The Galactic Cosmic-Ray Ionization Rate implied by observations of atomic and molecular ions

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Collaborators: Mark Wolfire, Nick Indriolo, Maryvonne Gerin, Javier Goicoechea, Paule Sonnentrucker, Michael Kaufman, David Hollenbach, Raymond Oonk, Xander Tielens

Funding: Herschel Project, NASA ADAP program

Outline

- Cosmic-rays: Introduction
- The CR ionization rate in diffuse *molecular* clouds, as determined from observations of H_3^+
- The CR ionization rate in diffuse *atomic* clouds, as determined from observations of OH^+, H_2O^+ and ArH^+
- Additional estimates from radio recombination lines
- Summary and conclusions

Introduction:

Discovery of cosmic rays by Victor Hess

Victor F. Hess, center, departing from Vienna about 1911, was awarded the Nobel Prize in Physics in 1936. (New York Times, August 7, 2012, page D4)

Introduction:

Their nature was controversial

"All the News That's Fit to Print."

The New York Times.

LATE CITY EDITION

NEW YORK, SATURDAY, DECEMBER 31, 1932.

MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

ROOSEVELT WORKS WITH HOUSE CHIEFS FOR FEDERAL CUTS

Mussolini Will Curb Industrial Output As a Means of Combating Depression

O'BRIEN TO EXTEND REFORM PROGRAM; TAKES OATH TODAY

LEHMAN TAKES OATH PRIVATELY TONIGHT IN CEREMONY HERE

REVELRY TO SPEED OLD YEAR, HAIL NEW

AMAZON WAR ZONE TOUCHES 4 NATIONS

WINTER QUITS POST IN ANTI-KOENIG ROW

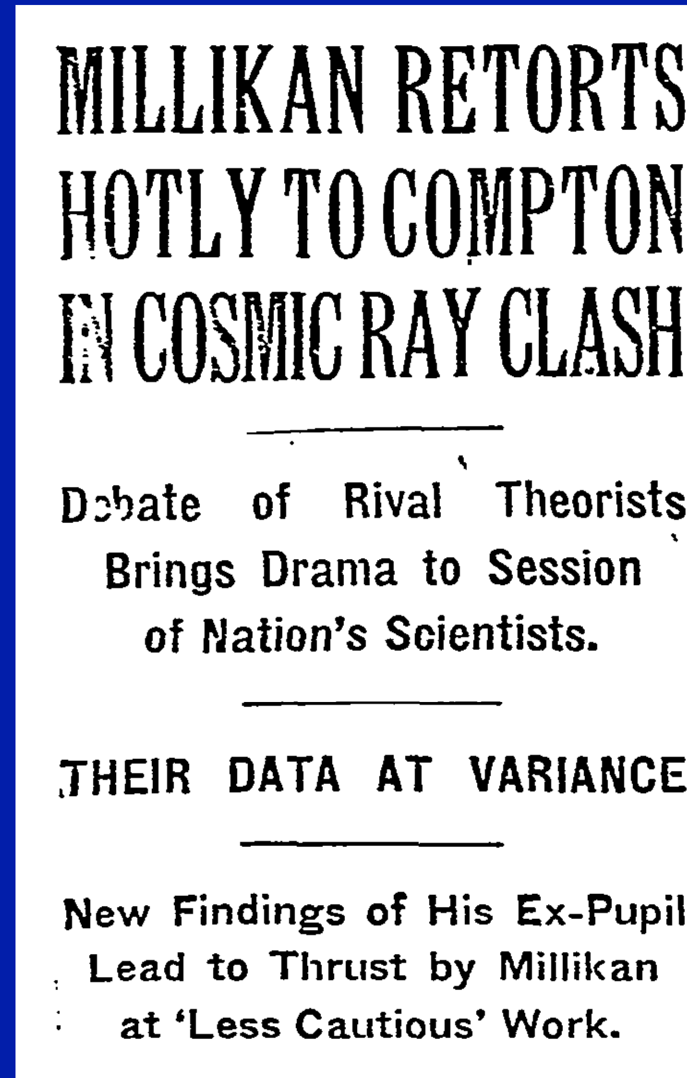
HOOVER HITS LUCK, GETS 7-FOOT FISH

Dill Proposes That Senators Test 3.2 Beer By Observing Effects on Jury of Tasters

Police Radio Alarm Foils Hold-Up of Club; 4 Thugs Seized Robbing 30 Men and Women

LEHMAN TAKES OATH PRIVATELY TONIGHT IN CEREMONY HERE

SHOW SUMMARY



MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

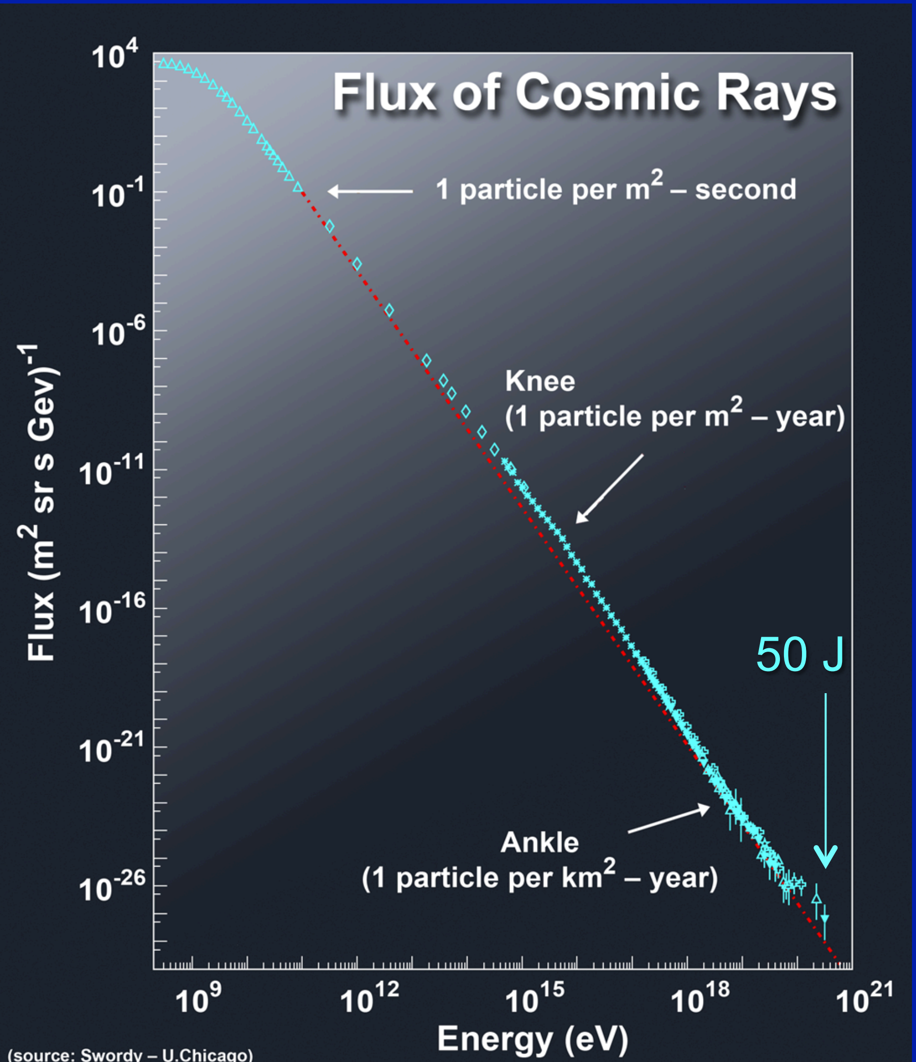
Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

Energy spectrum

CR are observed over a remarkable range of energies



Cosmic ray spectrum (credit: HAP / A. Chantelauze)

Maximum energy detected to date: 50 J
(~ K.E. of Roger Federer 2nd serve)

Total energy density ~ 1 eV cm^{-3}

… somewhat LARGER than that of starlight, the CMB, or the Galactic B-field

Table 1.5 Energy Densities in the Local ISM

Component	$u(\mathrm{eV\,cm^{-3}})$	Note
Cosmic microwave background ($T_{\mathrm{CMB}} = 2.725$ K)	0.265	*a*
Far-infrared radiation from dust	0.31	*b*
Starlight ($h\nu < 13.6$ eV)	0.54	*c*
Thermal kinetic energy $(3/2)nkT$	0.49	*d*
Turbulent kinetic energy $(1/2)\rho v^2$	0.22	*e*
Magnetic energy $B^2/8\pi$	0.89	*f*
Cosmic rays	1.39	*g*

a Fixsen & Mather (2002).
b Chapter 12.
c Chapter 12.
d For $nT = 3800\,\mathrm{cm^{-3}}$ K (see §17.7).
e For $n_{\mathrm{H}} = 30\,\mathrm{cm^{-3}}$, $v = 1\,\mathrm{km\,s^{-1}}$, or $\langle n_{\mathrm{H}} \rangle = 1\,\mathrm{cm^{-3}}$, $\langle v^2 \rangle^{1/2} = 5.5\,\mathrm{km\,s^{-1}}$.
f For median $B_{\mathrm{tot}} \approx 6.0\,\mu$G (Heiles & Crutcher 2005).
g For cosmic ray spectrum X3 in Fig. 13.5.

