Cosmic Rays in the Interstellar Medium

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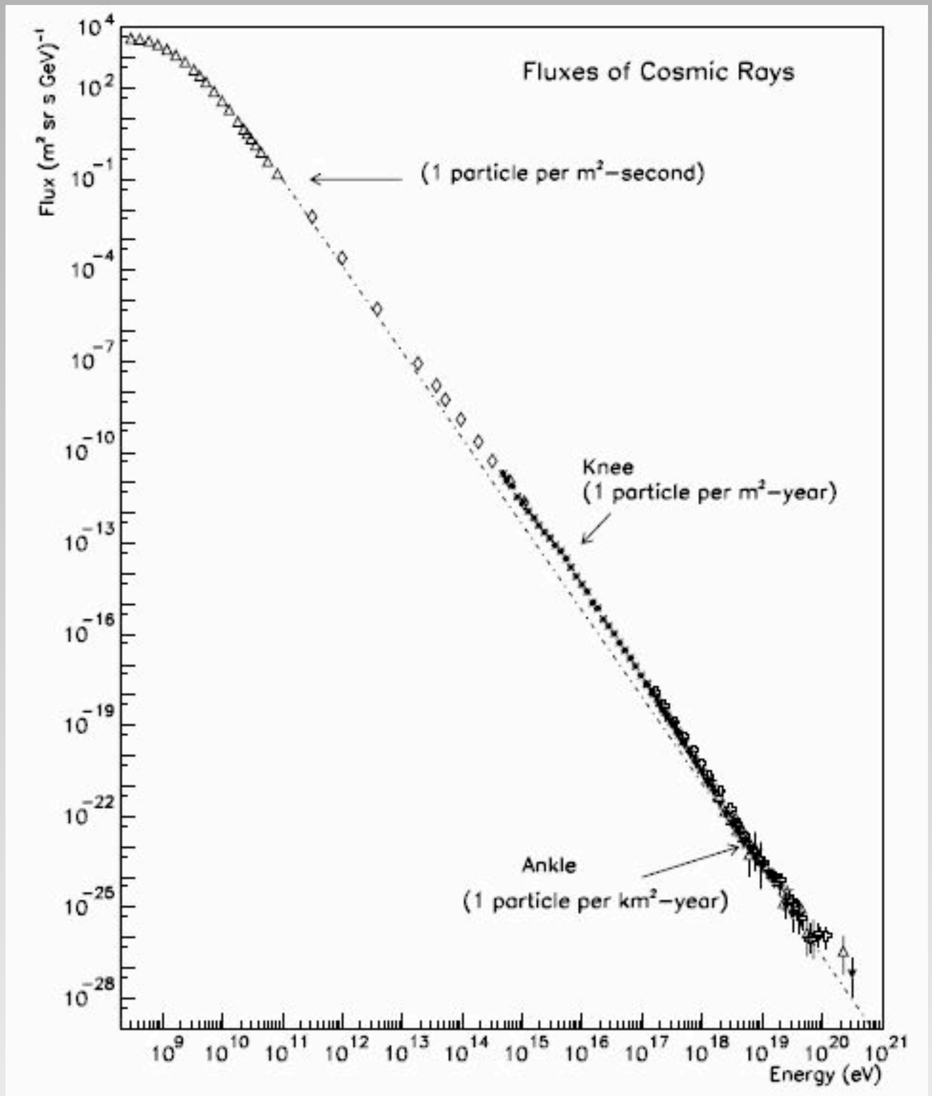
Cosmic Ray Basics

- Energetic charged particles and nuclei
- protons, alpha particles, heavy bare nuclei
- electrons & positrons
- Deflected by magnetic fields so they cannot be traced back to sources
- Ubiquitous throughout the ISM

