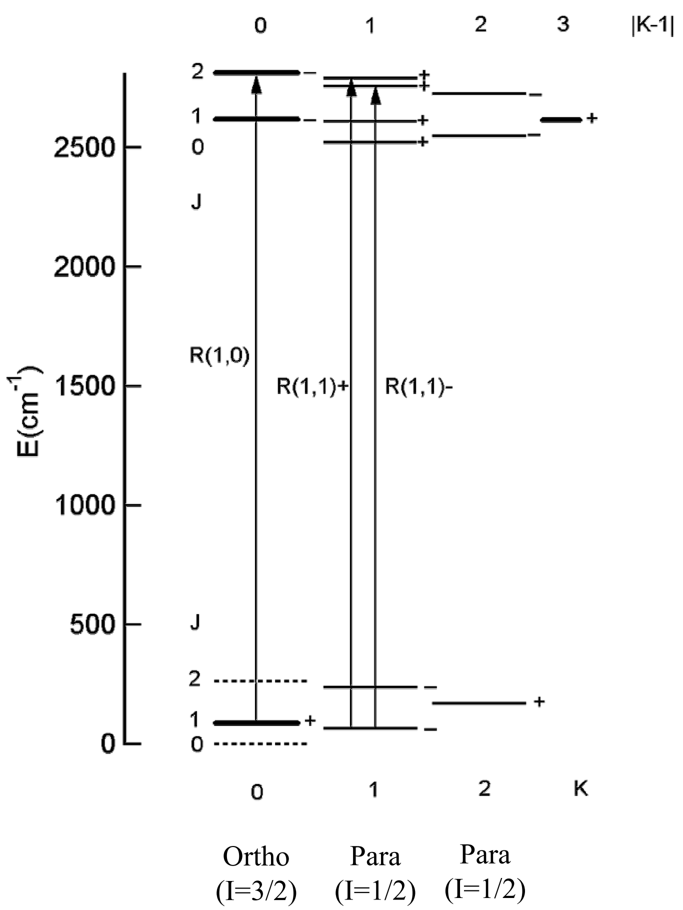
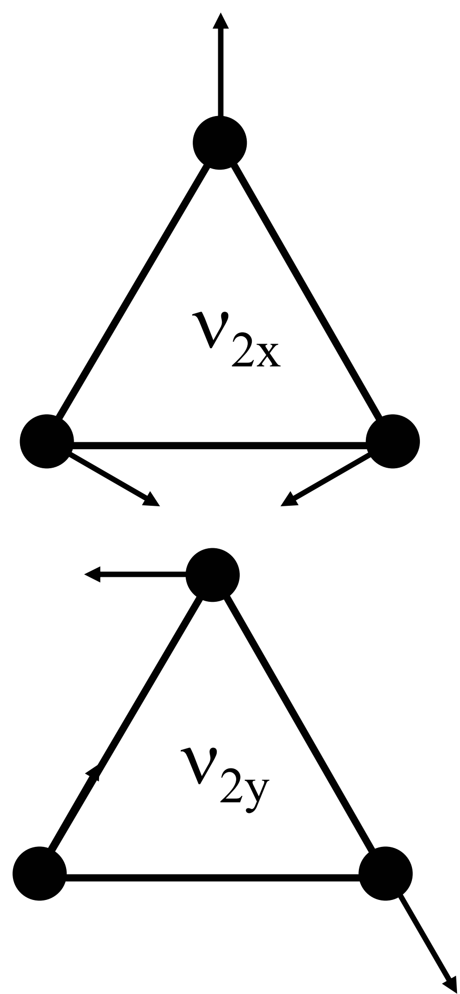
Why Study H_3^+ ?

Ben McCall

⇒ Most abundantly produced molecular ion
⇒ Initiates ion-neutral chemistry responsible for molecules in interstellar medium
⇒ Constant number density allows estimates of cloud parameters





Since H_3^+ has no electronic or rotational spectrum, it must be studied using the ν_2 infrared active degenerate bending mode

Formation of H_3^+

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Step 1: Cosmic-ray ionization of H_2:

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

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

Step 2: Ion-Molecule reaction with H_2:

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

[occurs on every collision]

The cosmic-ray ionization rate is estimated from various methods to be $\zeta \sim 3 \times 10^{-17}$ s^{-1}.

