Enigma of H_3^+ in Diffuse Interstellar Clouds

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Background

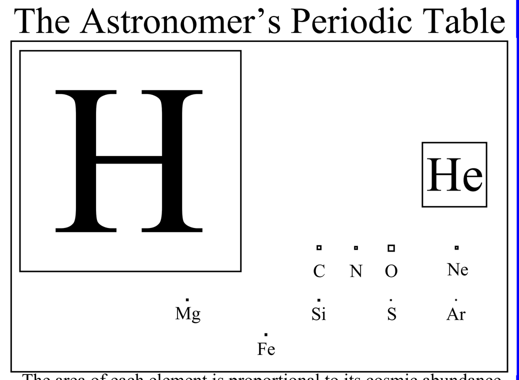
Importance of H_3^+

- Initiator of ion-neutral chemistry
- Produces important molecules (e.g. H_2O)
- Fundamental interest: the third hydrogenic probe (with H and H_2)
- Probe of interstellar conditions

$$H_3^+ + O \rightarrow OH^+ + H_2$$
$$OH^+ + H_2 \rightarrow H_2O^+ + H$$
$$H_2O^+ + H_2 \rightarrow H_3O^+ + H$$
$$H_3O^+ + e^- \rightarrow H_2O + H$$

H_3^+ protonates atoms and molecules to initiate chemistry.

The Astronomer's Periodic Table



The area of each element is proportional to its cosmic abundance.

Model of H_3^+ Chemistry

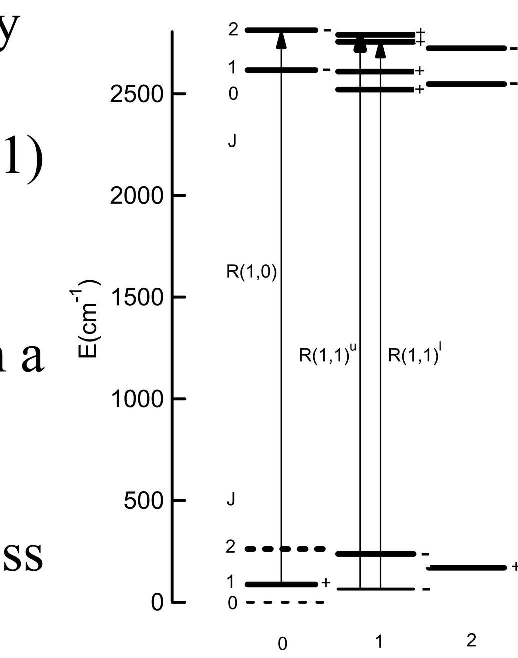
- H_3^+ formed by cosmic-ray ionization:
  - H_2 + cosmic ray $\rightarrow H_2^+$ (slow)
  - $H_2^+ + H_2 \rightarrow H_3^+ + H$ (fast)
  - Rate = $\zeta\,[H_2]$ (ionization $\zeta \sim 10^{-17}\ s^{-1}$)
- H_3^+ destroyed by dissociative recombination:
  - $H_3^+ + e^- \rightarrow H_2 + H$ or $H + H + H$
  - Rate = $k_e[H_3^+][e^-]$ ($k_e \sim 10^{-7}\ cm^3\ s^{-1}$?)
- Steady state (formation=destruction):
  - $[H_3^+] = (\zeta / k_e) \times ([H_2] / [e^-]) \sim 10^{-7}\ cm^{-3}$

H_3^+ as an Astronomical Probe

- Model $\rightarrow$ number density $[H_3^+]$ (cm^{-3})
- Observations $\rightarrow$ column density $N(H_3^+)$
  - [column density ~ number density × path length]
- We can then derive:
  - Path length: $L = N(H_3^+) / [H_3^+]$
  - Average density: $n = N(H_2) / L$
  - Temperature: T (ortho:para)
- H_3^+ *should* serve as a powerful probe of physical conditions in diffuse clouds!

