Observations of H_3^+ in the Diffuse Interstellar Medium

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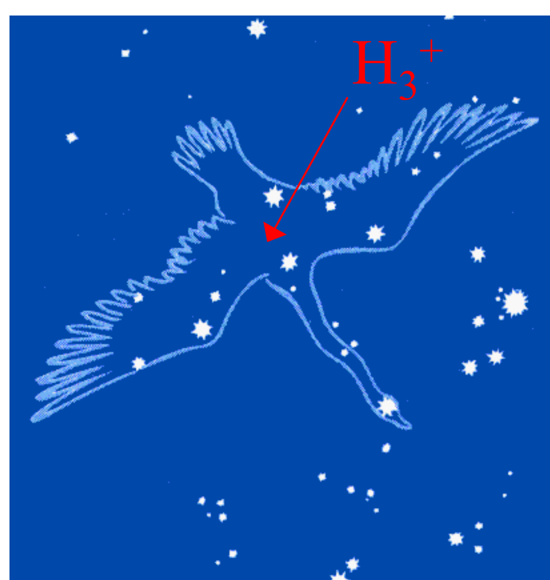


Importance of H_3^+

Ben McCall

H_3^+ is abundantly produced in the interstellar medium through the cosmic-ray ionization of H_2

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

$$H_2 + H_2^+ \rightarrow H_3^+ + H$$

H_3^+ initiates a network of ion-neutral reactions, which is responsible for most observed molecules

$$H_3^+ + X \rightarrow HX^+ + H_2$$

$$HX^+ + Y \rightarrow XY^+ + H$$

$$H_3^+ + O \rightarrow OH^+ + H_2$$

$$OH^+ + H_2 \rightarrow H_2O^+ + H$$

$$H_2O^+ + H_2 \rightarrow H_3O^+ + H$$

$$H_3O^+ + e^- \rightarrow H_2O + H$$

Dense Cloud Chemistry

Ben McCall

Formation of H_3^+:

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

$$H_2 + H_2^+ \rightarrow H_3^+ + H$$

$$\text{Rate} = \zeta\, n(H_2)$$

Destruction of H_3^+:

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

$$\text{Rate} = k_{CO}\, n(H_3^+)\, n(CO)$$

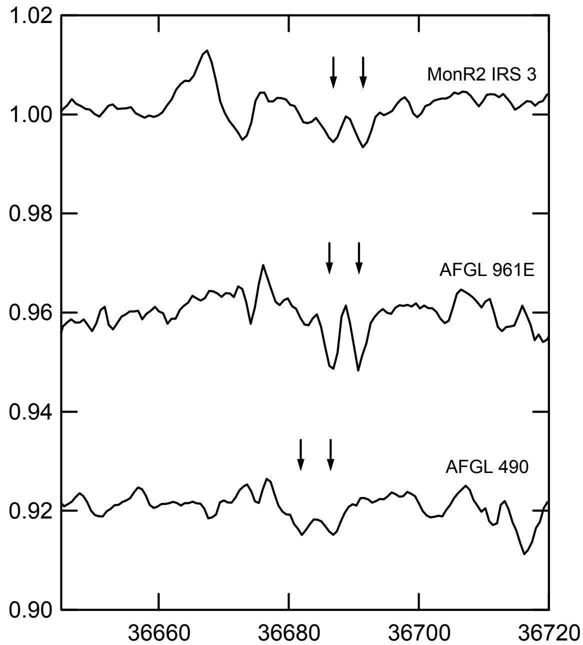
Steady State:

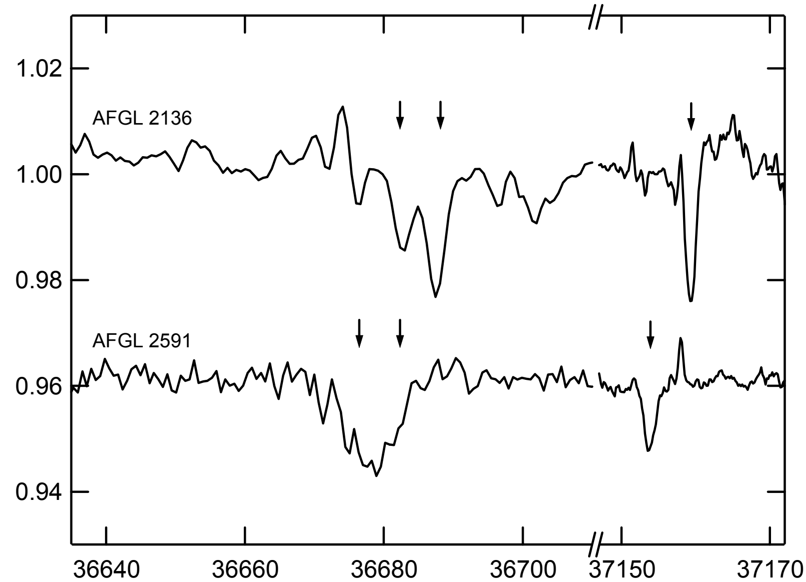
$$n(H_3^+) = \frac{\zeta}{k_{CO}} \frac{n(H_2)}{n(CO)} = \text{constant}$$

