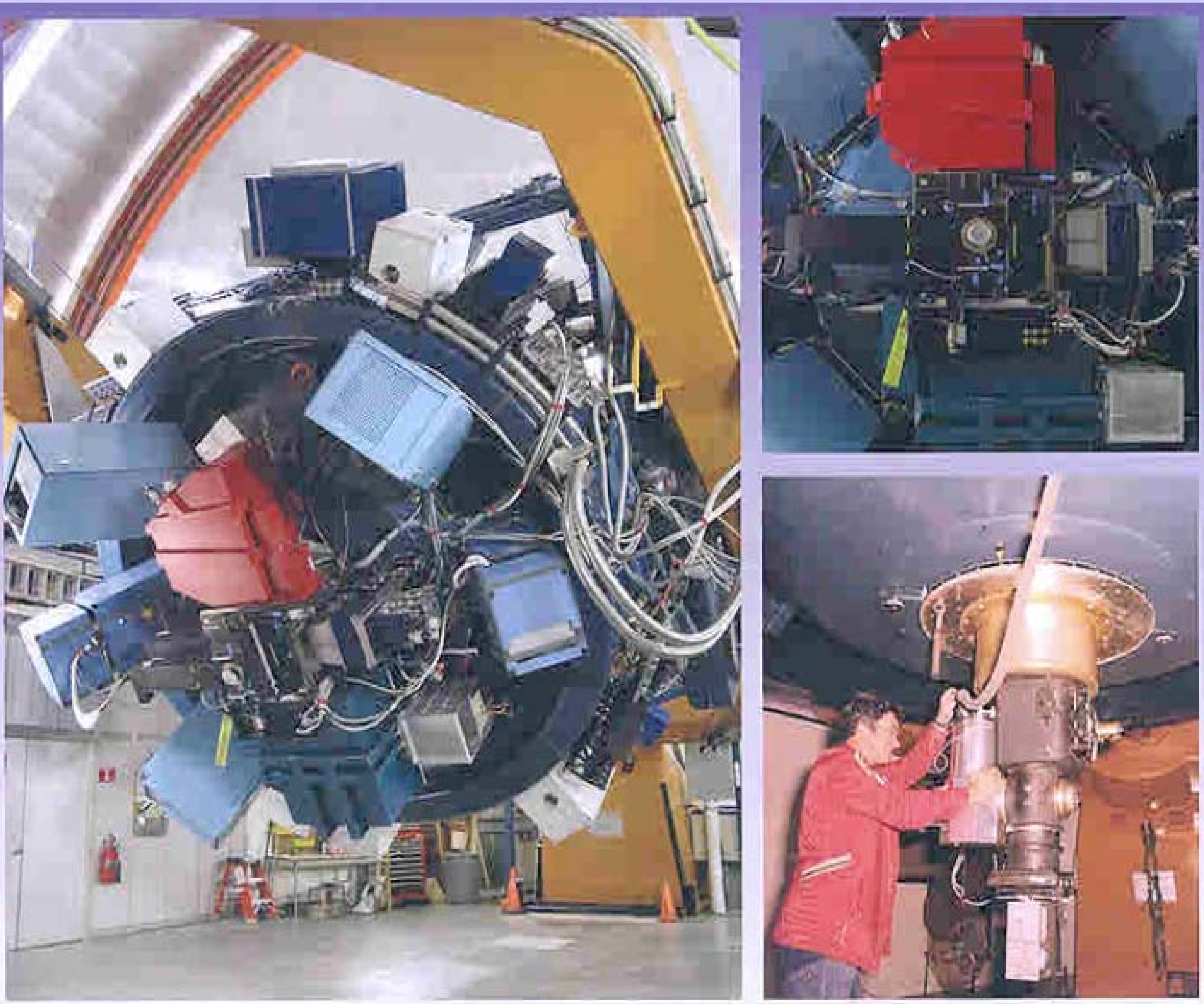
Almost 30 years of (Infrared) Spectroscopy of the Interstellar Medium at UKIRT

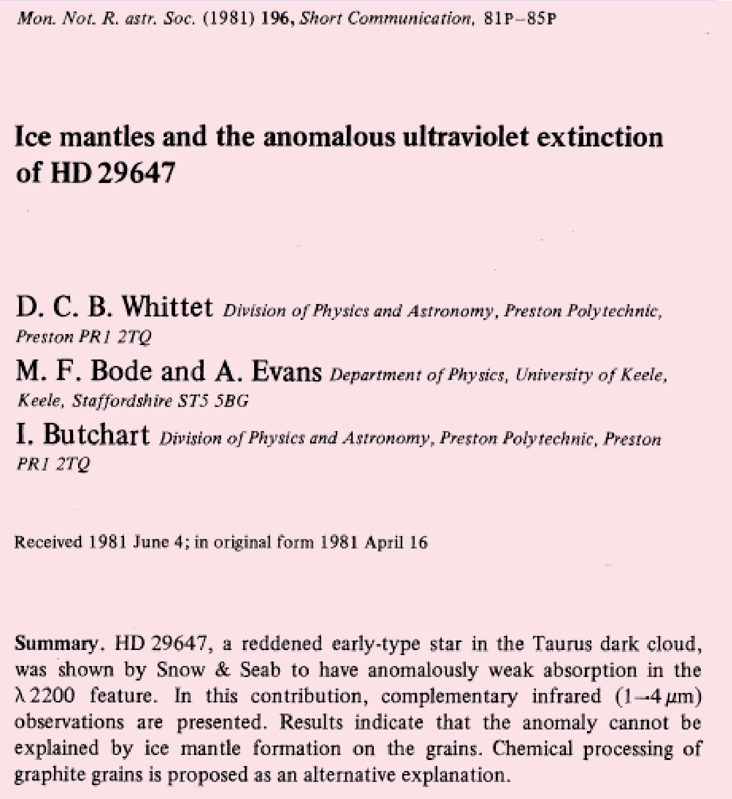


UKT6, UKT9(+FP), CGS1(+FP), CGS2(+FP), IRCAM+FP CGS3, CGS4, MICHELLE, UIST

Then and Now

30 years of UKIRT Cassegrain instrumentation

UKIRT'S FIRST INTERSTELLAR **IR** SPECTROSCOPY PAPERS



Mon. Not. R. astr. Soc. (1981) **196**, *Short Communication*, 81P–85P

Ice mantles and the anomalous ultraviolet extinction of HD 29647

D. C. B. Whittet *Division of Physics and Astronomy, Preston Polytechnic, Preston PR1 2TQ*
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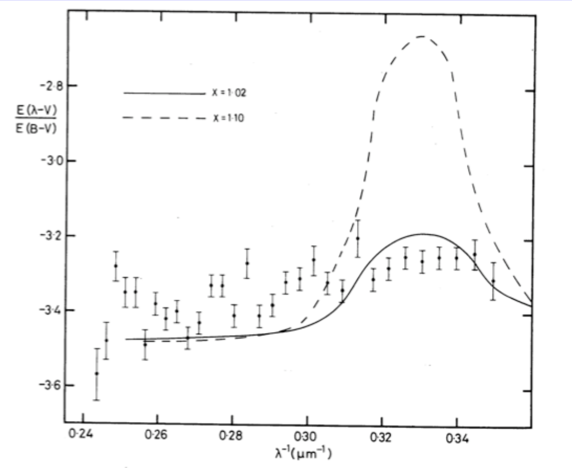
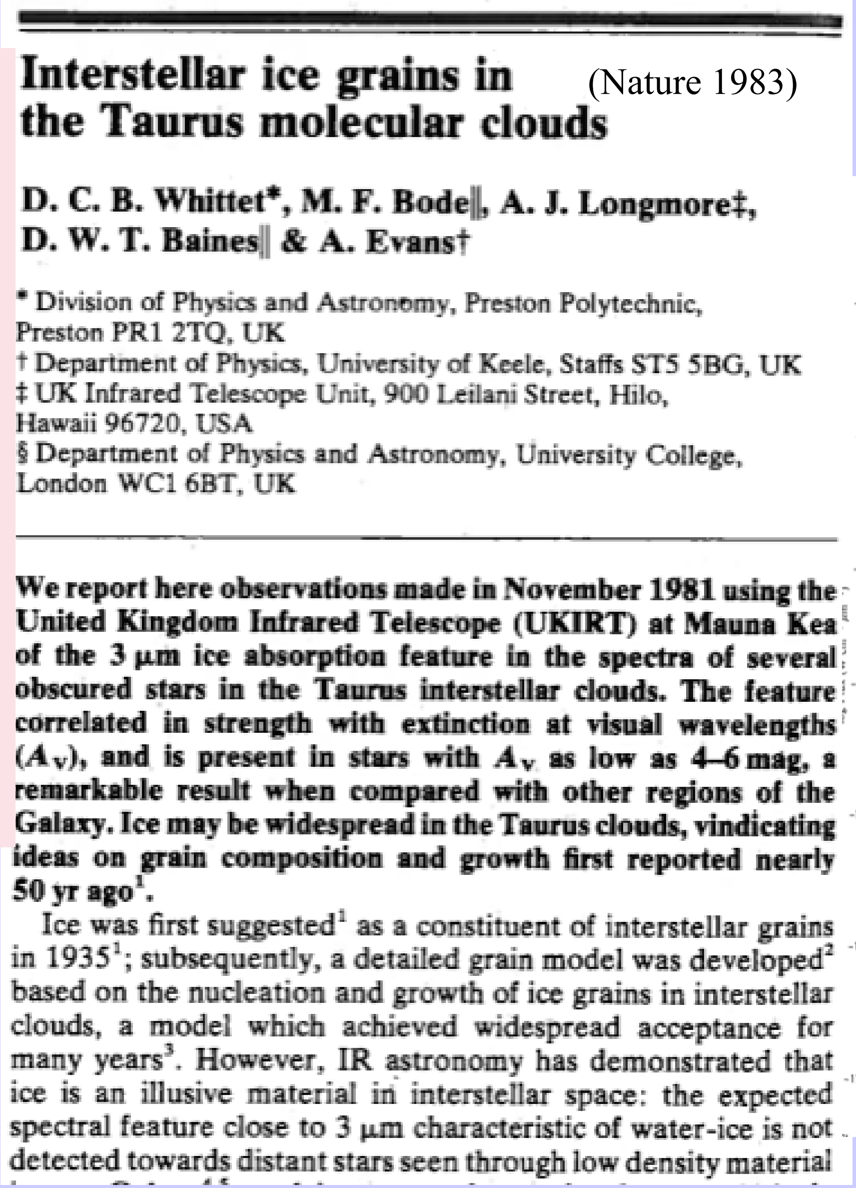
Received 1981 June 4; in original form 1981 April 16

