Optical and Infrared Observations of Diffuse Clouds

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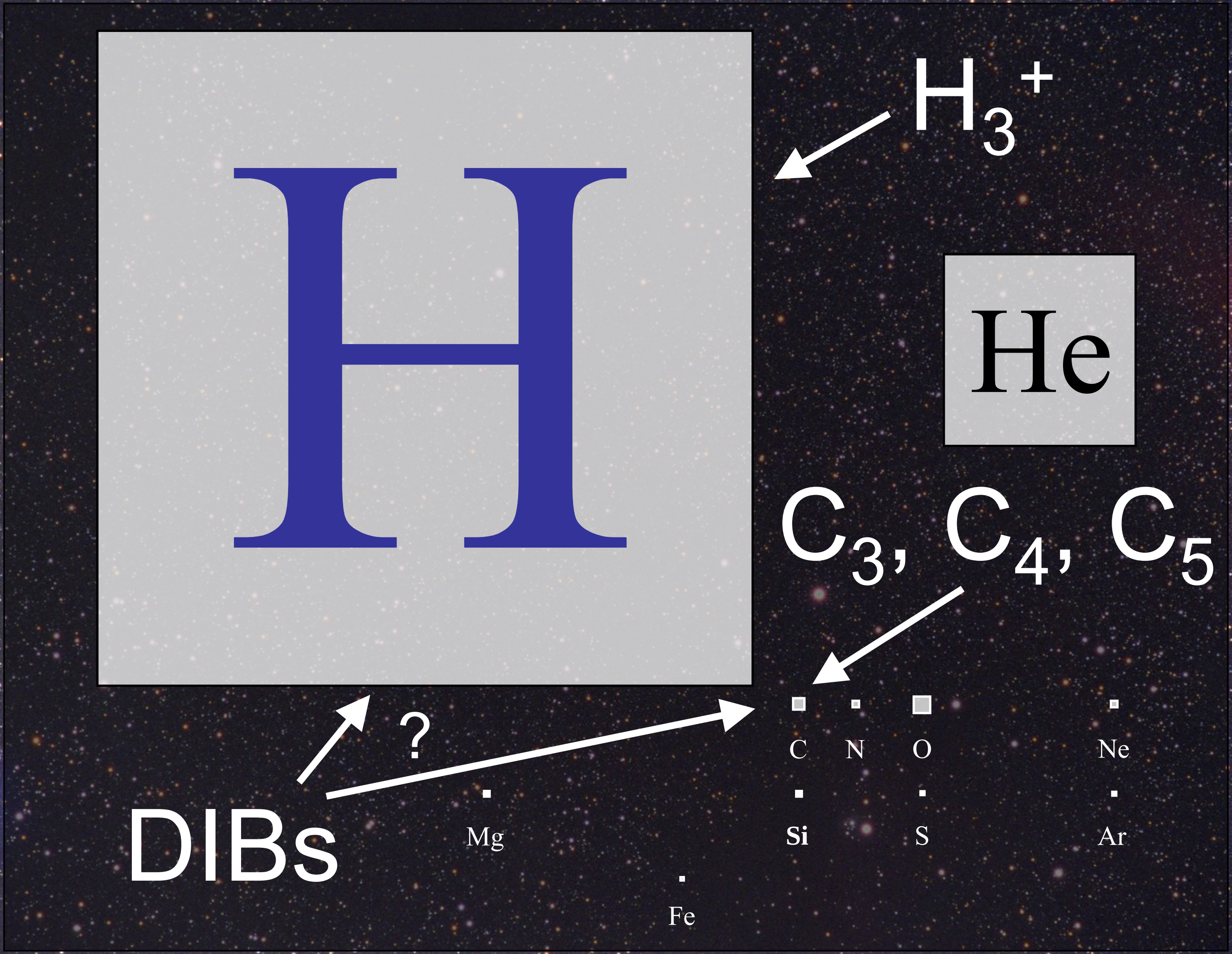
Astronomer's Periodic Table



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:

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


Barnard 68 (courtesy João Alves, ESO)

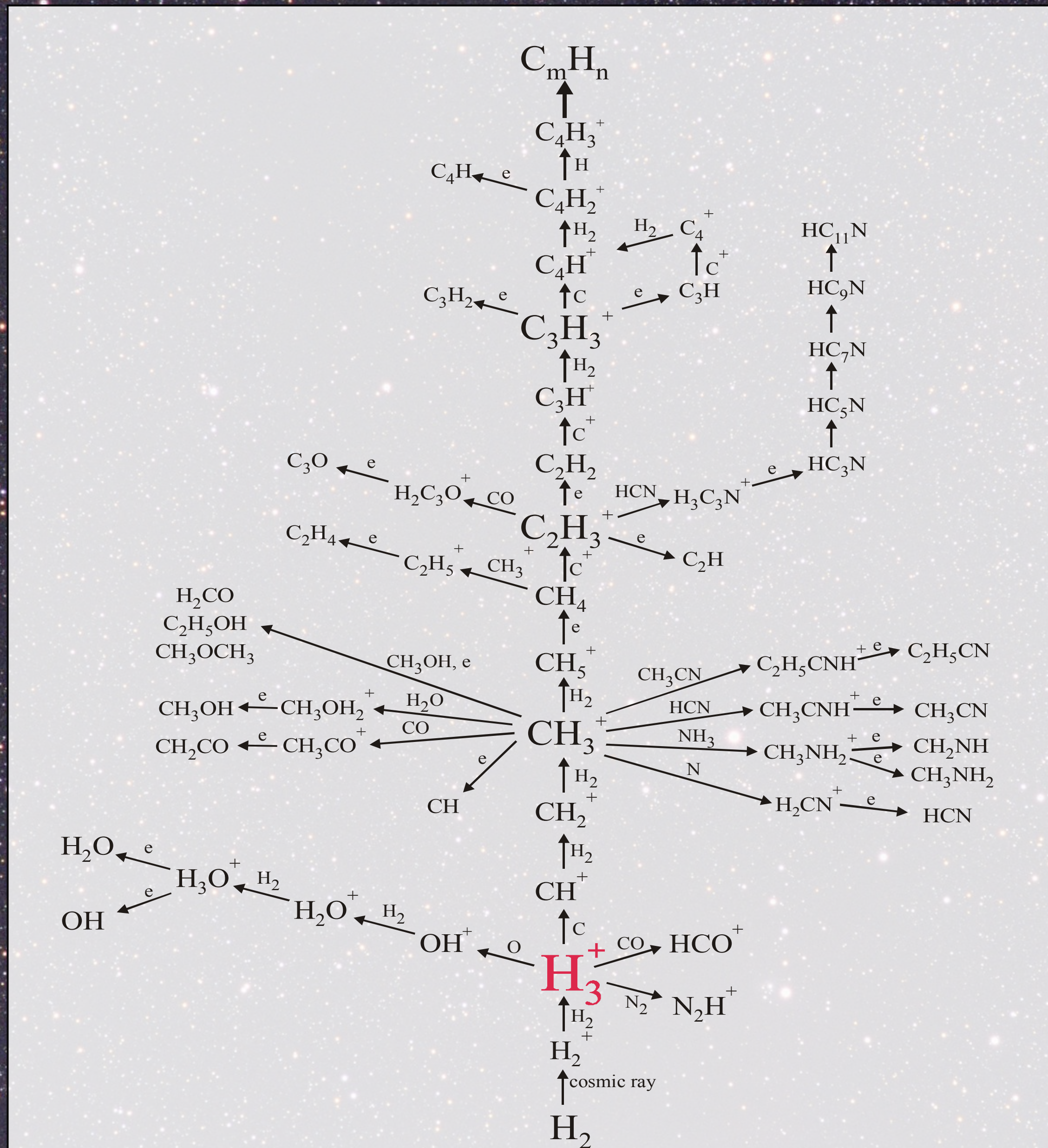
← ζ Persei

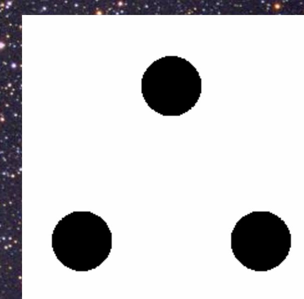
- Diffuse atomic clouds
  - H_2 << 10%
- Diffuse molecular clouds
  - H_2 > 10% (self-shielded)