Draine, 2011

Interaction with the interstellar gas

- High energy (E > 280 MeV) cosmic ray protons create γ-rays via

  $CR + p \rightarrow CR + p + \pi^0$

  $\pi^0 \rightarrow \gamma + \gamma$

- Lower energy cosmic rays ionize and heat the ISM

  $CR + H \rightarrow CR + H^+ + e$

  $CR + H_2 \rightarrow CR + H_2^+ + e$

- Secondary electrons can cause additional ionization and heating, and can excite UV emissions from H and H_2 (important in dense clouds where starlight is absent)

Interaction with the interstellar gas

- Key parameter: the Cosmic Ray Ionization Rate (CRIR)

  There are three quantities that are often used but not always distinguished

  $\zeta_p(H)$: Primary ionization rate per H atom

  $\zeta_t(H)$: *Total* ionization rate per H atom

  (i.e. including further ionizations by secondary e)

  $\zeta_t(H_2)$: Total ionization rate per H_2 molecule

The exact relationship depends on the ionization state of the gas (because the secondary electrons can lose energy through elastic collisions with cold electrons, but the rough ratios are (Glassgold and Langer 1974)

$\zeta_t(H) = 1.5\ \zeta_p(H)$ $\zeta_t(H_2) = 2.3\ \zeta_p(H)$

What CRIR is expected?

- Key obstacle in relating observations of cosmic-rays to the interstellar CRIR:

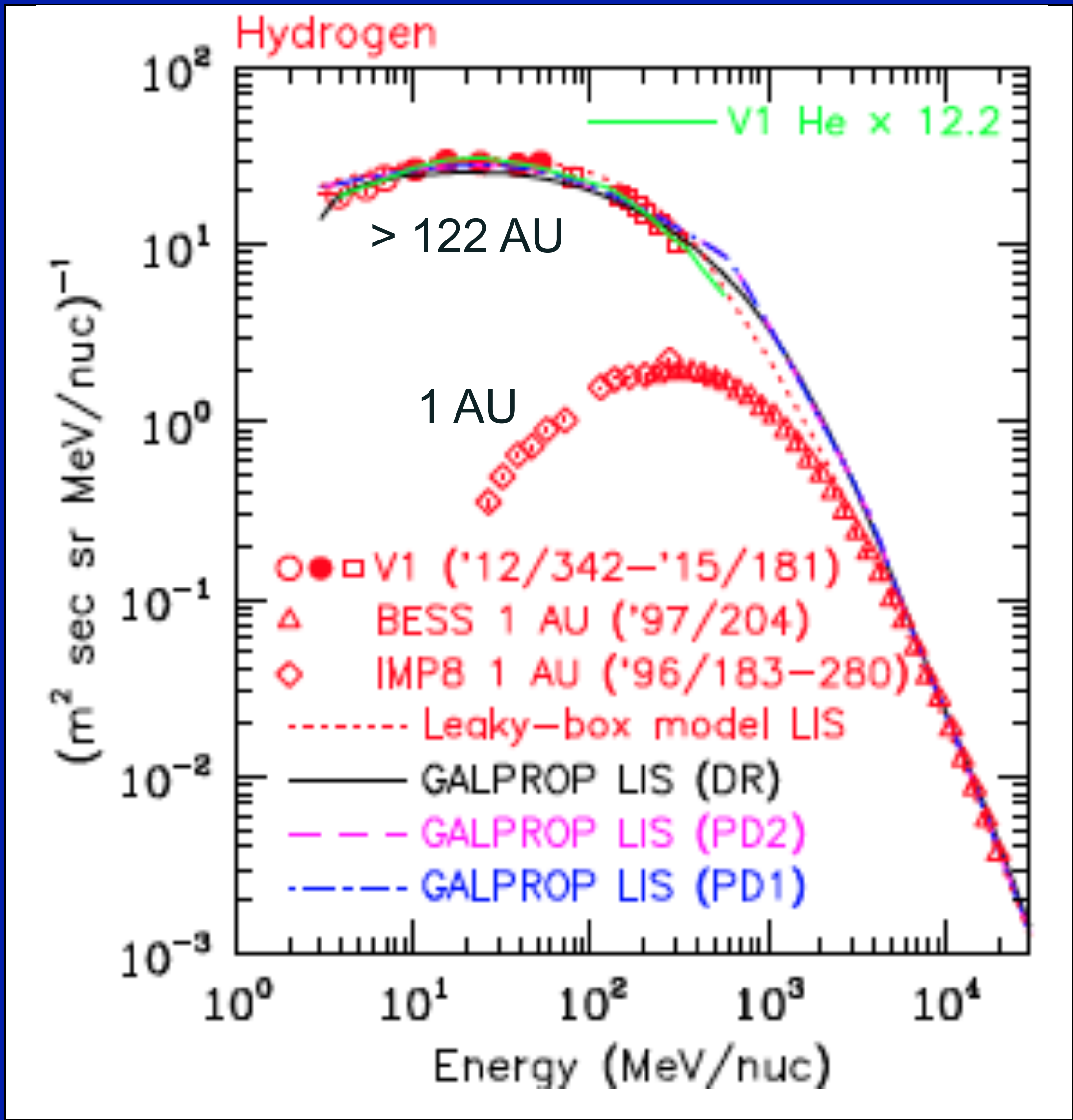
  The ionization rate is dominated by lower energy CR than any that can be detected

  At the location of the Earth, “solar modulation” (due to Sun’s B-field and the solar wind) reduces the flux of CR below ~ 1 GeV

What CRIR is expected?

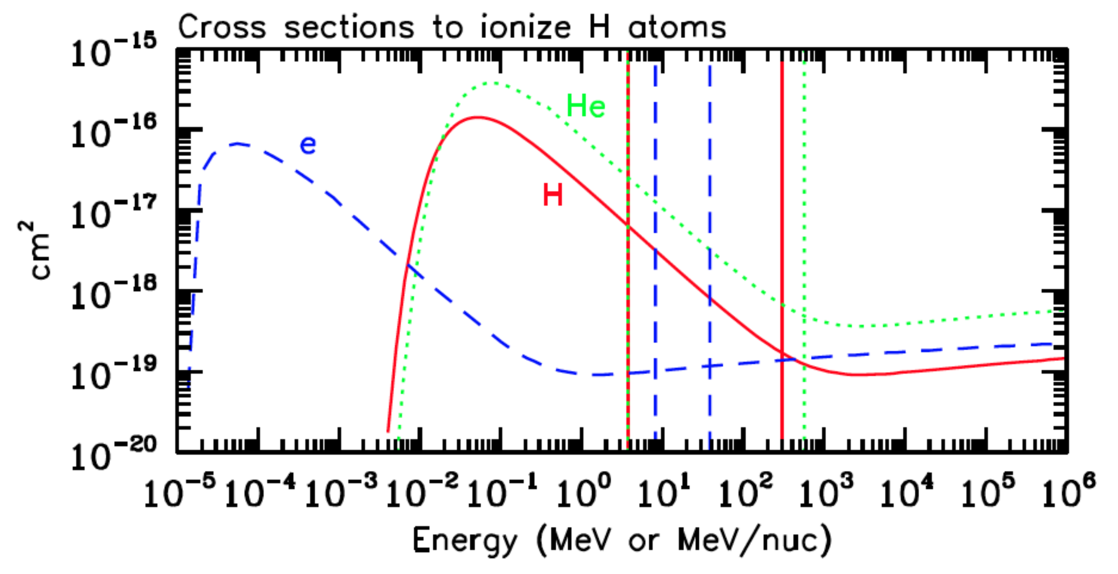
Cummings et al. 2016

In situ measurements by Voyager I show a large reduction in solar modulation effects beyond 122 AU



What CRIR is expected?

Cummings et al. 2016



Cummings et al. (2016) estimate the implied CRIR as

$$\zeta_p(H) = 1.1 \times 10^{-17}\ s^{-1}$$

However, there are three critical caveats

1) The ionization cross-sections peak at CR energies below what can be observed (even with Voyager I) ➔ still need to extrapolate the CR energy spectrum
2) It's not entirely clear whether solar modulation effects are still significant
3) In any case, the results apply only to the local ISM

What CRIR is inferred from observations of the ISM?