Summary. HD 29647, a reddened early-type star in the Taurus dark cloud, was shown by Snow & Seab to have anomalously weak absorption in the λ2200 feature. In this contribution, complementary infrared (1→4 μm) observations are presented. Results indicate that the anomaly cannot be explained by ice mantle formation on the grains. Chemical processing of graphite grains is proposed as an alternative explanation.





Interstellar ice grains in the Taurus molecular clouds

(Nature 1983)

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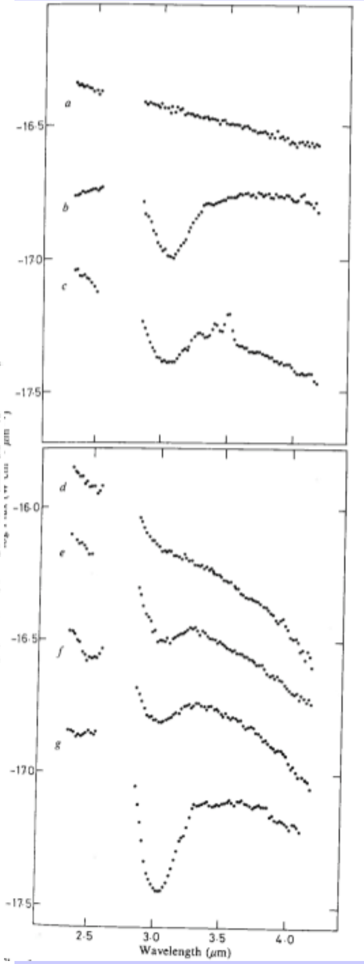
We report here observations made in November 1981 using the United Kingdom Infrared Telescope (UKIRT) at Mauna Kea of the 3 μm ice absorption feature in the spectra of several obscured stars in the Taurus interstellar clouds. The feature correlated in strength with extinction at visual wavelengths (A_V), and is present in stars with A_V as low as 4–6 mag, a remarkable result when compared with other regions of the Galaxy. Ice may be widespread in the Taurus clouds, vindicating ideas on grain composition and growth first reported nearly 50 yr ago[1].

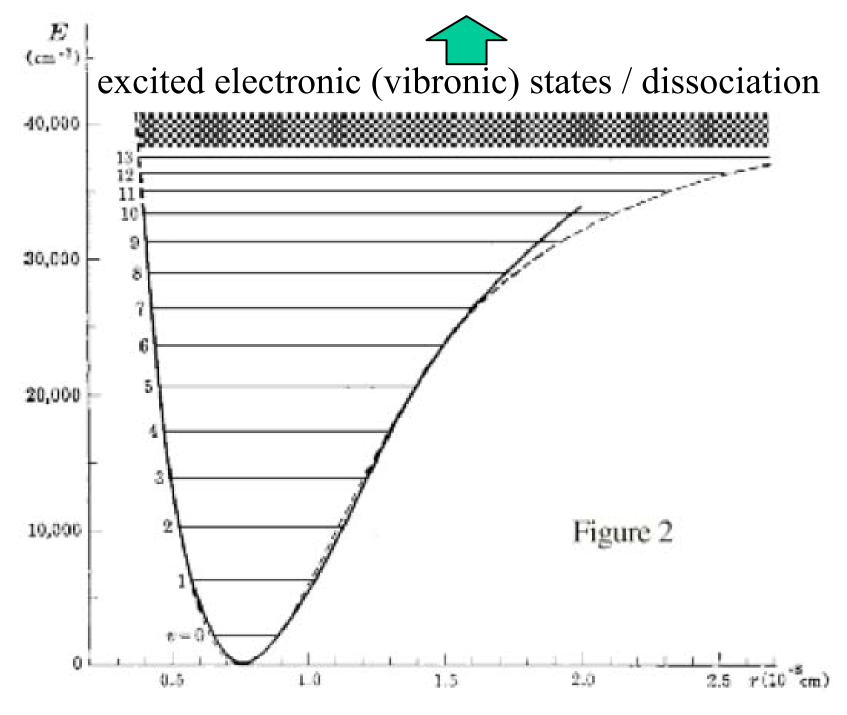
Ice was first suggested[1] as a constituent of interstellar grains in 1935[1]; subsequently, a detailed grain model was developed[2] based on the nucleation and growth of ice grains in interstellar clouds, a model which achieved widespread acceptance for many years[3]. However, IR astronomy has demonstrated that ice is an illusive material in interstellar space: the expected spectral feature close to 3 μm characteristic of water-ice is not detected towards distant stars seen through low density material

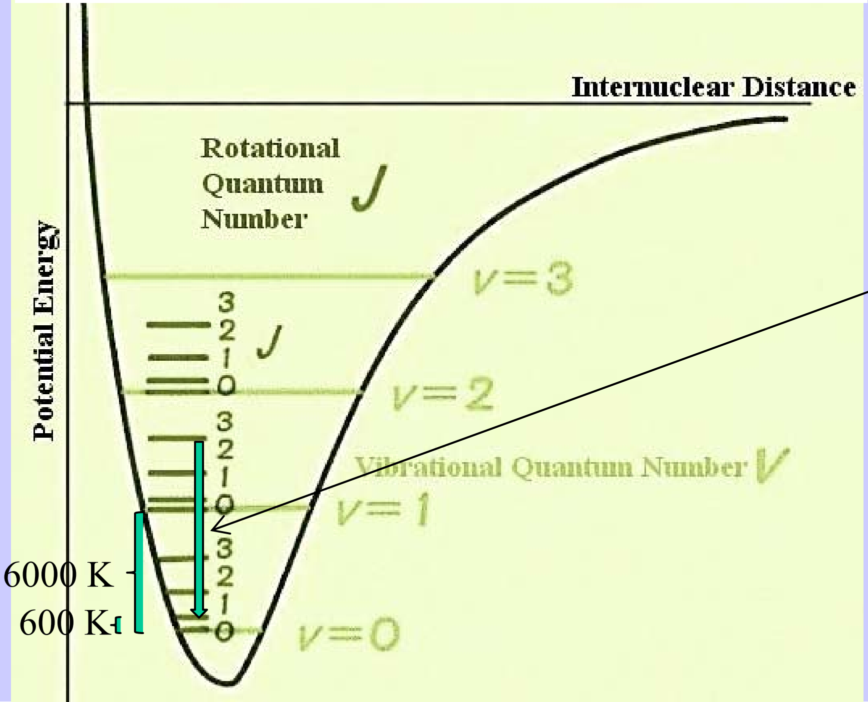


An early portent of the important contributions of UKIRT in interstellar infrared spectroscopy …

Some Highlights of IR Spectroscopy of the ISM

- H_2 and the physics of shock waves in molecular clouds
- Fluorescent H_2
- Dust in dense clouds
- Dust in diffuse clouds
- H_3^+ in the ISM