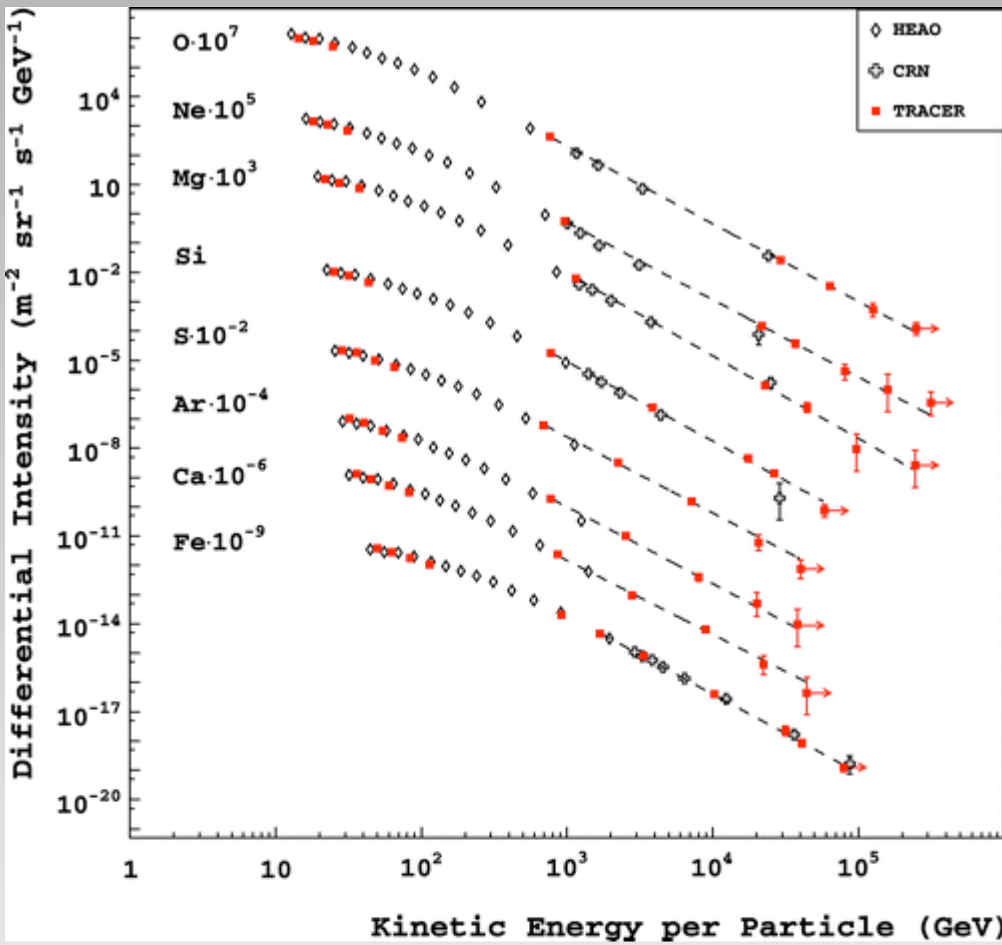
Particle Spectrum

- Energy covers over 15 orders of magnitude
- Flux varies by ~30 orders of magnitude
- Particles in different energy regimes are thought to be accelerated by different sources (winds, SNR, AGN)



Swordy 2001, Space Sci. Rev., 99, 85

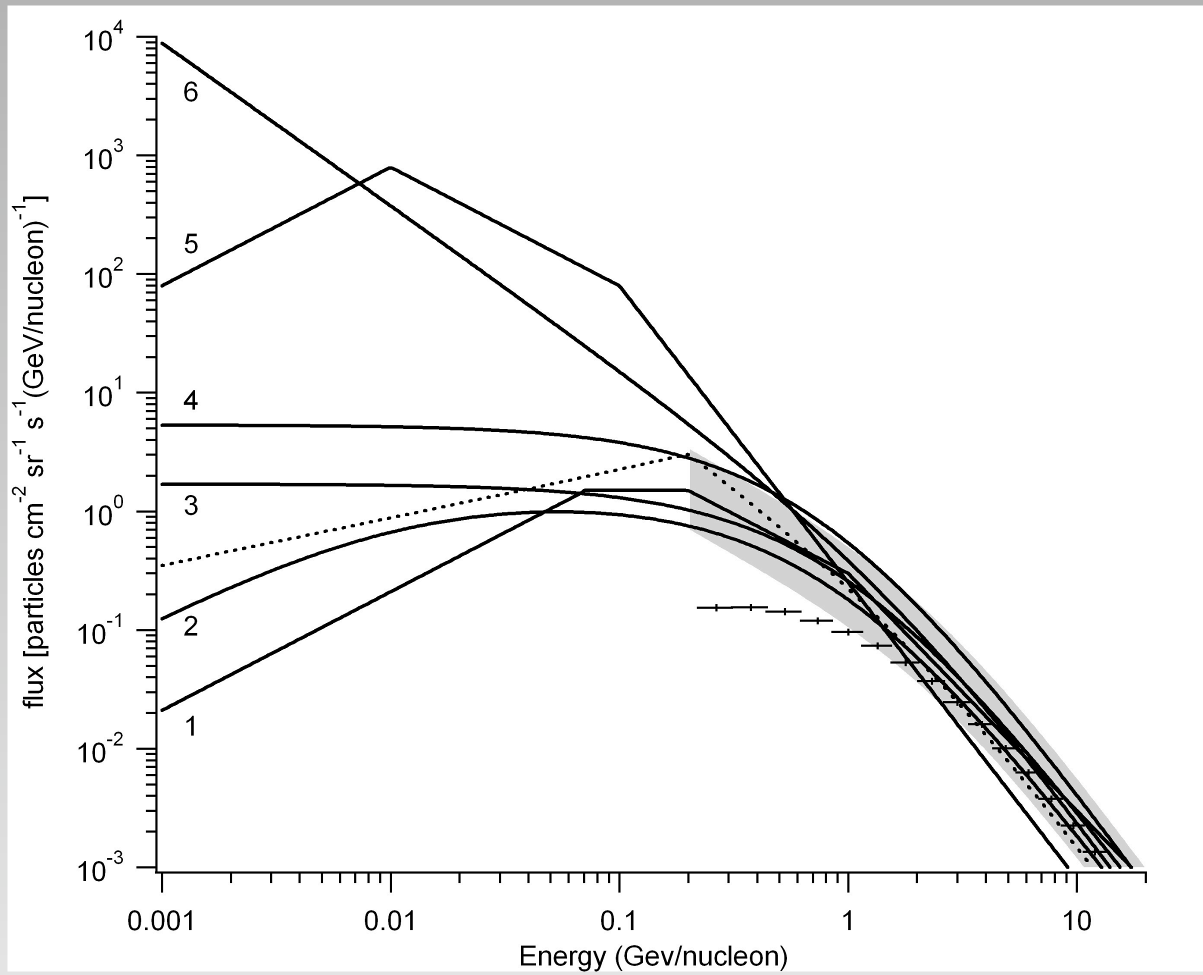
Particle Spectrum



Ave et al. 2008, ApJ, 678, 262

- Spectral shape is consistent for all species
- Abundances with respect to hydrogen tend to be enhanced when compared to solar system values
- ^{16}O
  - 7.4×10^{-4} solar
  - 3.7×10^{-3} GCR

