The Cosmic-Ray Ionization Rate in the implied by observations of H_3^+ (outside the Galactic Center)

David Neufeld
Johns Hopkins University

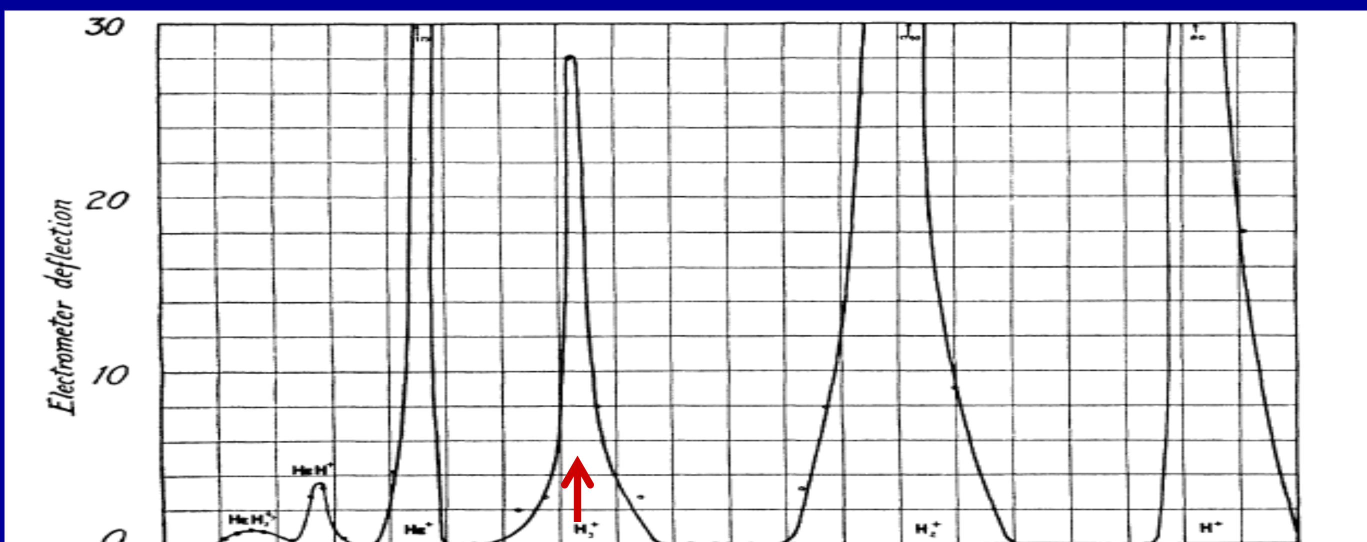
Collaborators: Mark Wolfire, Arshia Jacob, Nick Indriolo

1911

Discovery of H_3^+ by J. J. Thomson

1925

Example mass spectroscopy by Hogness and Lunn



e/m =	⅕	¼	⅓	½	1
	HeH^+	He^+	H_3^+	H_2^+	H^+

1980

Observation of the Infrared Spectrum of H_3^+

Takeshi Oka

Phys. Rev. Lett. **45**, 531 – Published 18 August 1980

ABSTRACT

The infrared ν_2 band of H_3^+ has been observed. A direct infrared absorption method combining a liquid-nitrogen-cooled multiple-reflection discharge cell and a difference-frequency laser system has been used for the detection. Fifteen absorption lines have been measured in the region of 2950-2450 cm^{-1} and assigned. This is the first spectroscopic detection of this fundamental molecular ion in any spectral range.

1996

Letter

Detection of H^+_3 in interstellar space

T. R. Geballe & T. Oka

Nature **384**, 334–335 (28 November 1996)
doi:10.1038/384334a0
Download Citation

Received: 14 August 1996
Accepted: 22 October 1996
Published: 28 November 1996

Abstract

THE H^+_3 ion is widely believed to play an important role in interstellar chemistry, by initiating the chains of reactions that lead to the production of many of the complex molecular species observed in the interstellar medium[1–5]. The presence of H^+_3 in the interstellar medium was first suggested[6] in 1961, and its infrared spectrum was measured[7] in the laboratory in 1980. But attempts[8–11] to detect it in interstellar space have hitherto proved unsuccessful. Here we report the detection of H^+_3 absorption in the spectra of two molecular clouds. Although the present results do not permit an accurate determination of the H^+_3 abundances, these ions appear nevertheless to be present in sufficient quantities to drive much of the chemistry in molecular clouds. It should soon be possible to obtain more accurate measurements, and thus better quantify the role of ion–neutral reactions in the chemical evolution of molecular clouds.