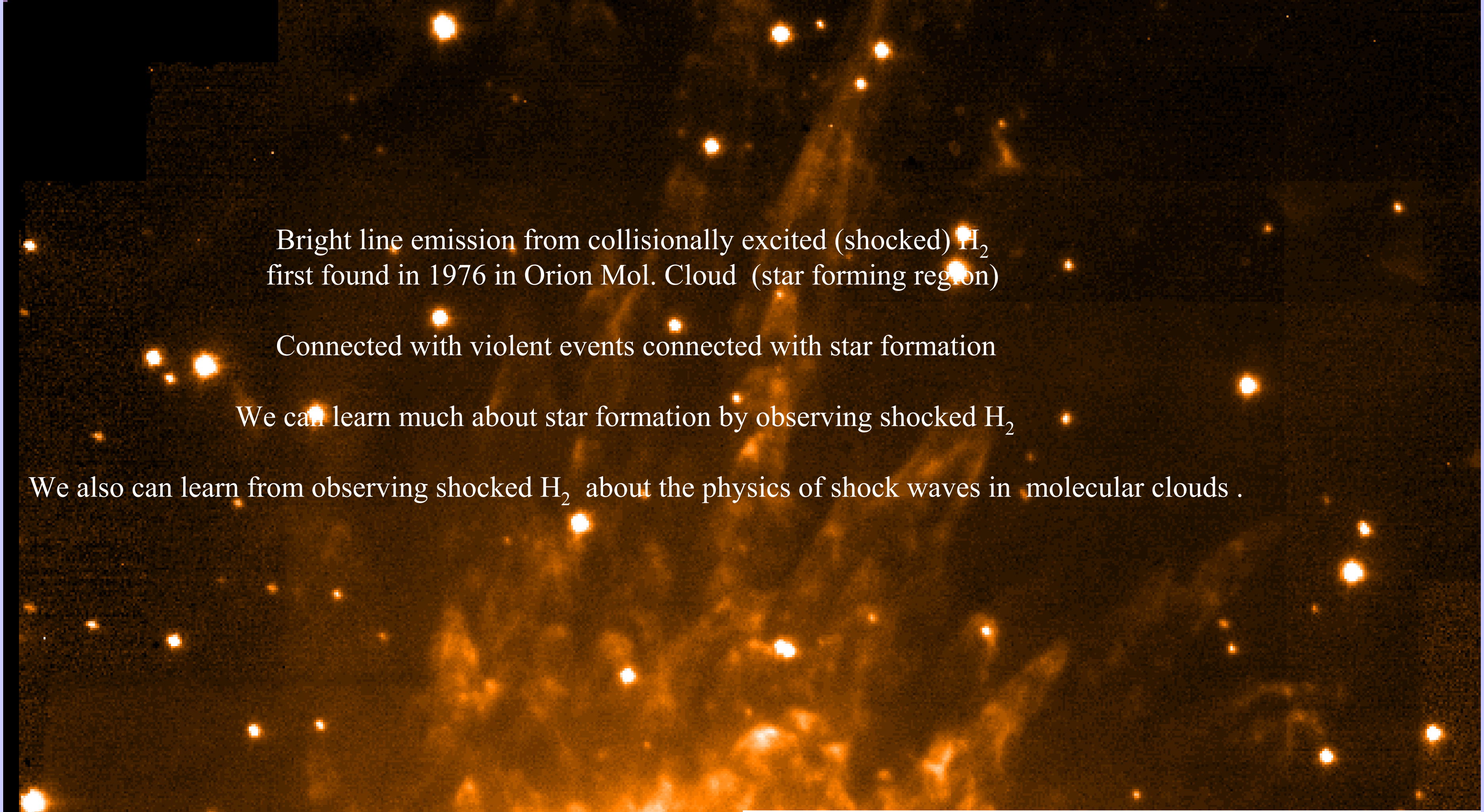




REVIEW OF H_2

Distinctive properties:

- Vibrational and rotational levels are widely spaced so only v=0 J=0 populated at typical cloud temperatures
- Doesn’t want to radiate (or absorb) $A_{1\text{-}0\ S(1)}^{-1}$ ~ 1 month
- Only way to excite vib-rot levels is by (energetic) collisions or by spontaneous decay from excited electronic levels



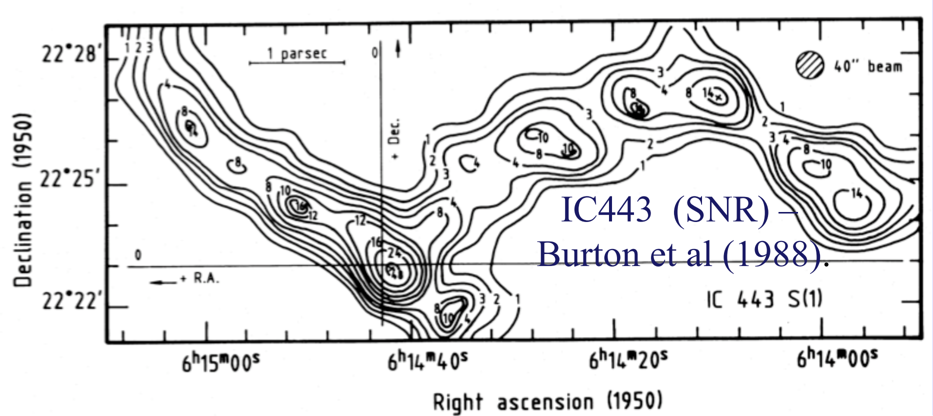
Bright line emission from collisionally excited (shocked) H_2 first found in 1976 in Orion Mol. Cloud (star forming region)

Connected with violent events connected with star formation

We can learn much about star formation by observing shocked H_2

We also can learn from observing shocked H_2 about the physics of shock waves in molecular clouds .

ORION (UFTI)



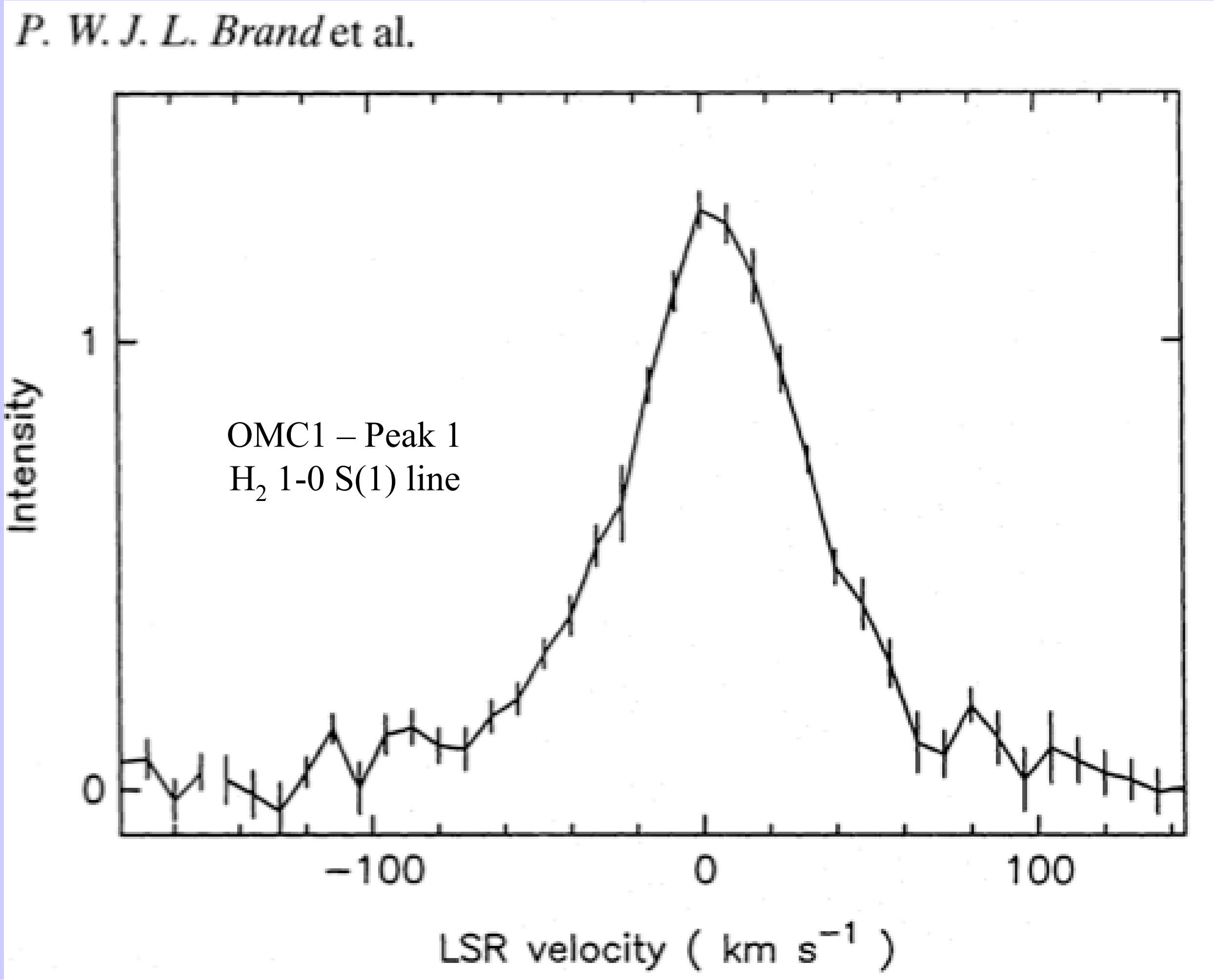
IC443 (SNR) – Burton et al (1988).

Major problem in understanding the very existence of the line emission:

How does the H_2 survive the shock?

