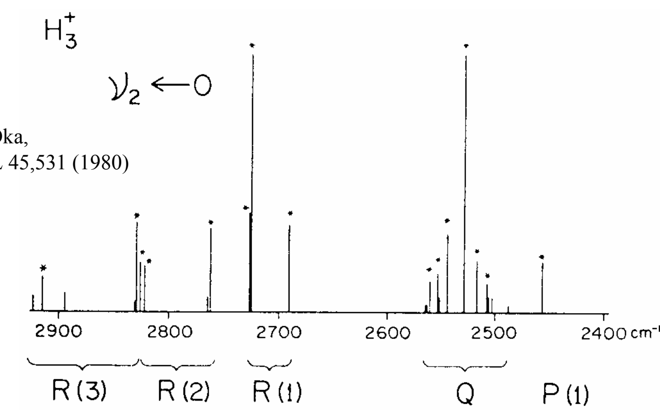
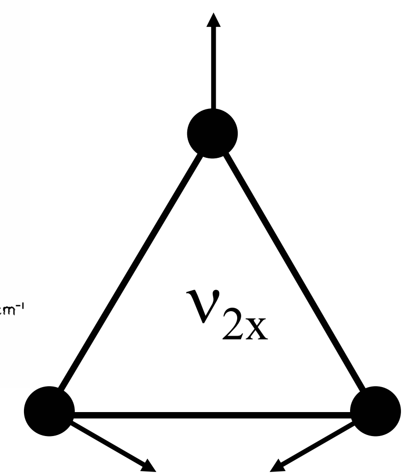
What is H_3^+ ?

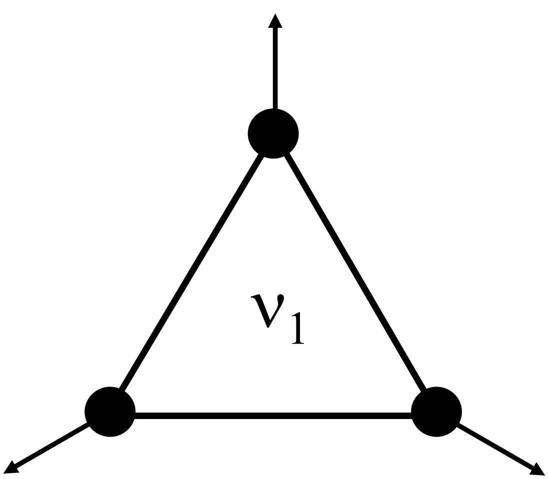
Ben McCall

→ Equilateral triangle structure
→ Simplest stable polyatomic molecule
→ No stable excited electronic states
→ No allowed rotational spectrum
→ Laboratory spectrum obtained in 1980

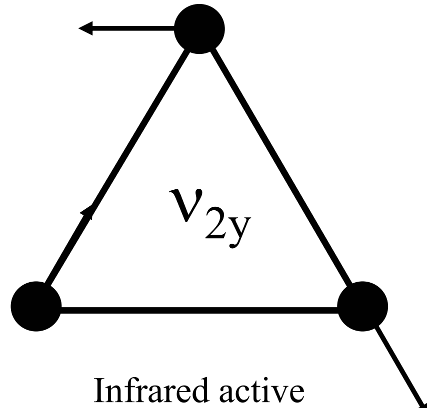
T. Oka,
PRL 45,531 (1980)







Infrared inactive
stretching mode



Infrared active
degenerate bending mode

Formation of H_3^+

Ben McCall

Step 1: Cosmic-ray ionization of H_2:

$$H_2 \xrightarrow{\text{cosmic ray}} H_2^+ + e^-$$

$$\text{Rate} = \zeta \cdot n(H_2)$$

Step 2: Ion-Molecule reaction with H_2:

$$H_2 + H_2^+ \rightarrow H_3^+ + H$$

[occurs on every collision]

The cosmic-ray ionization rate is estimated from various methods to be $\zeta \sim 10^{-17}$ s^{-1}. For a dense cloud with $n(H_2) \sim 10^5$ cm^{-3}, the rate of formation of H_3^+ is $\sim 10^{-12}$ cm^{-3} s^{-1}.