H_3^+ Ro-vibrational Transitions

- (J,K)=(0,0) forbidden by Pauli principle
- Two states (1,0) and (1,1) populated at low T
- R(1,0) and $R(1,1)^u$ form a convenient ortho/para "doublet" ~ 3.668 μm
- $R(1,1)^l$ ~ 3.715 μm is less affected by atmosphere



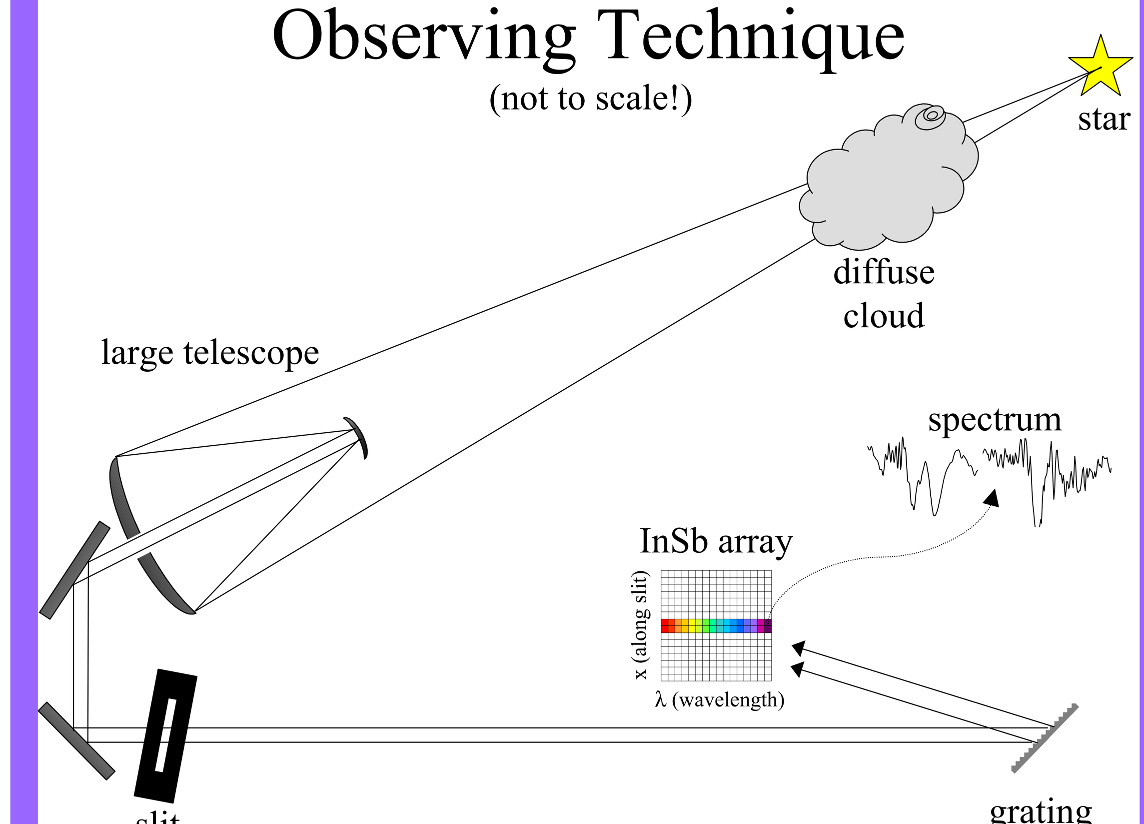
Observations

The Diffuse Cloud Environment

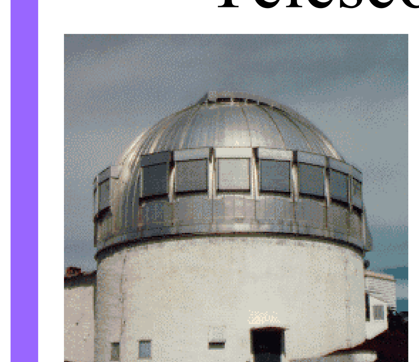
- Starlight is "reddened" by small amount of dust in diffuse clouds ($E_{B-V} \leq 1$ mag)
- Low density ~ 20–1000 cm^{-3} (H, H_2 mix)
- "Transparent" to visible & UV starlight
- Photons > 11.3 eV convert $C \rightarrow C^+ + e^-$
  - High electron fraction
  - Recombination efficiently destroys H_3^+
- Chemically "barren"
- Until recently, no polyatomics observed

Observing Technique

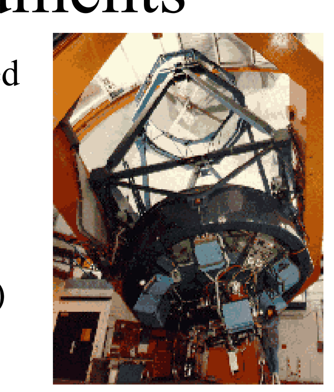
(not to scale!)



