	30	5.9×10^{22}
50.........	3.2×10^{23}	160	3.2×10^{23}
100.......	1.2×10^{24}	600	1.2×10^{24}



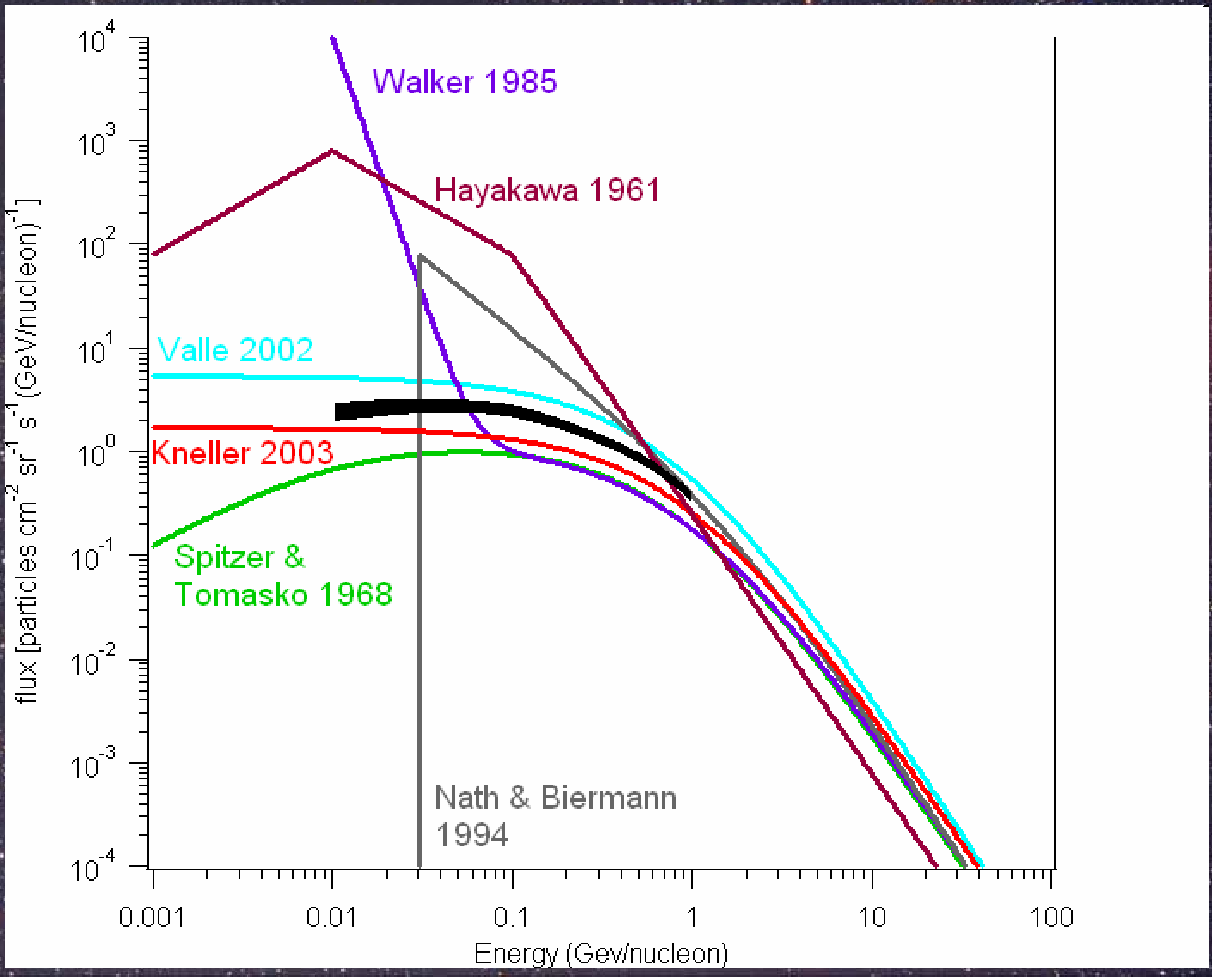
M.D. Stage, G. E. Allen, J. C. Houck, J. E. Davis, Nat. Phys. 2, 614 (2006)