$(\sim 10^{-4}\ \text{cm}^{-3})$

H_3^+ in Dense Clouds

Ben McCall





$$L = \frac{N(H_3^+)}{n(H_3^+)} \quad \Rightarrow \quad \sim 1 \text{ parsec}$$

$$\langle n(H_2) \rangle = \frac{N(H_2)}{L} \quad \Rightarrow \quad \sim 10^4\text{–}10^5 \text{ cm}^{-3}$$

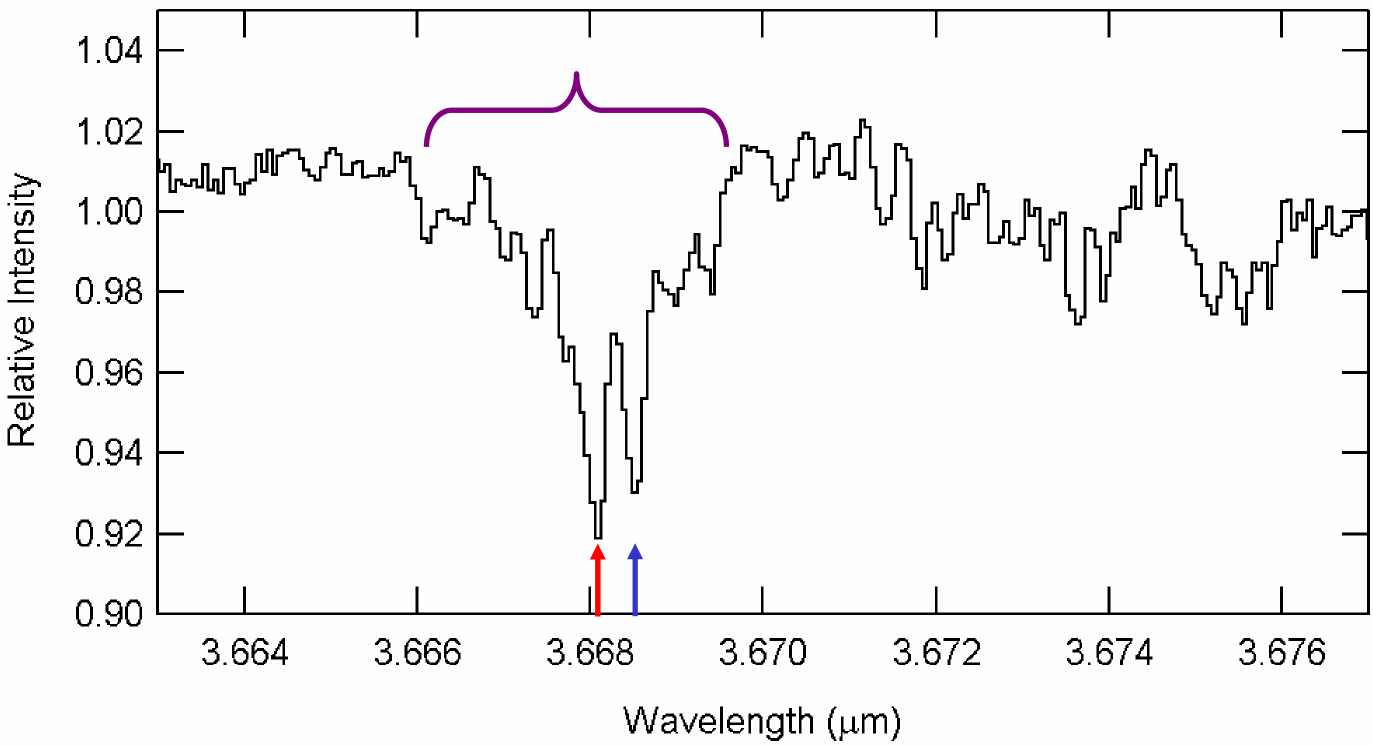
$$\frac{N_{ortho}(H_3^+)}{N_{para}(H_3^+)} = \frac{g_{ortho}}{g_{para}} e^{-\frac{\Delta E}{kT}} \quad \Rightarrow \quad \sim 25\text{–}50 \text{ K}$$

Agreement with canonical dense cloud values confirms ion-neutral reaction scheme.