* Snow & McCall, *ARAA*, in preparation

Photo: Jose Fernandez Garcia

H_3^+: Cornerstone of Interstellar Chemistry





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)

Probe of n, L; consistent with observations

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

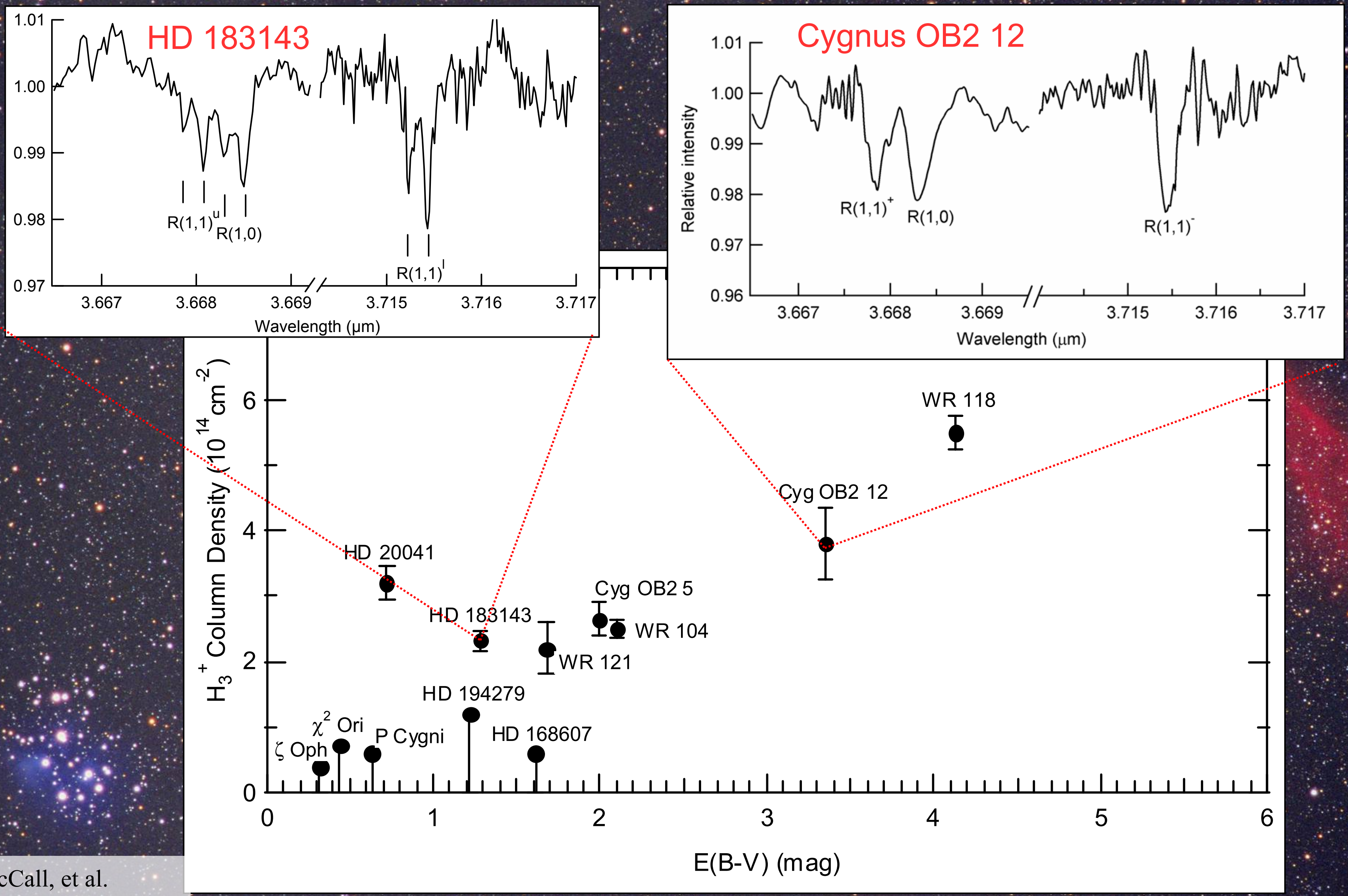
$$[H_3^+] = \frac{\zeta}{k_e}\frac{[H_2]}{[e^-]} = \frac{(3\times10^{-17}\ \text{s}^{-1})}{(5\times10^{-7}\ \text{cm}^3\ \text{s}^{-1})} \times (2400)$$

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

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!

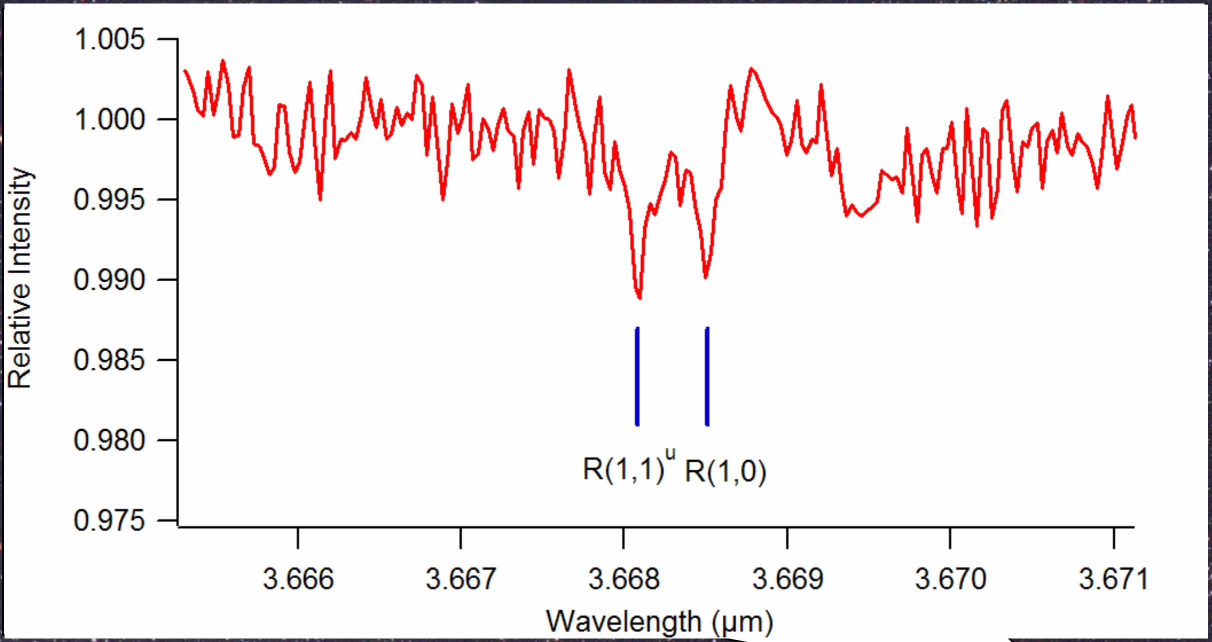
★ 2-3 orders of magnitude!!