$H_2 – H_2$ collisions at more than 20 km/s dissociate

Simplest (J) shocks ruled out in many cases (incl. Orion)

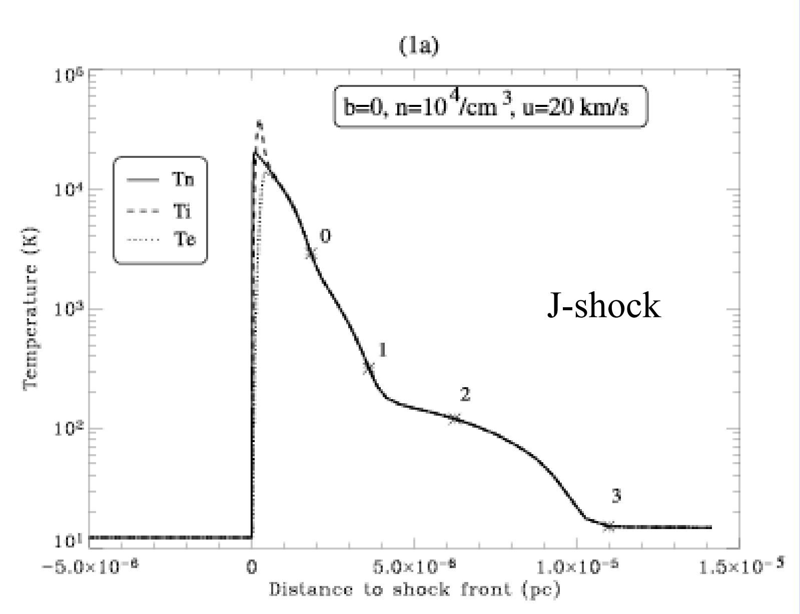


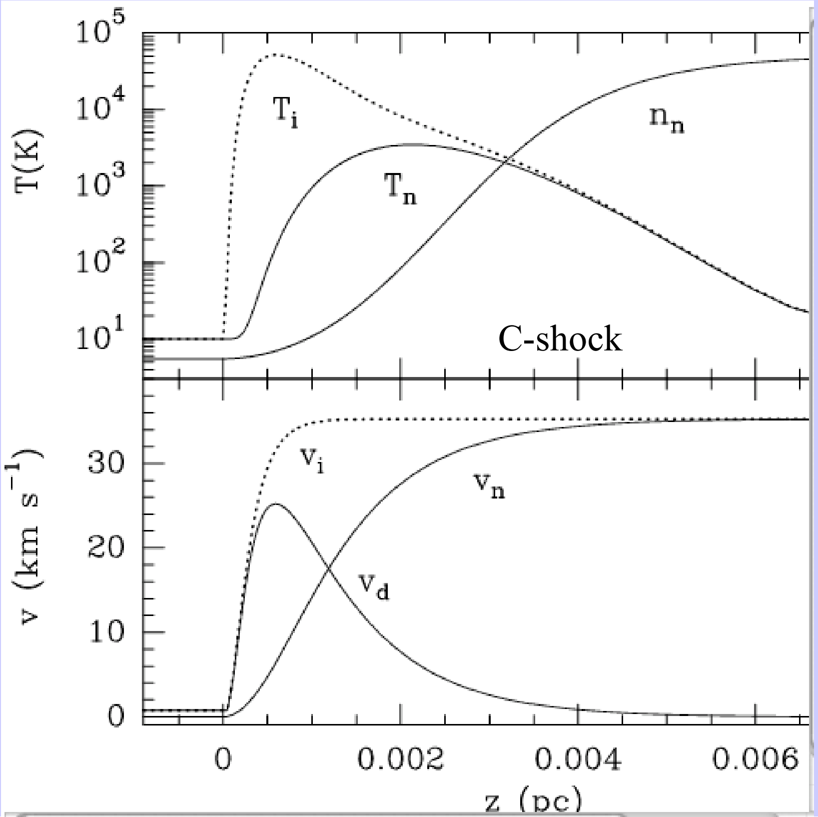
OMC1 – Peak 1
H_2 1-0 S(1) line

A possible explanation:
C shocks with magnetic precursors

J-shock (20 km/s):
nearly instantaneous heating and acceleration;
gas reaches high temperature

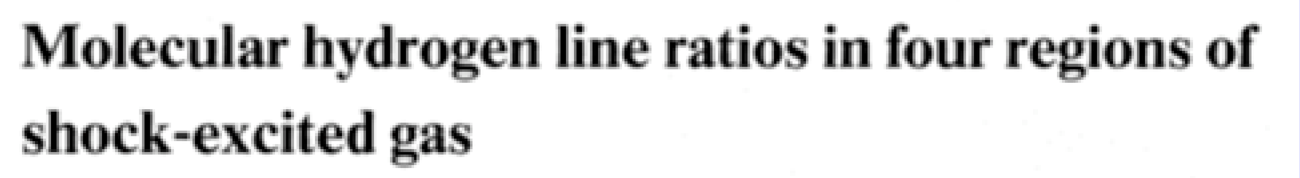
C-shock (35 km/s) with precursor:
more gentle acceleration and heating;
ions accelerated before neutrals;
ambient gas is slowly accelerated



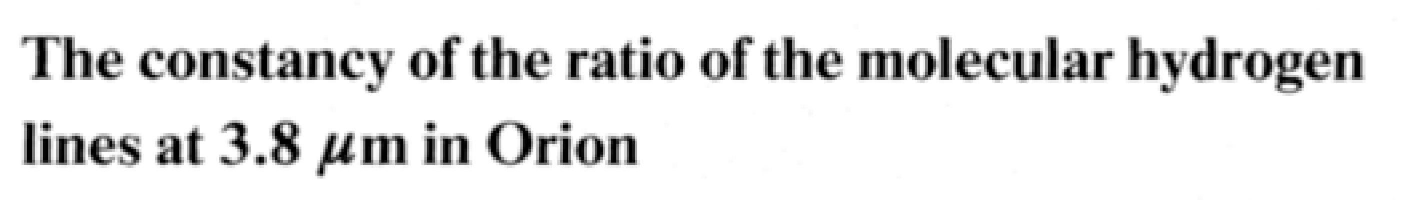


Late 1980s:
Brand and students (Burton, Moorhouse, Bird, Toner)
plus collaborators test shock models in Orion and
elsewhere in a variety of ways.

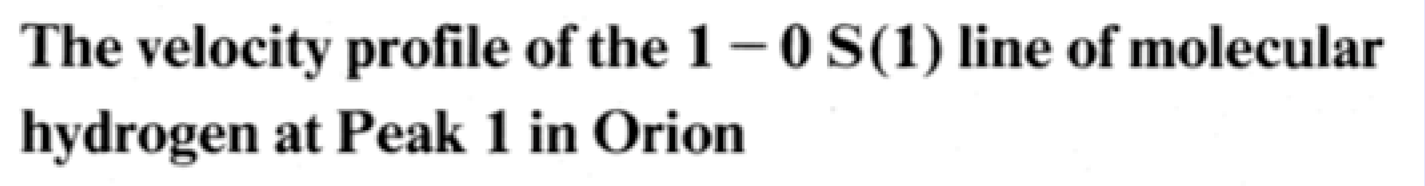
RATIOS OF MOLECULAR HYDROGEN LINE INTENSITIES IN SHOCKED GAS: EVIDENCE FOR COOLING ZONES



Molecular hydrogen line ratios in four regions of shock-excited gas



The constancy of the ratio of the molecular hydrogen lines at 3.8 μm in Orion



The velocity profile of the $1-0$ S(1) line of molecular hydrogen at Peak 1 in Orion

Conclusion: C shocks in which the H_2 survives cannot explain the observations.

Example – from paper 1 (deep CGS2 spectrum):

Lines detected from
v=0 to 4; J=1 to 13
(energy levels from 2,000K to 26,000K
– line strengths yield level populations

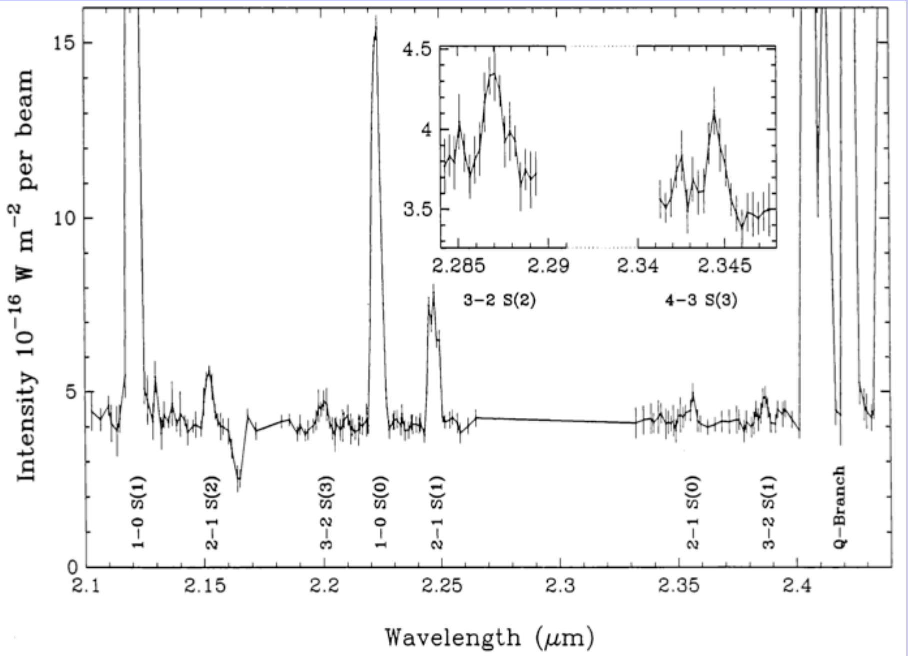
Ratios of level population ratios imply
gas cooling from a high temperature,
as opposed to a long pathlength of
~const. (lower) temperature gas.