Particle Spectrum



1 - Herbst & Cuppen 2006, PNAS, 103, 12257
2 - Spitzer & Tomasko 1968, ApJ, 152, 971
3 - Kneller et al. 2003, ApJ, 589, 217

4 - Valle et al. 2002, ApJ, 566, 252
- Hayakawa et al. 1969, PASJ, 13, 184
Nath & Biermann 1994, MNRAS, 267, 447

5 dotted - Indriolo et al. 2009, ApJ, 694, 257
6 - shaded - Mori 1997, ApJ, 478, 225

Interactions with the ISM

- Excitation and ionization of atoms and molecules
- Spallation of ambient nuclei
- Fusion with ambient nuclei
- Excitation of nuclear states
- Pion production
- Heating and desorption of ice mantles

Reaction Rates

- Using cross sections for these interactions, we can compute the rate at which they proceed given a cosmic-ray spectrum

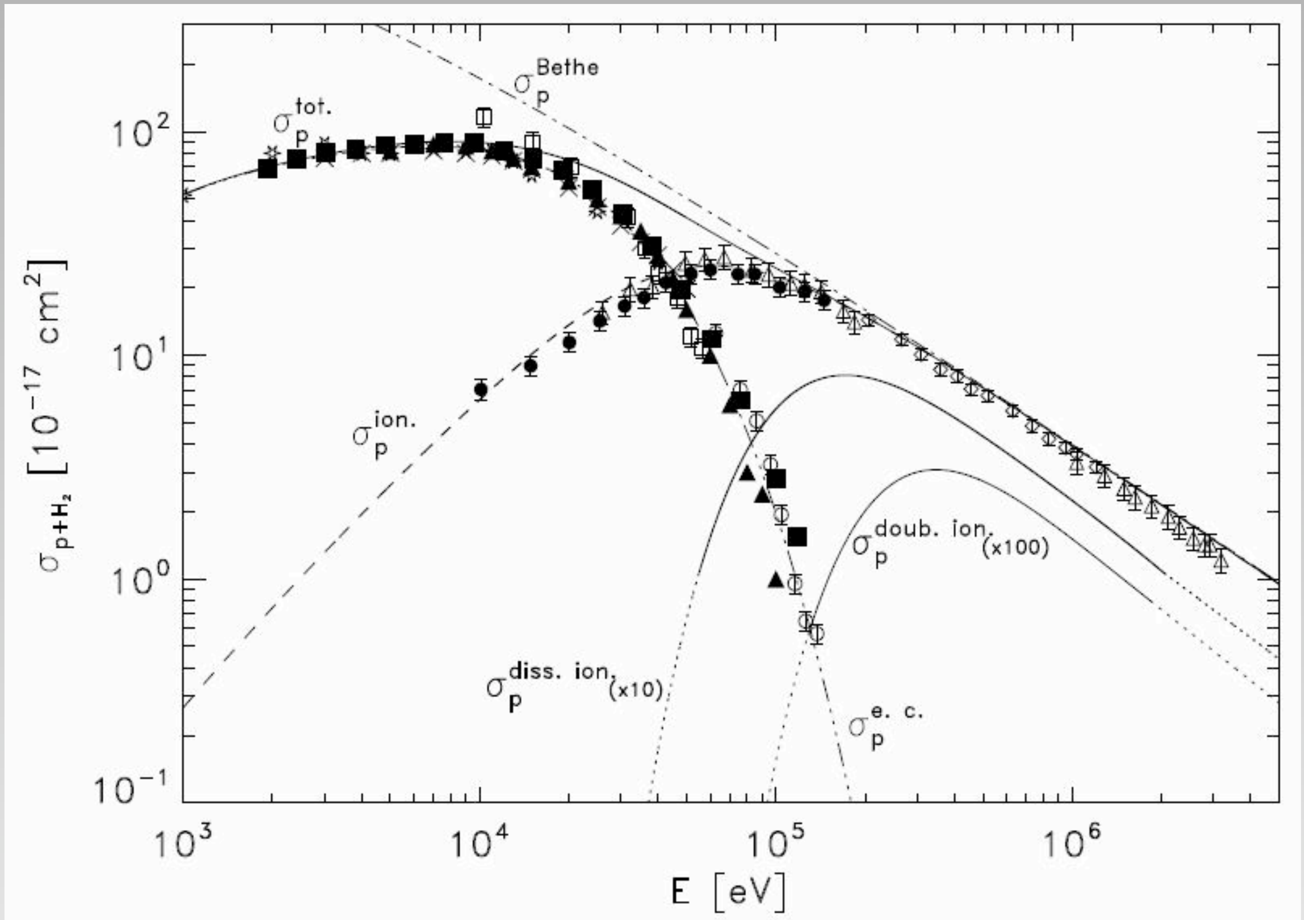
$$\zeta = 4\pi \int_{E_{\mathrm{low}}}^{E_{\mathrm{high}}} \phi(E)\sigma(E)dE$$

- Various processes are primarily dependent on different regimes of the cosmic-ray energy spectrum

Excitation & Ionization

- $p + \mathrm{H(1s)} \rightarrow \mathrm{H(2s)} + p'$
- $p + \mathrm{H} \rightarrow \mathrm{H}^+ + e^- + p'$
- $p + \mathrm{He} \rightarrow \mathrm{He}^+ + e^- + p'$
- $p + \mathrm{H}_2 \rightarrow \mathrm{H}_2^+ + e^- + p'$