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

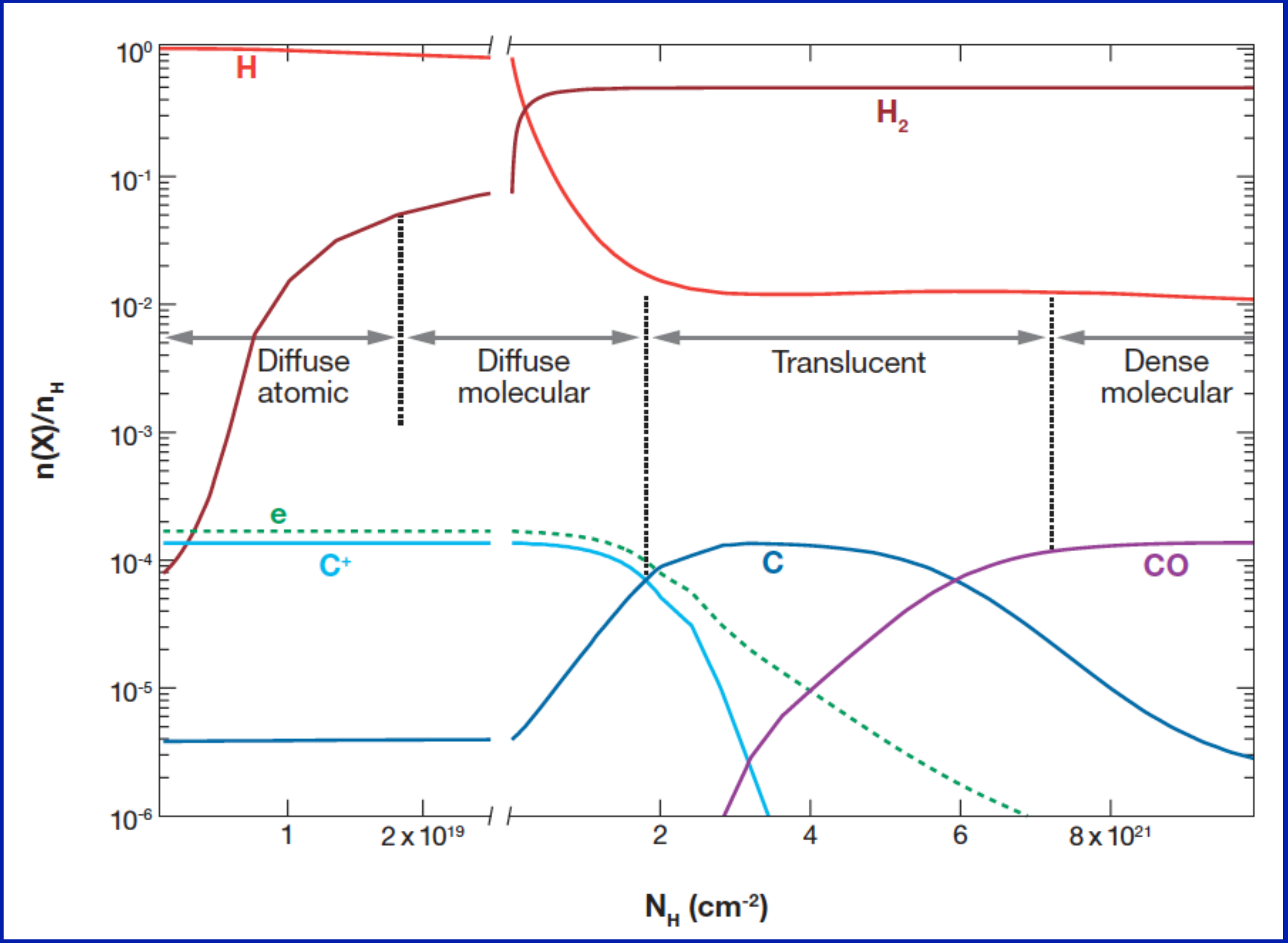


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Table 1 Classification of Interstellar Cloud Types

	Diffuse Atomic	Diffuse Molecular	Translucent	Dense Molecular
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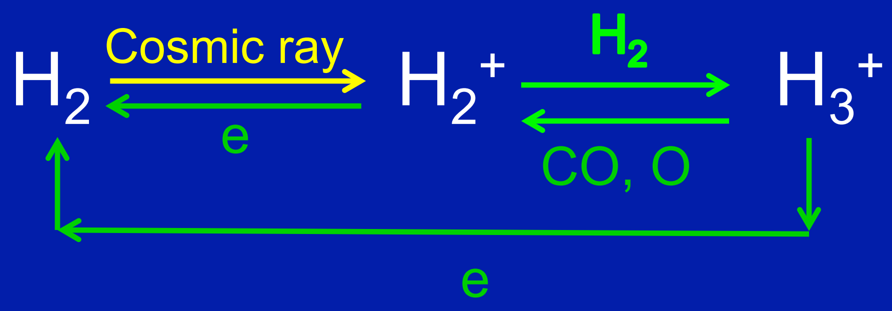
Observations of $H^{13}CO^+$
➔ Avg. $\zeta_p(H) = 1.1 \times 10^{-17}\ s^{-1}$
(van der Tak & van Dishoeck 2000)

Temperature of starless cores
(Keto & Caselli 2008)
➔similar results

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

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

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.

MENU

nature
International journal of science

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

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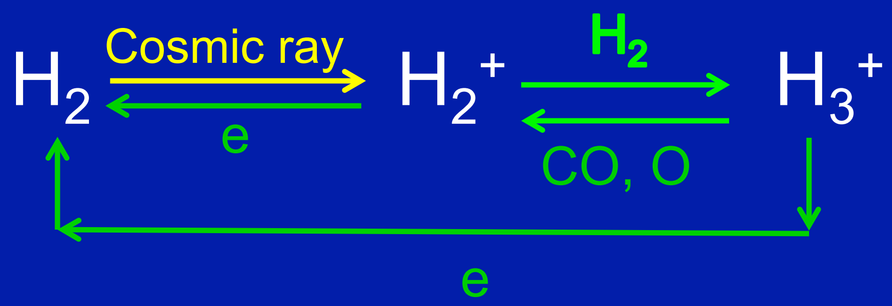

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$\zeta_p(H) = 5 \times 10^{-16}\ s^{-1}$

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

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

Variation with cloud $N(H_2)$:

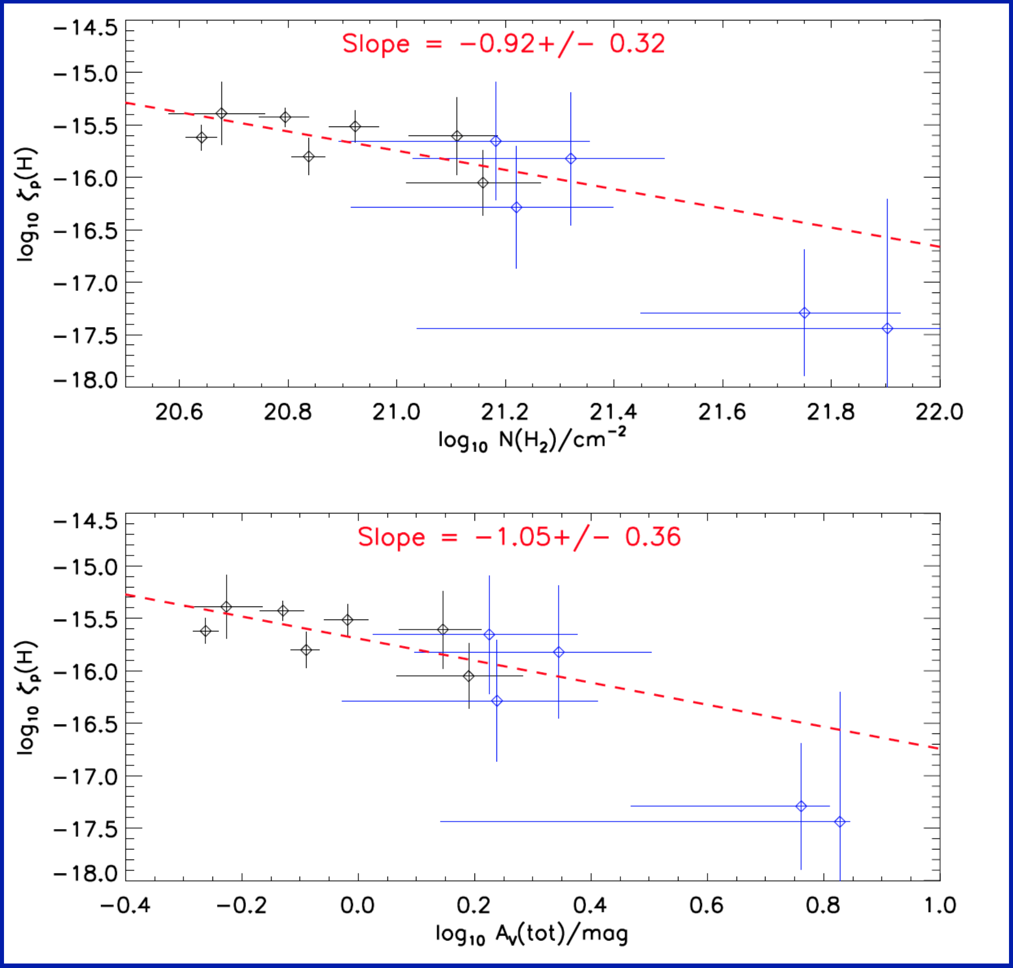
Black points: clouds <u>with</u> direct measurements of H_2 and density estimates from C_2

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

What CRIR is inferred from observations of the ISM?

