H_3^+ in Diffuse Interstellar Clouds: A Tracer for the Cosmic-Ray Ionization Rate

Nick Indriolo[1], Thomas R. Geballe[2], Takeshi Oka[3], and Benjamin J. McCall[1]

[1] University of Illinois at Urbana-Champaign

[2] Gemini Observatory

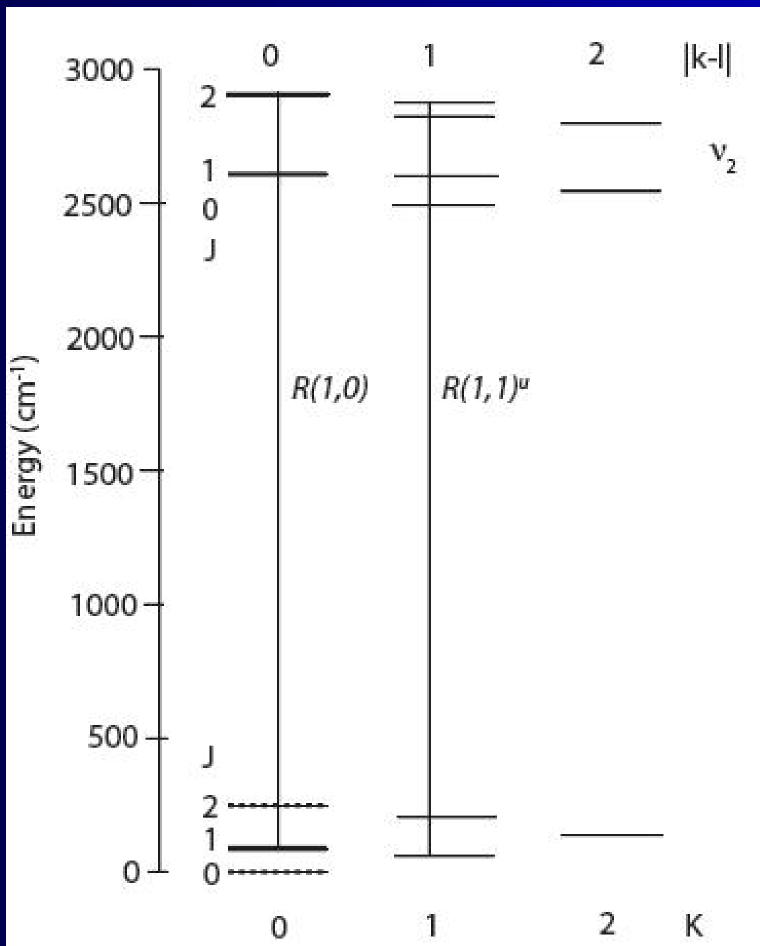
[3] University of Chicago

June 19, 2007

Motivations

- H_3^+ is the cornerstone of ion-molecule reactions in the interstellar medium (ISM)
- Simple chemistry allows for the inference of various physical parameters (density, temperature, ionization rate, cloud size)