2003

Letter

An enhanced cosmic-ray flux towards ζ Persei inferred from a laboratory study of the H_3^+–e^- recombination rate

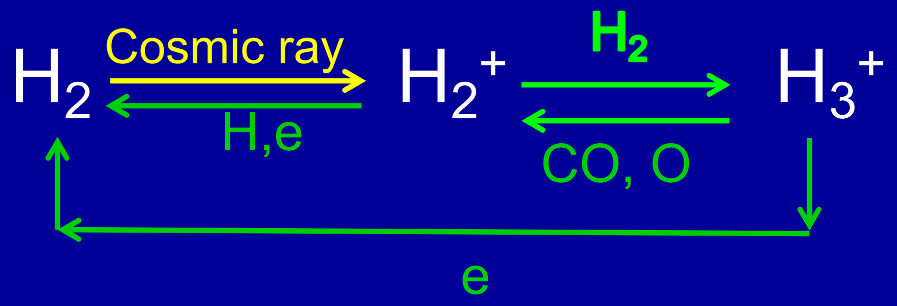
B. J. McCall, A. J. Huneycutt, R. J. Saykally, T. R. Geballe, N. Djuric, G. H. Dunn, J. Semaniak, O. Novotny, A. Al-Khalili, A. Ehlerding, F. Hellberg, S. Kalhori, A. Neau, R. Thomas, F. Österdahl & M. Larsson

Nature **422**, 500–502 (03 April 2003)
doi:10.1038/nature01498
Download Citation

Received: 19 November 2002
Accepted: 17 February 2003