Telescopes & Instruments

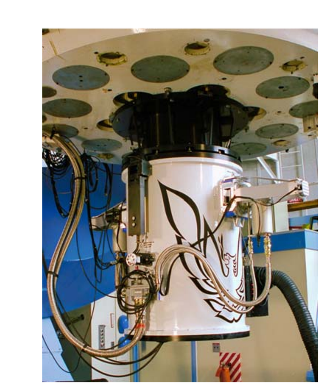


United Kingdom Infrared Telescope (UKIRT)
[Mauna Kea, HI]



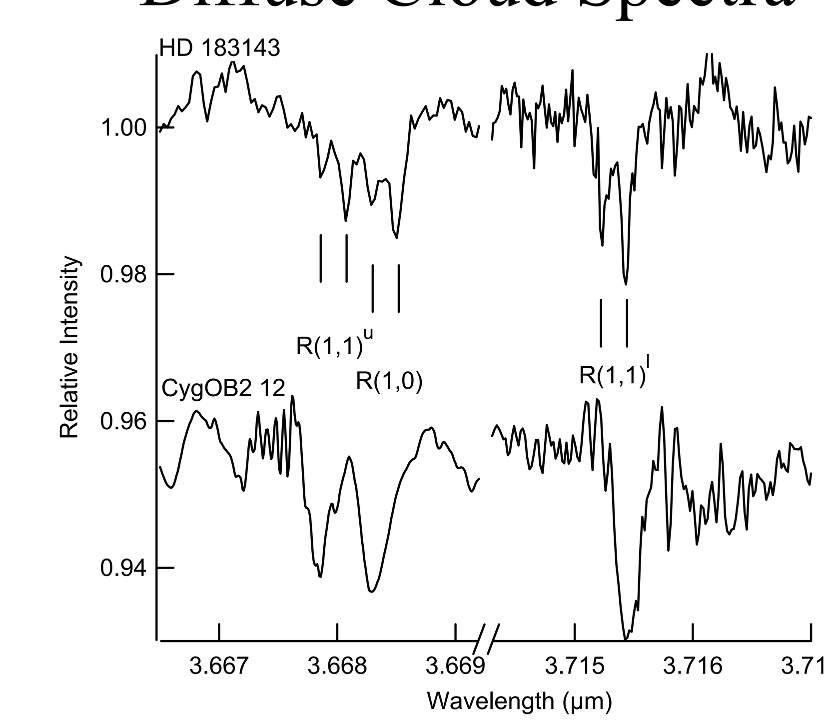
Cooled Grating Spectrometer 4 (CGS4)
[λ/Δλ ~ 40,000]

Nicholas U. Mayall Telescope
[Kitt Peak, AZ]



Phoenix Spectrometer
[λ/Δλ ~ 75,000]

Diffuse Cloud Spectra



The diffuse gas towards HD 183143 has two velocity components, so each transition appears as a doublet. Cygnus OB2 12 shows a more complicated velocity structure.

Analysis

Derived Column Densities

- Because the H_3^+ lines are weak, the areas of absorption lines ("equivalent widths") are a direct measure of the column density.
- Diffuse clouds have $N(H_3^+) \sim 10^{14}\ cm^{-2}$, similar to the values in dense (molecular) clouds!
- But H_3^+ should be less abundant in diffuse clouds, due to dissociative recombination!

Derived Cloud Properties

- Path length $L = N(H_3^+) / [H_3^+]$
  $\sim (10^{14}\ cm^{-2}) / (10^{-7}\ cm^{-3})$
  $\sim 10^{21}$ cm ~ 1000 light-years
  - a large fraction of the distance to the star!
- Number density $n = N(H_2) / L$
  $\sim (10^{22}\ cm^{-2}) / (10^{21}\ cm)$
  $\sim 10\ cm^{-3}$
  - so low, H will not all be in form of H_2!
  - in conflict with other observations

What's Wrong?!?!?

One of the model parameters must be off by about 2 orders of magnitude!

$$[H_3^+] = \frac{\zeta}{k_e} \cdot \frac{[H_2]}{[e^-]}$$

- ζ: cosmic-ray ionization rate
  - well-established in dense clouds
  - very surprising if different in diffuse clouds!
- $[e^-]/[H_2]$: electron fraction
  - well-established in less reddened diffuse clouds
  - very interesting if much lower in our sources!
- k_e: dissociative recombination rate constant
  - a subject of great controversy
  - varied by 4 orders of magnitude in 20 years!

Conclusions

- The present uncertainty in the value of k_e is hindering the use of H_3^+ as a probe of diffuse interstellar clouds.
- We urge the dissociative recombination community to resolve this important issue as quickly as possible.