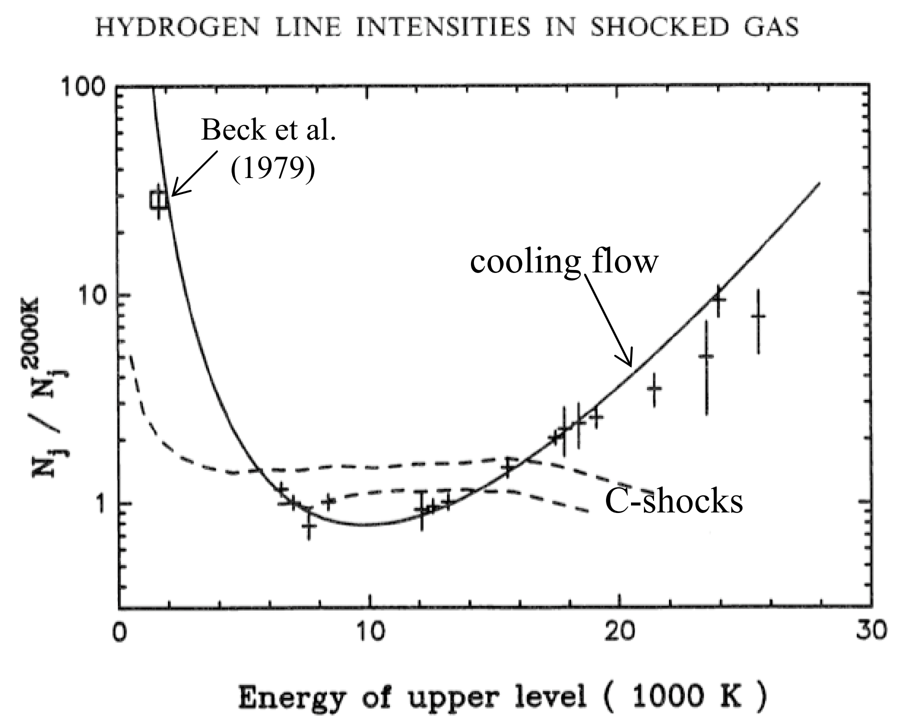
Possible explanations:

1. Many C-shocks of varying temperatures in beam
2. Contribution from fluorescent H_2 emission
3. H_2 is destroyed but reforms behind the shock

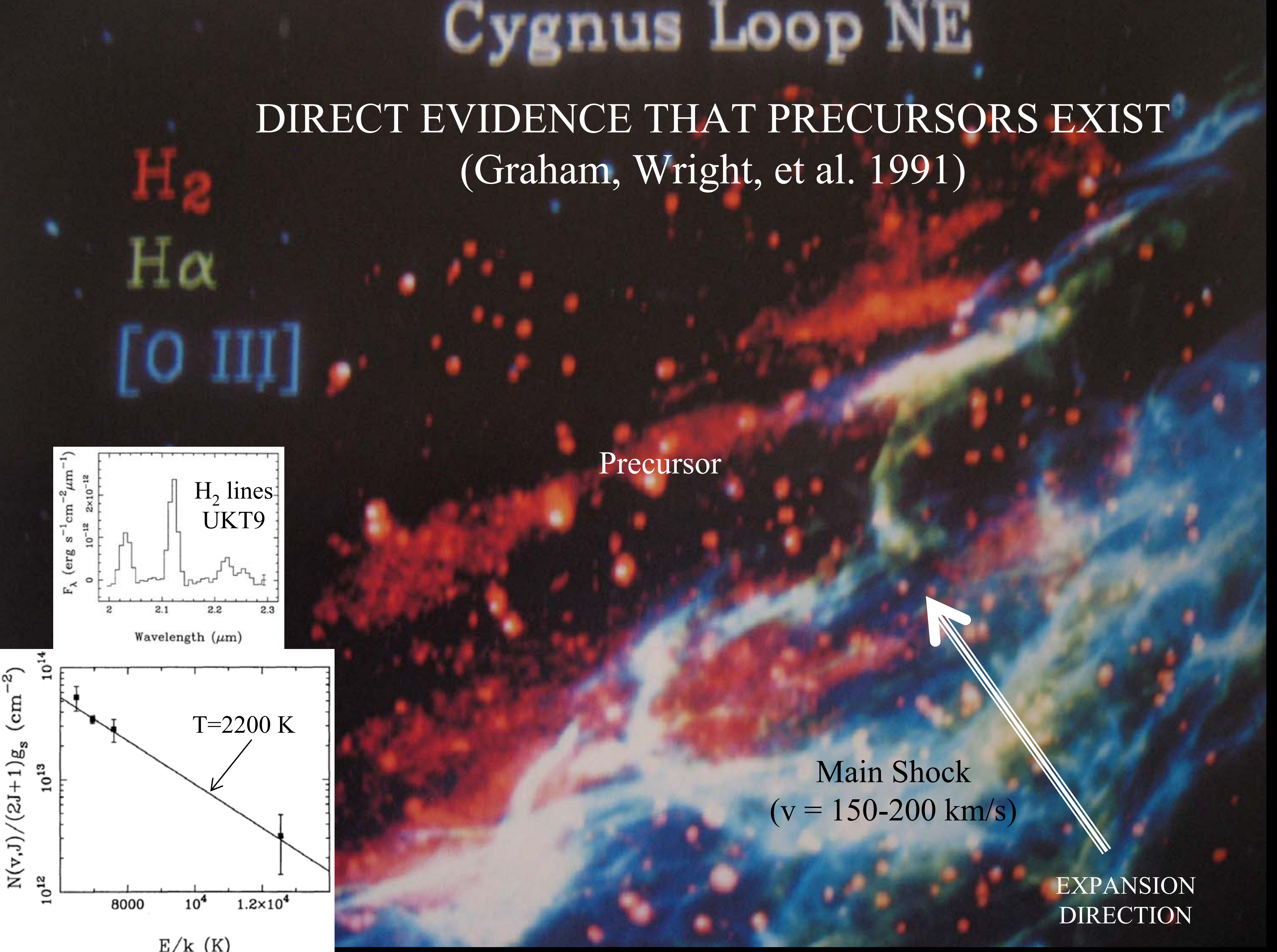
One should not / need not abandon C-shocks with precursors, but nobody has rigorously addressed the questions posed by the Brand et al. data.

Figures from Brand et al. (1988)





DIRECT EVIDENCE THAT PRECURSORS EXIST
(Graham, Wright, et al. 1991)



H_2 lines
UKT9

T=2200 K

Precursor

Main Shock
(v = 150-200 km/s)

EXPANSION
DIRECTION

Fluorescent Molecular Hydrogen in Photodissociation Regions

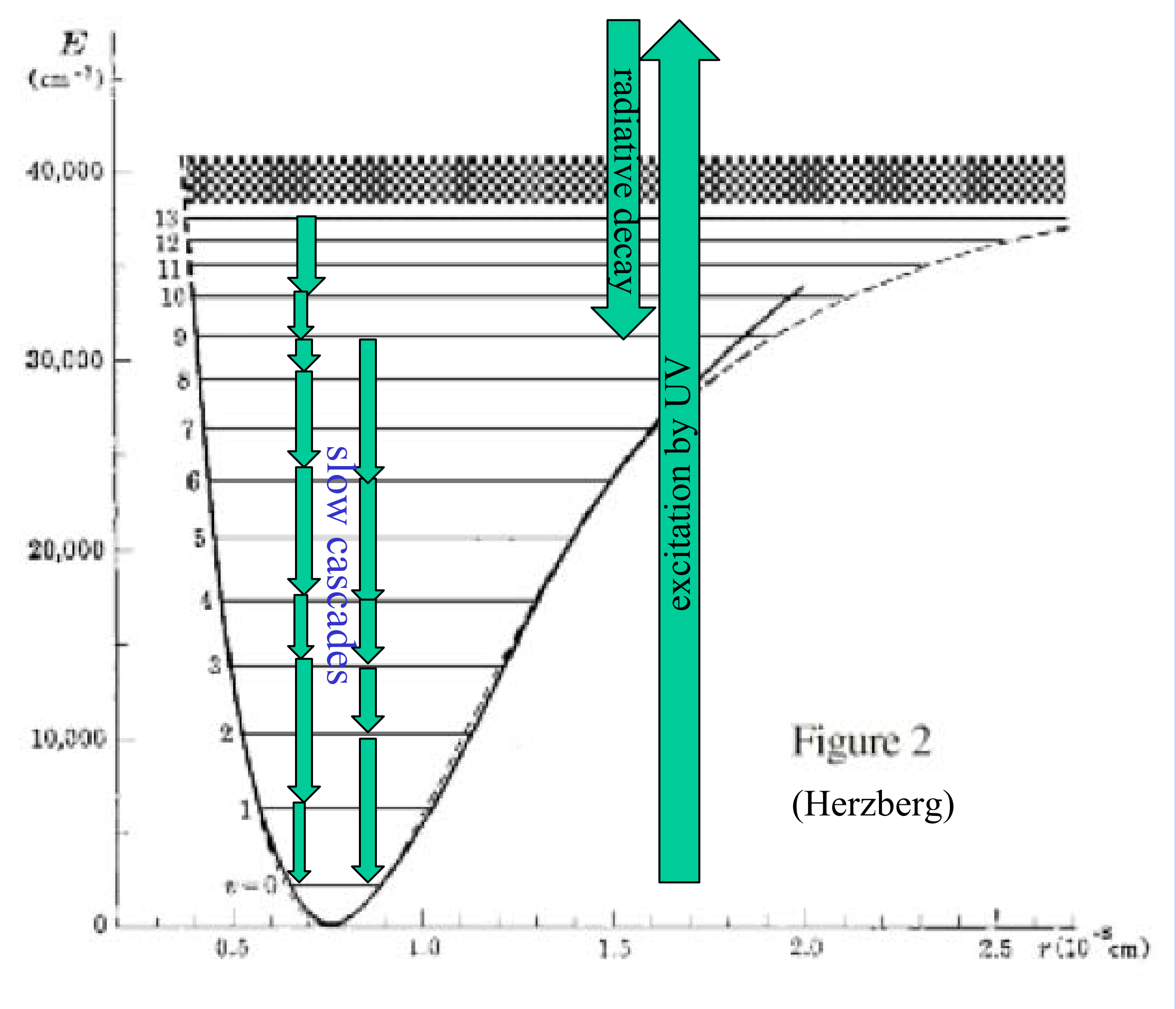
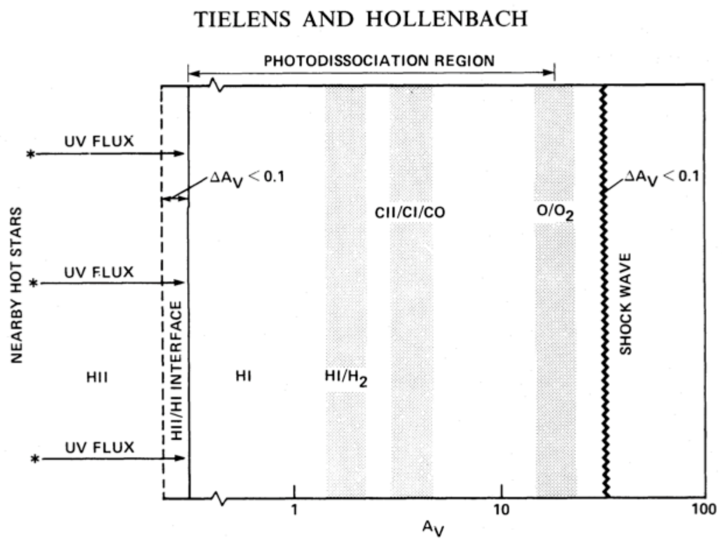