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

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

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

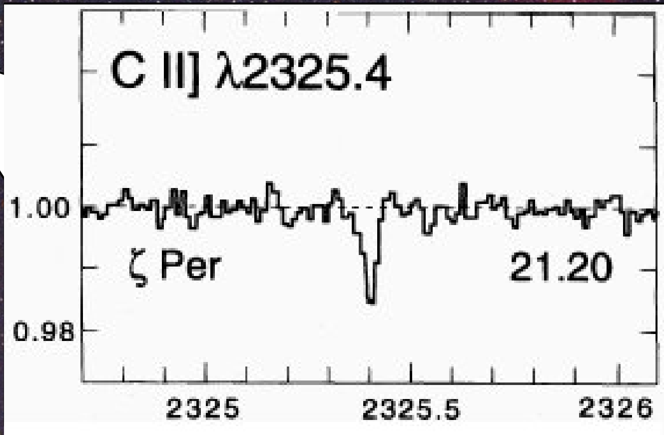
H_3^+ toward ζ Persei



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

$[e^-]/[H_2]$
not to blame

N(C^+) from HST



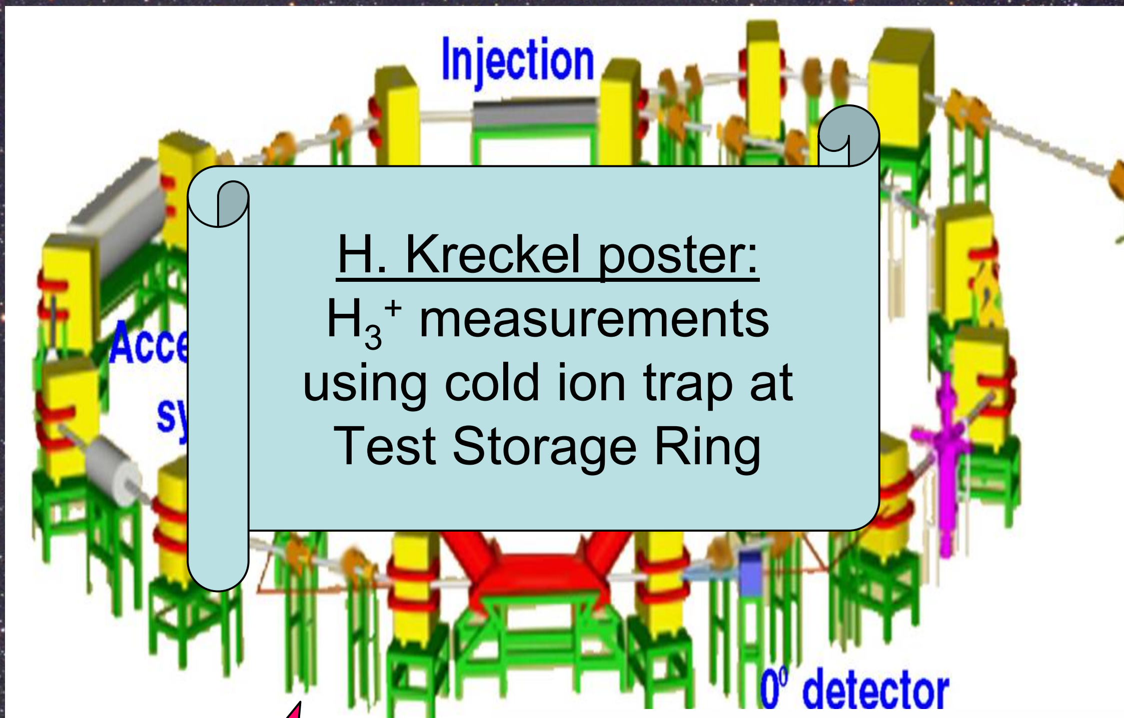
Cardelli et al. ApJ 467, 334 (1996)

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 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	O9.5 Ia	.32	1164	20.34	20.90	21.09

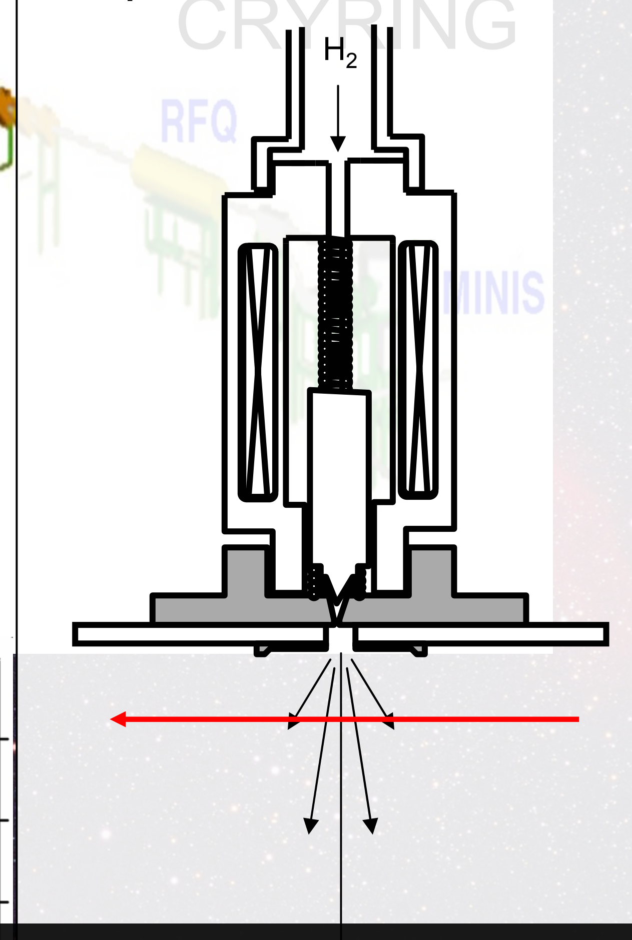
Savage et al. ApJ 216, 291 (1977)

H_3^+ Dissociative Recombination

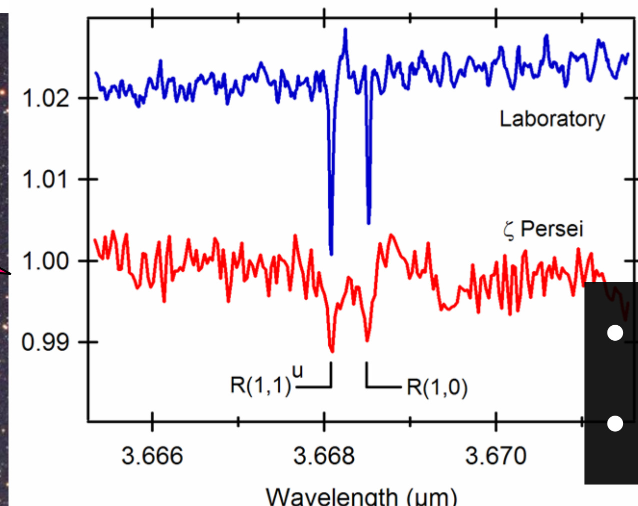


H. Kreckel poster:
H_3^+ measurements using cold ion trap at Test Storage Ring

Supersonic Ion Source



k_e not at fault



- $k_e = 2.6 \times 10^{-7}$ cm^3 s^{-1}
- Factor of two smaller

McCall, et al.
Phys. Rev. A 70, 052716 (2004)

A High Ionization Rate?

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

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

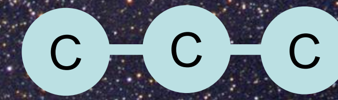
- ~~Smaller recombination rate constant k_e~~
- ~~Smaller electron fraction $[e^-]/[H_2]$~~
- Higher ionization rate ζ (only in diffuse clouds)

- Padoan & Scalo, ApJ 624, L97 (2005)
- Le Petit, Roueff, & Herbst, A&A 417, 993 (2004)