For a dense cloud,
$n(H_2) \sim 10^5$ cm^{-3} $\Rightarrow$ Rate $\sim 3 \times 10^{-12}$ cm^{-3} s^{-1}.

For a diffuse cloud,
$n(H_2) \sim 10^2$ cm^{-3} $\Rightarrow$ Rate $\sim 3 \times 10^{-15}$ cm^{-3} s^{-1}.

H_3^+ Destruction

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In Dense Clouds:

In dense clouds, H_3^+ is destroyed by ion-neutral reactions with molecules (primarily CO), leading to the variety of molecules observed using infrared and radio astronomy.

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

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

$k_{CO} \sim 2\times10^{-9}$ cm^3 s^{-1}
(measured in lab)

In Diffuse Clouds:

Since molecules (e.g. CO) are less abundant than in dense clouds, the dominant destruction path of H_3^+ is electron recombination.

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

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

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

$k_e \sim 2\times10^{-7}$ cm^3 s^{-1}
(measured in lab)

H_3^+ Number Density

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Assuming steady-state, the H_3^+ number density can be derived by equating the rates of formation and destruction.

In Dense Clouds:

Rearrange the equation $\zeta\, n(H_2) = k_{CO}\, n(CO)\, n(H_3^+)$ to find:

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

(~ 1×10^{-4} cm^{-3})

In Diffuse Clouds:

Rearrange the equation $\zeta\, n(H_2) = k_e\, n(e^-)\, n(H_3^+)$ to find:

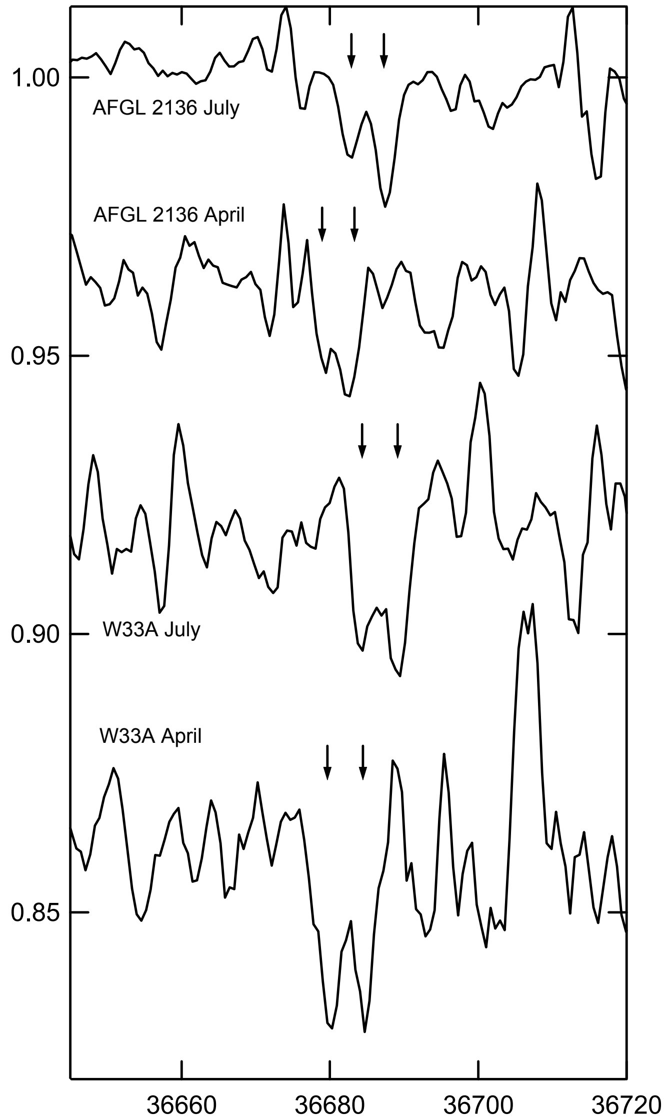
$$n(H_3^+) = \frac{\zeta}{k_e} \frac{n(H_2)}{n(e^-)} = \text{constant!}$$

(~ 4×10^{-7} cm^{-3})

⇒ Note that in both cases the number density of H_3^+, unlike most molecules, is independent of the total (hydrogen) number density!