McCall, Geballe, Hinkle, & Oka
ApJ, Sep. 1, 1999

Galactic Center

Ben McCall



$N_{para} = 5.1(1.7) \times 10^{14}\ cm^{-2}$

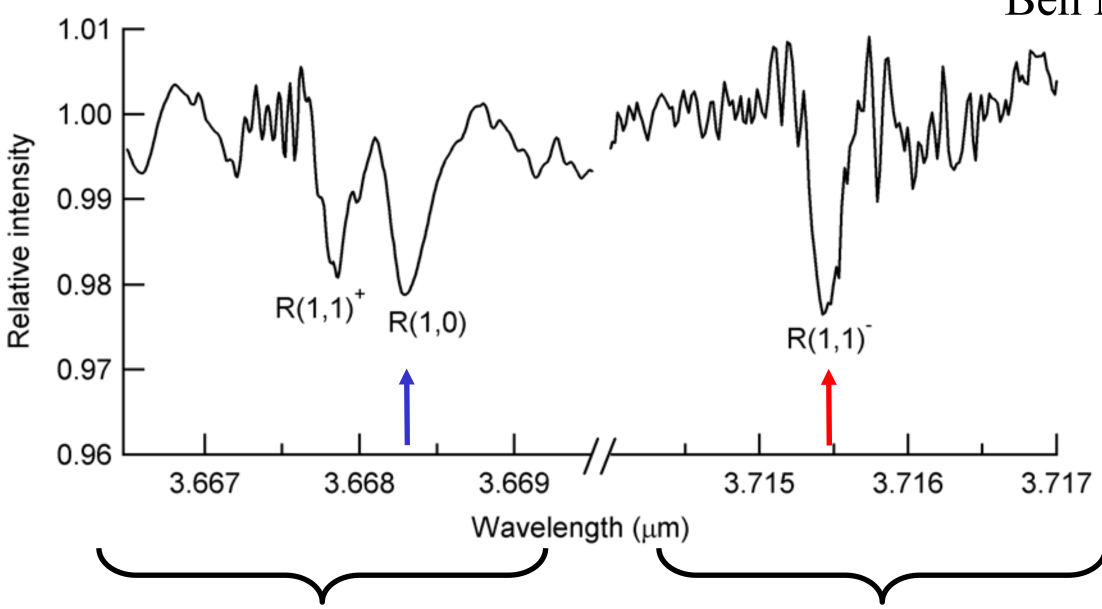
$N_{ortho} = 2.4(1.1) \times 10^{14}\ cm^{-2}$

$N_{broad} = 17.5(3.9) \times 10^{14}\ cm^{-2}$

Geballe, McCall, Hinkle, & Oka
ApJ, 510, 251 (1999)