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

Table 1 Classification of Interstellar Cloud Types

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From H_3^+
$\zeta_p(H) =$ **2.3 ± 0.6 × 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× 10^{-17} s^{-1}**

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Can be addressed (using OH^+, H_2O^+ and ArH^+ observations)

Revisited in this talk with (RRL observations)

Not considered further in this talk

Thermochemistry for different elements

Element	Ionization Potential (eV)	Endothermicity (Kelvin equivalent $\Delta E/k_B$) for			Driver
		$X + H_2 \rightarrow XH + H$	$X^+ + H_2 \rightarrow XH^+ + H$	$X + H_3^+ \rightarrow XH^+ + H_2$	
C	11.260	11000	4640 ✓		Warm gas
N	14.534	15000	230	10000	?
O	13.618	940 ✓	✓	✓	Warm gas or cosmic rays
F	17.423	✓		10000	None needed
Ne	21.564	No reaction	Exothermic, but primary channel is to $Ne + H + H^+$	27000	
Si	8.152	17000	15000		Warm gas
P	10.487	19000	13000		Warm gas
S	10.360	10000	10000 ✓		Warm gas
Cl	12.968	450	✓		UV with $h\nu > 12.97$ eV
Ar	15.760	No reaction	✓	6400	Cosmic rays

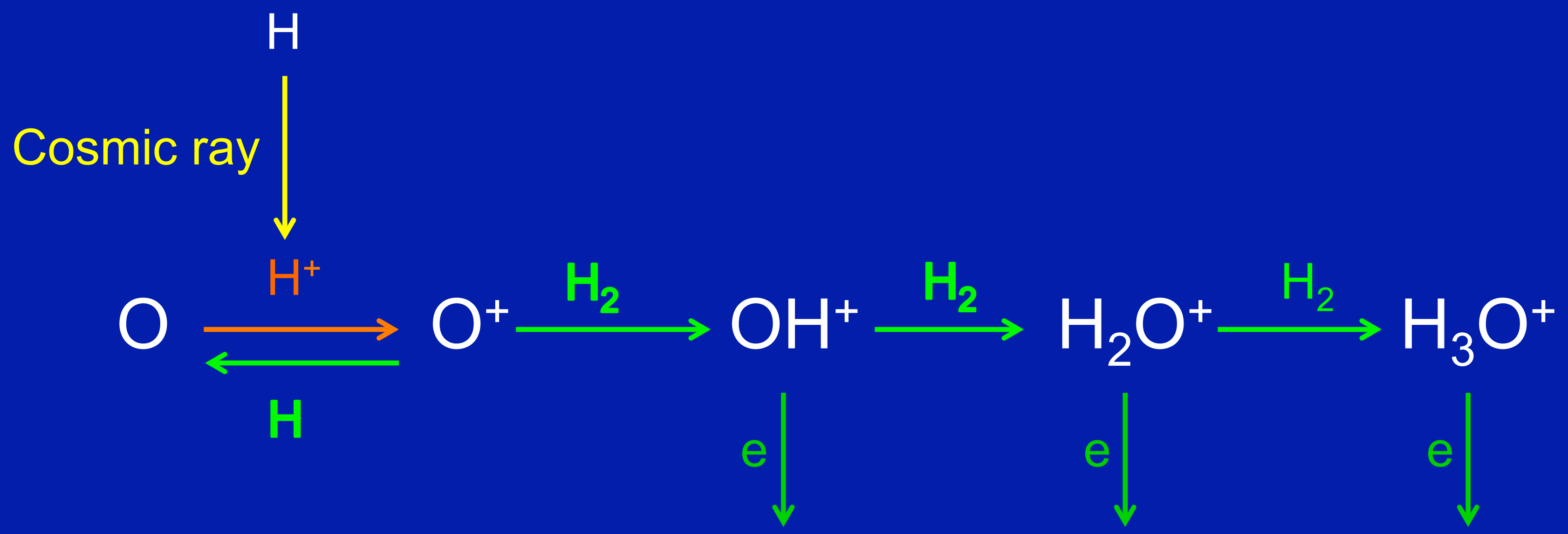
✓ Important formation pathway

Gerin et al. ARAA 2016

- Exothermic reaction of element in its main ionization state
- Endothermic reaction of element in its main ionization state
- Exothermic reaction of element **not** in main ionization state
- Endothermic reaction of element **not** in main ionization state

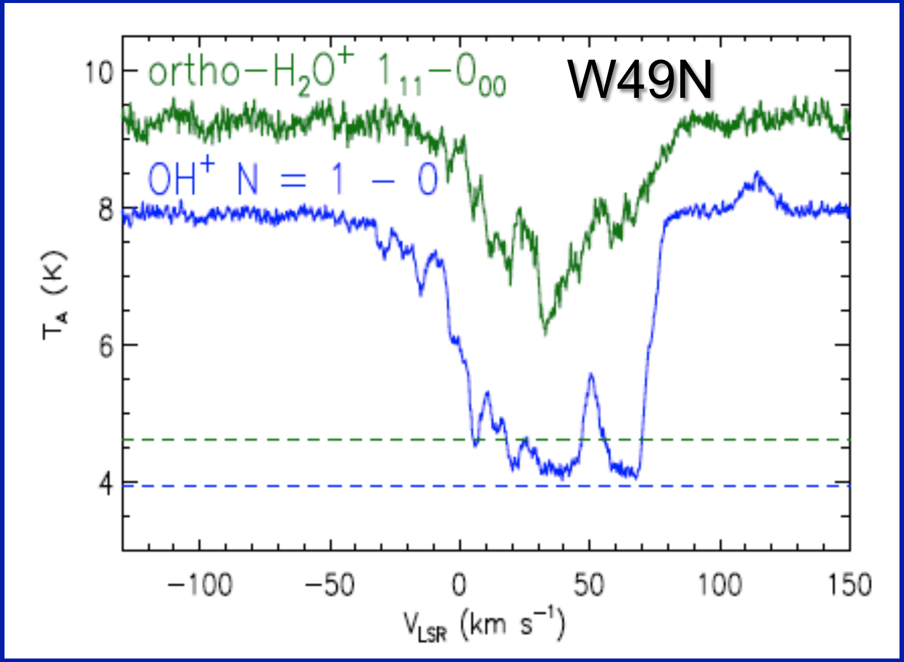
Measuring the cosmic-ray ionization rate with OH^+ and H_2O^+

O is not ionized by UV radiation longward of the Lyman limit, so OH^+ and H_2O^+ formation must be initiated by cosmic ray ionization



Measuring the cosmic-ray ionization rate with OH^+ and H_2O^+

OH^+ and H_2O^+ are observable with Herschel/HIFI



Neufeld, Goicoechea, Sonnentrucker et al. 2010, A&A

Full dataset provides ~ 100 column density measurements (Indriolo et al. 2015, ApJ)