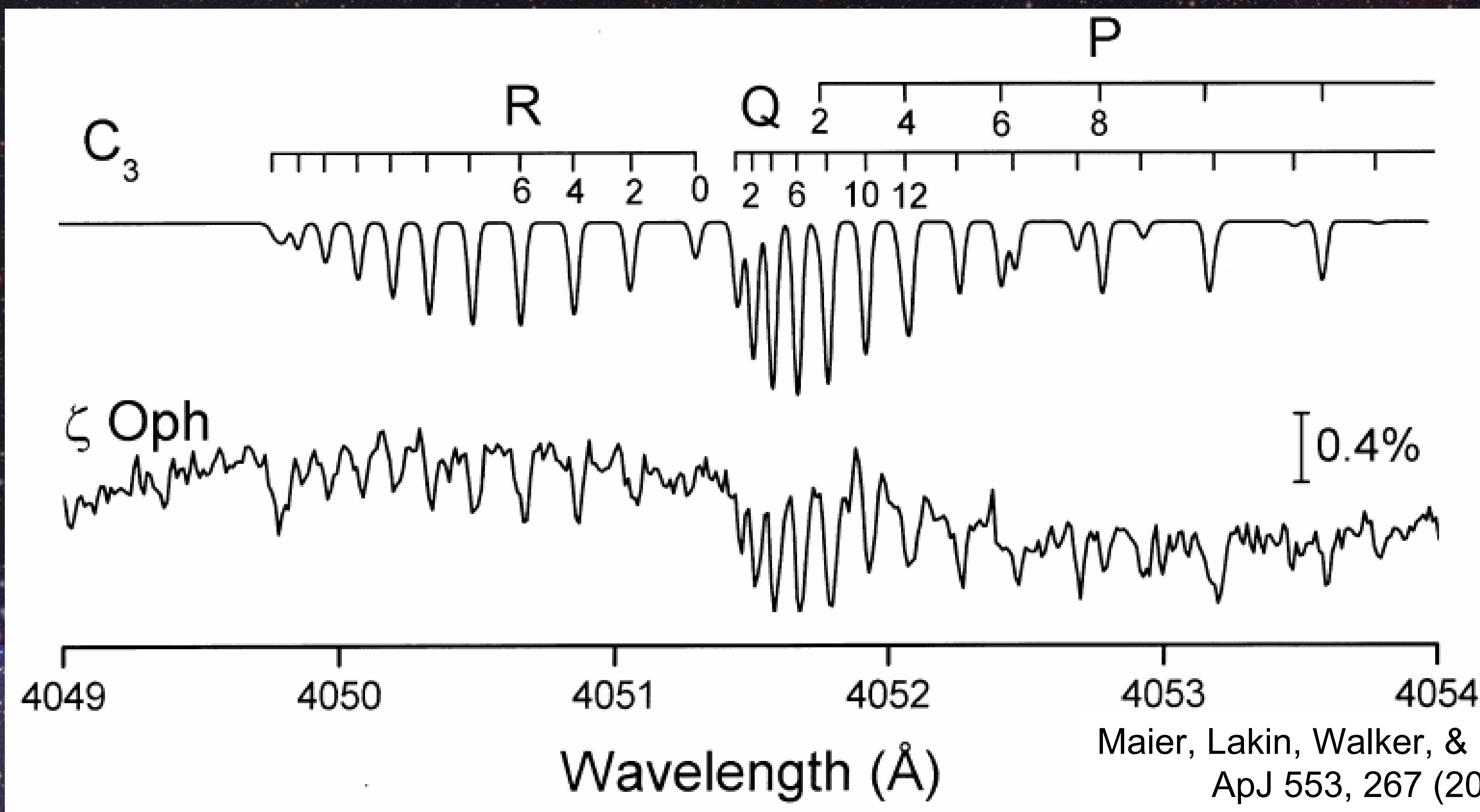
H_3^+ in the Galactic Center!

<u>T. R. Geballe poster:</u>
Detection of metastable
H_3^+ (J=K=3) level
→ low n, high T clouds!

Triatomic Carbon: C_3



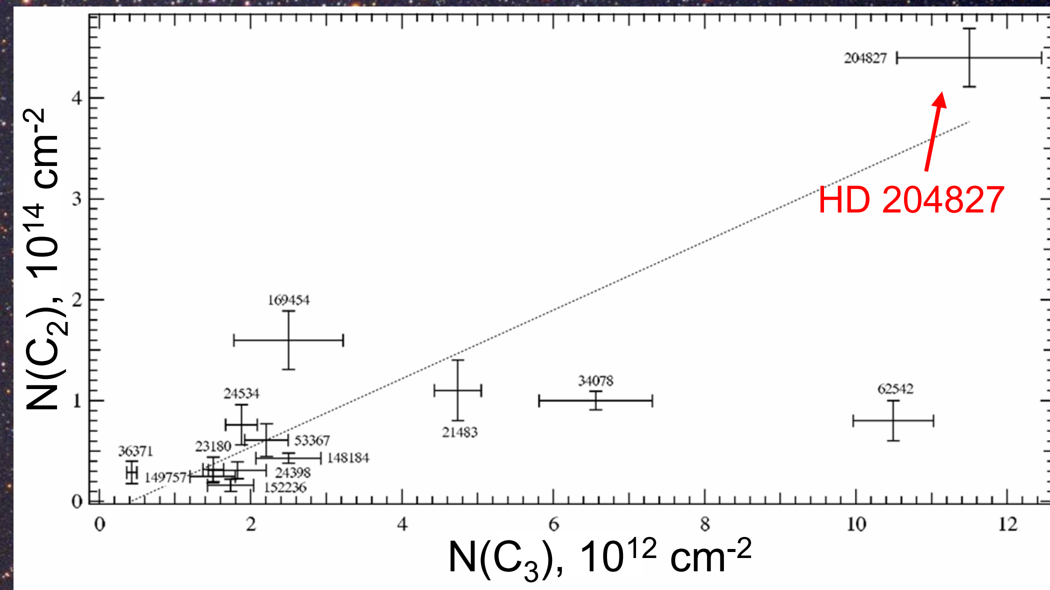
- Detected toward ζ Oph, ζ Per, 20 Aql
  - A $^1\Pi_u$ – X $^1\Sigma_g^+$ 0-0 band
  - first seen by Huggins in a comet in 1881

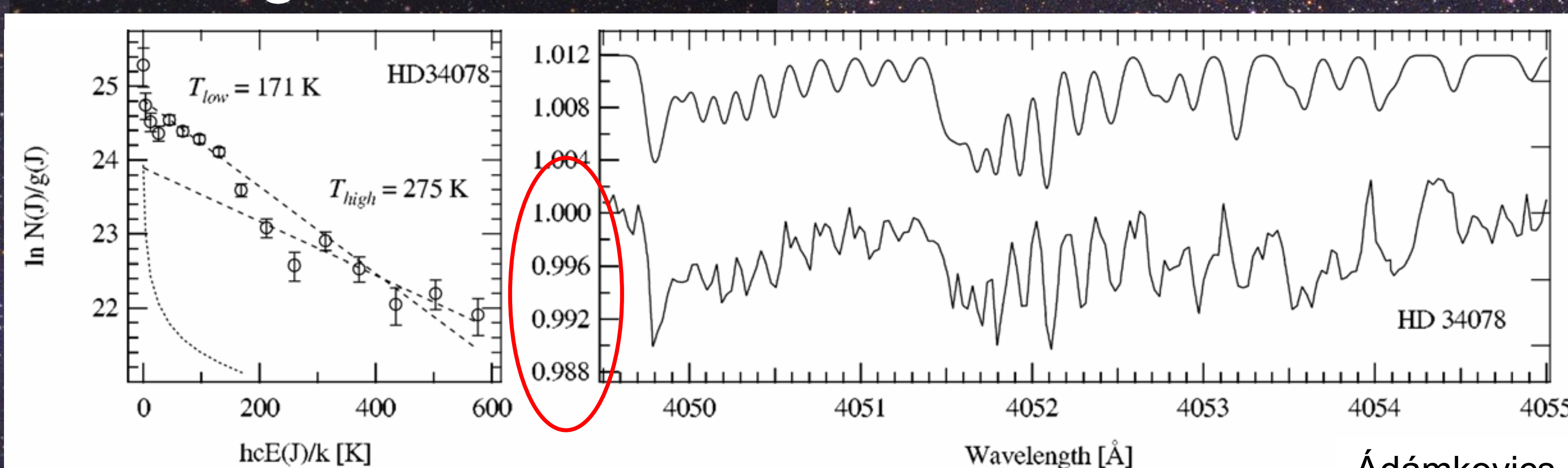


Maier, Lakin, Walker, & Bohlender, ApJ 553, 267 (2001)

Keck/Lick Survey of C_3

- High resolution
  - followup Oka survey*
- High signal/noise
- Fit each N(J)
- Probe of n, T
  - Roueff et al. (2002)
  - model still unpublished!
- 10 sightlines