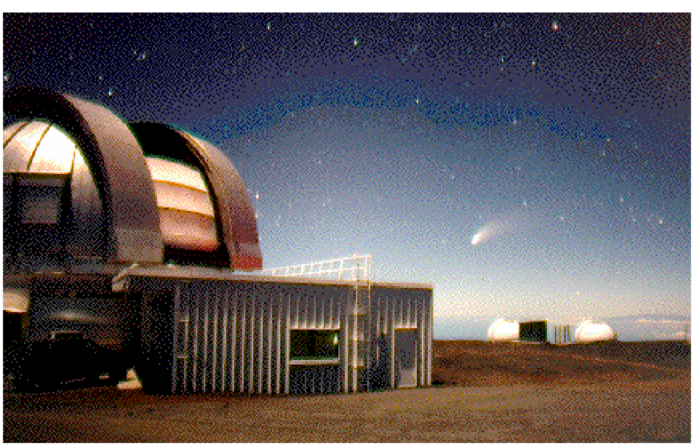
Cygnus OB2 #12

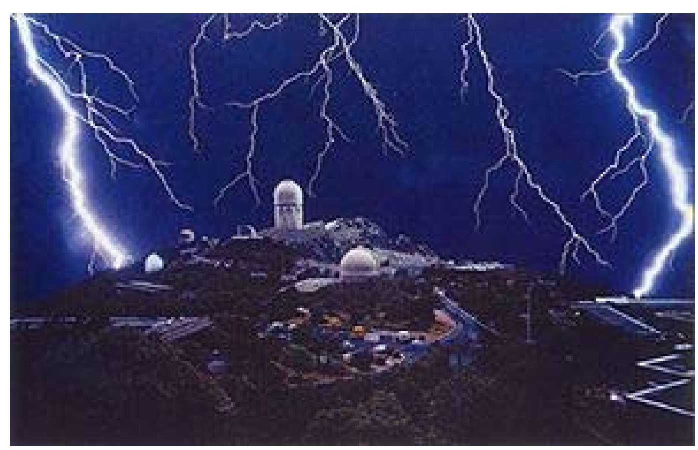
Ben McCall



observed at UKIRT

observed at Kitt Peak



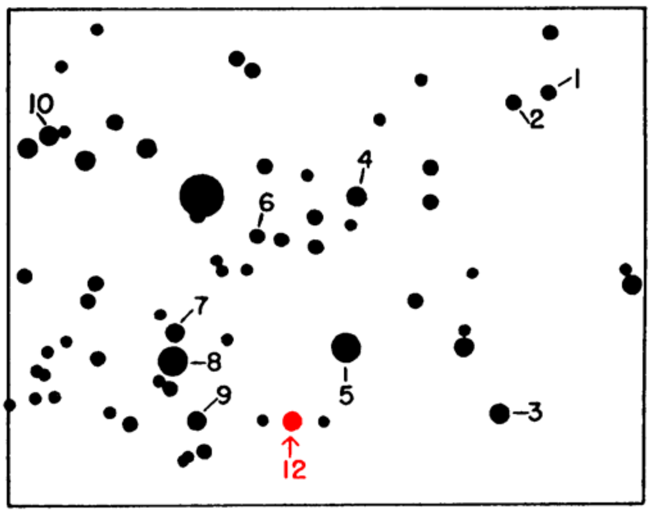


$$N_{para} = 2.4(3) \times 10^{14}\ \mathrm{cm}^{-2}$$
$$N_{ortho} = 1.4(2) \times 10^{14}\ \mathrm{cm}^{-2}$$

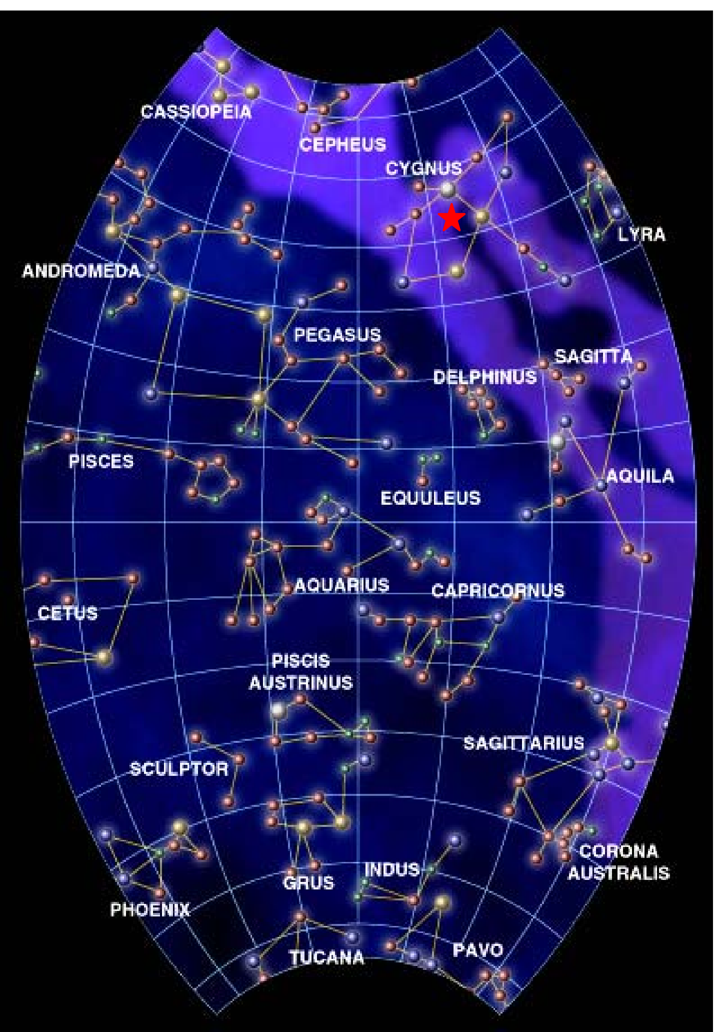
Similar column density to dense clouds!!

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

About Cyg OB2 #12



Morgan, Johnson, & Roman
PASP 66, 85 (1954)



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- ★ d ~ 1.7 kpc
- ★ ℓ ~ 80°, b ~ 0°
- ★ A_V ~ 10 mag
- ★ N(H) ~ 2 × 10^{22} cm^{-2}
- ★ M_V ~ -10 mag!
- ★ spectral type B5Ie
- ★ stellar wind ~ 1400 km/s

- ★ no 3.08 μm ice feature
  ⇒ no dense clouds
- ★ strong 3.4 μm C-H band
  ⇒ diffuse clouds
- ★ CH, C_2 observations
  suggest n ~ 300 cm^{-3}

Is it Really Diffuse?