Ion-Neutral Chemistry

Ben McCall

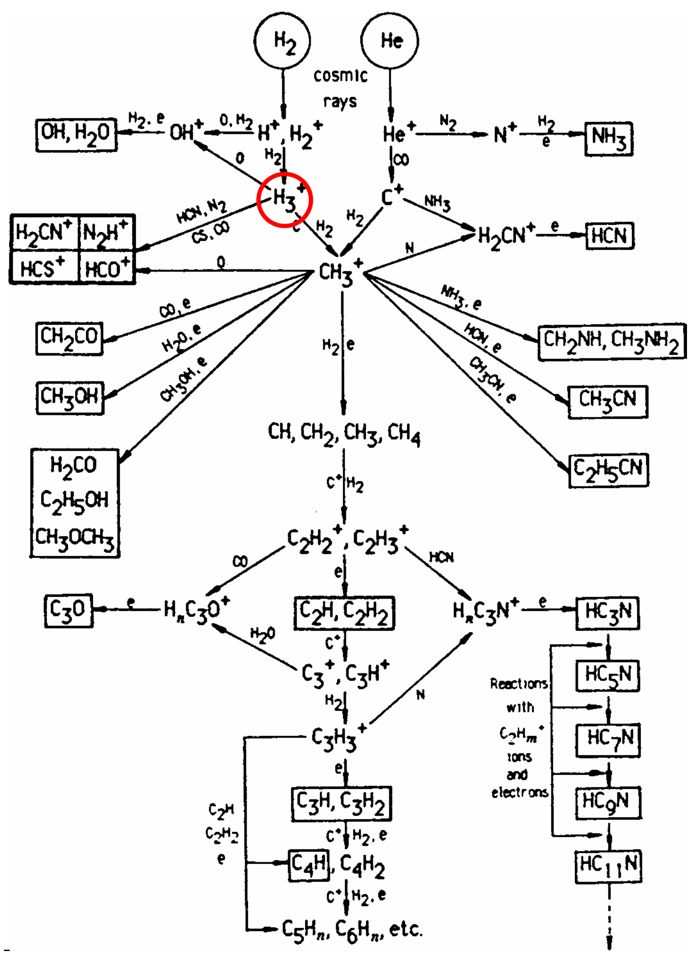
$$H_3^+ + CO \rightarrow HCO^+ + H_2$$
$$H_3^+ + X \rightarrow HX^+ + H_2$$

$$HX^+ + Y \rightarrow XY^+ + H$$

H_3^+ initiates a network of ion-molecule chemical reactions, leading to the production of H_2O and other molecules. Were Earth's oceans made by H_3^+?

The destruction of H_3^+ in molecular cloud is dominated by reaction with the most abundant reaction partner, CO. This rate can be expressed as $k_{CO}\, n(H_3^+)\, n(CO)$.

$k_{CO} \sim 2\times10^{-9}$ cm^3 s^{-1}
(measured in lab)



H_3^+ Number Density

Ben McCall

Assuming steady-state, the H_3^+ number density can be derived by equating the rates of formation and destruction.

Formation Rate (cosmic rays): $\zeta \; n(H_2)$

Destruction Rate (rxn with CO): $k_{CO} \; n(CO) \; n(H_3^+)$

Rearrange the equation $\zeta \; n(H_2) = k_{CO} \; n(CO) \; n(H_3^+)$ to find:

$$n(H_3^+) = \frac{\zeta}{k_{CO}} \frac{n(H_2)}{n(CO)} = \text{constant!}$$

Adopted values:

$\zeta \sim 10^{-17}$ s^{-1} (derived from observations)