Figure 2

(Herzberg)



Molecular clouds exist near (or they surround) hot stars.
Beyond the H II region is the PDR:
stellar UV longward of 13.6eV dissociates molecules, ionizes some atoms, heats gas

For H_2 , UV excites an electronic state, leading either to dissociation or radiative decays to vibrationally excited ground electronic states.

Slow cascade down vibrational ladder to v=0

Well understood – line intensities and intensity ratios are predictable, density-dependent and different from those in post-shock gas

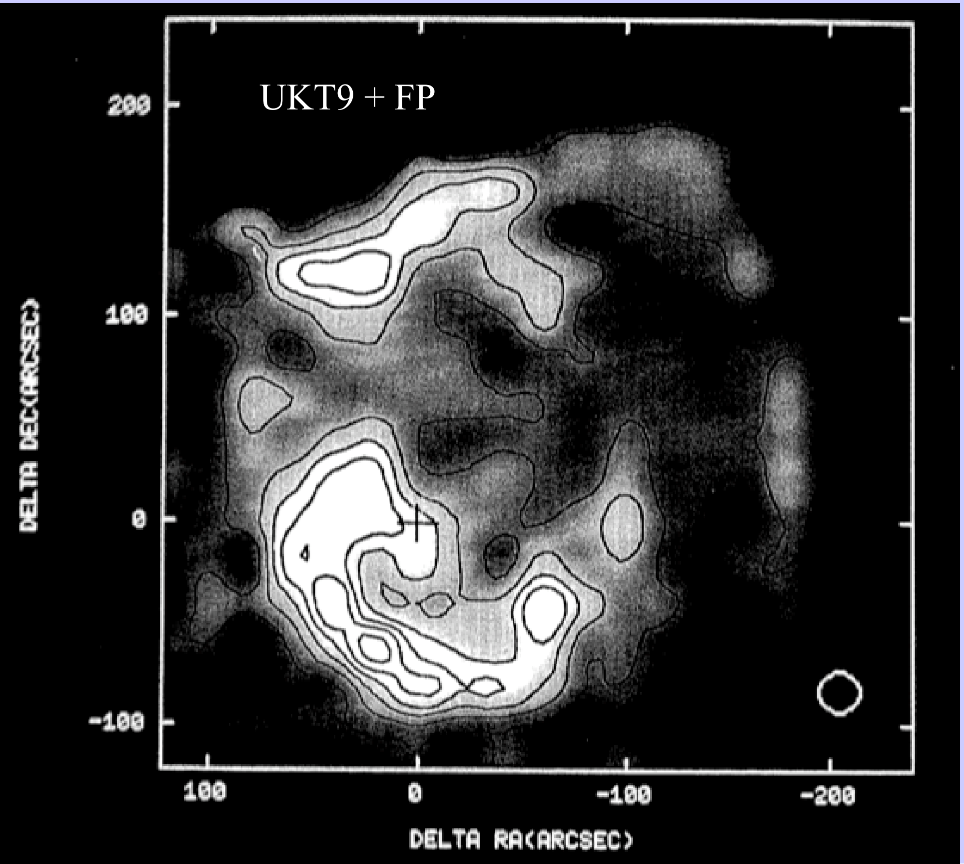
But not detected.

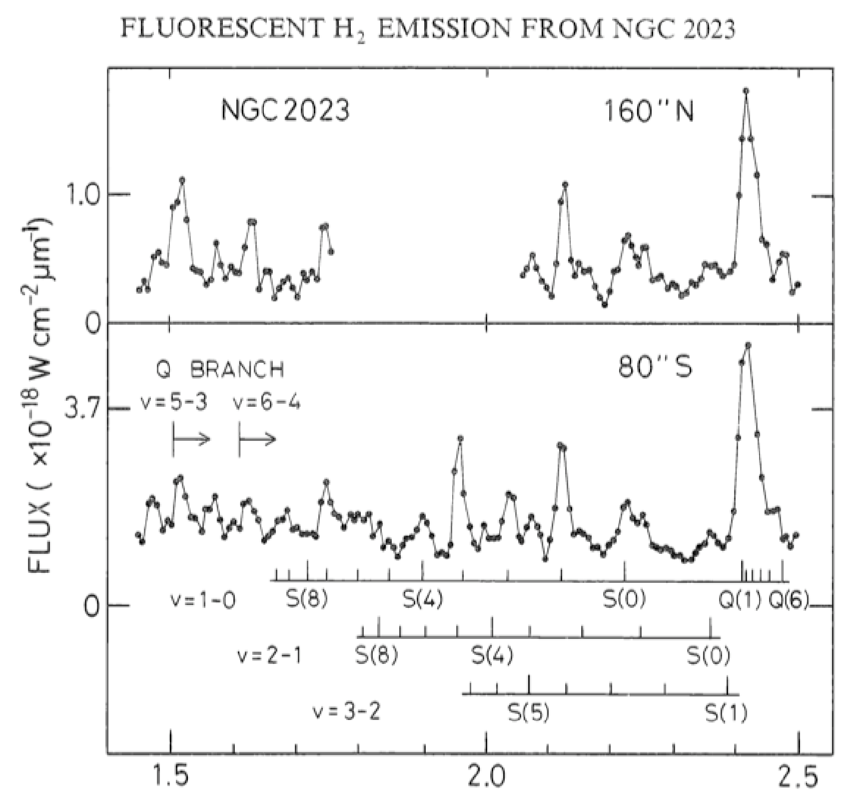
H_2 *line emission was likely to be very extended and low surface brightness – not well suited to standard techniques of IR astronomy in 1970s and1980s.*

UKIRT + UKT6/9 :

the pixels with the largest *etendu* (AΩ) in IR astronomy (ever?)
3.8 m diameter x 19.6 arcsec diameter

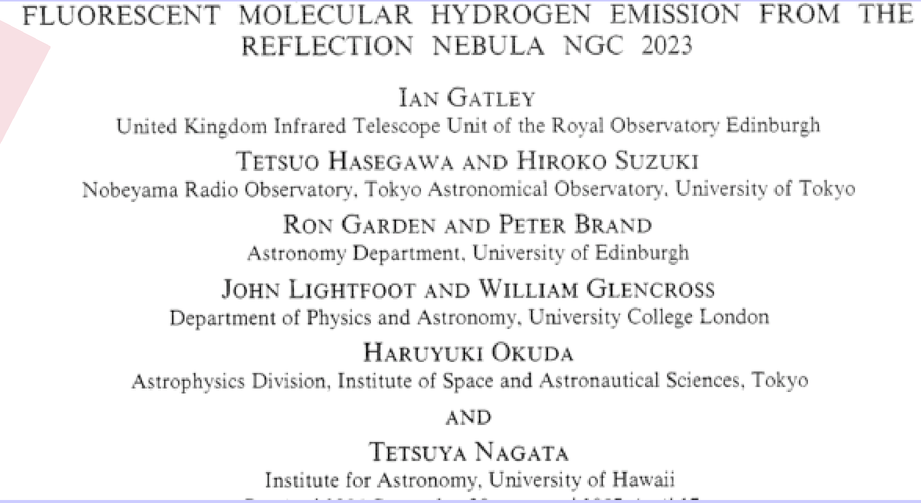
Exploited by Hayashi, Gatley and collaborators in 1984 and 1985
to detect faint fluorescent H_2


UKT9 + FP


FLUORESCENT H_2 EMISSION FROM NGC 2023

UKT9 (CVF)