Excitation & Ionization

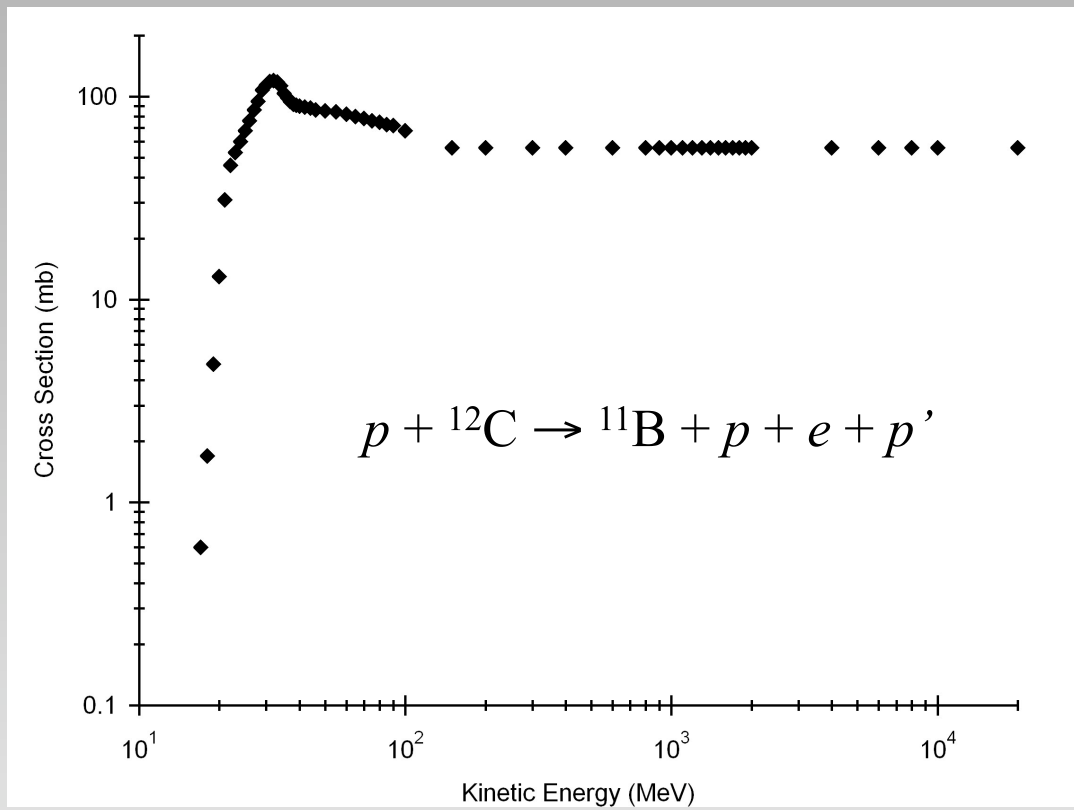


Padovani et al. 2009, A&A, 501, 619 (and references therein)

Spallation & Fusion Reactions

- $[p, \alpha] + [^{12}C, ^{14}N, ^{16}O] \rightarrow$
  $[^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B]$ + fragments
- $\alpha + \alpha \rightarrow [^{6}Li, ^{7}Li]$ + fragments
- ^{6}Li, ^{9}Be, and ^{10}B are *only* produced via these reactions
- Ratios of these 3 isotopes are sensitive to the cosmic-ray spectrum

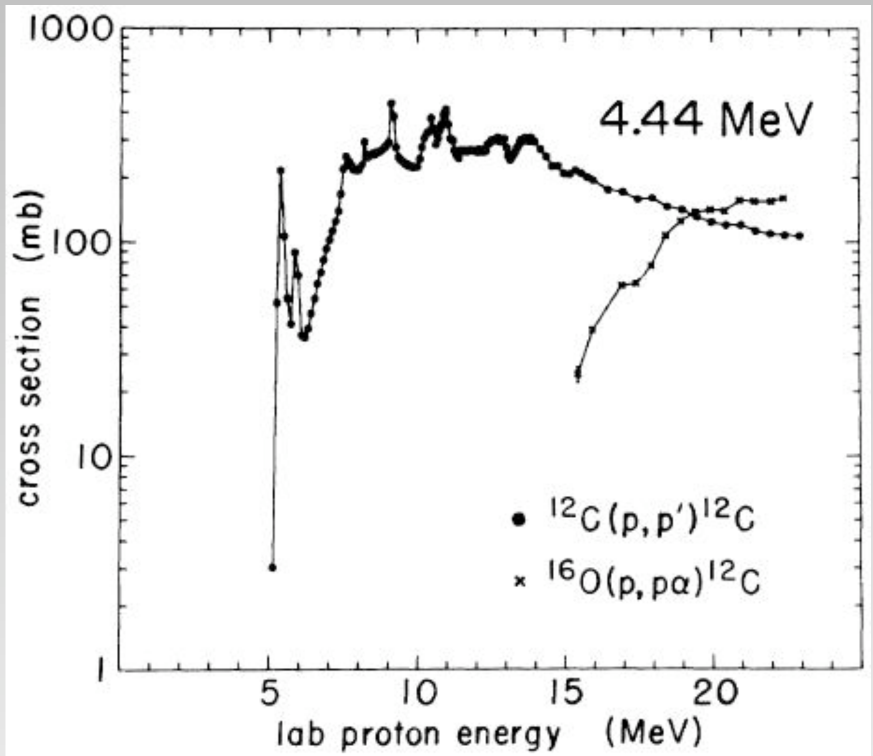
Spallation & Fusion Reactions



Read & Viola 1984, At. Data Nucl. Data Tables, 31, 359

Nuclear Excitation

- $[p, \alpha] + {}^{12}C \rightarrow {}^{12}C^* \rightarrow {}^{12}C + \gamma_{4.44\ \mathrm{MeV}}$
- $[p, \alpha] + {}^{16}O \rightarrow {}^{16}O^* \rightarrow {}^{16}O + \gamma_{6.13\ \mathrm{MeV}}$