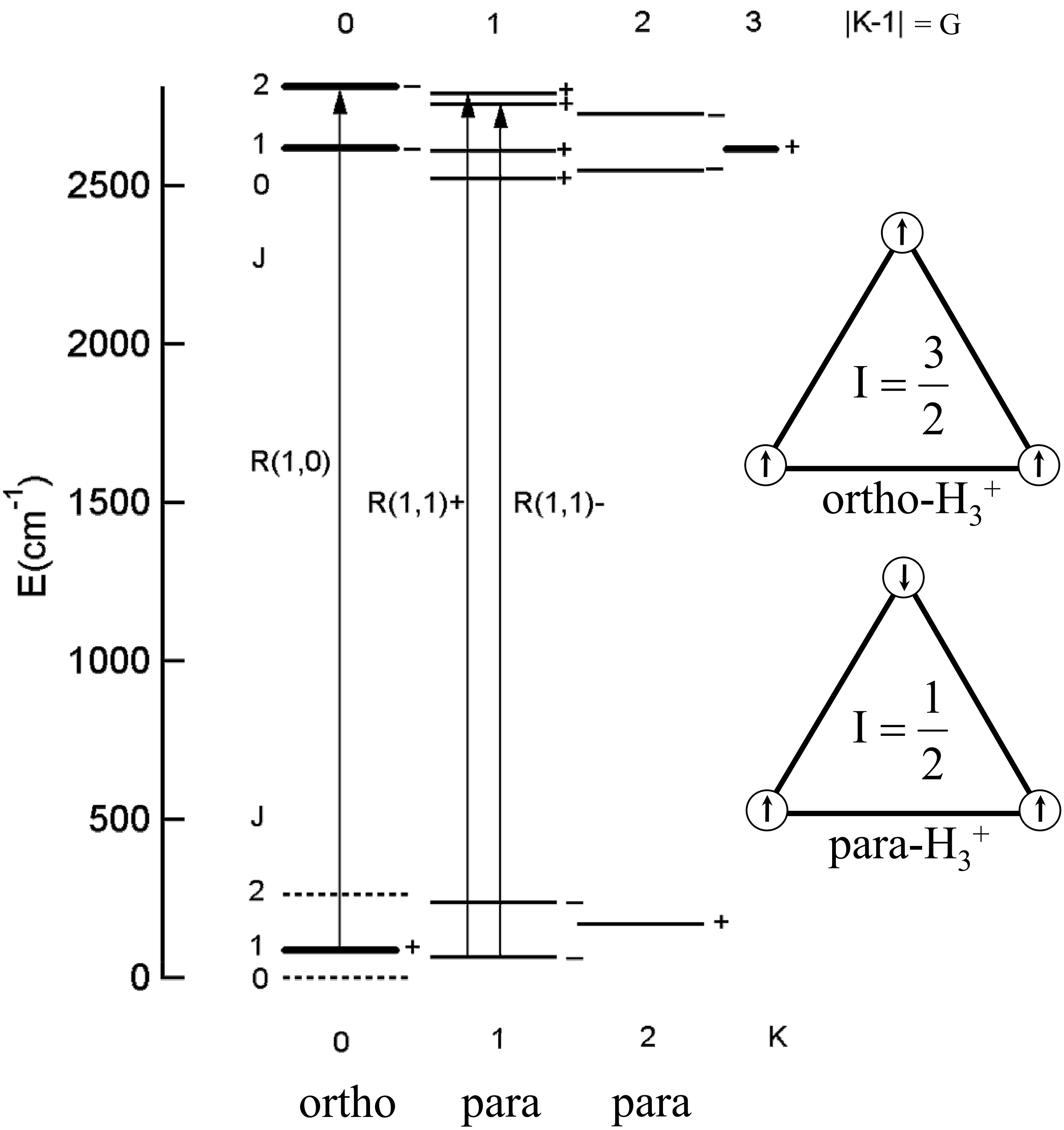
$k_{CO} = 2\times10^{-9}$ cm^3 s^{-1} (measured in lab)

$n(H_2)/n(CO) \sim 6.7\times10^3$ (from model calculations)

$n(H_3^+)$ is constant $\sim 3\times10^{-5}$ cm^{-3} which is independent of the density of the cloud!