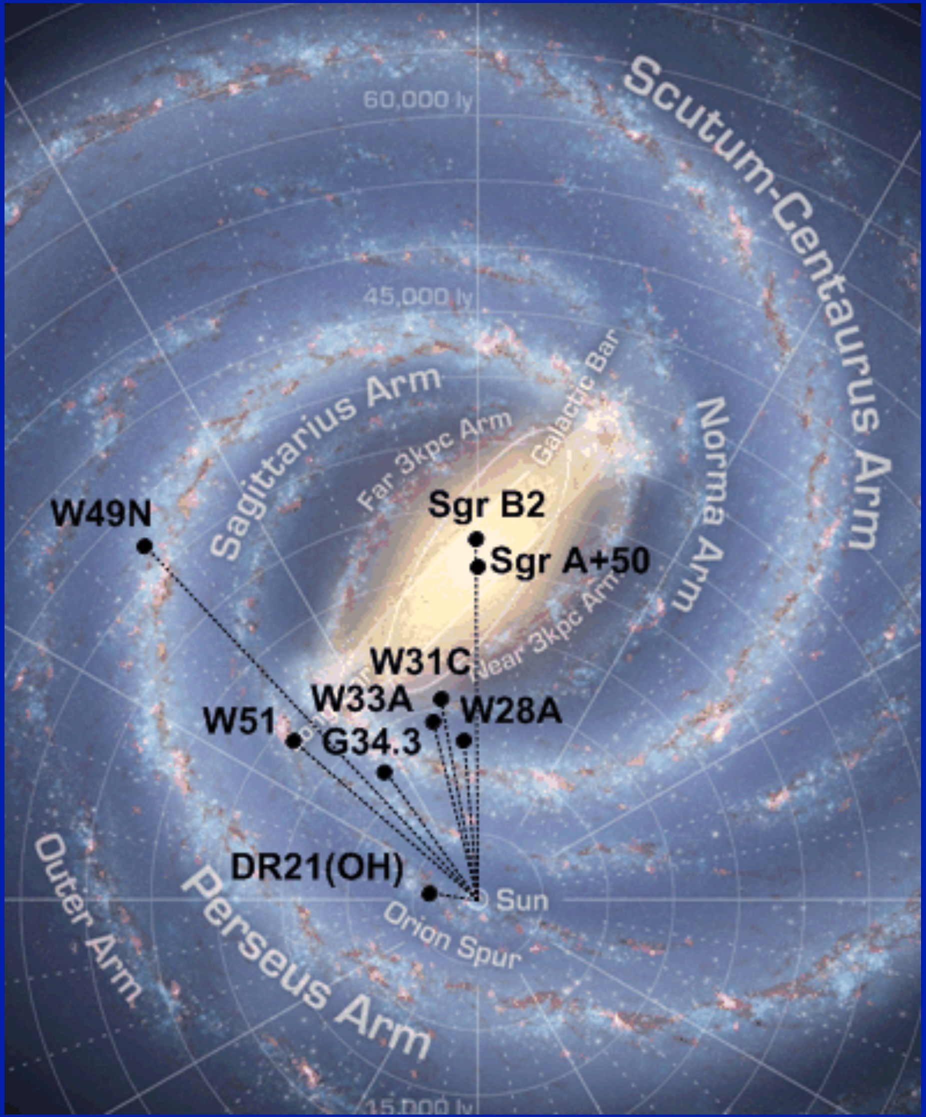
PRISMAS Herschel Key Program

PRobing the **ISM** with **A**bsorption line **S**tudies

High spectral-resolution observations of diffuse clouds lying along the sight-line to bright THz continuum sources

A very "clean" experiment providing robust estimates of molecular column densities

H column densities available from 21 cm observations with VLA (Winkel et al. 2017)



Credit: NASA/SSC

Detailed diffuse cloud models: OH^+ and H_2O^+ abundances

Current model (Neufeld & Wolfire 2017) refines earlier treatment by Hollenbach et al. (2012): constant density slab models in steady-state

Extensive parameter study carried out for 2880 combinations of relevant parameters. Note: results scale with χ_{UV} / n_H and $\zeta_p(H) / n_H$

UV radiation field relative to Draine (1978) estimate

Total extinction through cloud

Metallicity relative to ISM in solar neighborhood

Parameter	Number of values	Values
χ_{UV}	10	0.05, 0.1, 0.2, 0.3, 0.5, 1.0, 2.0, 3.0, 5.0, 10.0
$\zeta_p(H)/10^{-16}\,s^{-1}$	9	0.006, 0.02, 0.06, 0.2, 0.6, 2.0, 6.0, 20, 60
$A_V(tot)/mag$	16	0.0003, 0.001, 0.003, 0.01, 0.03, 0.1, 0.2, 0.3, 0.5, 0.8, 1.0, 1.5, 2.0, 3.0, 5.0, 8.0
Z/Z_{std}	2	1.0, 2.0
n_H	1	$50\,cm^{-3}$

In gas phase: O/H = 3.9×10^{-4}, C/H = 1.6×10^{-4}, Ar/H = 3.2×10^{-6}

Detailed diffuse cloud models: OH^+ and H_2O^+ abundances

Predicted column density ratios (Neufeld and Wolfire 2017), with observed values from Indriolo et al. (2015)

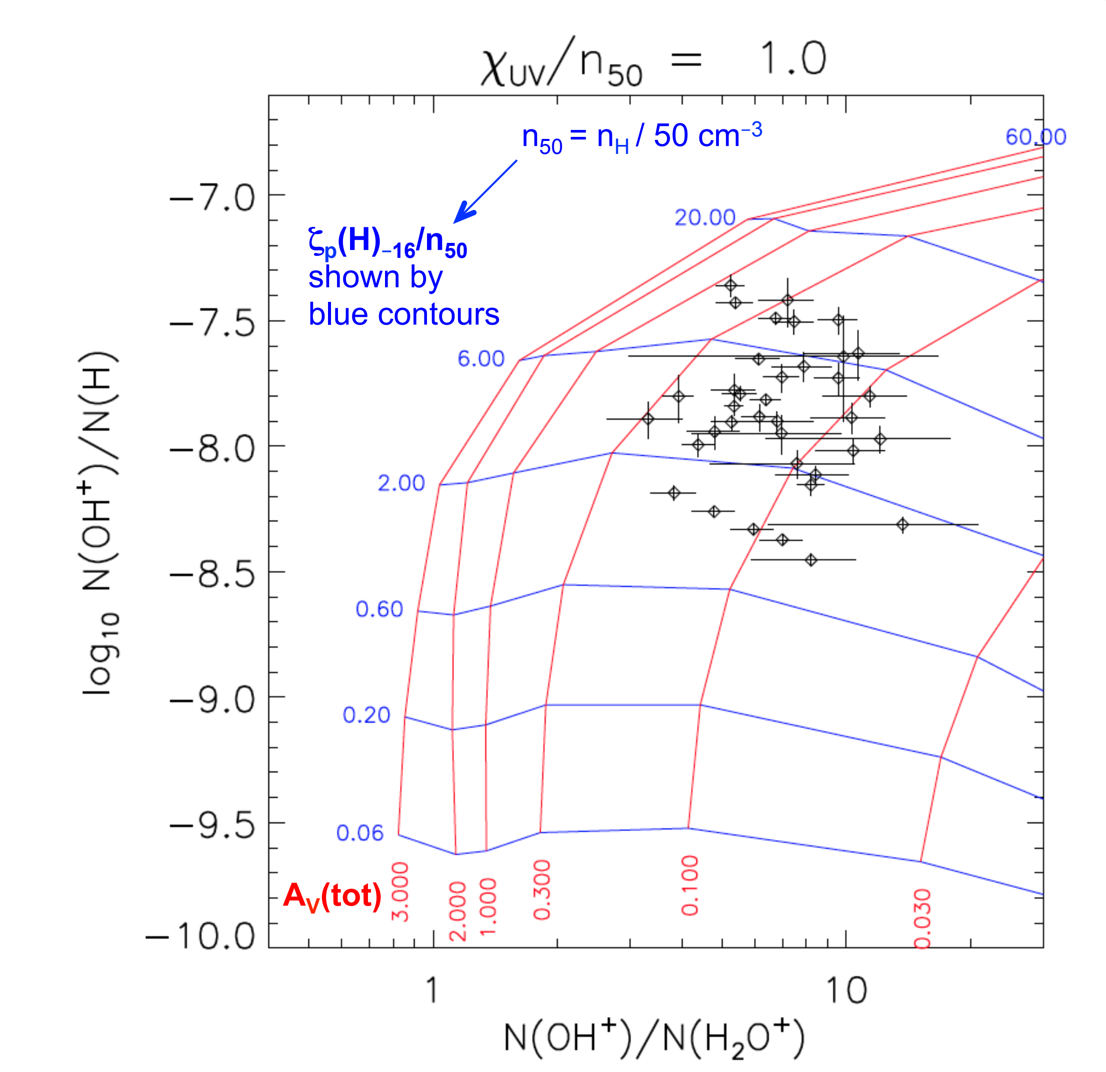
Key predicted behaviors

Predicted $N(OH^+)/N(H_2O^+)$ decreases with A_V(tot)

Larger A_V(tot) means more H_2 , which means more H_2O^+

Predicted $N(OH^+)/N(H)$ increases with ζ_p(H)

Reaction pathway initiated by H ionization



Additional constraints from ArH^+

Argonium (ArH^+) has been widely observed in the diffuse ISM through its 617 GHz $J = 1 – 0$ absorption line (identified by Barlow et al. 2013 only several years after it was first detected)