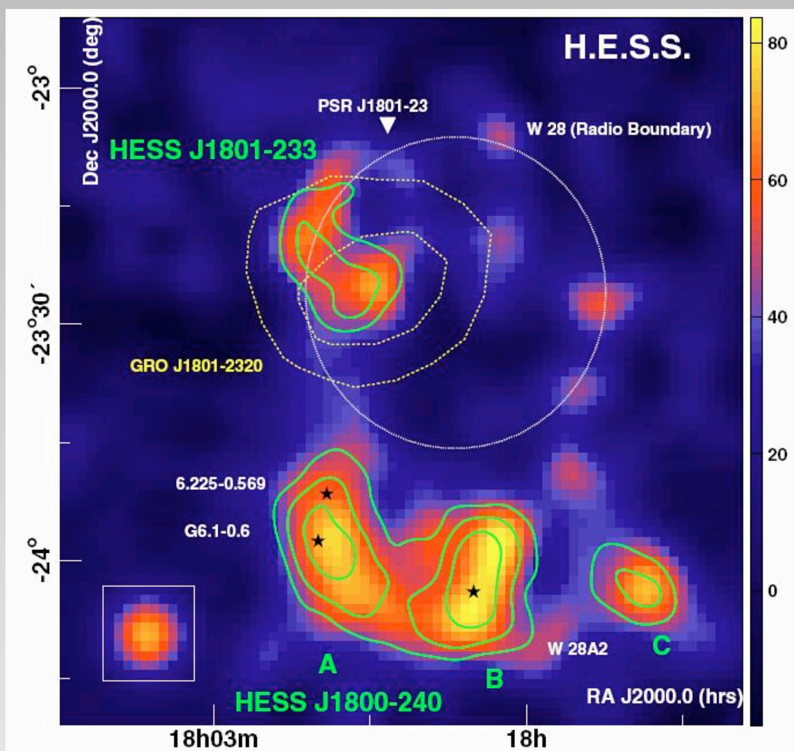


Dyer et al. 1981, Phys. Rev. C, 23, 1865

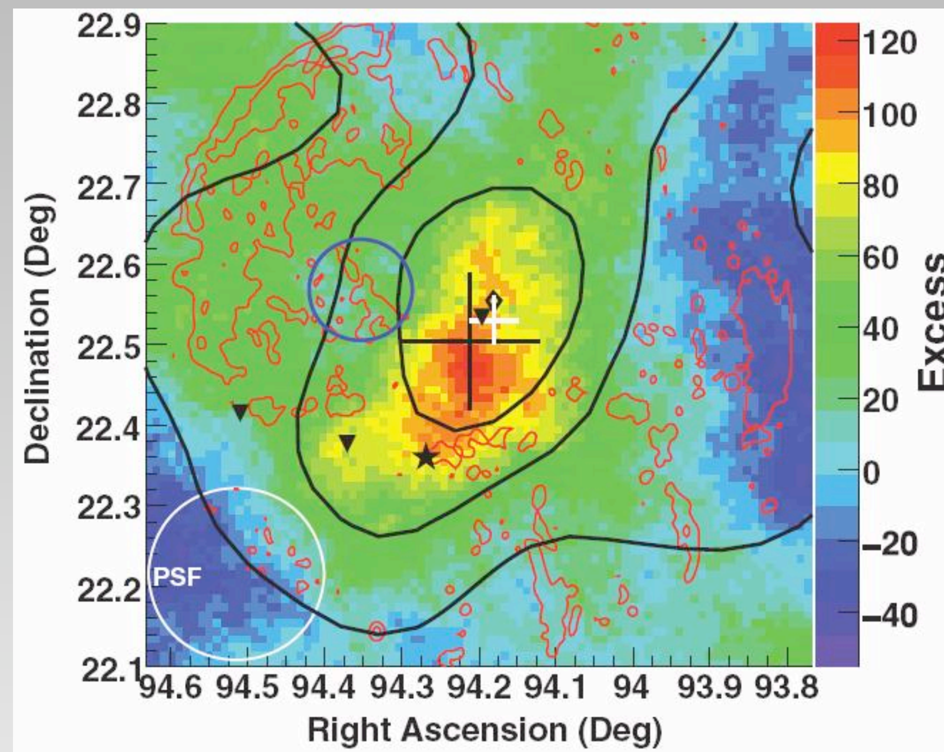
Pion Production

$p + \mathrm{H} \rightarrow p' + \mathrm{H} + \pi^0$ $\quad E_{\mathrm{kin}} > 300$ MeV