H_3^+ Transitions

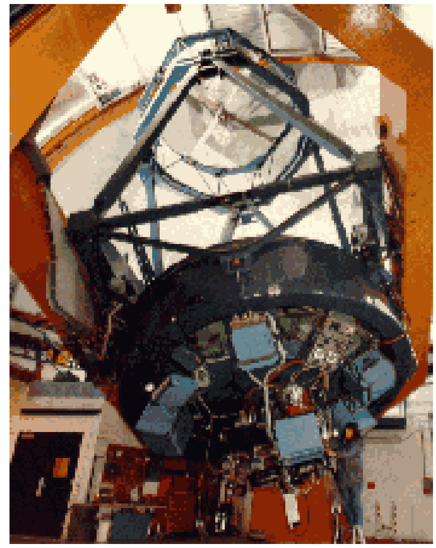
Ben McCall



Telescopes & Instruments

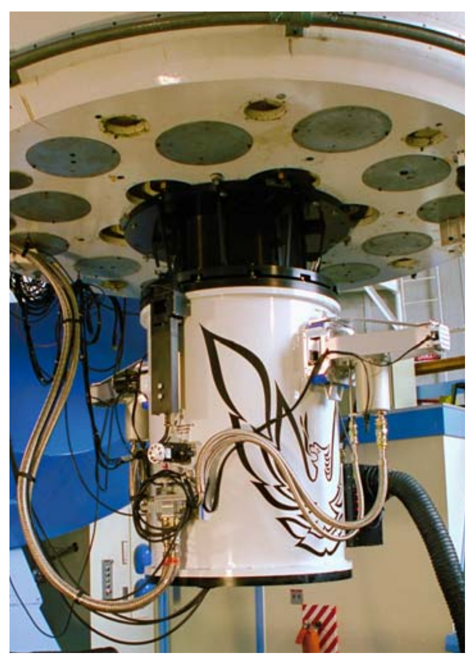
Ben McCall

United Kingdom Infrared Telescope (UKIRT)
Mauna Kea, Hawaii



Cooled Grating Spectrometer 4 (CGS4)
R ~ 20,000

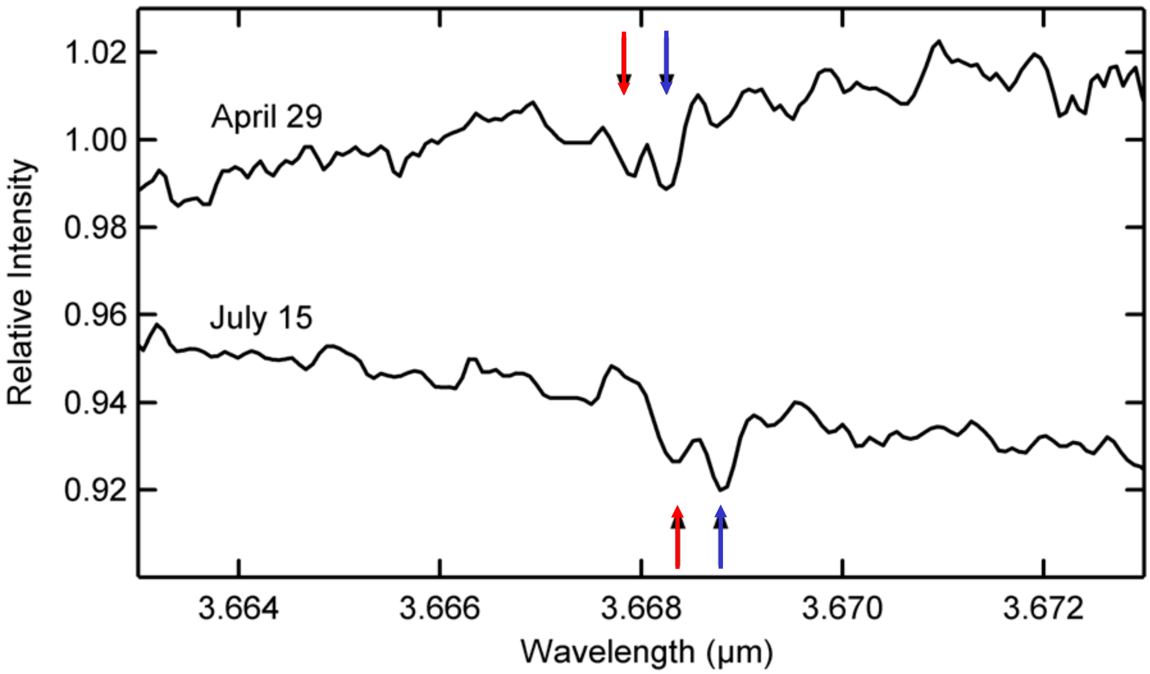
Nicholas U. Mayall Telescope
Kitt Peak, AZ



Phoenix Spectrometer
R ~30,000

GL 2136

Ben McCall



Molecular Cloud GL2136. This source provided the first detection of interstellar H_3^+. Using the CGS4 spectrometer at UKIRT, it observed at two times separated by nearly three months. The Earth's orbital motion around the Sun caused the spectral lines of H_3^+ to be Doppler shifted – compelling evidence that the lines are genuine.

$$N_{para} = 4.0(9) \times 10^{14}\ \mathrm{cm}^{-2}$$

$$N_{ortho} = 3.0(6) \times 10^{14}\ \mathrm{cm}^{-2}$$

T. R. Geballe & T. Oka
Nature 384, 334 (1996)

H_3^+ – Interstellar Probe

Ben McCall

Measurements of H_3^+ provide:

→ path length of cloud
→ number density of H_2
→ kinetic temperature

Path Length:

$$L = \frac{N(H_3^+)}{n(H_3^+)} = \frac{3 \times 10^{14}\,\mathrm{cm}^{-2}}{3 \times 10^{-5}\,\mathrm{cm}^{-3}} = 10^{19}\,\mathrm{cm} \approx 3\mathrm{pc}$$

Number Density:

$$n(H_2) = \frac{N(H_2)}{L} = \frac{10^{24}\,\mathrm{cm}^{-2}}{10^{19}\,\mathrm{cm}} = 10^{5}\,\mathrm{cm}^{-3}$$

Temperature:

$$\frac{N_{ortho}(H_3^+)}{N_{para}(H_3^+)} = \frac{g_{ortho}}{g_{para}} e^{-\frac{\Delta E}{kT}} = 2e^{-\frac{32.87}{T}}$$

$$\Rightarrow T \sim 27\ \mathrm{K}$$

Other Detections

Ben McCall