H_3^+ in Dense Clouds

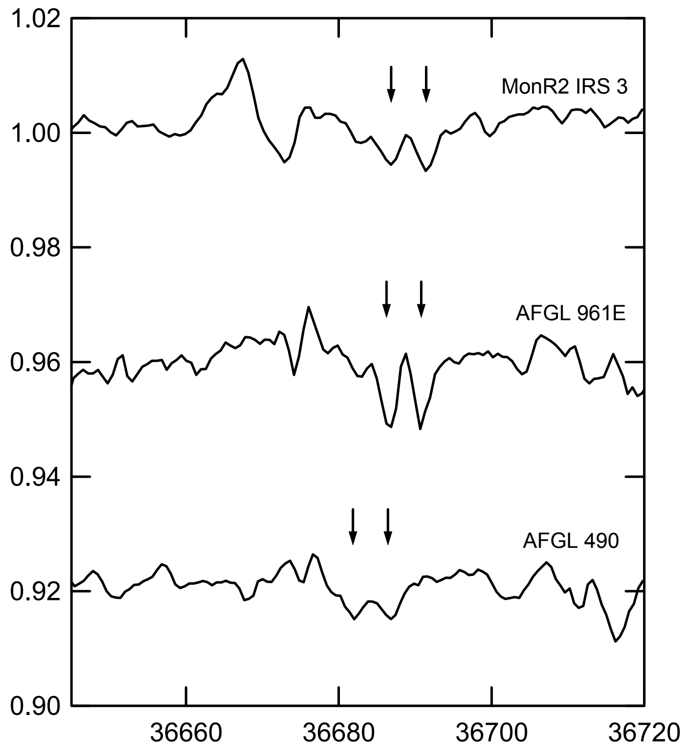
Ben McCall



These molecular clouds provided the first detections of interstellar H_3^+. Using the CGS4 spectrometer at UKIRT, they were observed on two nights separated by nearly three months. The Earth's orbital motion caused the spectral lines of H_3^+ to be Doppler shifted – compelling evidence that the lines are genuine.

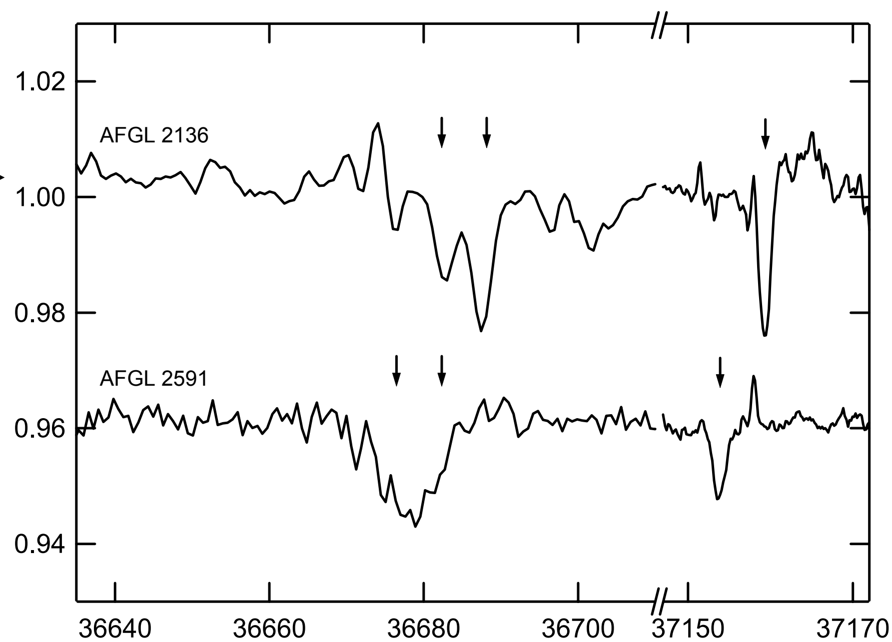
Dense Cloud Detections

Ben McCall



H_3^+ detections toward Mon R2 IRS 3, AFGL 961E, and AFGL 490 from UKIRT's CGS4.