$\quad\quad\quad\quad\quad\quad\quad\quad\;\; \hookrightarrow \gamma + \gamma$



H.E.S.S. image of W 28
Aharonian et al. 2008, A&A, 481, 401



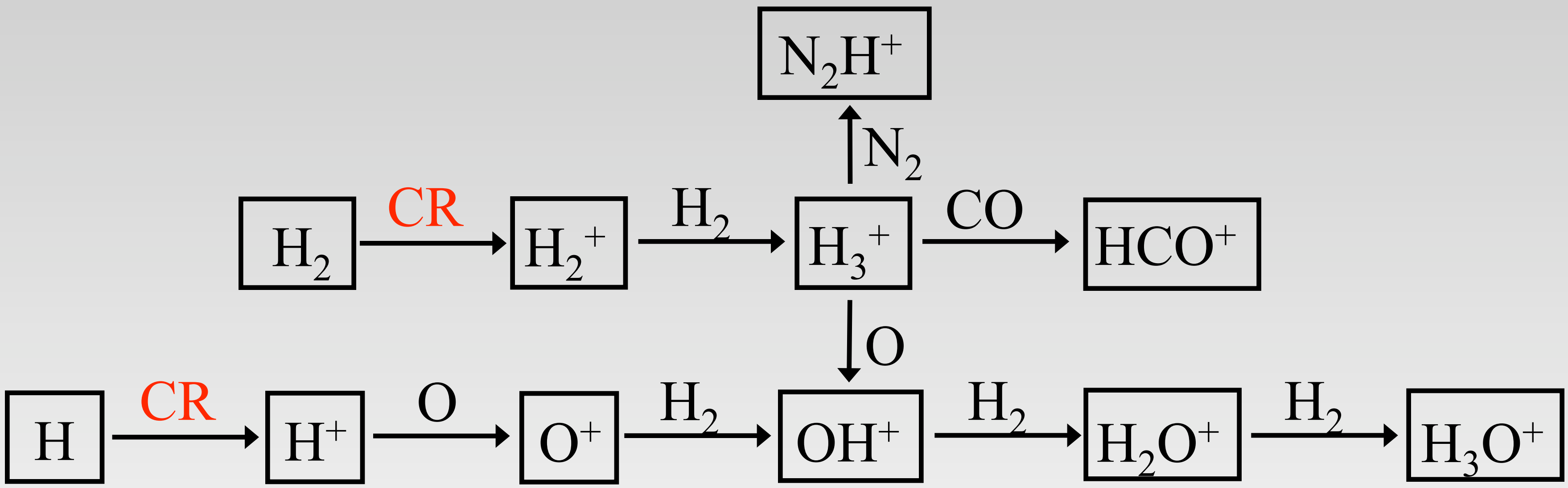
VERITAS image of IC 443
Acciari et al. 2009, ApJ, 698, L133

Resulting Observables

- ionization : molecules (H_3^+, OH, HCO^+)
  - UV, optical, IR, THz, and radio spectra
- spallation : light element isotopes (LiBeB)
  - UV, optical, and THz spectra
- nuclear excitation : γ-ray lines (6.13 MeV)
- inelastic collisions : pionic γ-rays

Importance to Chemistry

- In terms of interstellar molecules and molecular ions, ionization is the most important effect of cosmic rays
- Ionization initiates the network of fast ion-molecule reactions in the ISM



Cosmic-Ray Ionization Rate

- Some of the earliest estimates were made theoretically by Spitzer & Tomasko 1968
  - $\zeta > 6.8\times10^{-18}$ s^{-1} (integration)
  - $\zeta < 1.2\times10^{-15}$ s^{-1} (supernova energetics)
- Observational estimates of ζ based on HD and OH
  - $\zeta=1–3\times10^{-17}$ s^{-1} (Hartquist et al. 1978, A&A, 68, 65)
  - $\zeta=1–10\times10^{-17}$ s^{-1} (Federman et al. 1996, ApJ, 463, 181)

Cosmic-Ray Ionization Rate

- Estimates using OH and HD rely on charge transfer from H^+ to O and D
  - $H^+ + O \rightarrow H + O^+$ (endothermic by ~230 K)
  - $H^+ + D \rightarrow H + D^+$ (endothermic by ~40 K)
  - assume every H ionization led to OH or HD
  - ignored charge exchange to grains
  - net effect: underestimate the ionization rate

Cosmic-Ray Ionization Rate

- Chemistry associated with H_3^+ is simpler
- Formation
  - $CR + H_2 \rightarrow H_2^+ + e^- + CR'$
  - $H_2^+ + H_2 \rightarrow H_3^+ + H$
- Destruction
  - $H_3^+ + e^- \rightarrow H_2 + H$ or $H + H + H$ (diffuse)
  - $H_3^+ + CO \rightarrow HCO^+ + H_2$ (dense)
  - $H_3^+ + O \rightarrow OH^+ + H_2$ (dense)

Cosmic-Ray Ionization Rate

Steady-State Analysis

Diffuse Clouds

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

Dense Clouds

$$\zeta_2 n(\mathrm{H}_2) = [k_{\mathrm{CO}} n(\mathrm{CO}) + k_{\mathrm{O}} n(\mathrm{O})] n(\mathrm{H}_3^+)$$