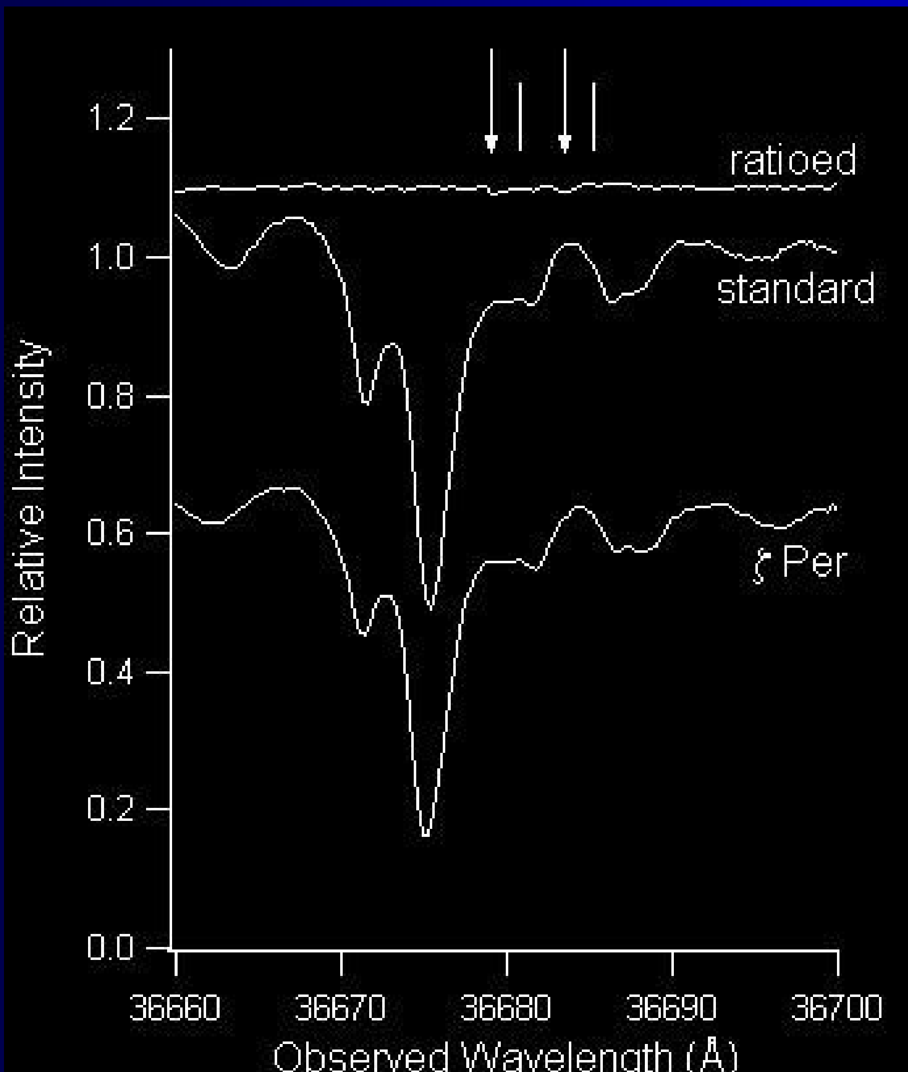
Observations



adapted from McCall et al. (1999)

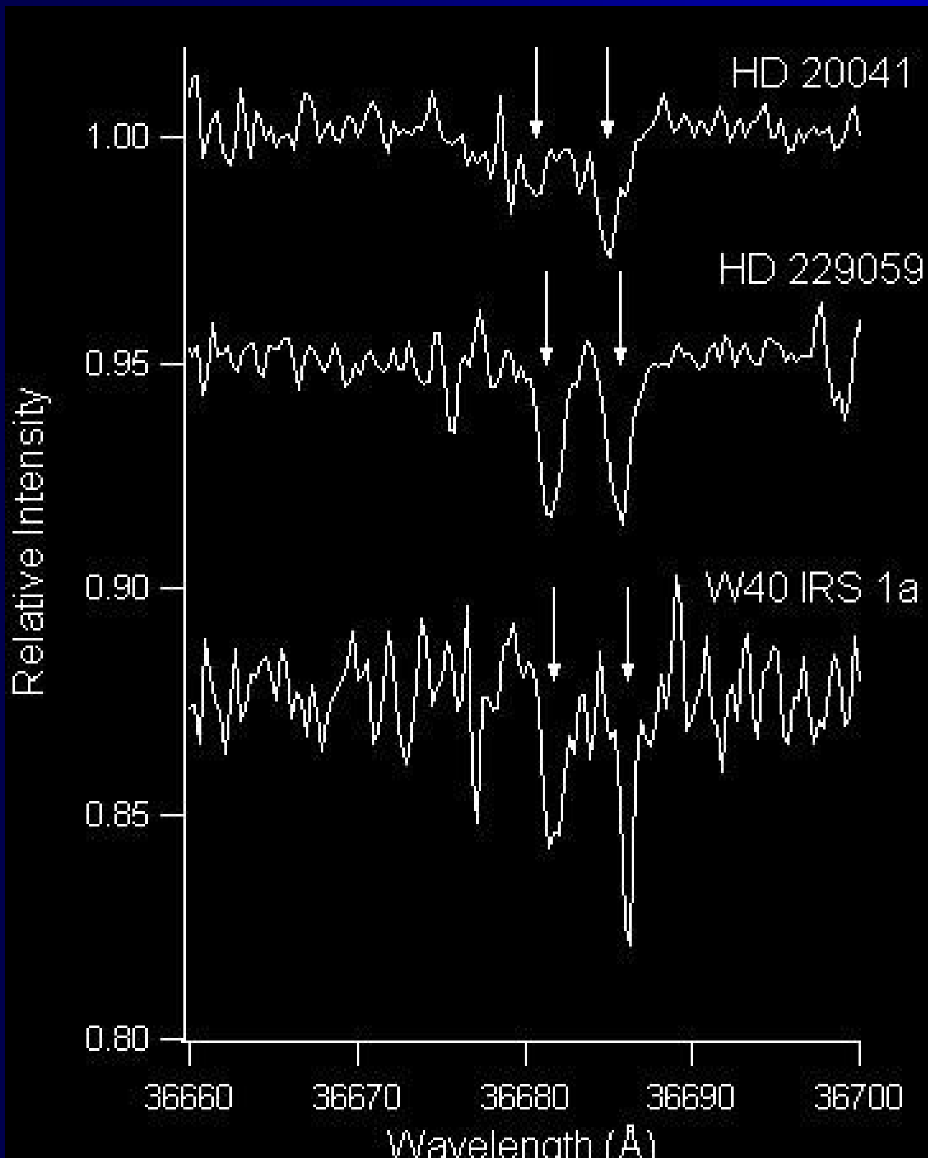
CGS4 spectrometer on the United Kingdom Infrared Telescope (UKIRT)