It is rapidly destroyed by H_2 in the reaction

$$ArH^+ + H_2 \rightarrow Ar + H_3^+$$

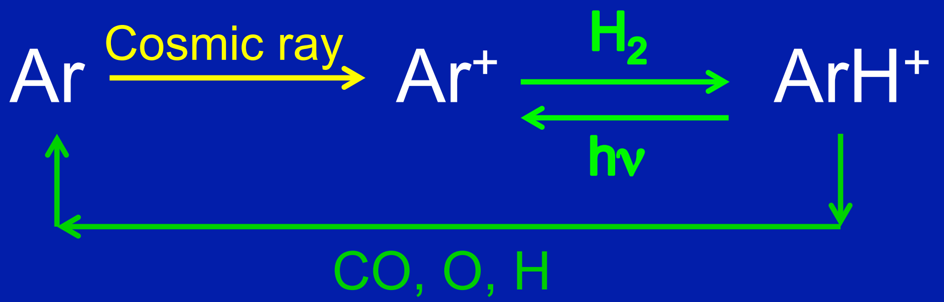
and attains its maximum abundance when

$f_{H2} = 2n(H_2) / [2n(H_2) + n(H)] \sim 10^{-4}$

A molecular tracer of *almost purely atomic* gas

Additional constraints from ArH^+

Argon production is initiated by direct ionization of Ar by cosmic-rays



Observed ArH^+ , OH^+ and H_2O^+ abundances imply that ~ 20 – 50% of the cold neutral ISM is in a separate population of material with $f_{H2} = 10^{-5}$ to 10^{-2} and A_V(tot) < 0.02 mag (Neufeld & Wolfire, 2016)

The CRIR in diffuse *atomic* clouds

Average value obtained from 32 determinations of the CRIR

$$\langle \zeta_p(H) \rangle = (2.2 \pm 0.3) \times 10^{-16}\ s^{-1}$$

↑ standard error on the mean (statistical)

Intrinsic variation in the CRIR

$$\sigma(\log_{10} [\zeta_p(H) / n_{50}]) = 0.23 \text{ (a factor 1.7)}$$

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From HCO^+ (van der Tak & van Dishoeck 2000)
ζ_p(H) = 1.1× 10^{-17} s^{-1}

The CRIR in diffuse *atomic* clouds

Important caveat: uncertainty estimates include only statistical errors and not uncertainties in reaction rates

Key reactions:

$H^+ + PAH \rightarrow PAH^+ + H$	(1)
$H^+ + O \rightarrow O^+ + H$	(2)
$O^+ + H \rightarrow H^+ + O$	(3)
$O^+ + H_2 \rightarrow OH^+ + H$	(4)
$OH^+ + H_2 \rightarrow H_2O^+ + H$	(5)
$OH^+ + e \rightarrow O + H$	(6)

CRIR estimates are

(1) an increasing function of k_5 and k_6
(2) inversely proportional to k_4
(3) proportional to k_1 and k_3/k_2

In LTE, k_3/k_2 is fixed by detailed balance, but in diffuse clouds OI is subthermally populated

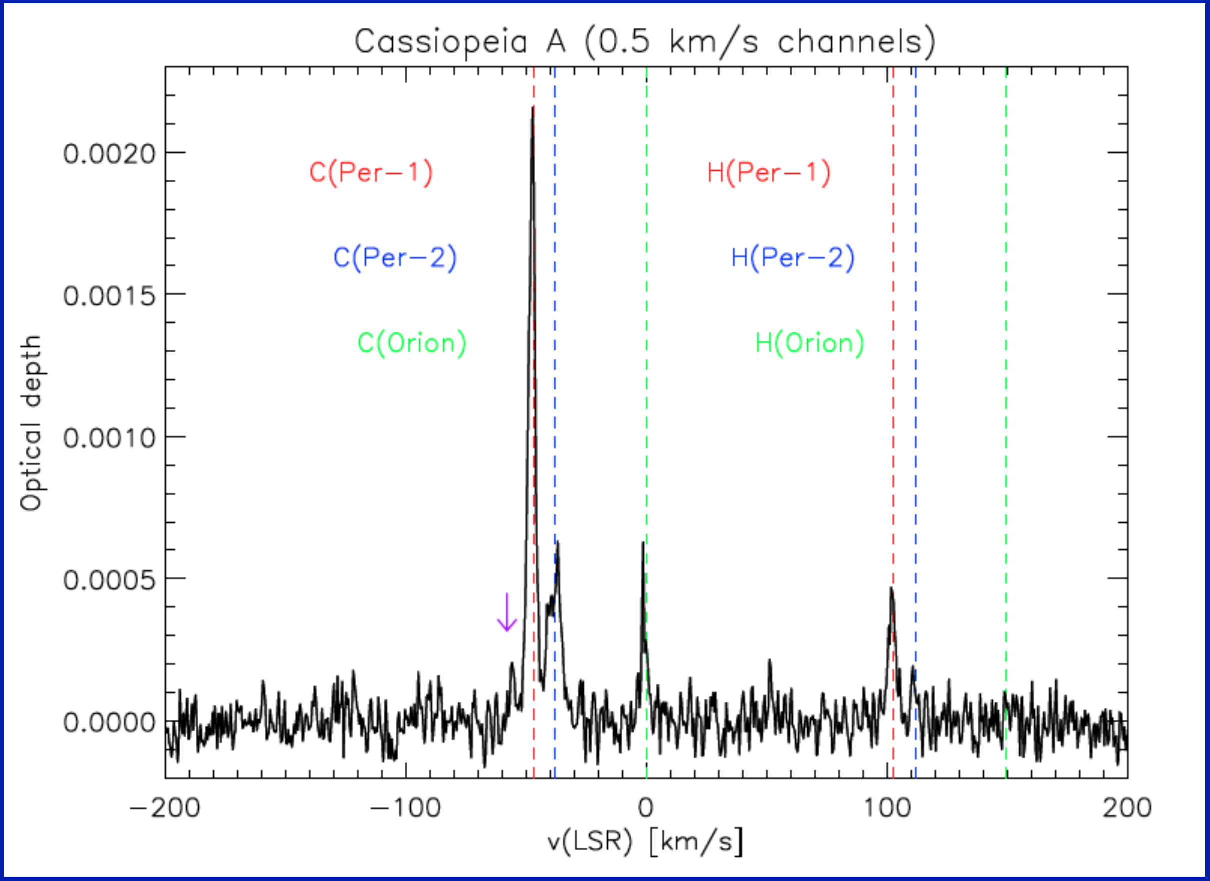
If rate k_2 for $O(^3P_2)$ is abnormally low (suggested by Spirko et al. 2003), then CRIR must increase to match data.

Radio recombination lines

Lines of very high principal quantum number *n* (~ 250 to 900) are detectable from diffuse atomic clouds (rather than HII regions)

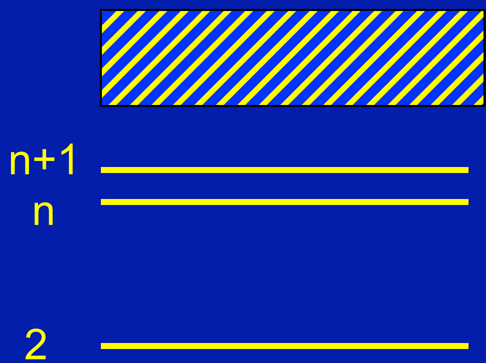
Best example: stacked absorption spectra obtained toward Cas A by Oonk et al. (2017) using the Westerbork Synthesis Radio Telescope (WSRT)

Cnα lines are shifted relative to Hnα lines by -149 km s^{-1} (due to smaller reduced mass)



Oonk et al. (2017)