Published: 03 April 2003

Measuring the cosmic-ray ionization rate in *diffuse* molecular clouds with H_3^+

In diffuse *molecular* clouds, H_3^+ production follows ionization of H_2



McCall et al. (2003): CRIR along sight-line to ζ Per

$\zeta_p(H) = 5 \times 10^{-16}\ s^{-1}$

Indriolo & McCall (2012): Best-estimate of average CRIR

$\zeta_p(H) = 1.5 \times 10^{-16}\ s^{-1}$

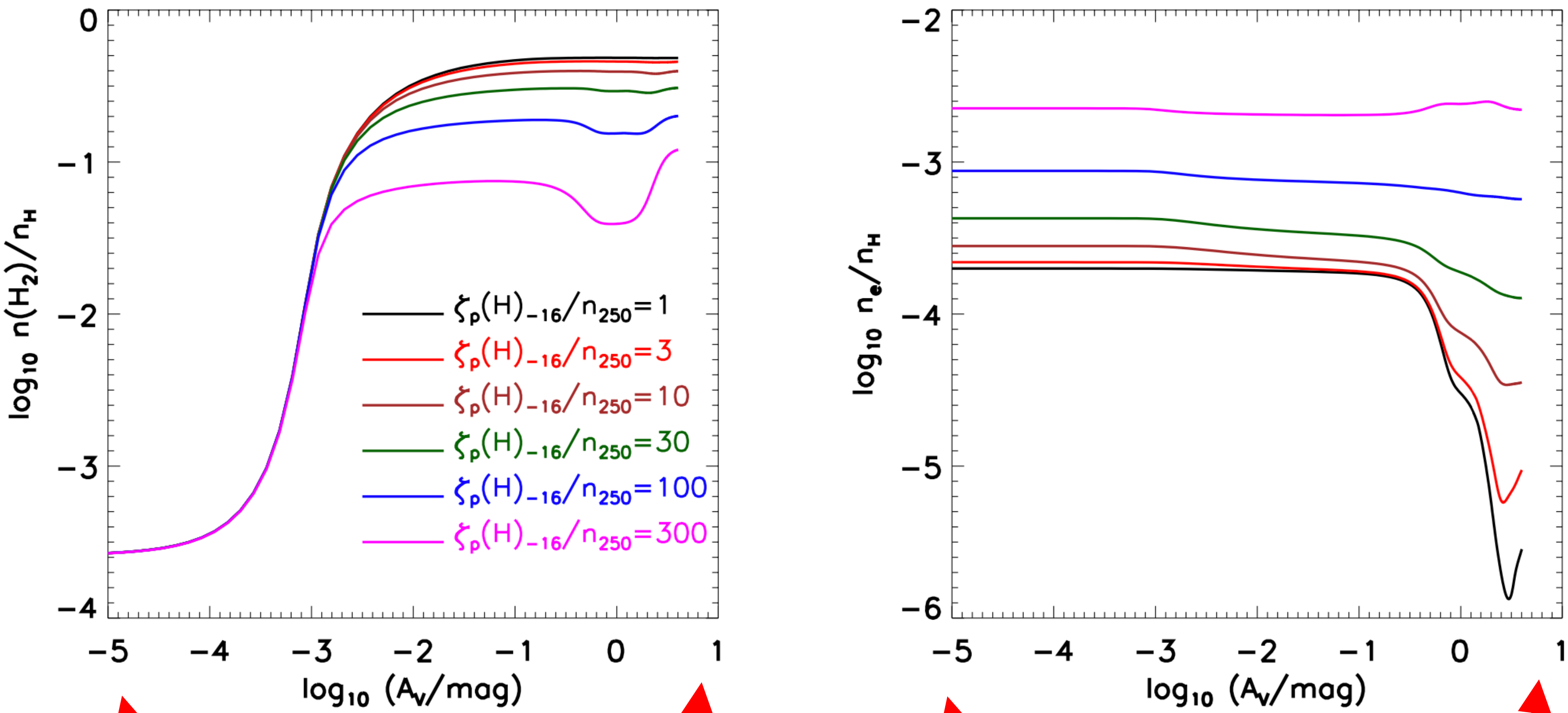
The CRIR in diffuse *molecular* clouds revisited with detailed models