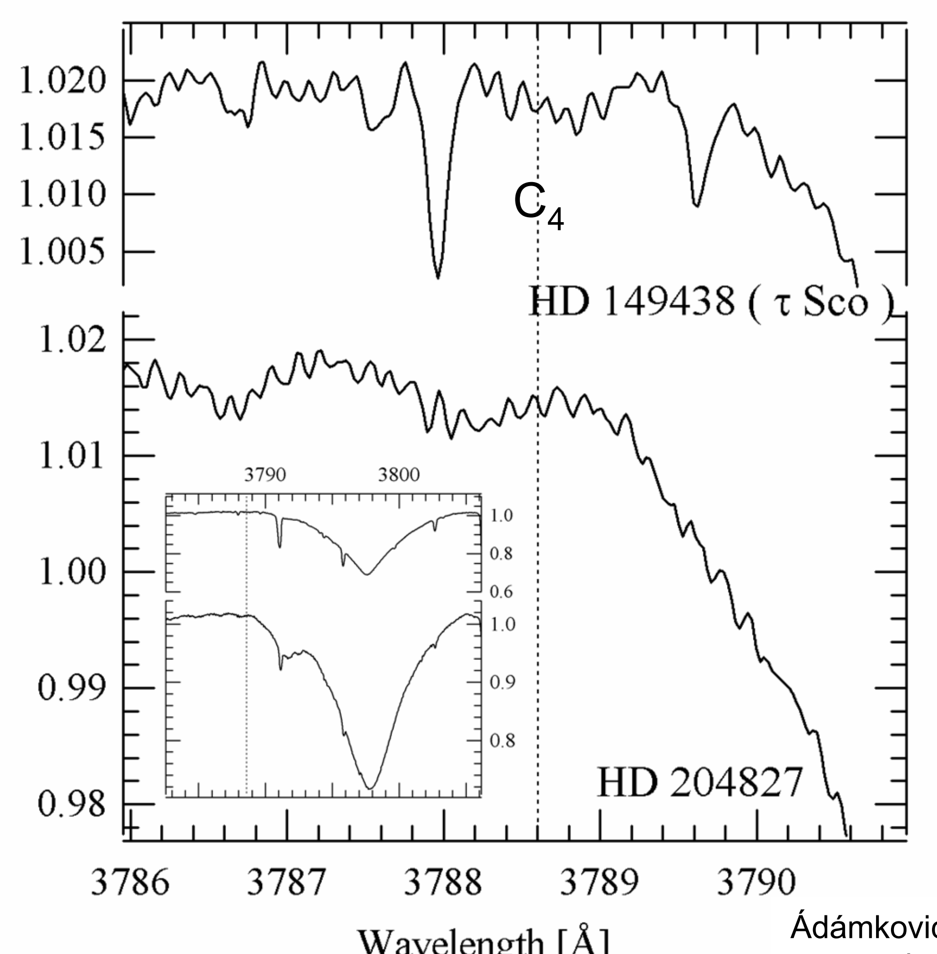
Ádámkovics, Blake, & McCall, ApJ 595, 235 (2003)

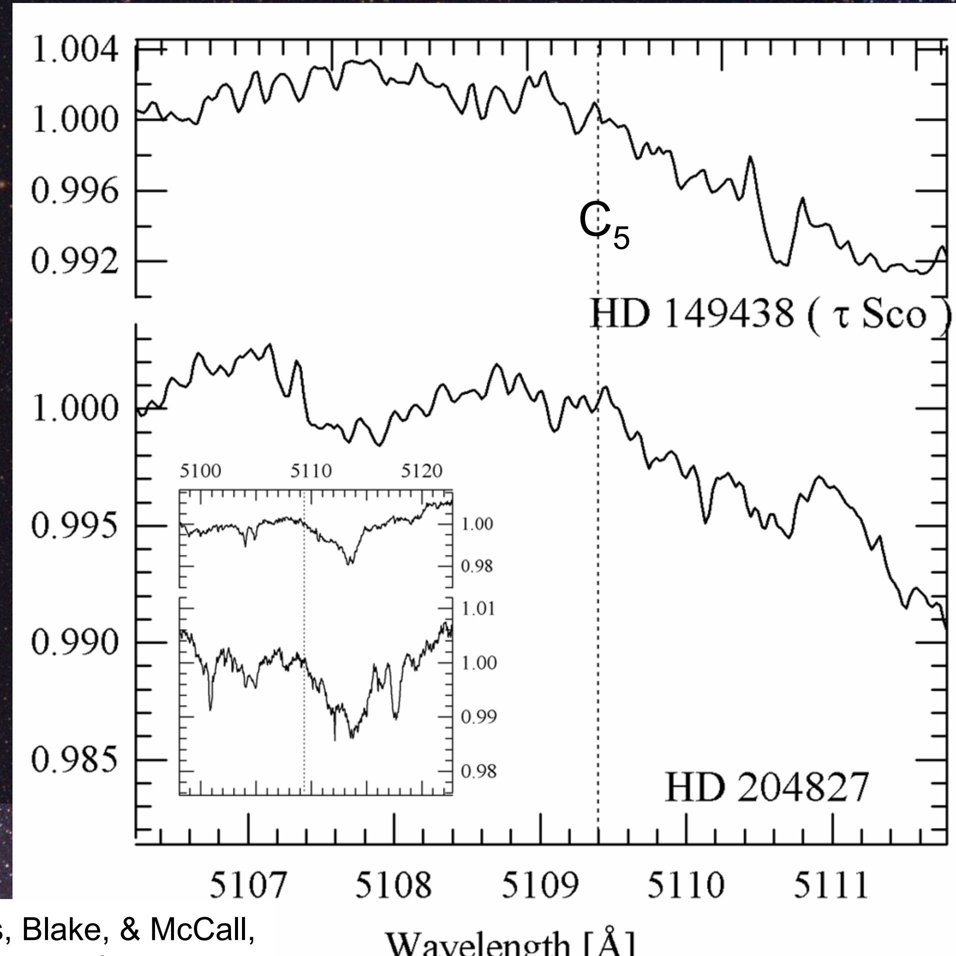
*Oka et al., ApJ 582, 823 (2003)

Keck Search for C_4 & C_5

ApJ 602, 286 (2004)