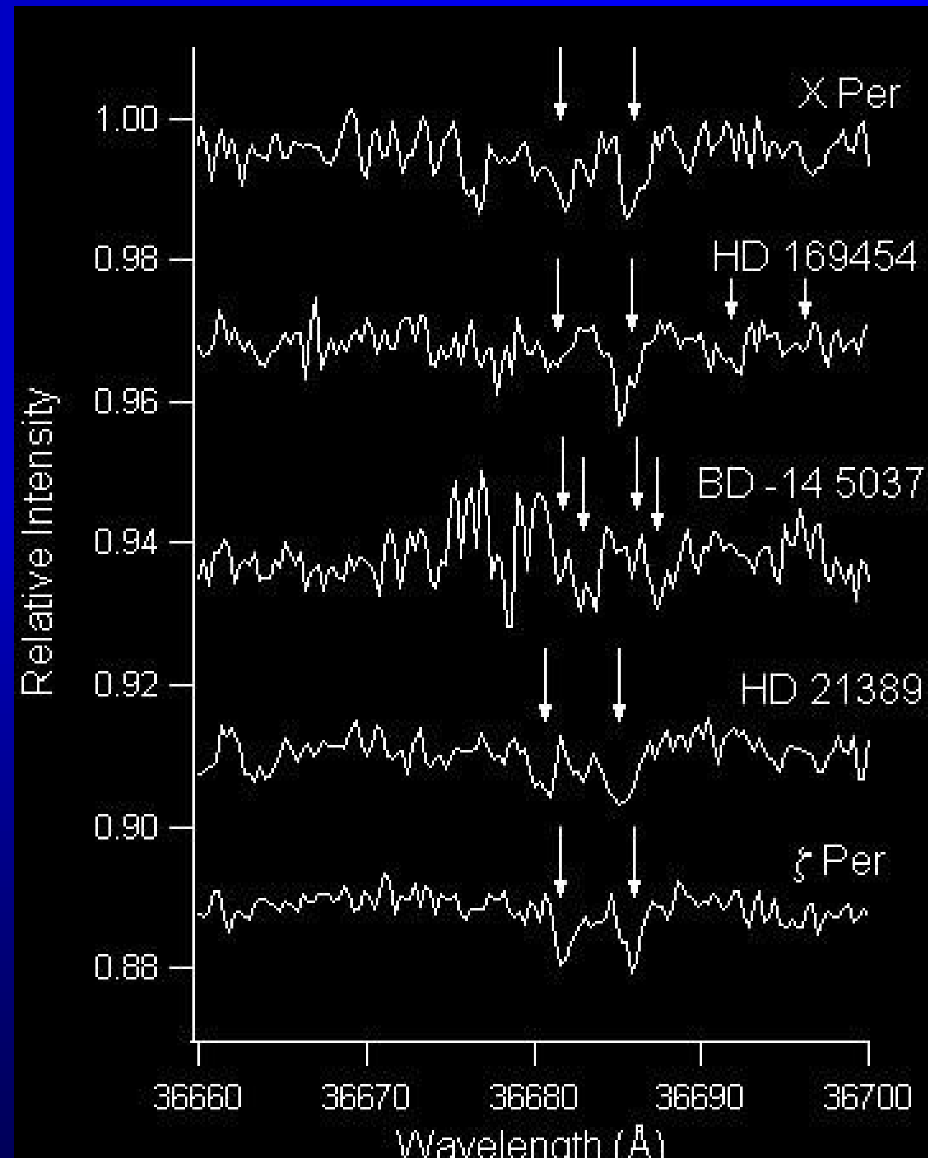
Atmospheric Interference



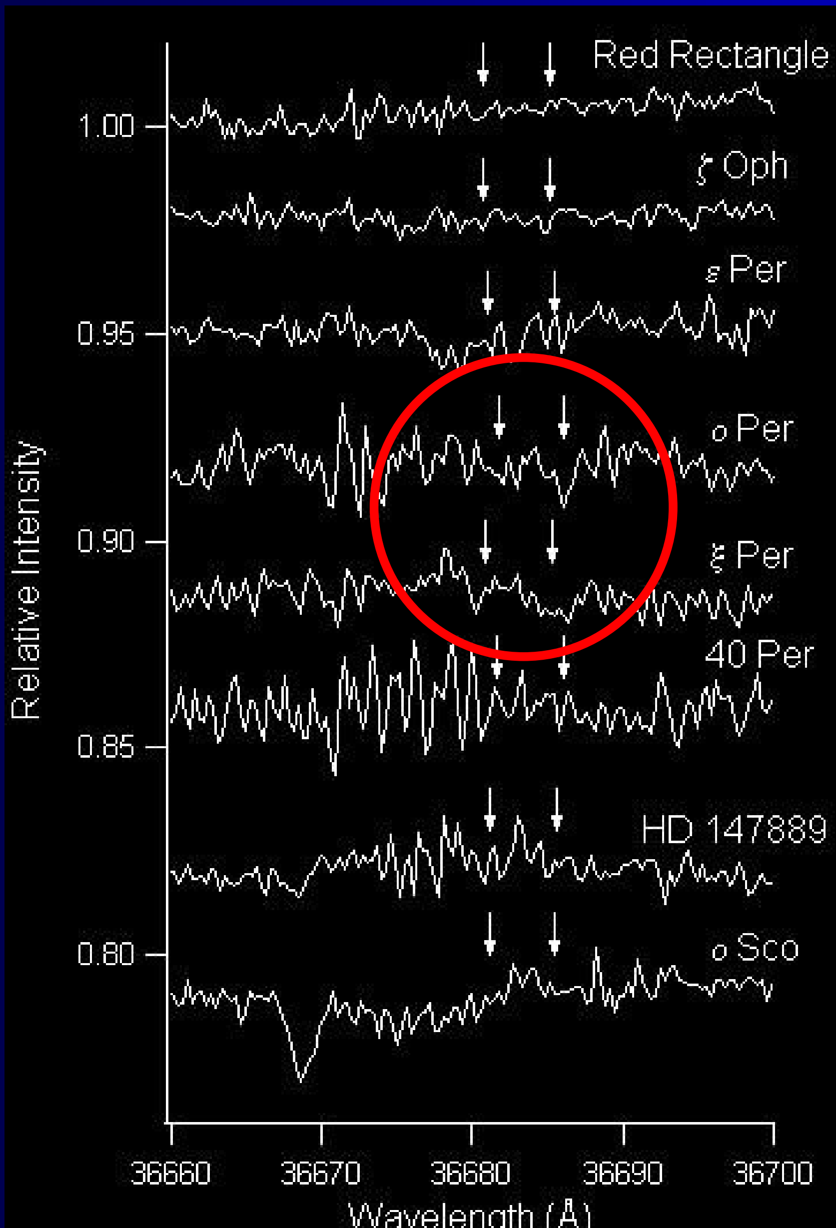
- complex of CH_4 lines centered at 36675.3 Å reduces transmission to about 50%
- various HDO lines also crowd the region and cut transmission to about 80%
- H_3^+ lines only have about 1-2% absorption, so a high S/N is necessary