H_3^+ detections toward AFGL 2136 and AFGL 2591 from UKIRT (left doublet) and Phoenix (right singlet).



Cloud Parameter Estimates

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Measurements of H_3^+ in dense clouds provide estimates of:

⇒ path length of cloud
⇒ mean number density of H_2
⇒ kinetic temperature

Path Length:

$$L = \frac{N(H_3^+)}{n(H_3^+)} = \frac{3\times10^{14}\,\text{cm}^{-2}}{1\times10^{-4}\,\text{cm}^{-3}} = 3\times10^{18}\,\text{cm} \approx 1\text{pc}$$

Number Density:

$$\langle n(H_2)\rangle \sim \frac{N(H_2)}{L} \sim \frac{2\times10^{23}\,\text{cm}^{-2}}{3\times10^{18}\,\text{cm}} \sim 6\times10^{4}\,\text{cm}^{-3}$$

Temperature:

$$\frac{N_{ortho}(H_3^+)}{N_{para}(H_3^+)} = \frac{g_{ortho}}{g_{para}} e^{-\frac{\Delta E}{kT}} = 2e^{-\frac{32.87}{T}}$$

$\Rightarrow T \sim 25\text{-}50\ \text{K}$

Dense Cloud Results

Ben McCall

Object	L(pc)	$\langle n(H_2) \rangle$	T(K)
AFGL 2136	1.3	6×10^4	47
W33A	1.7	5×10^4	36
MonR2/3	0.5	5×10^4	31
AFGL 961E	0.6	2×10^4	25
AFGL 490	0.4	6×10^4	26
AFGL 2591	0.7	6×10^4	38

H_3^+ Column Densities:

Detections:		Upper Limits:	
AFGL 2136	3.8×10^{14} cm^{-2}	Orion BN	$< 2.5 \times 10^{14}$ cm^{-2}
W33A	5.2×10^{14} cm^{-2}	NGC 2024/2	$< 1.4 \times 10^{14}$ cm^{-2}
MonR2/3	1.4×10^{14} cm^{-2}	MonR2/2	$< 2.0 \times 10^{14}$ cm^{-2}
AFGL 961E	1.7×10^{14} cm^{-2}	AFGL 989	$< 1.2 \times 10^{14}$ cm^{-2}
AFGL 490	1.1×10^{14} cm^{-2}	Elias 29	$< 2.4 \times 10^{14}$ cm^{-2}
AFGL 2591	2.2×10^{14} cm^{-2}	M17/1	$< 11 \times 10^{14}$ cm^{-2}
		W3/5	$< 1.1 \times 10^{14}$ cm^{-2}
		S140/1	$< 0.5 \times 10^{14}$ cm^{-2}
		LkHα 101	$< 1.4 \times 10^{14}$ cm^{-2}

McCall, Geballe, Hinkle, & Oka
ApJ, submitted

H_3^+ in Diffuse Clouds!