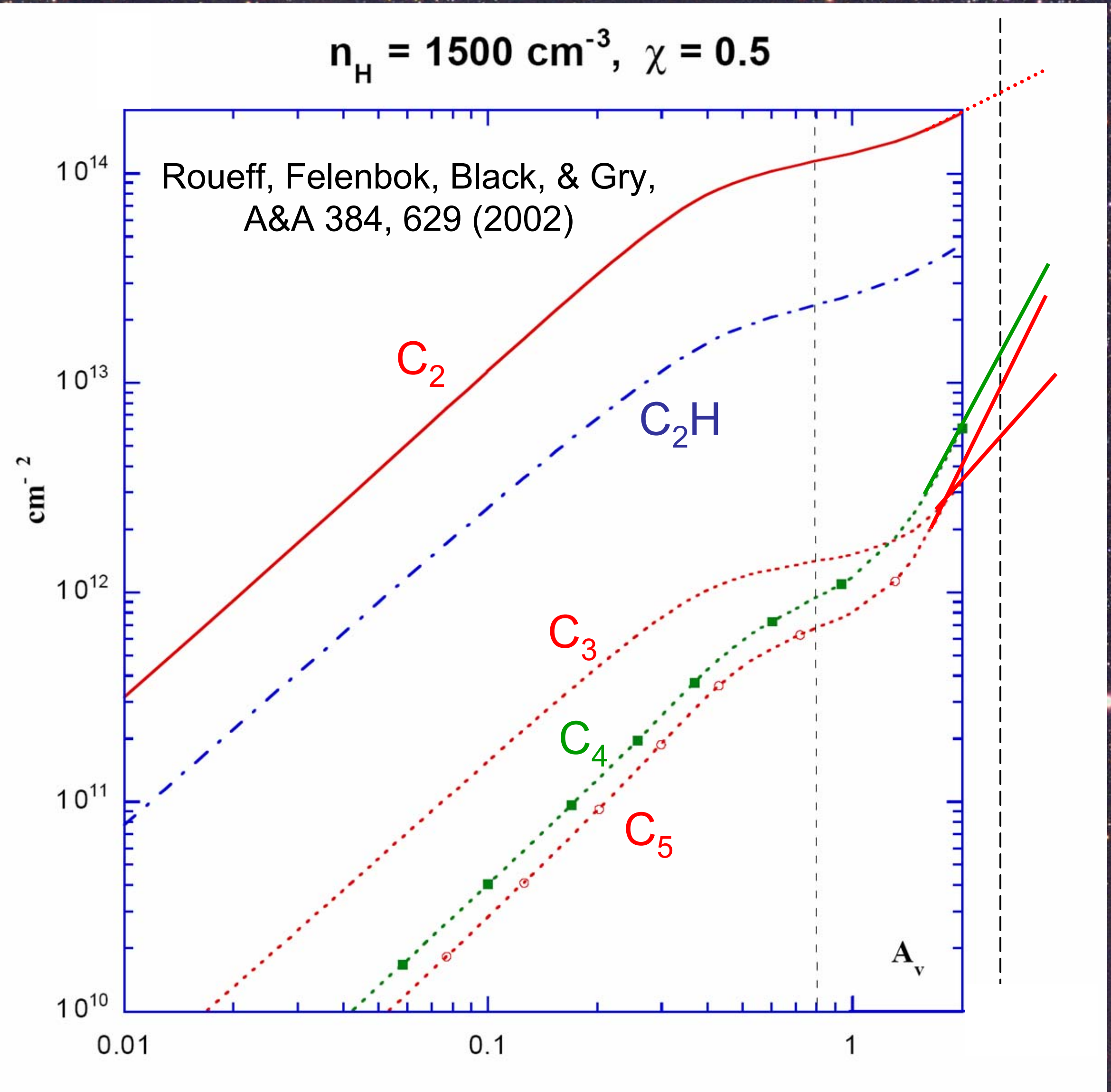
- Maier, Walker, Bohlender → limit toward ζ Oph (V=2.56)
- HD 204827 (V=7.94); 2 nights @ Keck → S/N~1000





Ádámkovics, Blake, & McCall, in preparation

Comparison to Roueff Model

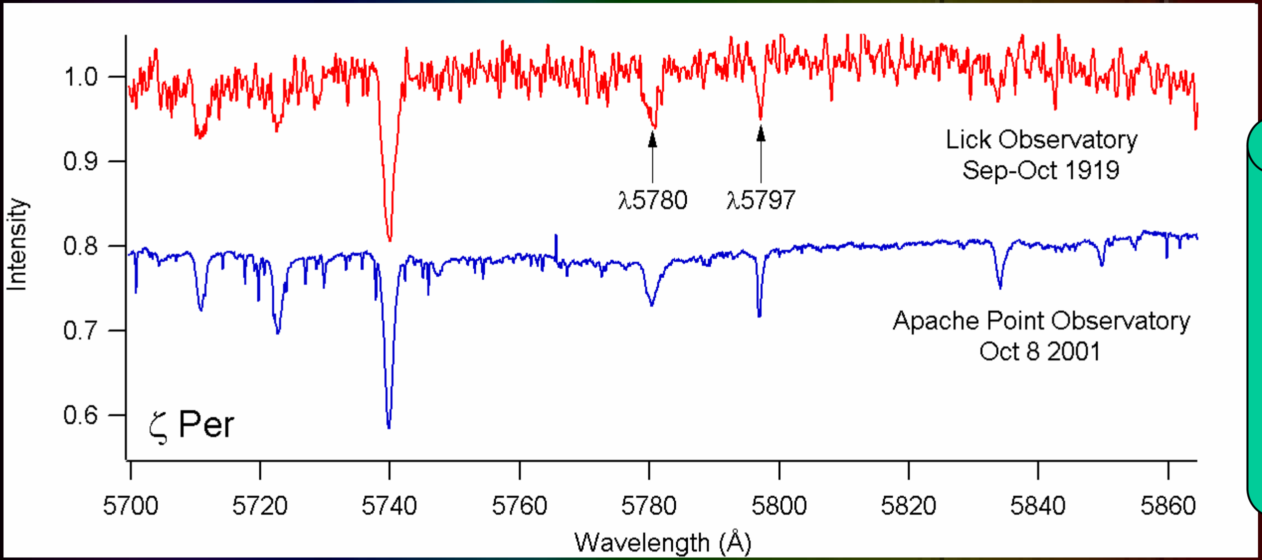


	HD 204827 (A_V=2.6)	
C_2	4.4×10^{14}	(630)
C_3	1.1×10^{13}	(16)
C_4	$< 4 \times 10^{12}$	(<6)
C_5	$< 7 \times 10^{11}$	(<1)

- C_4, C_5 overpredicted
- Multiple clouds with lower A_V ?

Diffuse Interstellar Bands (DIBs)

- Series of >200 absorption lines at visible wavelengths
  - seen in spectra "reddened" stars (obscured by dust & gas)
  - associated with diffuse atomic clouds
- Discovered by Mary Lea Heger
  - $\lambda\lambda$5780, 5797 towards ζ Per, ρ Leo
  - Lick Observatory, 1919

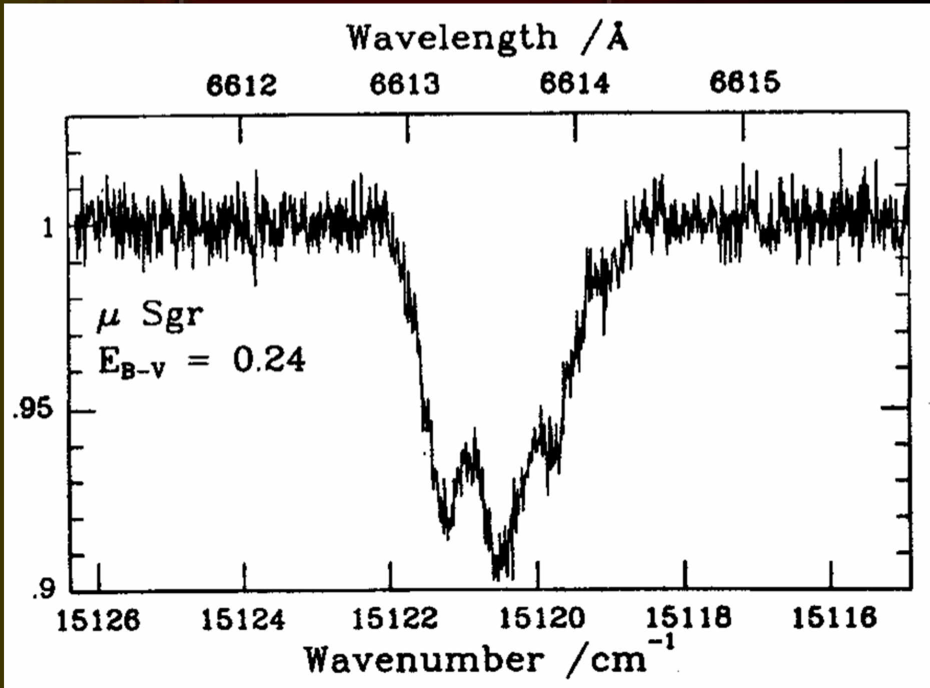


B. J. McCall, in preparation

Related posters:
Cami, Cox, Drosback, Galazutdinov, Huisken, Nirski, Sarre

What are the DIBs?