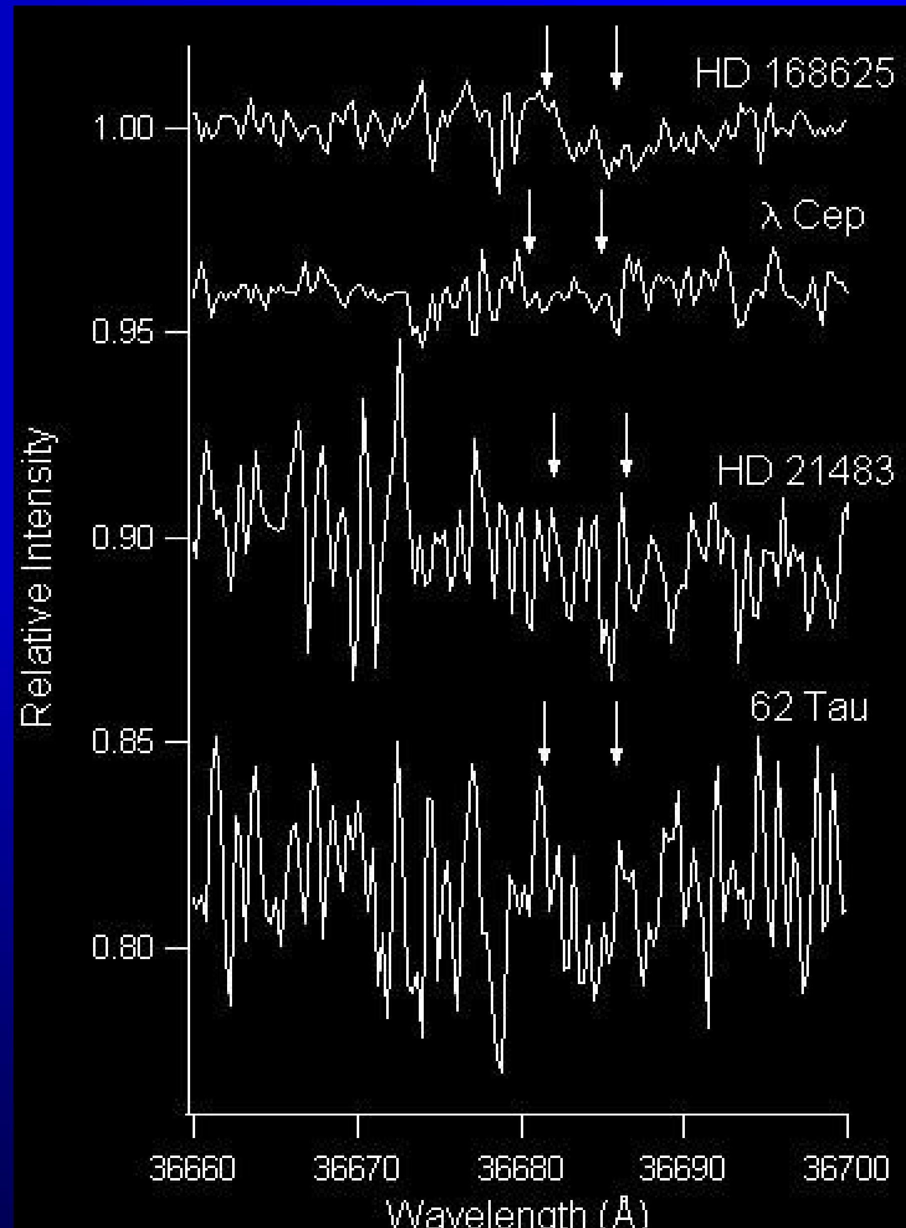
Detections


HD 20041
HD 229059
W40 IRS 1a
Relative Intensity
1.00
0.95
0.90
0.85
0.80
36660
36670
36680
36690
36700
Wavelength (Å)


X Per
HD 169454
BD -14 5037
HD 21389
ζ Per
Relative Intensity
1.00
0.98
0.96
0.94
0.92
0.90
0.88
36660
36670
36680
36690
36700
Wavelength (Å)

Non-detections





Relating column density to cosmic-ray ionization rate

- Formation pathway
  - $CR + H_2 \rightarrow CR + H_2^+ + e^-$
  - $H_2 + H_2^+ \rightarrow H_3^+ + H$
- Destruction mechanism
  - $H_3^+ + e^- \rightarrow H_2 + H$ or $3H$
- Using the steady-state approximation we obtain...

$$n(\mathrm{H}_2)\zeta_2 = k_e n(\mathrm{H}_3^+) n(e)$$

$$n(\mathrm{H}_3^+) = \frac{N(\mathrm{H}_3^+)}{L} \qquad f = \frac{2n(\mathrm{H}_2)}{n_\mathrm{H}}$$