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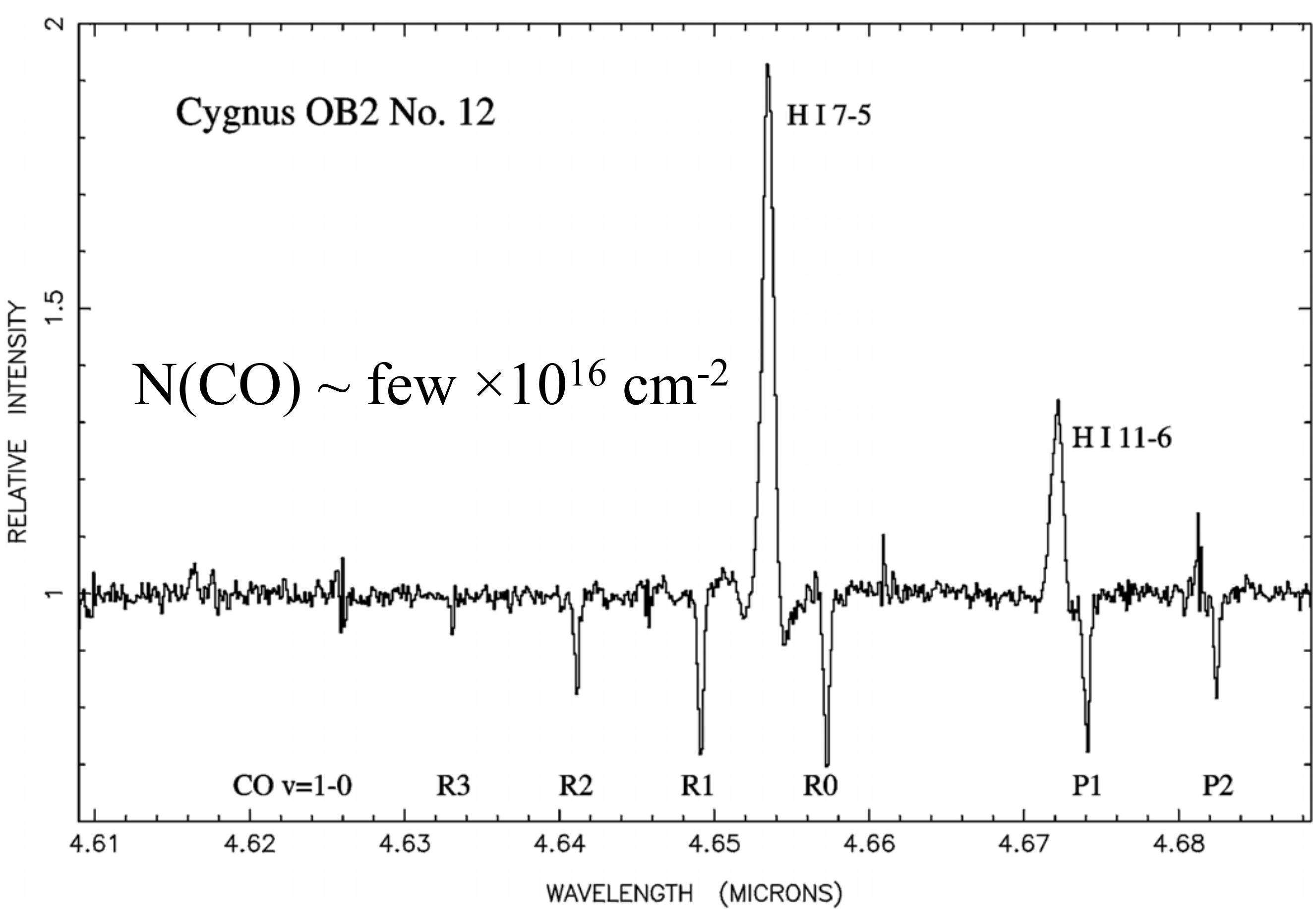
- ★ Absence of 3.08 μm ice feature
- ★ Presence of 3.4 μm band
- ★ N(CO)/N(ΣC) < 5%



Maybe Partly Diffuse?

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Suppose we put all of the observed CO in a dense cloud — can this cloud explain the H_3^+ absorption?

$$N(CO) \sim \text{few} \times 10^{16}\ \text{cm}^{-2}$$
$$\Downarrow$$
$$N(H_2) \sim \text{few} \times 10^{20}\ \text{cm}^{-2}$$

$$n(H_3^+) \sim 10^{-4}\ \text{cm}^{-3} \text{ and } N(H_3^+) = 4 \times 10^{14}\ \text{cm}^{-2}$$
$$\Downarrow$$
$$L \sim 4 \times 10^{18}\ \text{cm}$$
$$\Downarrow$$
$$n(H_2) \sim 100\ \text{cm}^{-3}$$

Not a dense cloud density! $\Rightarrow\Leftarrow$

Diffuse Cloud Chemistry

Ben McCall

Formation of H_3^+:

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

$$H_2 + H_2^+ \rightarrow H_3^+ + H$$

$$\text{Rate} = \zeta\, n(H_2)$$

Destruction of H_3^+:

$$H_3^+ + e^- \rightarrow H + H + H \quad (75\%)$$

$$\rightarrow H + H_2 \quad (25\%)$$

$$\text{Rate} = k_e\, n(H_3^+)\, n(e^-)$$

Steady State:

$$n(H_3^+) = \frac{\zeta}{k_e} \frac{n(H_2)}{n(e^-)} = \text{constant}$$

Diffuse Cloud Results

Ben McCall

$$n(H_3^+) = \frac{\zeta}{k_e} \frac{n(H_2)}{n(e^-)} = \frac{\zeta}{k_e} f(H_2) \frac{n(\Sigma H)}{n(\Sigma C)}$$

<u>Adopted Constants:</u>

$\zeta = 3 \times 10^{-17}$ s^{-1}

$k_e = 2 \times 10^{-7}$ cm^3 s^{-1}

$f(H_2) \sim 1/4$

$H/C \sim 10^4$

$$n(H_3^+) \sim 4 \times 10^{-7} \text{ cm}^{-3}$$

But $N(H_3^+) = 4 \times 10^{14}$ cm^{-2}

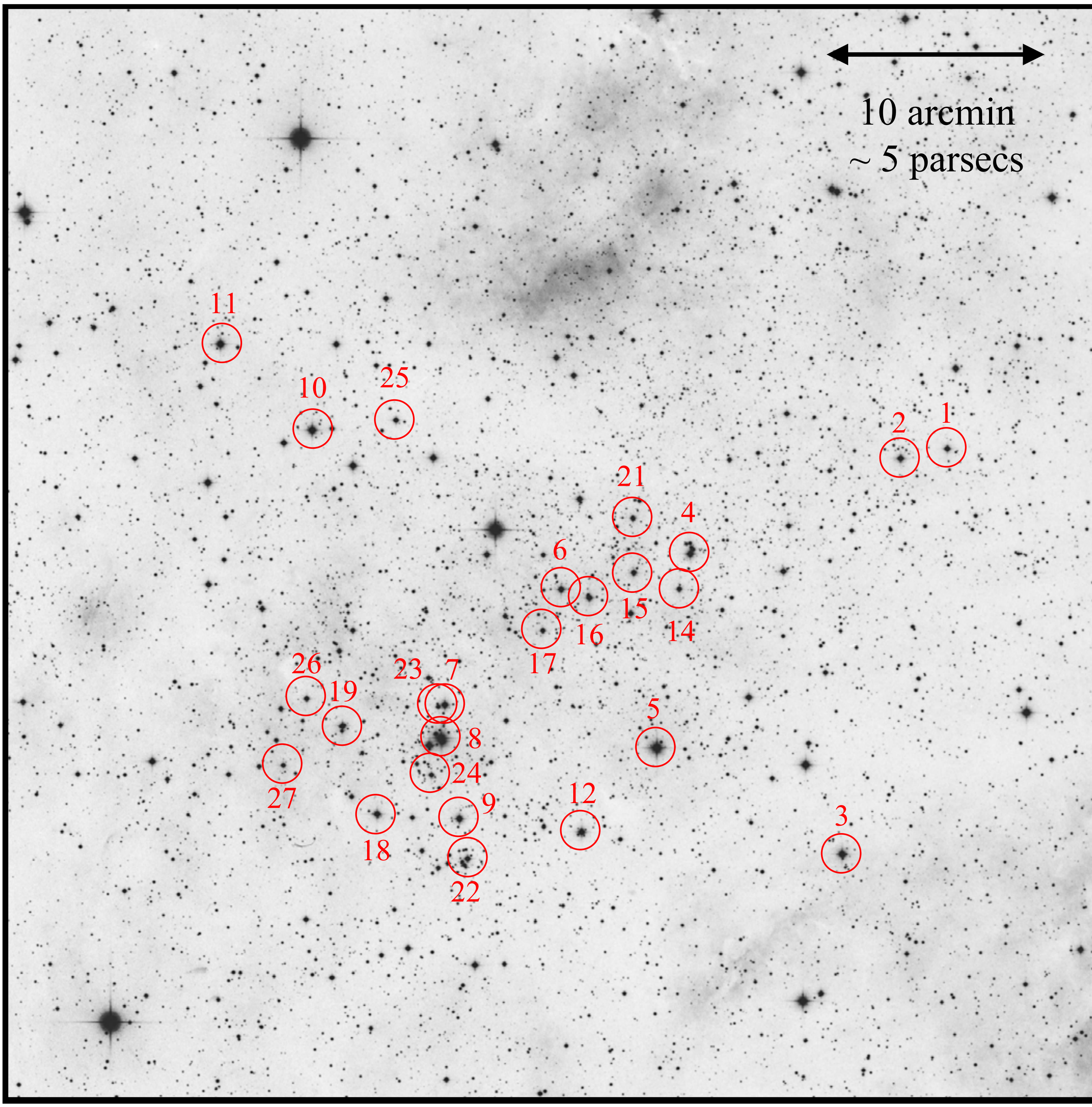
$\Downarrow$

so $L \sim 10^{21}$ cm ~ 300 pc!