To compute the electron abundance more precisely, and to include the destruction of H_3^+ by neutral species and of H_2^+ by H, we need to model the structure of diffuse molecular gas clouds

In Neufeld and Wolfire (2017), we adopted a 1-D slab model

Abundance of H_2 and electrons

Neufeld and Wolfire 2017, ApJ, with updates



Cloud edge

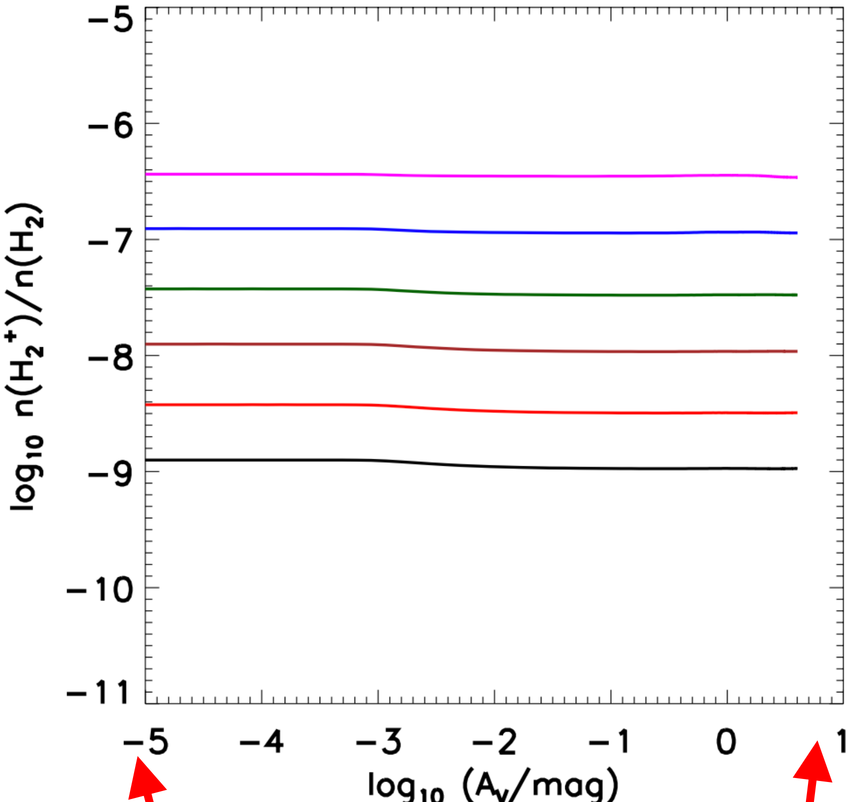
Cloud center

Cloud edge

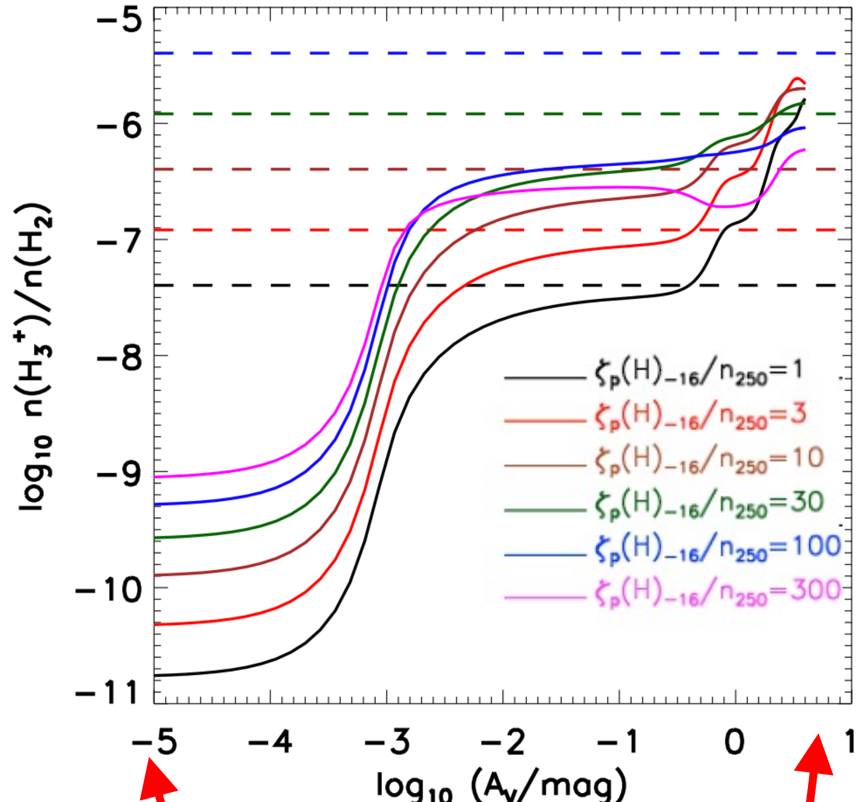
Cloud center

Local H_2^+/H_2 and H_3^+/H_2 ratios

$n(H_2^+)/n(H_2)$



$n(H_3^+)/n(H_2)$



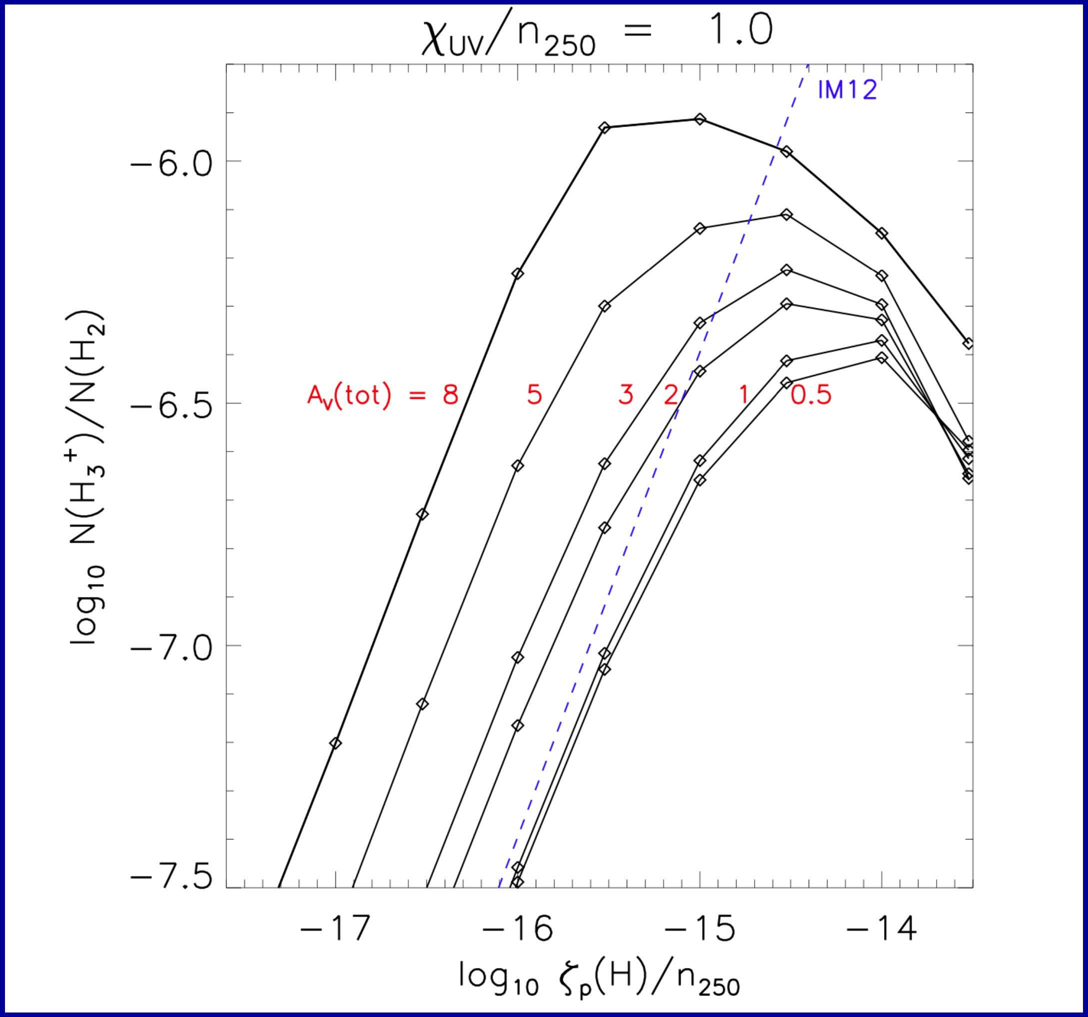
Cloud edge

Cloud center

Cloud edge

Cloud center

H_3^+/H_2 column density ratio



Neufeld and Wolfire 2017, ApJ, with updates

Key behaviors:

1) At large A_V

$N(H_3^+)/N(H_2)$ increases as C^+ recombines and the electron abundance drops

2) At large ζ

$N(H_3^+)/N(H_2)$ decreases as the ionization of H or H_2 contributes additional electrons and H_2^+ is destroyed by charge transfer to H

Non-monotonic behavior also found by Le Petit et al. 2016

The CRIR in diffuse *molecular* clouds revisited with detailed models

Variation with cloud $N(H_2)$:

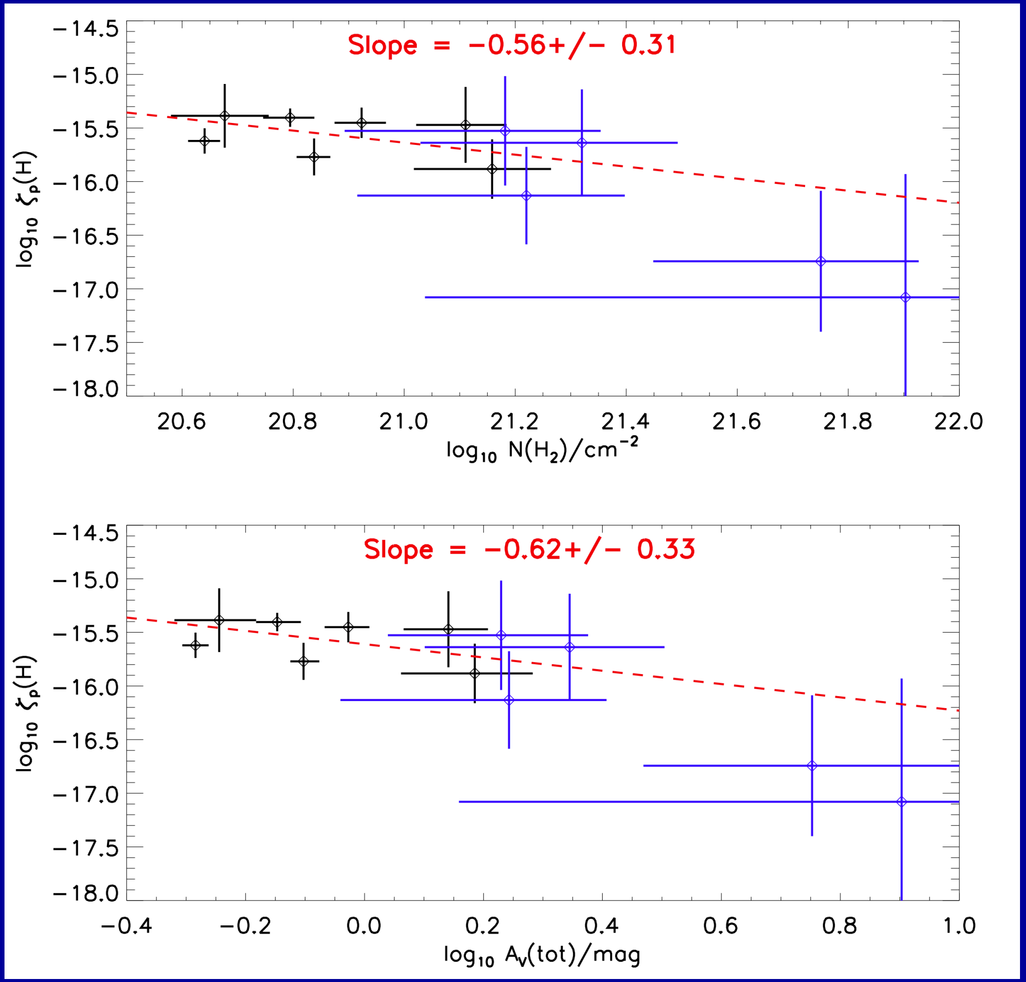
Black points: clouds <u>with</u> direct measurements of H_2 and density estimates from C_2

Blue points: clouds <u>without</u> direct measurements of H_2 but with density estimates from C_2

Marginally significant evidence for a decline in $\zeta_p(H)$ with $N(H_2)$ or A_V(tot)

Effect of shielding?

Consistent with the difference between the CRIRs derived for diffuse and dense molecular clouds (factor ~ 20)



Neufeld and Wolfire 2017, ApJ, with modifications

What CRIR is inferred from observations of the local ISM?

Cloud types in the ISM (Snow and McCall, 2006, ARAA)

Table 1 Classification of Interstellar Cloud Types

	Diffuse Atomic	Diffuse Molecular	Translucent	Dense Molecular
Defining Characteristic	$f^n_{H_2} < 0.1$	$f^n_{H_2} > 0.1$ $f^n_{C+} > 0.5$	$f^n_{C+} < 0.5$ $f^n_{CO} < 0.9$	$f^n_{CO} > 0.9$
A_V (min.)	0	~0.2	~1–2	~5–10
Typ. n_H (cm^{-3})	10–100	100–500	500–5000?	$>10^4$
Typ. T (K)	30–100	30–100	15–50?	10–50
Observational Techniques	UV/Vis H I 21-cm	UV/Vis IR abs mm abs	Vis (UV?) IR abs mm abs/em	IR abs mm em

From H_3^+
$\zeta_p(H) = 2.7 \pm 0.6 \times 10^{-16}$ s^{-1}
(with marginal evidence for decline with A_V(tot))

From HCO^+ (van der Tak & van Dishoeck 2000)
$\zeta_p(H) = 1.1 \times 10^{-17}$ s^{-1}

Next step: models in which the CR ionization rate varies with depth

Adopt a depth dependent ionization rate of the form

$$\zeta = \frac{\zeta_0}{(1 + \frac{N_H}{N_0})^{\alpha}}$$

Create a grid of models for each cloud (in which the CRIR varies with position)