- Roughly correlated with amount of dust extinction
  - but “level off” at high A_V → diffuse atomic clouds only?
  - for a long time, solid state carriers favored
- Several characteristics argue against dust:
  - constancy of λ
  - lack of emission
  - fine structure!
- Present consensus:
  - gas-phase molecules
  - probably large
  - likely carbon-based
  - reservoir of organic material

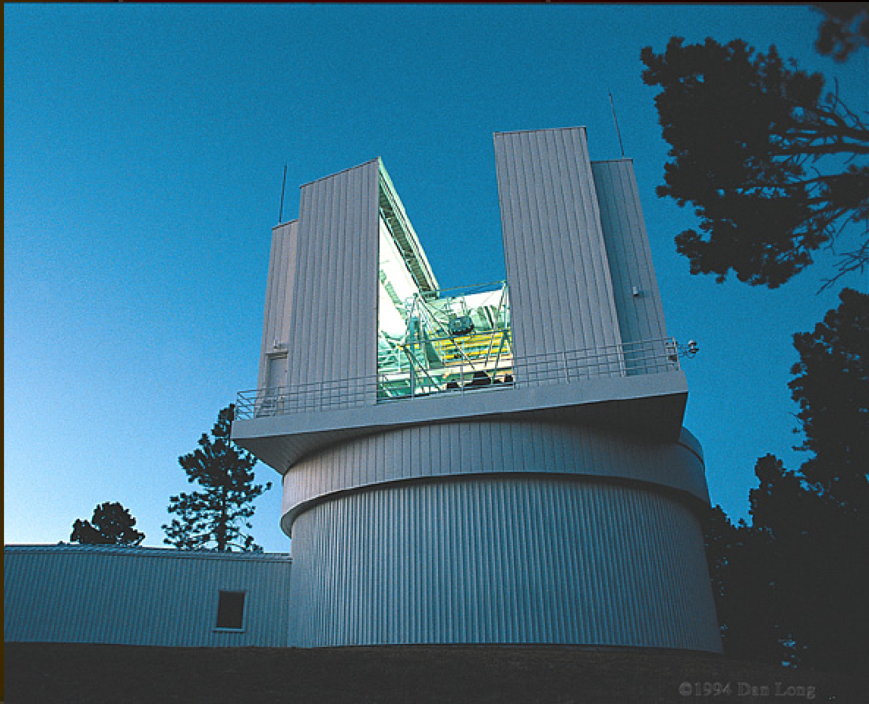


Sarre et al., MNRAS 277, L41 (1995)

- Greatest unsolved mystery in spectroscopy!

The APO DIB Survey

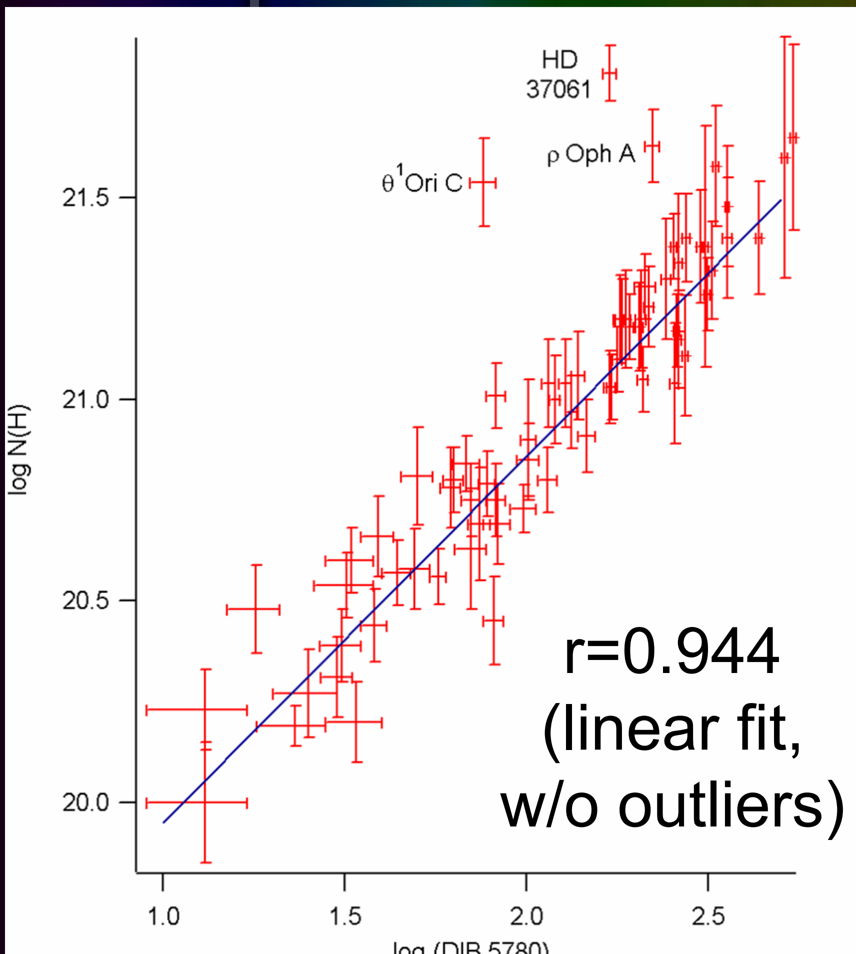
- Apache Point Observatory 3.5-meter
- 3,600–10,200 Å ; $\lambda/\Delta\lambda$ ~ 37,500 (8 km/s)
- 119 nights, from Jan 1999 to Jan 2003
- S/N (@ 5780Å) > 500 for **160** stars (115 reddened)
- Measurements & analysis still very much underway



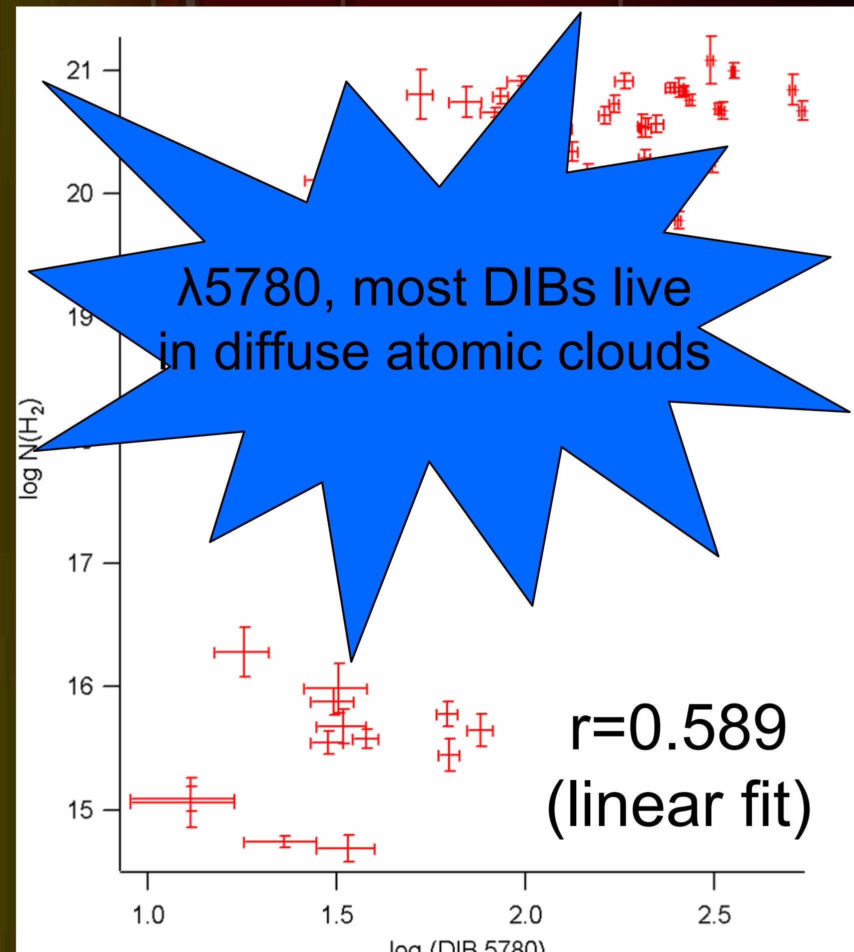
λ5780 and N(H)

well correlated with H

[a la Herbig ApJ 407, 142 (1993)]