Cosmic Ray Observations

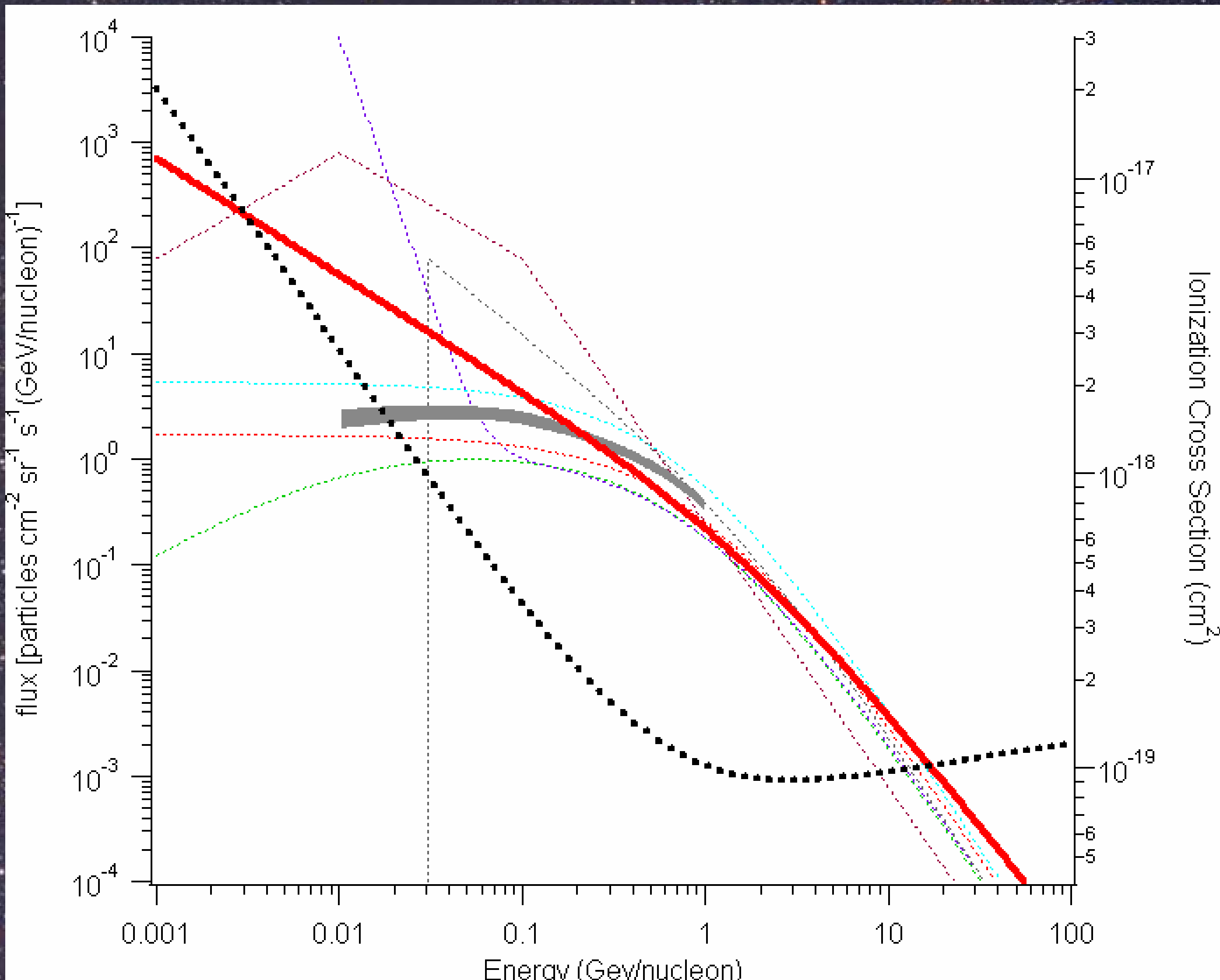


W.R.Webber, ApJ 506, 329 (1998)