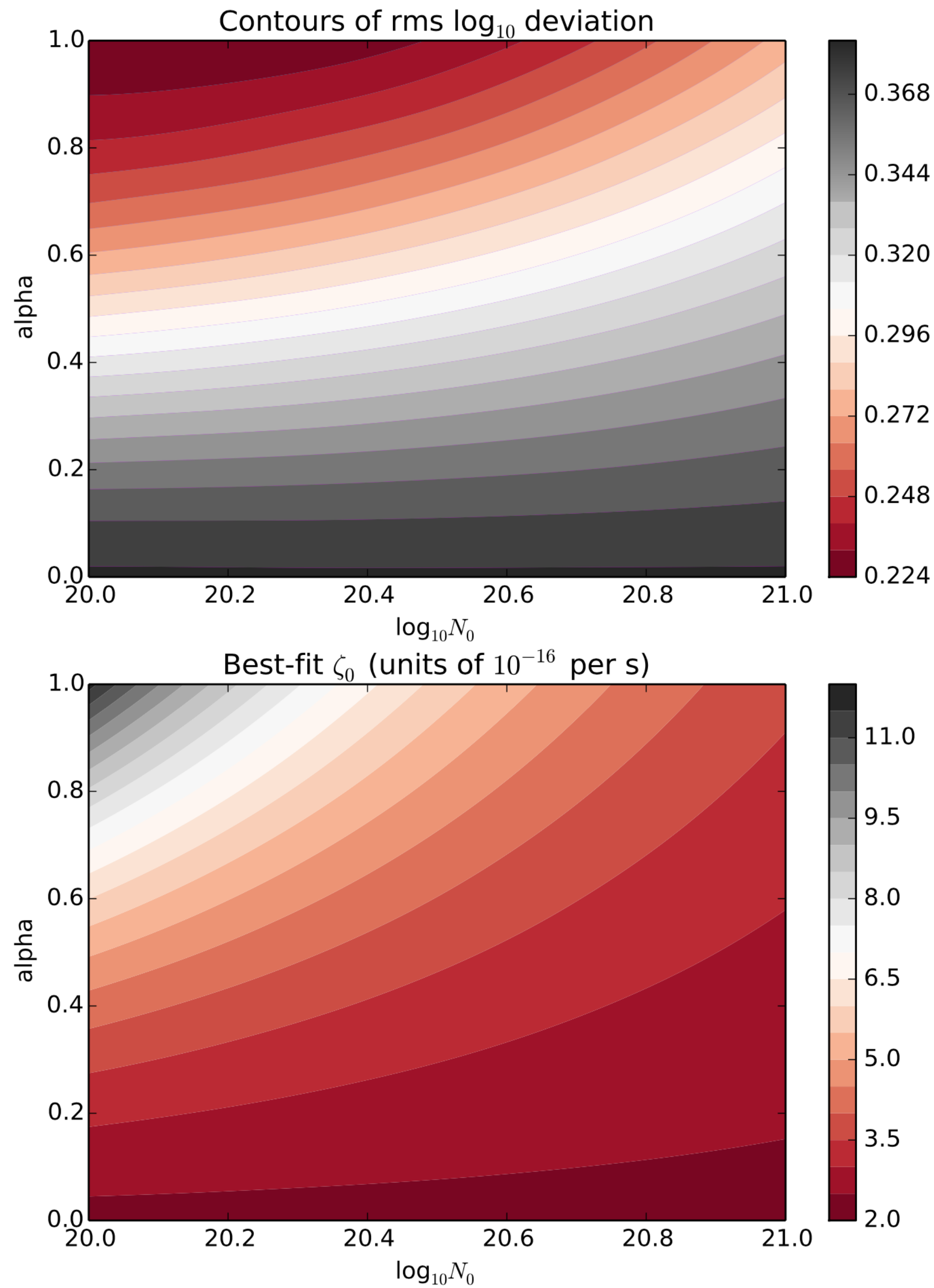
Vary ζ_0, N_0 and α to obtain the best overall fit to the observed $N(H_3^+)/N(H_2)$ in a sample of 12 clouds of known n_H and $N(H_2)$

Goodness of fit

Upper panel:
rms $\log_{10}$ deviation for the optimal ζ_0 at each α and N_0

α = 0 disfavored at ~ 2.5 σ level

Lower panel:
optimal ζ_0 at each α and N_0



Next steps

Additional searches for H_3^+ absorption under way at IRTF (led by Nick Indriolo)

DR rate for rotationally-cold H_3^+ to be measured at the new CSR storage ring in Heidelberg (H. Kreckel and collaborators)

Astrophysical models for $N(H_3^+)/ N(H_2)$ in a turbulent multiphase medium (e.g. B. Godard et al.)

Compare with other tracers of the CRIR in less shielded gas (OH^+; led by Arshia Jacob) and also more shielded (e.g. Session 1-b in this meeting)