Rydberg states

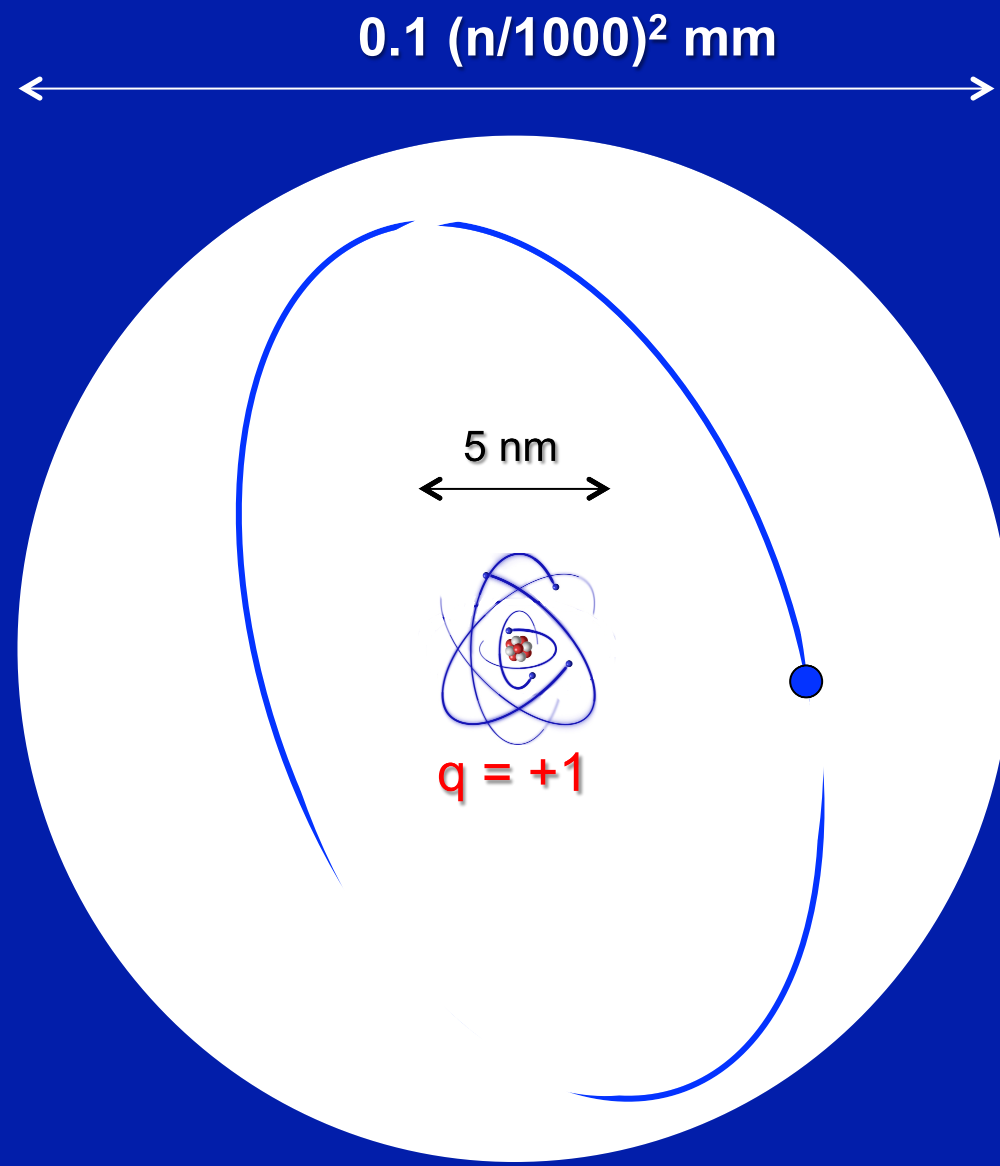


E_n = Ry/n^2

h$\nu_{Cn\alpha}$ ~ 2 Ry/n^3

Ry = R$_\infty$/(1+ m$_e$/m$_N$)

1



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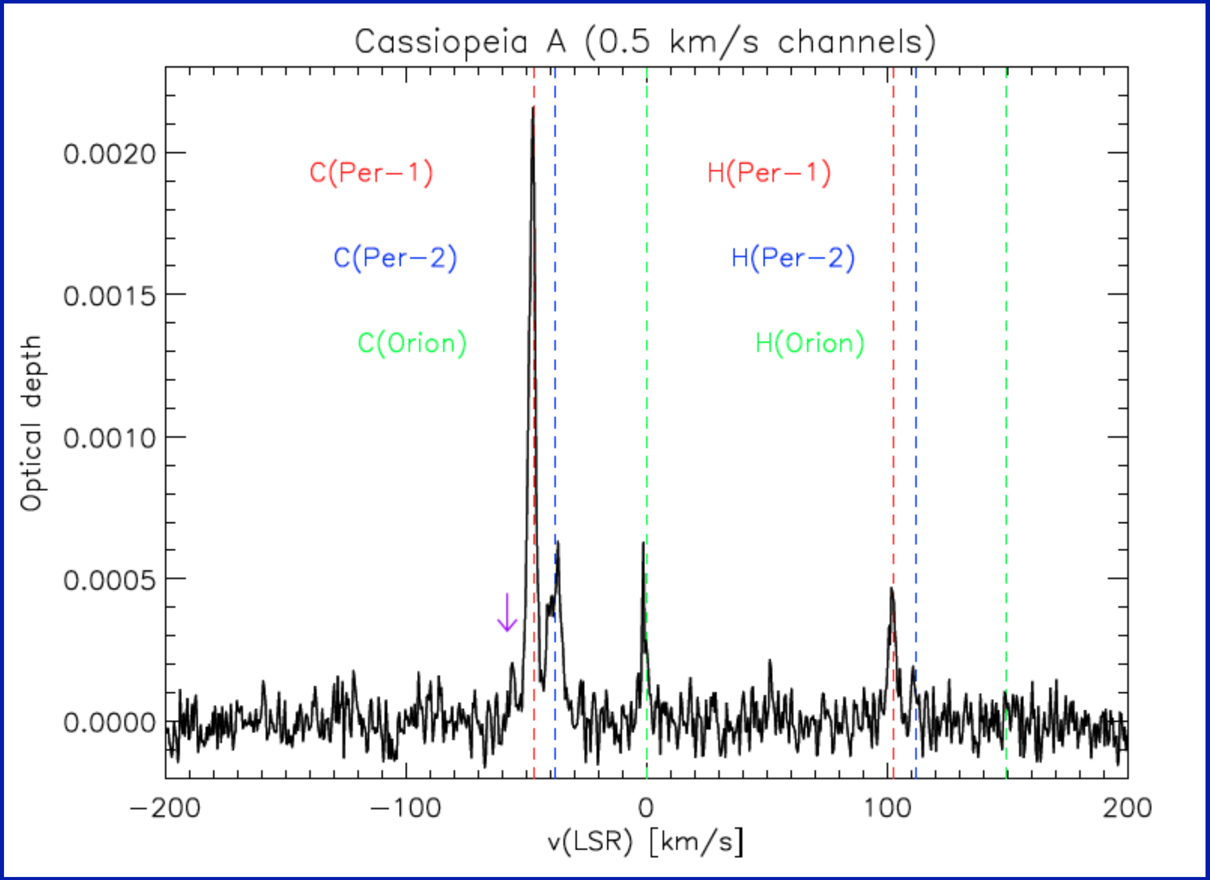
Best example: stacked absorption spectra obtained toward Cas A by Oonk et al. (2017) using the Westerbork Synthesis Radio Telescope (WSRT)

Cnα lines are shifted relative to Hnα lines by -149 km s^{-1} (due to smaller reduced mass)



Oonk et al. (2017)

Radio recombination lines

- Dependence of line strength on *n*
  - ➔ probe of density and temperature

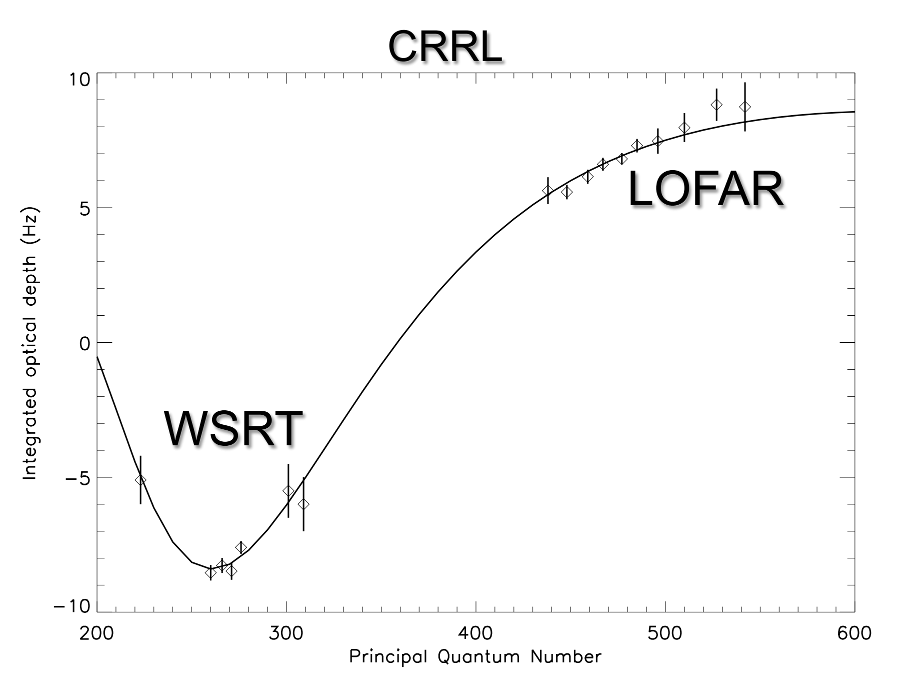
- Ratio of HRRL to CRRL strengths
  - ➔ probe of CRIR in diffuse atomic gas