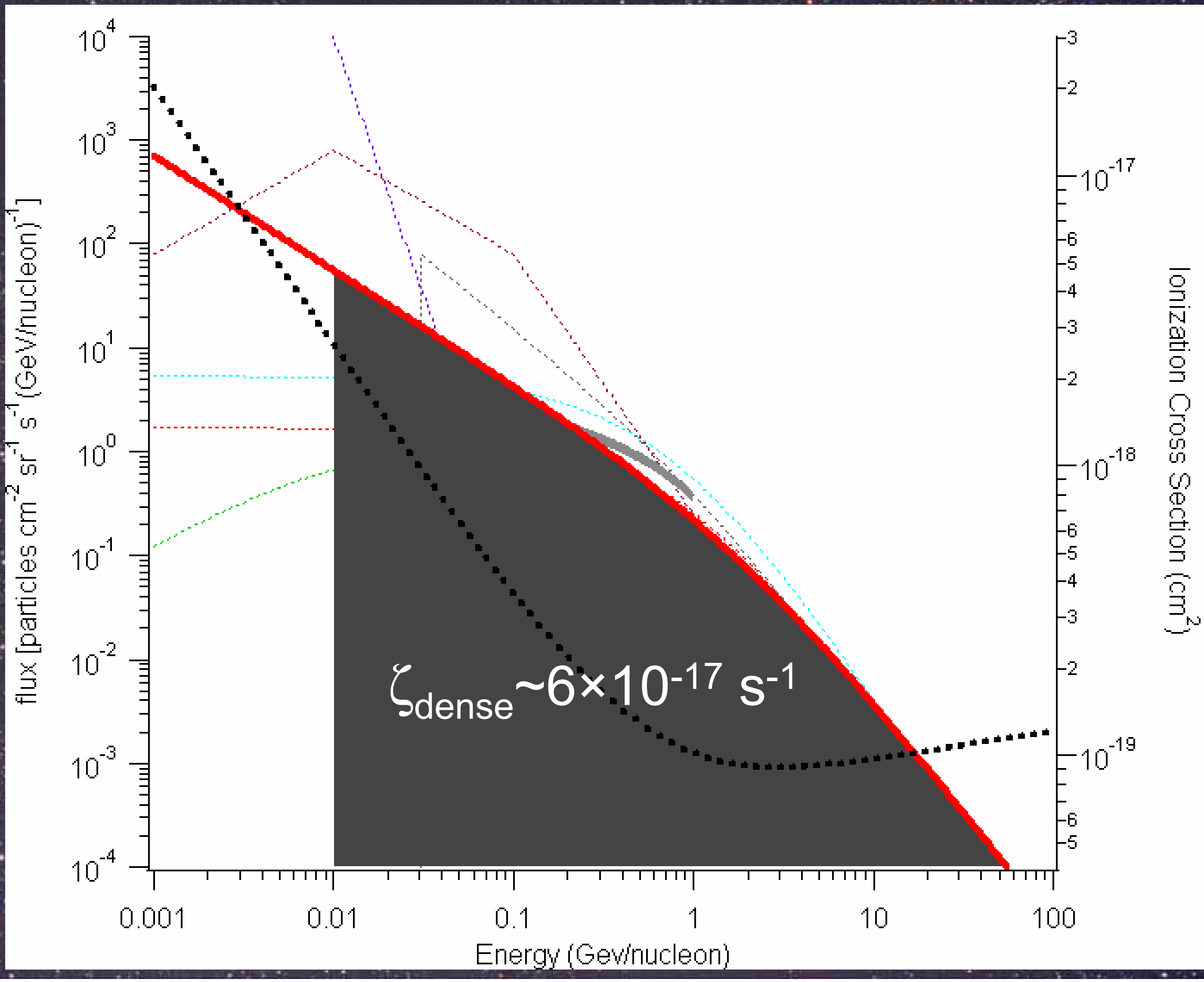
Theoretical Spectra



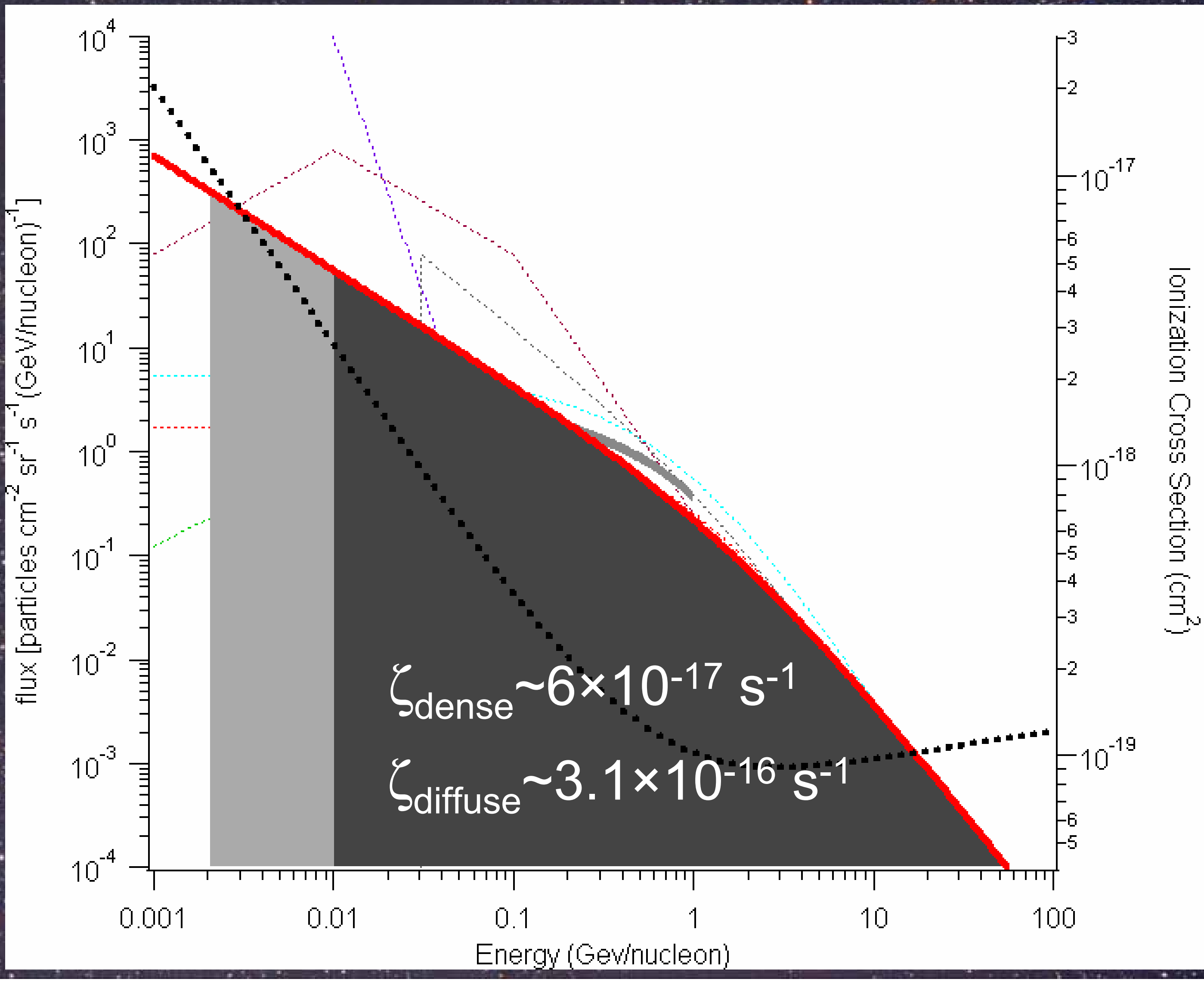
Our "Source" Spectrum



Inferred Ionization Rate



Inferred Ionization Rate



Observational Consequences?

- Energy required for acceleration
  - about 0.2×10^{51} ergs/century
- Heating of diffuse clouds
  - about 1/10 of photoelectric heating
- Production of LiBeB (spallation)
  - roughly consistent with observed abundances
- γ-ray line production (nuclear excitation)
  - below detectable limits

→ our spectrum is not excluded by observations!

Summary

- H_3^+ surprisingly abundant in diffuse clouds
- H_3^+ is direct probe of ionization rate
- Ionization rate ~10× higher than thought
  - only in diffuse clouds
- Two proposed explanations
  - MHD self-confinement (Padoan & Scalo)
  - high flux of low energy cosmic rays

The Future (The Dream?)

- Improved precision in ζ determinations
  - improved density estimates
  - more sophisticated cloud models
- Measure H_3^+ in wider range of sightlines
  - diffuse, translucent, dense clouds
- Infer $\zeta(A_V) \rightarrow$ cosmic ray spectrum
  - information on acceleration mechanism(s)
  - information on galactic propagation

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http://astrochemistry.uiuc.edu

Nick Indriolo

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