$$n_\mathrm{H} = n(\mathrm{H\ I}) + 2n(\mathrm{H}_2)$$

$$\zeta_2 = N(\mathrm{H}_3^+)\frac{k_e}{L}\frac{2}{f}\frac{n(e)}{n_\mathrm{H}}$$

Variables & Assumptions

$$\zeta_2 = N(\mathrm{H}_3^+)\frac{k_e}{L}\frac{2}{f}\frac{n(e)}{n_\mathrm{H}}$$

- $N(\mathrm{H}_3^+)$ is measured
- k_e is known from experiments ($\sim 10^{-7}$ cm^3 s^{-1})
- $n(e)/n_\mathrm{H}$ is relatively constant in diffuse clouds (1.4×10-4 assuming electrons come from ionized carbon)
- 2 is certainly still 2
- f can be approximated using measured H I and H_2 column densities
- $L = N_\mathrm{H}/n_\mathrm{H}$
  - N_H can be measured or estimated from $E(B\text{-}V)$
  - n_H is estimated in various ways (C I levels, C_2 levels, J=4 level of H_2)
- $\zeta_2 = 2.3\zeta_\mathrm{p}$

$$\zeta_\mathrm{p} = \frac{2}{2.3}N(\mathrm{H}_3^+)\frac{n_\mathrm{H}}{f}\frac{k_e}{N_\mathrm{H}}\left[\frac{n(e)}{n_\mathrm{H}}\right]$$

Results

Object	$N(H_3^+)$ (10^{14} cm^{-2})	ζ_p (10^{-16} s^{-1})	Object	$N(H_3^+)$ (10^{14} cm^{-2})	ζ_p (10^{-16} s^{-1})
HD 20041	1.6	2.9	HD 21483	< 2.2	< 5.7
HD 21389	1.0	1.8	40 Per	< 0.9	< 2.6
ζ Per	0.7	3.2	*o* Per	< 0.6	< 5.0
X Per	0.8	3.1	ε Per	< 0.5	< 2.4
HD 169454	0.6	0.9	ξ Per	< 0.5	< 4.5
HD 229059	3.9	2.9	62 Tau	< 2.7	< 14
BD -14 5037	0.6	0.5	*o* Sco	< 0.5	< 0.9
W40 IRS 1a	3.4	1.5	HD 147889	< 0.6	< 1.6
WR 104	2.3	1.4	ζ Oph	< 0.3	< 1.5
WR 118	6.5	2.0	HD 168625	< 0.8	< 0.8
WR 121	2.2	1.7	λ Cep	< 0.8	< 1.3
Cyg OB2 12	3.8	1.8	HD 168607	< 0.6	< 0.5
Cyg OB2 5	2.6	1.5	HD 194279	< 1.2	< 1.3
HD 183143	2.3	2.3	χ^2 Ori	< 0.7	< 2.1
			P Cyg	< 0.6	< 1.2

Cosmic-Ray Ionization Rates: Measured and Modeled

ζ_p (10^{-16} s^{-1})

ζ Per	*o* Per	ε Per	ξ Per	ζ Oph	Reference	Method
3.2	<5.0	<2.4	<4.5	<1.5	this work	H_3^+
0.22	2.50	0.01	0.06	0.17	Hartquist et al. (1978)	OH & HD
0.17	1.30	…	≤0.26	…	Federman et al. (1996)	OH & HD
1-2	≥8	…	…	≥4	van Dishoeck & Black (1986)	models
5.2	…	…	…	…	McCall et al. (2003)	H_3^+
2.5	…	…	…	…	Le Petit et al. (2004)	models

Possible Explanations for Differences

- smaller value of k_e used in the past
- charge transfer H^+ to O is endothermic
- grain neutralization ‘removes’ H^+
- N(D I)/N(H I) overestimates deuterium fraction n_D/n_H

Conclusions

- H_3^+ is common and abundant in diffuse interstellar clouds
- Due to its simple chemistry, H_3^+ can be used to infer the cosmic-ray ionization rate
- ζ_p in diffuse clouds is relatively constant and an order of magnitude larger than previously believed

Future Prospects

- Observing run at UKIRT June 29-July 2 to re-visit 4 sightlines and investigate 4 new sightlines
- 36 hours in January at UKIRT to get better S/N on Perseus sources
- Proposal submitted for time on Gemini South in December to investigate the diffuse ISM in the Large Magellanic Cloud

Acknowledgments

- UKIRT staff
- NSF

- References

  - Federman, S. R., Weber, J., & Lambert, D. L. 1996, ApJ, 463, 181
  - Hartquist, T. W., Doyle, H. T., & Dalgarno, A. 1978 A&A, 68, 65
  - Le Petit, F., Roueff, E., & Herbst, E. 2004, A&A, 417, 993
  - McCall, B. J., Geballe, T. R., Hinkle, K. H., & Oka, T. 1999, ApJ, 522, 338
  - McCall, B. J., et al. 2003, Nature, 422, 500
  - van Dishoeck, E. F., & Black, J. H. 1986, ApJS, 62, 109