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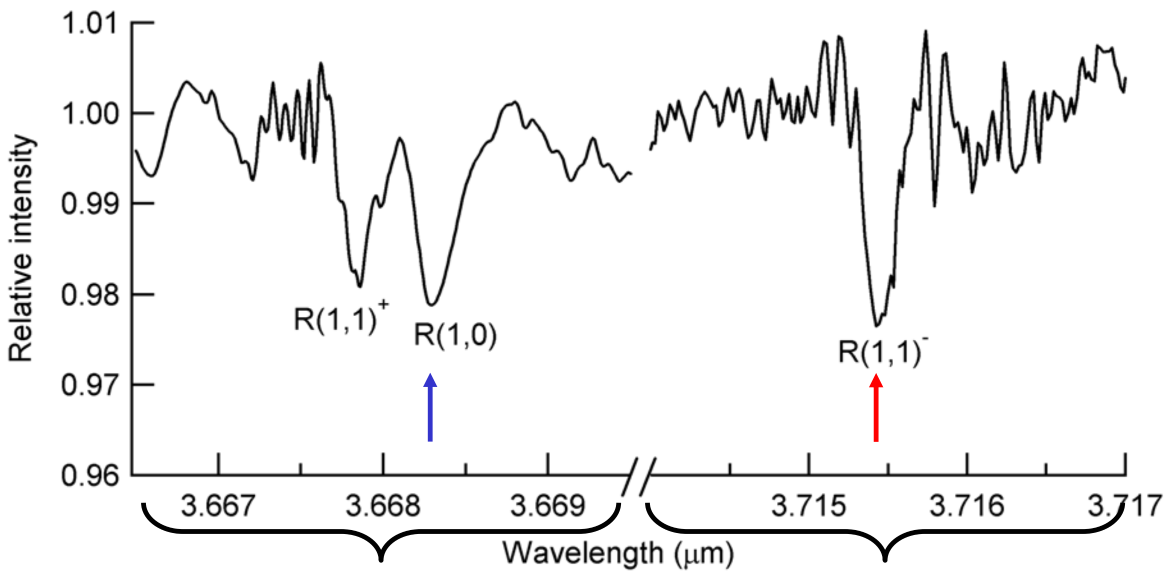
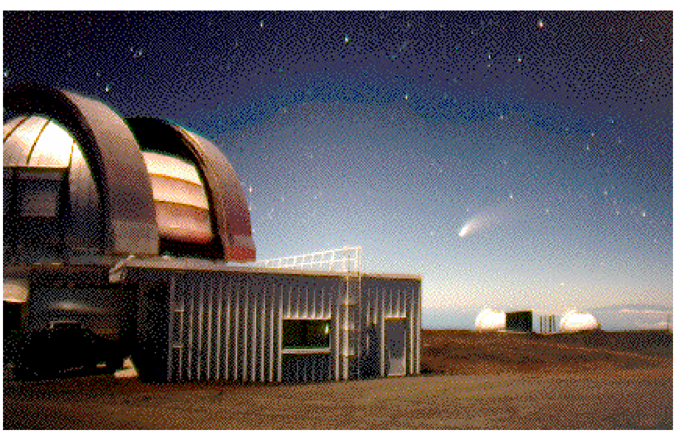