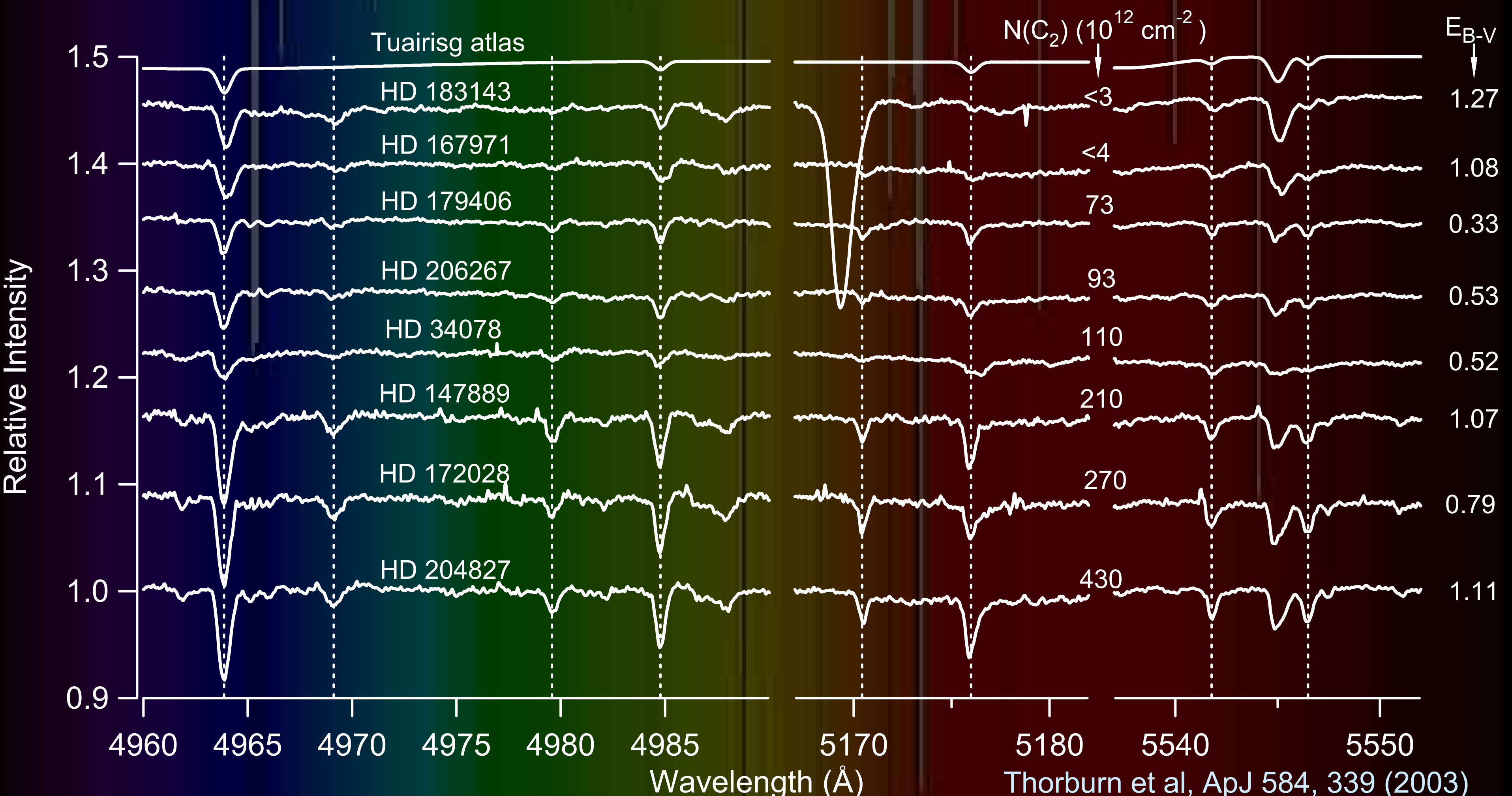


no correlation with H_2



York et al., in preparation

The “C_2 DIBs”

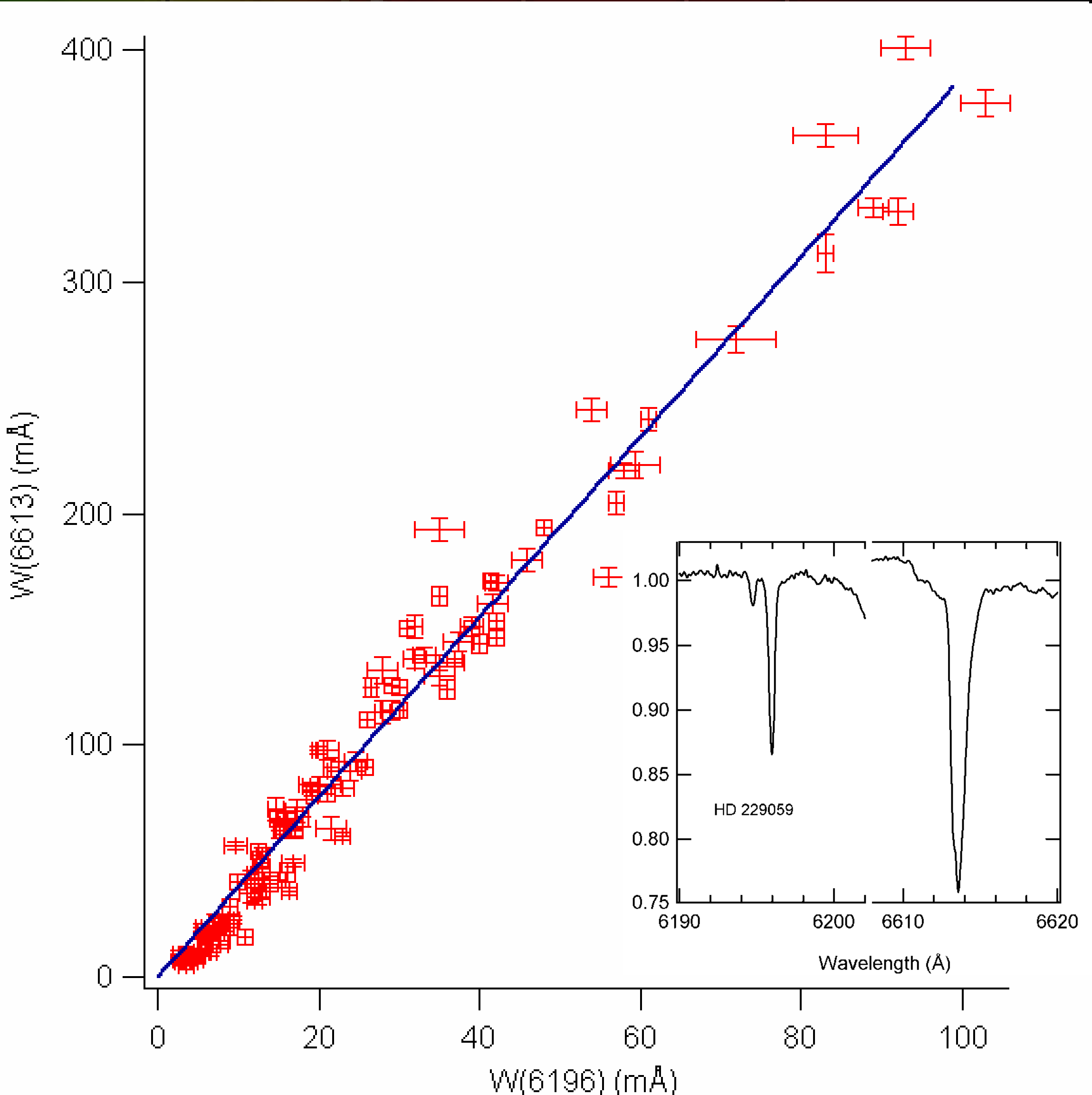


- Seen in HD 62542 → abundant in diffuse molecular clouds?

Ádámkovics, Blake, & McCall ApJ 625, 857 (2005)

Two DIBs from One Molecule?

- Expect most molecules to show >1 vibronic band
- Search for DIBs with same intensity ratio from sightline to sightline
- Plot one DIB intensity vs another, compute correlation coefficient
- λ6613 & λ6196 r=0.986
- Pretty close to perfect!!
- Same molecule?
  - errors underestimated?
- Closely related molecules?
  - can chemistry be so consistent?



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H_3^+ Storage Ring:

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M. Larsson

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T. Oka

Carbon Chains:

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