Seems unreasonably long...

Cygnus OB2 Association

Ben McCall



Cyg OB2 #5 Spectrum

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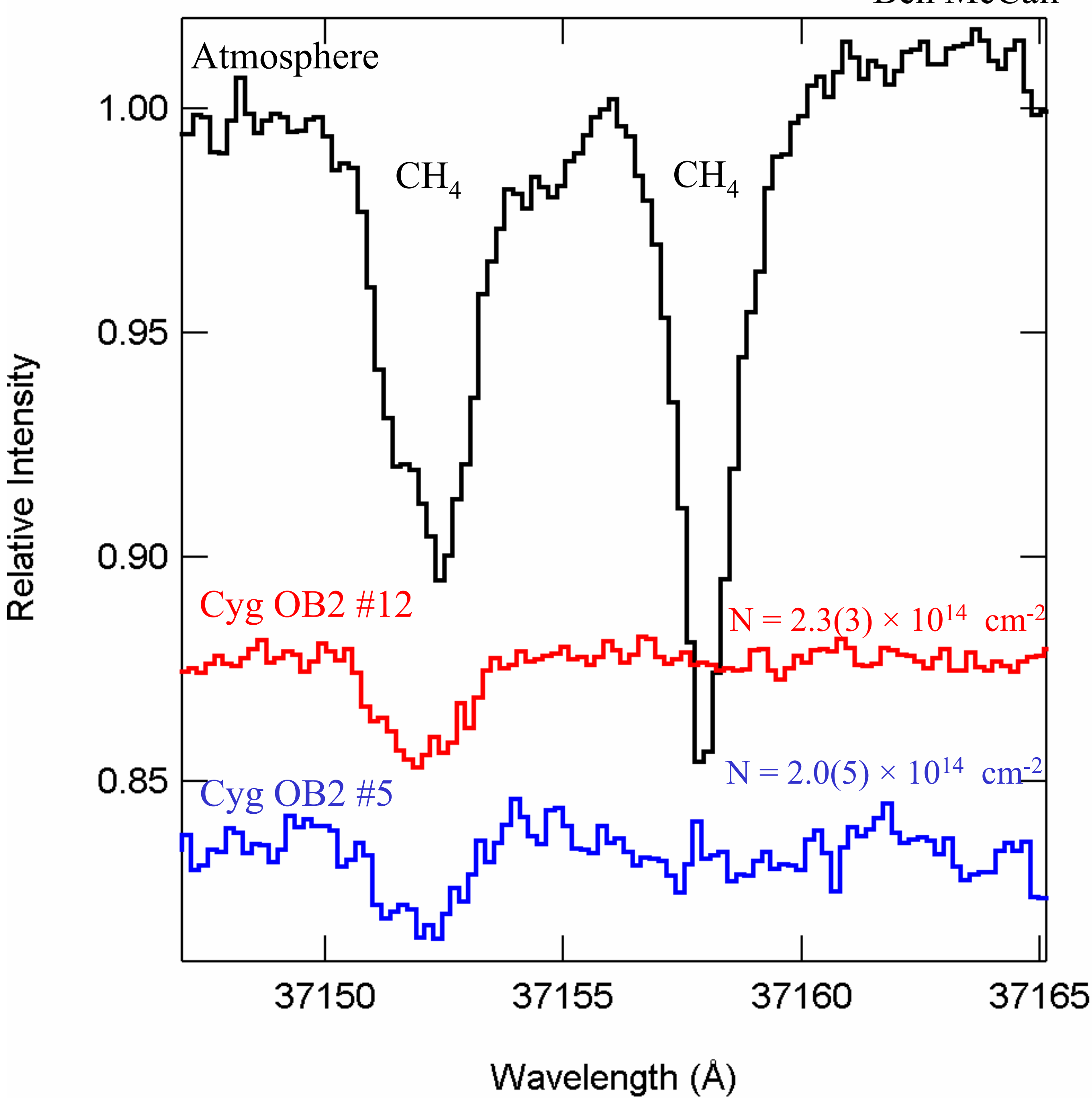


Same $N(H_3^+)$ and same v_{LSR} ~ 2.5 pc away

What's Up?!?!?