observed at UKIRT



observed at Kitt Peak

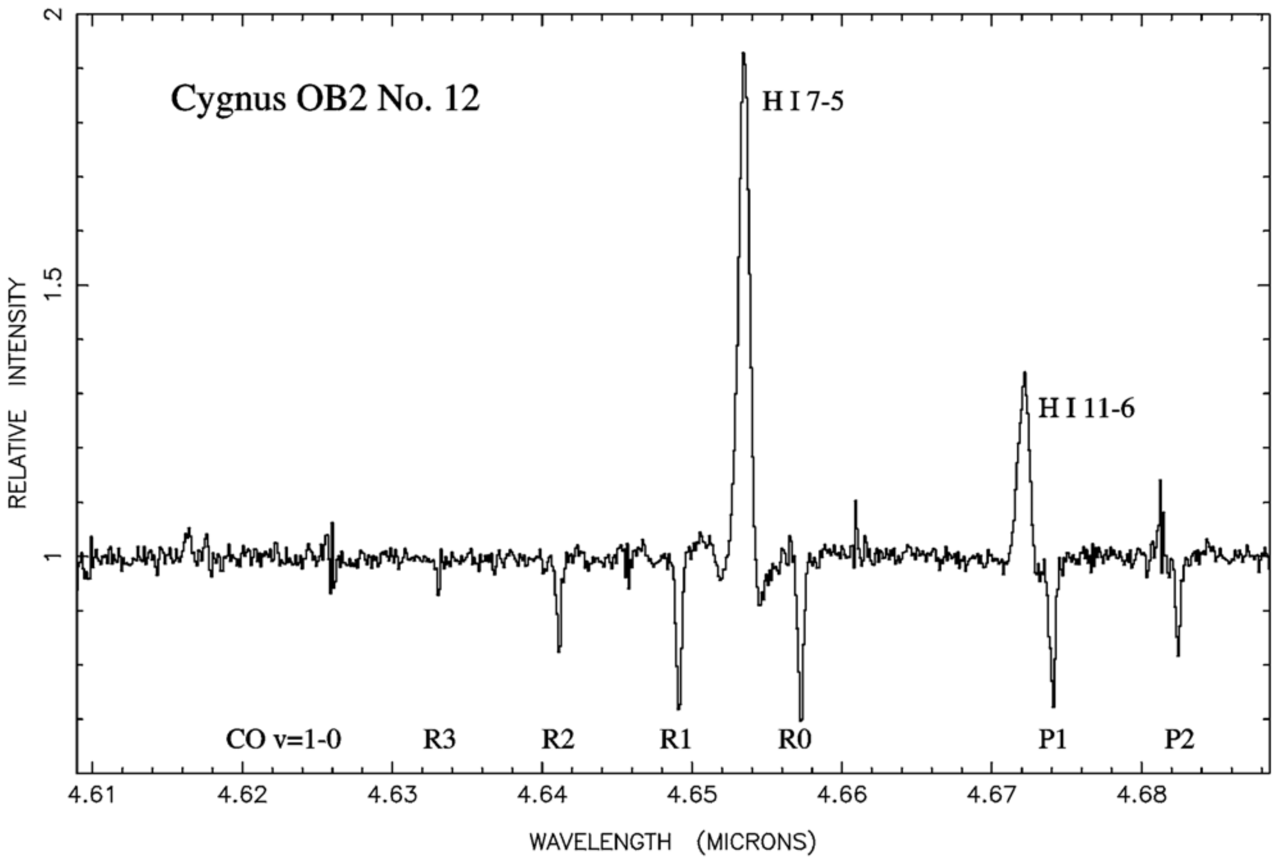
$N_{para} = 2.4(3) \times 10^{14}$ cm^{-2}
$N_{ortho} = 1.4(2) \times 10^{14}$ cm^{-2}

Similar column density to dense clouds!!

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

Infrared CO

Ben McCall



This spectrum of CO in absorption was obtained using CGS4 at UKIRT. The low column density, N(CO) ~ 10^{16} cm^{-3}, compared with N(H) ~ 10^{22} cm^{-3}, suggests that only about 1% of carbon is in the form of CO. This eliminates the possibility that the H_3^+ absorption is due to dense clouds.

Diffuse Cloud Parameters

Ben McCall

For Cygnus OB2 No. 12, the observed column density is $N(H_3^+) = 3.8 \times 10^{14}$ cm^{-2} and the predicted number density is $n(H_3^+) \sim 4 \times 10^{-7}$ cm^{-3}.

Path Length:

$$L \sim \frac{N(H_3^+)}{n(H_3^+)} \sim \frac{3.8\times10^{14}\,\mathrm{cm}^{-2}}{4\times10^{-7}\,\mathrm{cm}^{-3}} \sim 1\times10^{21}\,\mathrm{cm} \sim 300\,\mathrm{pc!}$$

Density:

$$[H_2] \sim \frac{N(H_2)}{L} \sim \frac{2\times10^{22}\,\mathrm{cm}^{-2}}{3\times10^{21}\,\mathrm{cm}} \sim 10\,\mathrm{cm}^{-3}$$