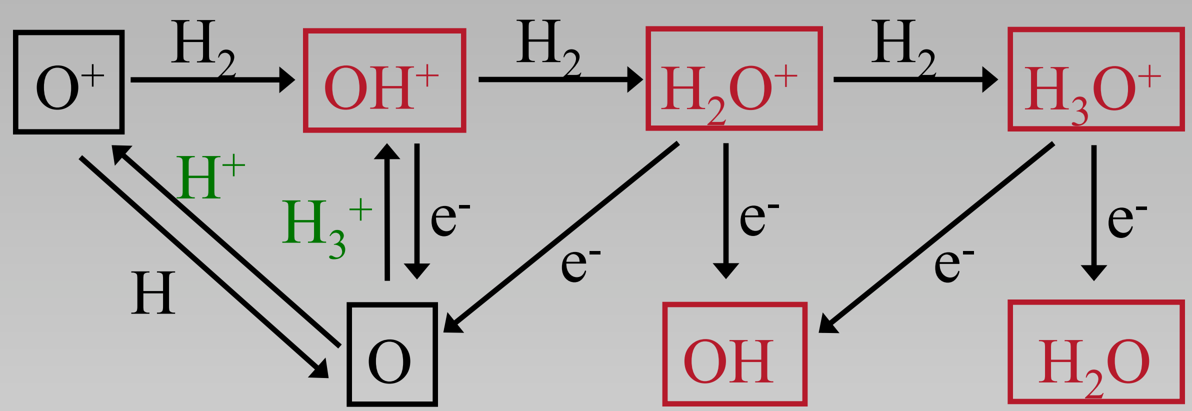
H_3^+ Results

- Surveyed about 50 diffuse Galactic sight lines and detected H_3^+ in 20 of those
- Average ionization rate: $\zeta_2 = 5\times10^{-16}\ s^{-1}$
- Individual sight lines range 10^{-16}–$10^{-15}\ s^{-1}$
- 3σ upper limits as low as $\zeta_2 < 8\times10^{-17}\ s^{-1}$
- Recent observations near the supernova remnant IC 443 show $\zeta_2 \sim 2\times10^{-15}\ s^{-1}$
- Suggests variability in cosmic-ray flux

Ionization Rate in Dense Clouds

- HCO^+ in embedded protostars
  - $\zeta_2=(0.6–6)\times10^{-17}$ s^{-1} (van der Tak & van Dishoeck 2000, A&A, 358, L79)
- H_3O^+ in Sgr B2 region
  - $\zeta_2\sim4\times10^{-16}$ s^{-1} (van der Tak et al. 2006, A&A, 545, L99)
- $HCNH^+$ in DR 21(OH)
  - $\zeta_2=3.1\times10^{-18}$ s^{-1} (Hezareh, et al. 2008, ApJ, 684, 1221)
- Variability in dense clouds as well?
- What new information does *Herschel* offer?

Oxygen Chemistry

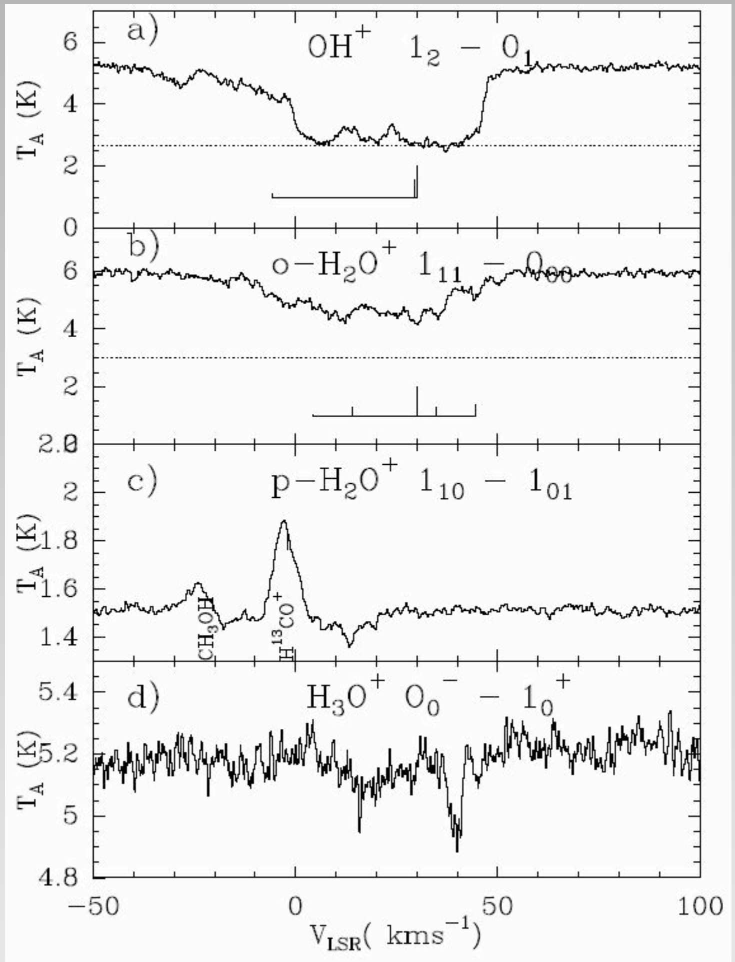


Select Observable Transitions

OH^+	972 GHz	OH	1835 GHz
o-H_2O^+	1115 GHz	H_2O	1113 GHz
p-H_2O^+	607 GHz	$H_2{}^{18}O$	1102 GHz
H_3O^+	985 GHz		