Ben McCall

Given the expressions for the number density and path length of H_3^+:

$$n(H_3^+) = \frac{\zeta}{k_e} f(H_2) \frac{n(\Sigma H)}{n(\Sigma C)} \qquad L = \frac{N(H_3^+)}{n(H_3^+)}$$

There are three possibilities:

We must accept the long path of ~ 300 pc

or

The laboratory rate constant k_e is wrong

or

The ionization rate ζ is wrong

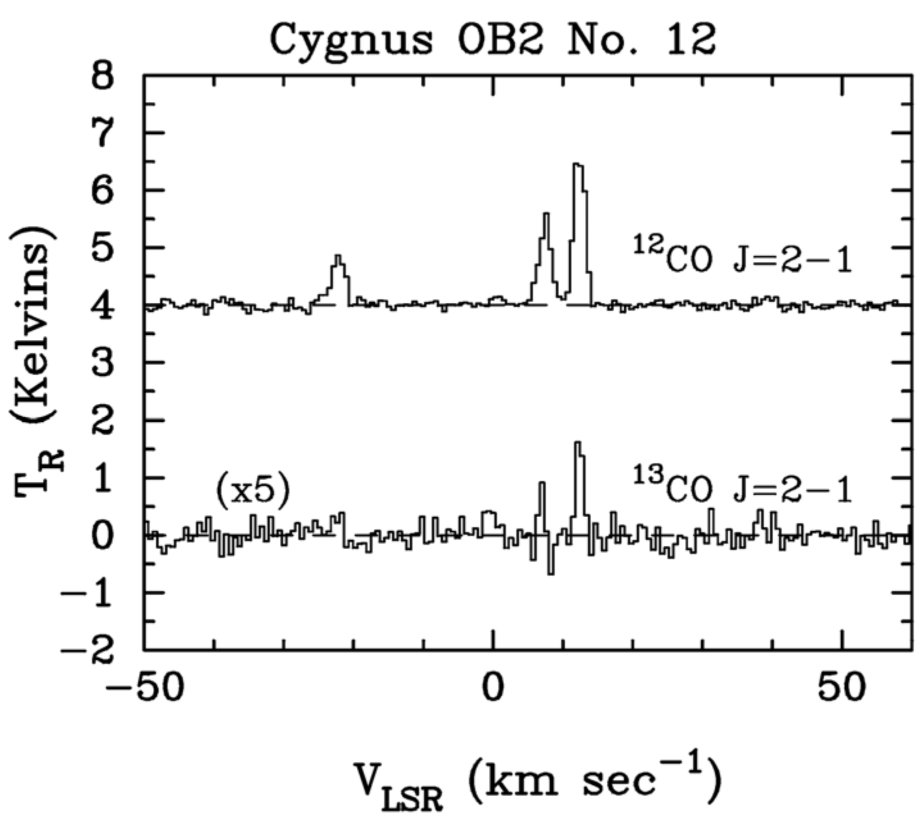
Long Path Unreasonable

Ben McCall

For $N(H_2) \sim 2 \times 10^{22}$ cm^{-2}
(inferred from E_{B-V} and X-ray spectral analysis),

$$\langle n(H_2) \rangle \sim \frac{N(H_2)}{L} \sim \frac{2 \times 10^{22}}{10^{21}} \sim 20 \text{ cm}^{-3}$$

This low density is inconsistent with the observed CO distribution from infrared and millimeter-wave spectroscopy, which suggest n ~ 400–2000 cm^{-3}



Electron Recombination

Ben McCall

The experimental determination of the rate constant for the dissociative recombination of H_3^+ has been a matter of some controversy.

For a long time, everyone thought ~ 10^{-7} cm^3 s^{-1}

Then Adams & Smith said < 2×10^{-8} cm^3 s^{-1}

Then Adams & Smith said ~ 10^{-11} cm^3 s^{-1}

Then Amano said ~ 10^{-7} cm^3 s^{-1}

Today, storage ring methods have been used to prepare H_3^+ exclusively in its v=0 state, providing a very clean determination of k_e and a value of ~ 2×10^{-7} cm^3 s^{-1}

(but theory still disagrees, giving a low k_e)

The Mysterious ζ

Ben McCall

The H_2 ionization rate ζ is not well-determined in diffuse clouds, but has generally been assumed to be the same as in dense clouds (3×10^{-17} s $^{-1}$).

There are three possible ways to increase ζ :

1. UV ionization: $IP(H_2) = 15.4$ eV > 13.6 eV
2. X-irradiation: $L_X \leq 10^{35}$ erg s $^{-1}$
3. Low-energy cosmic-rays?

If ζ is a factor of 30–100 higher in diffuse clouds, then $n(H_2) \sim 600$–2000 cm^{-3}, L ~ 3–10 pc, and $n(H_3^+) \sim 10^{-6} – 4\times10^{-5}$ cm^{-3}

Impact of H_3^+

Ben McCall

Dense Clouds:

→ Path length
→ H_2 number density
→ Kinetic temperature

→ Confirmation of ion-neutral scheme

Diffuse Clouds:

Apparently long path lengths

New physics (k_e)
or
New astrophysics (ζ)