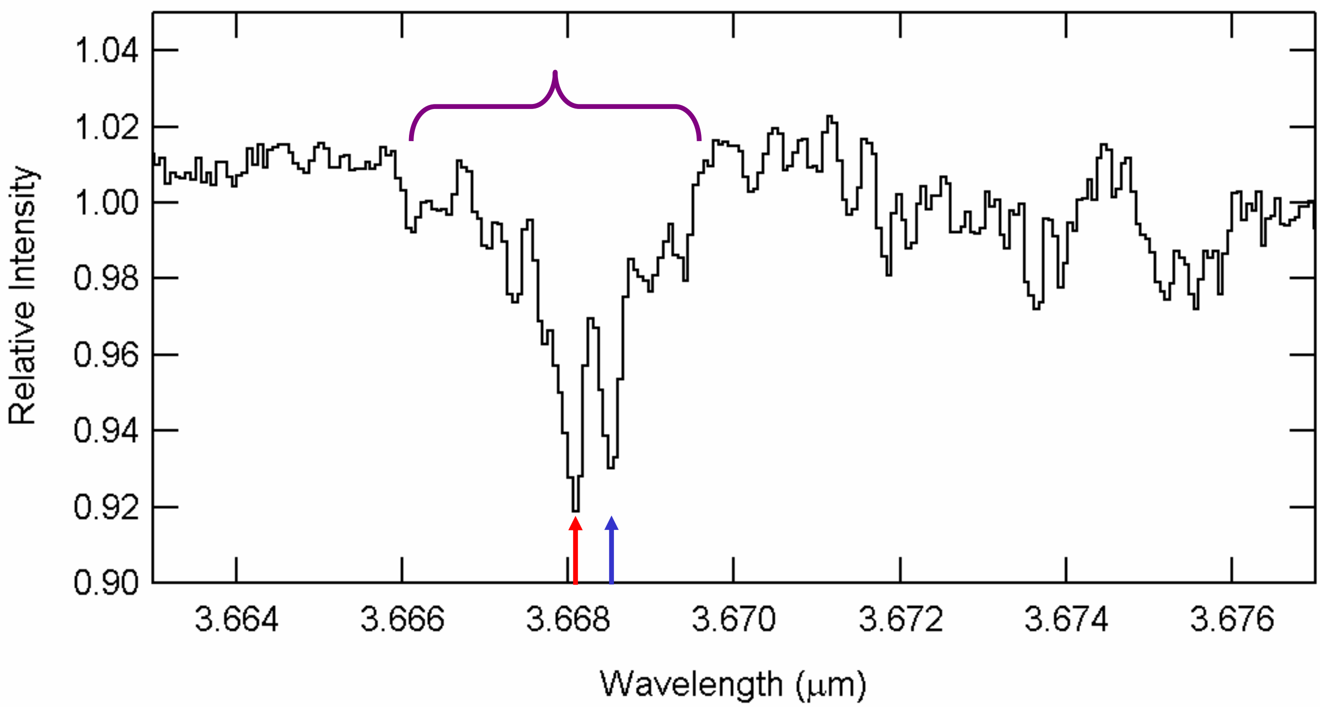
Problem: Extremely long path length!!
⇒ expect H_3^+ "everywhere"
⇒ barely consistent with linewidth

Solutions?:
⇒ ζ may be much higher?
⇒ k_e may be lower?
⇒ maybe it's true??

Upcoming Observations:
⇒ higher spectral resolution (constrain linewidth)
⇒ nearby objects (spatial extent of H_3^+)
⇒ other diffuse cloud sources (maybe this is a fluke?)

Galactic Center

Ben McCall



Much to our surprise, the Galactic Center sources IRS 3 (shown above) and GCS 3-2 show deep H_3^+ absorptions. In the case of IRS 3, both a narrow and a broad component was observed. Since the line of sight to the Galactic Center crosses both dense and diffuse clouds, it is difficult to separate the two contributions to the H_3^+ absorption.

$$N_{para} = 5.1(1.7) \times 10^{14}\ \mathrm{cm}^{-2}$$
$$N_{ortho} = 2.4(1.1) \times 10^{14}\ \mathrm{cm}^{-2}$$
$$N_{broad} = 17.5(3.9) \times 10^{14}\ \mathrm{cm}^{-2}$$

Geballe, McCall, Hinkle, & Oka
ApJ, Jan 1, 1999