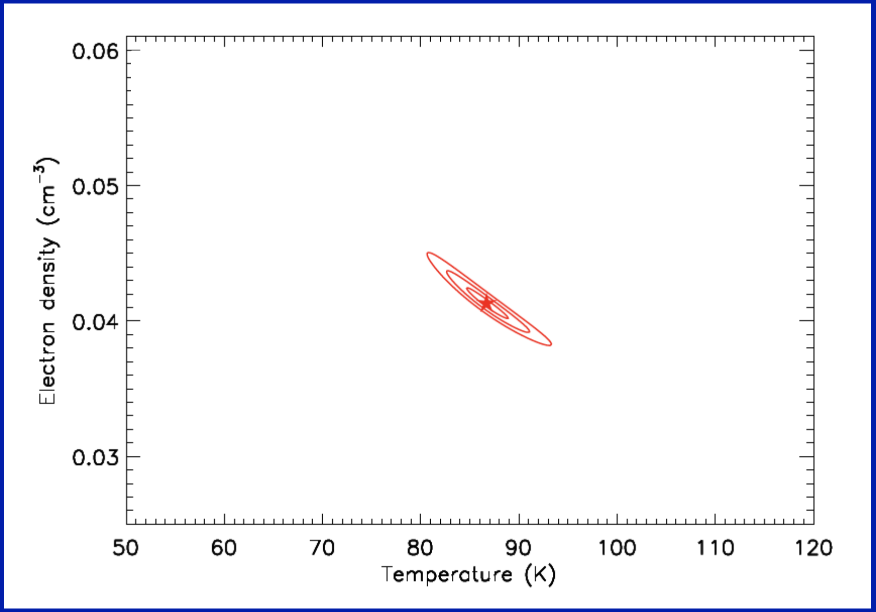
CRRL come from C^+, produced by photoionization

HRRL come from H^+, produced by CR ionization

(First discussed by Sorochenko and Smirnov 1987)

Radio recombination lines





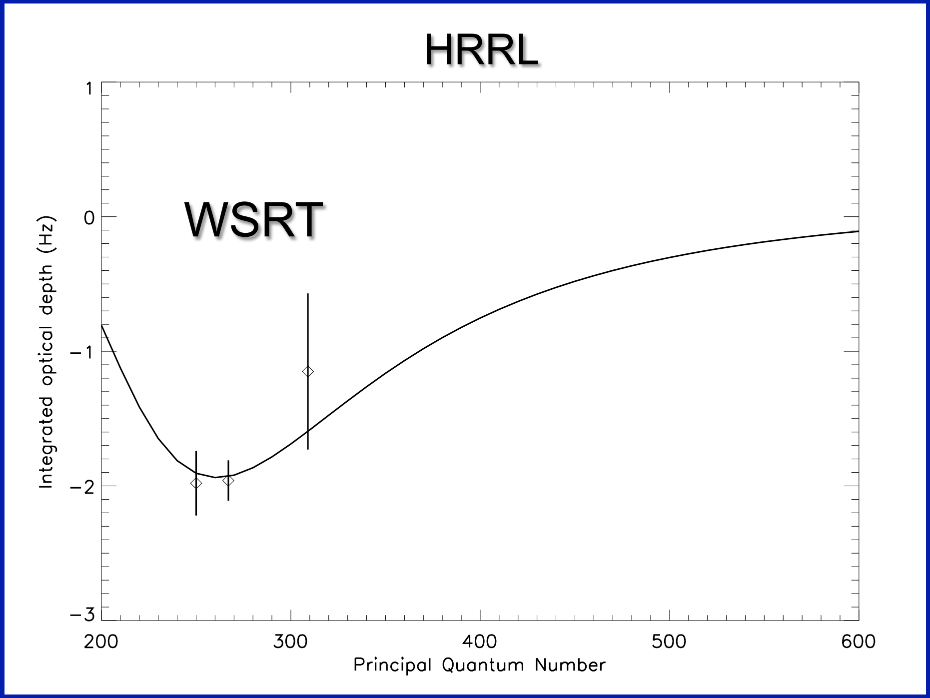
Best-fit parameters

$T = 87 \pm 2$ K

$n_e = 0.041 \pm 0.001$ cm^{-3}

*1 sigma statistical uncertainties

Radio recombination lines



Ratio of HRRL/CRRL places constraints on CRIR

From this, Oonk et al 2017 got a lower limit of 1.1 x 10^{-18} s^{-1} on $\zeta_p(H)$, by assuming that H^+ is destroyed solely by radiative recombination

However, two additional processes are much more important in removing H^+

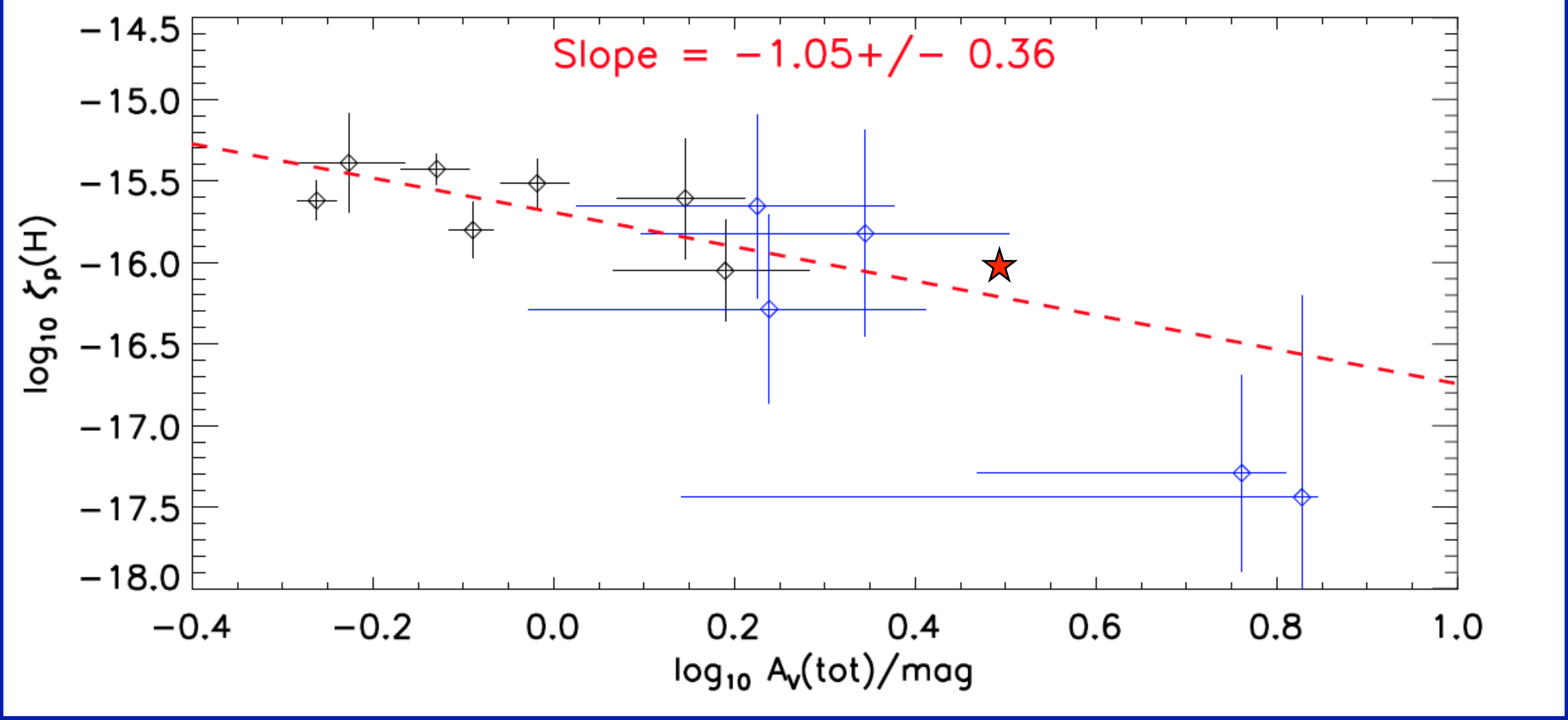
$H^+ + PAH \rightarrow H + PAH^+$
$H^+ + O \rightarrow H + O^+$
(followed by $O^+ + H_2 \rightarrow OH^+ + H$)

Radio recombination lines

$\zeta_p(H) = 8 \times 10^{-17}\ s^{-1}$ (Neufeld et al. 2018, ApJ, submitted)

UV field = 6 x mean IS field

$n_H = 220\ cm^{-3}$



What CRIR is inferred from observations of the 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 OH^+, H_2O^+ and ArH^+
$\zeta_p(H) = 2.2 \pm 0.3 \times 10^{-16}\ s^{-1}$

From H and C RRL
$\zeta_p(H) = 8 \times 10^{-17}\ s^{-1}$

From H_3^+
$\zeta_p(H) = 2.3 \pm 0.6 \times 10^{-16}\ s^{-1}$
(with marginal evidence for decline with A_V(tot))

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

Summary and conclusions

- Remarkable concordance between three independent methods for estimating the CRIR in diffuse atomic and molecular clouds: all yield $\zeta_p(H) = 0.8 - 2.3 \times 10^{-16}\ s^{-1}$

- CRIR in diffuse clouds is a factor of 20 to 30 larger than that estimated for dense clouds

  Suggests that CR are excluded from dense clouds

  NB: Observations of diffuse molecular clouds do show (marginal) evidence for CRIR decreasing with N_H

- CRIR in diffuse clouds is a factor of 20 to 30 larger than estimates based on latest Voyager data

  Possible explanations: LISM is atypical, solar modulation is still important at current location of Voyager I, X-ray ionization is important in ISM, and/or extrapolation of CR spectrum is wrong