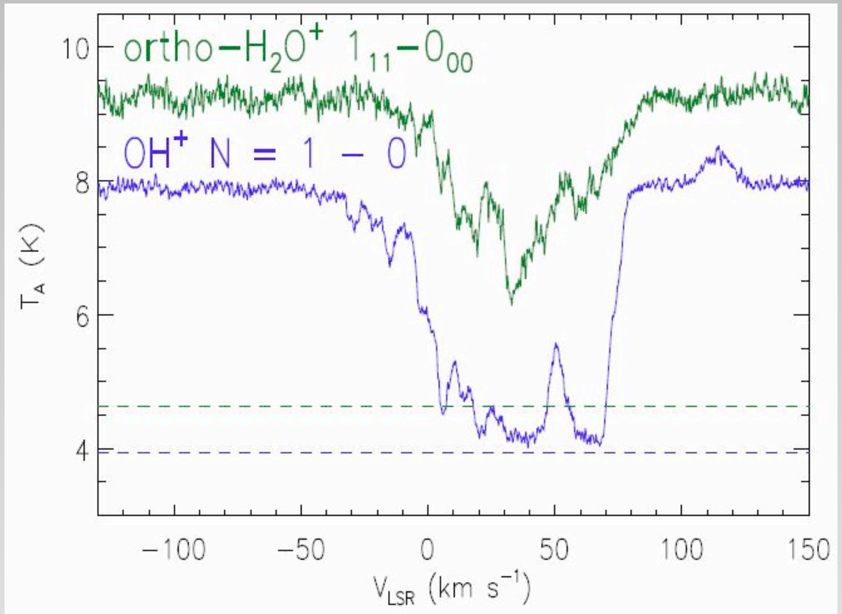
HIFI Observations

G10.6-0.4 (W 31 C)



Gerin et al. 2010, A&A, 518, L110

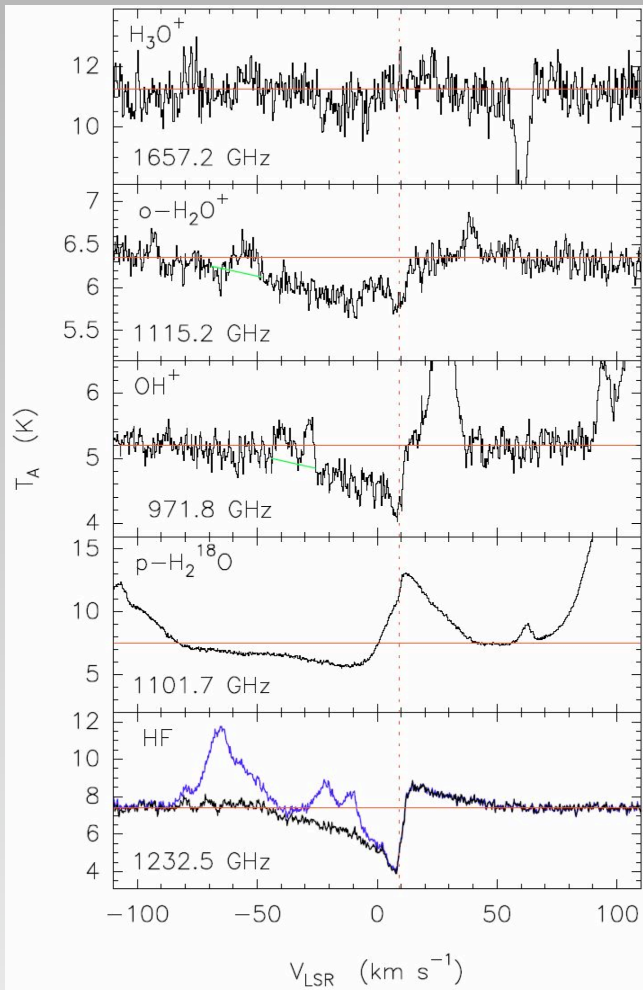
W49N



Neufeld et al. 2010, A&A, 521, L10

HIFI Observations

Orion KL



Gupta et al. 2010, A&A, 521, L47

- Inferred ionization rates
  - Gerin et al. 2010
    - $\zeta_H > 1.8\times10^{-19} n(\mathrm{H})\ s^{-1}$
  - Neufeld et al. 2010
    - $\zeta_H = 0.6–2.4\times10^{-16}\ s^{-1}$
  - Gupta et al. 2010
    - $\zeta > 1–2\times10^{-14}\ s^{-1}$
  - diffuse
    - $\zeta_2 \sim 0.7–20\times10^{-16}\ s^{-1}$
  - dense
    - $\zeta_2 \sim 0.03–4\times10^{-16}\ s^{-1}$

Prospects

- HEXOS: Herschel/HIFI Observations of Extraordinary Objects
- WISH: Water In Star-forming regions with Herschel
- PRISMAS: Probing Interstellar Molecules with Absorption Line Studies
- O, OH, OH^+, H_2O, $H_2{}^{18}O$, H_2O^+, H_3O^+

Prospects

- Search for HCl in IRC +10216 with SPIRE and PACS gives upper limit from ^{7}LiH J=1←0 transition : $x(^{7}\mathrm{LiH})<2\times10^{-9}$

  (Cernicharo et al. 2010, A&A, 518, L136)

- Solar system abundance $x(^{7}\mathrm{Li})\sim2\times10^{-9}$

  (Lodders 2003, ApJ, 591, 1220)

- LiH/Li ?
- J=2←1 transition of ^{7}LiH at 887 GHz
- J=2←1 transition of ^{6}LiH at 906 GHz

Summary

- HIFI is capable of observing molecules linked to cosmic-ray initiated chemistry
- Early science results from HIFI are adding new constraints to the cosmic-ray ionization rate
- Variable ionization rate, or misunderstood chemistry?
- Key projects will generate copious amounts of new data

Acknowledgments

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Thank you!