The molecular hydrogen emission associated with the Orion bright bar



FLUORESCENT MOLECULAR HYDROGEN EMISSION FROM THE REFLECTION NEBULA NGC 2023

IAN GATLEY
United Kingdom Infrared Telescope Unit of the Royal Observatory Edinburgh
TETSUO HASEGAWA AND HIROKO SUZUKI
Nobeyama Radio Observatory, Tokyo Astronomical Observatory, University of Tokyo
RON GARDEN AND PETER BRAND
Astronomy Department, University of Edinburgh
JOHN LIGHTFOOT AND WILLIAM GLENCROSS
Department of Physics and Astronomy, University College London
HARUYUKI OKUDA
Astrophysics Division, Institute of Space and Astronautical Sciences, Tokyo
AND
TETSUYA NAGATA
Institute for Astronomy, University of Hawaii

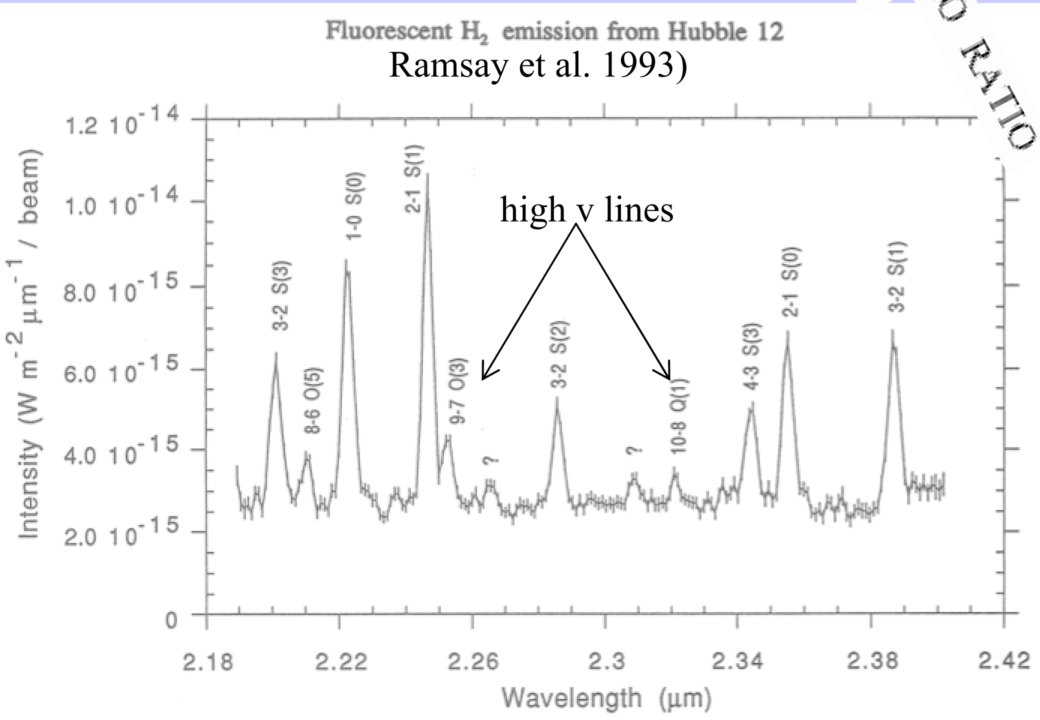
LEVEL POPULATION AND PARA - ORTHO RATIO OF FLUORESCENT H_2 IN NGC 2023

Now detected in numerous PDRs,
H II regions (galactic and extragalactic),
planetary nebulae, proto-planetaries

Important test for models of diffuse ISM and PDRs
(eg Black & van Dishoeck)

Ortho para-ratio typically 1-2; implies different contributions of UV self shielding (favors para but can only produce 1.7:1)
and H_2 formation temperature (favors para)

Improved spectra (e.g., Ramsay et al.) show high vibrational excitation lines. Excellent fits with models.



Fluorescent H_2 emission from Hubble 12
Ramsay et al. 1993)

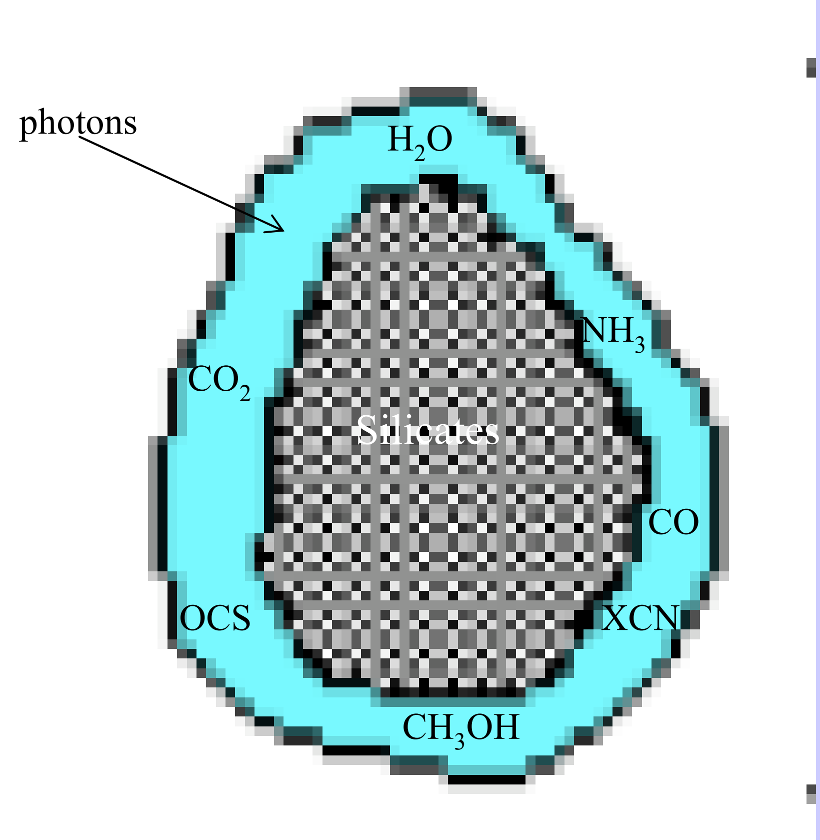
high v lines

CHEMCAL COMPOSITION OF DUST IN DARK CLOUDS

Studied with all UKIRT spectrographs – UKT6, CGS3,3,4, Michelle, UIST

Essentials of dust in dark clouds:

Amorphous Silicate cores
overcoated with H2O, CO, …
and other more complex molecules if exposed to heat, UV, …

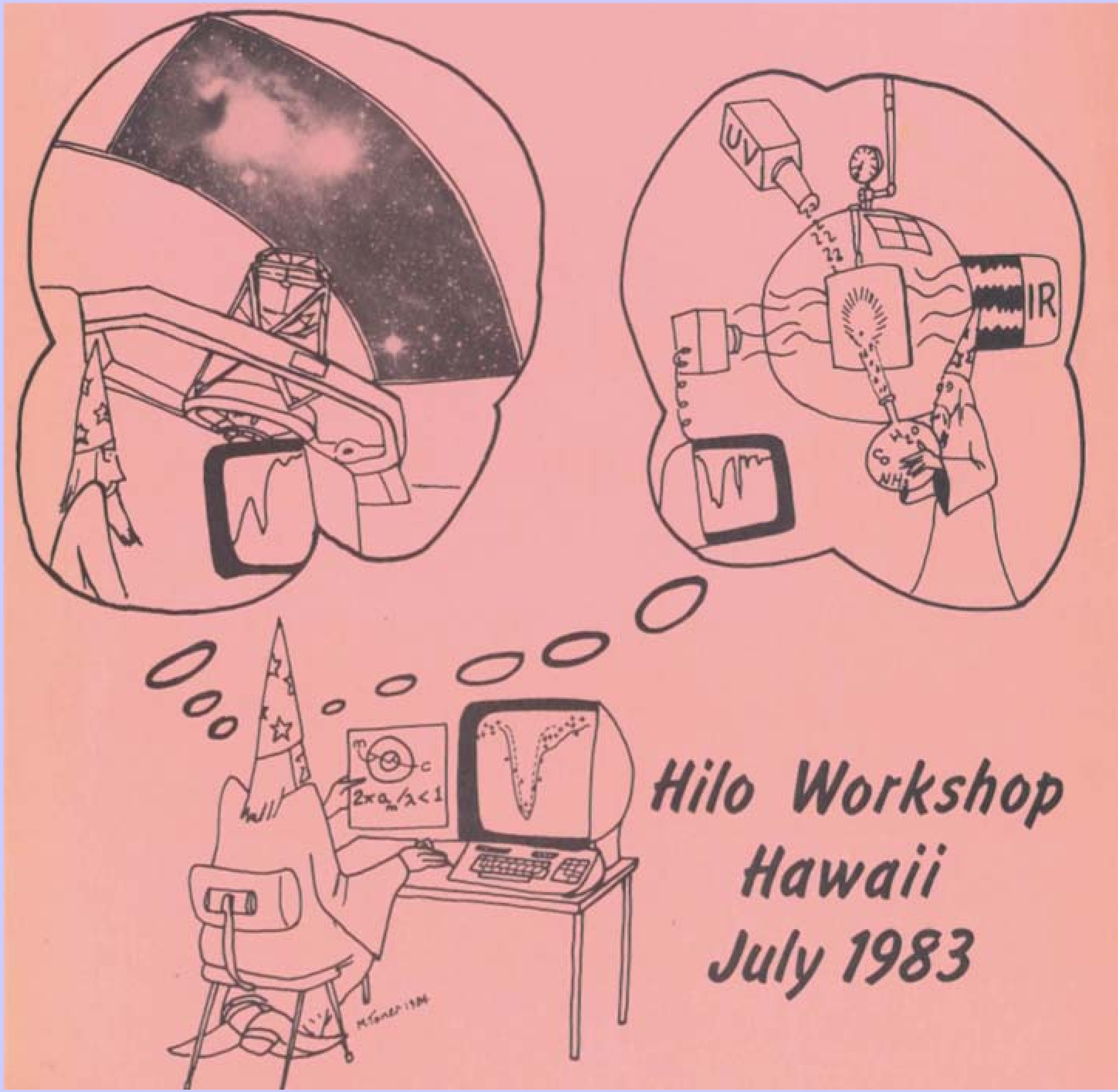


Essential feature of studies of grains mantles:

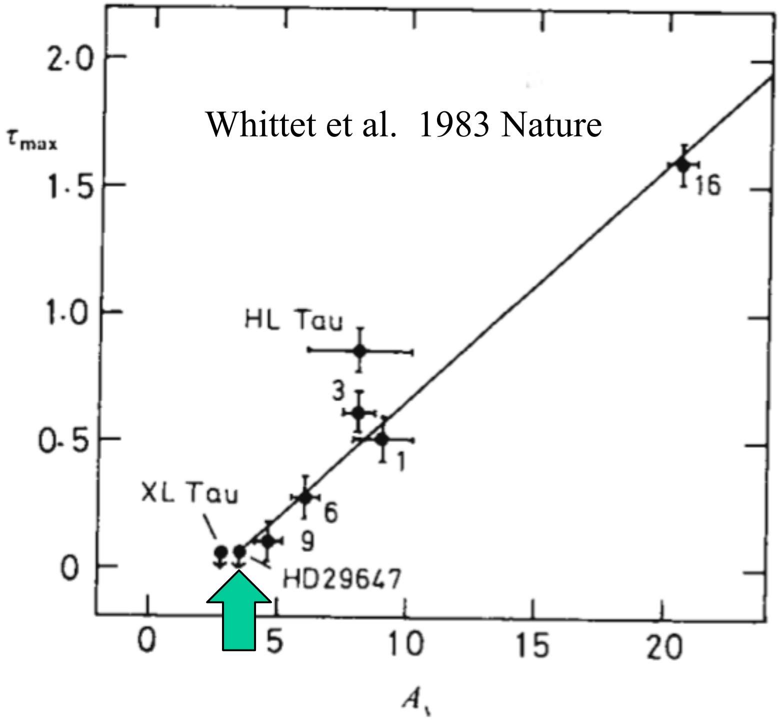
the interplay between laboratory simulations and astronomical data

Lab data essential for basic identifications of mantle chemicals

Detailed comparisons with Lab data also can determine how different ices are distributed on surface

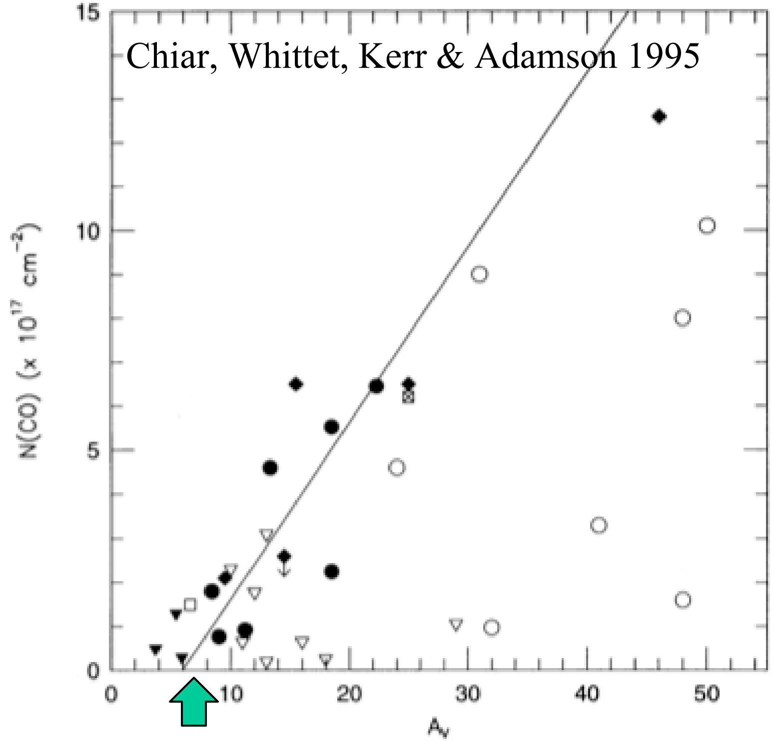


Thresholds for ice mantle formation in Taurus



Whittet et al. 1983 Nature

Fig. 2 Plot of peak optical depth (τ_{max}) in the 3-μm feature against visual extinction (A_V). The best straight line for the Elias sources is shown.



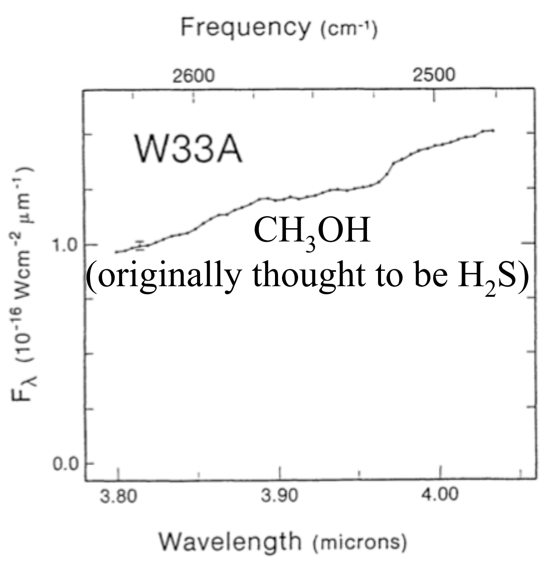
Chiar, Whittet, Kerr & Adamson 1995

FIG. 3.—Plot of N(CO) vs. A_V. The symbols have the same meaning as in Fig. 2. The solid line is the least-squares fit to the Taurus field stars (excluding limiting values and Elias 15): $N(CO) = 0.4(A_V - 6.0) \times 10^{17}$ cm^{-2}.

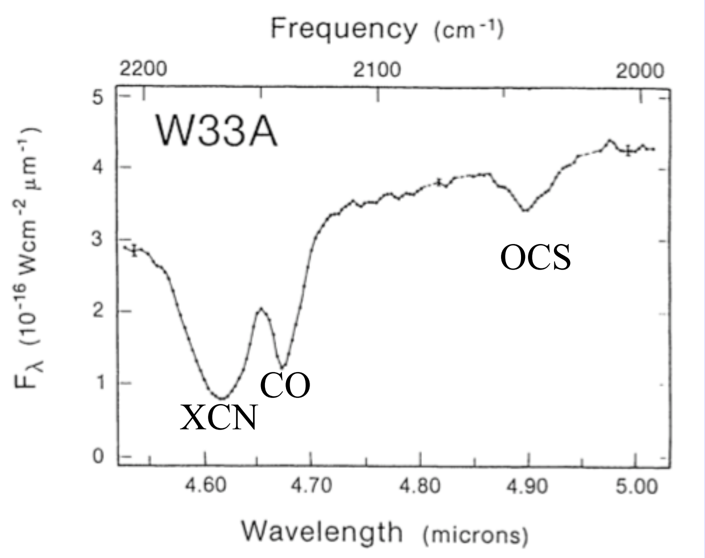
Water ice in Taurus Dark Cloud: Av>3 mag   CO ice in Taurus Av>6 mag

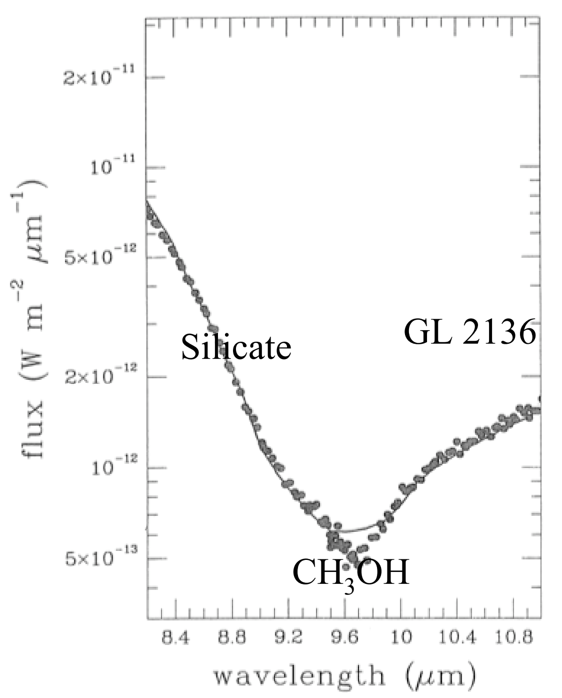
Water ice in Ophiucus Dark Cloud: Av > 6 mag

New detections from UKIRT



Geballe,
Baas,
Greenberg,
& Schutte
(1985)
CGS3





Skinner,
Tielens,
Barlow
& Justannont
(1992)
CGS3

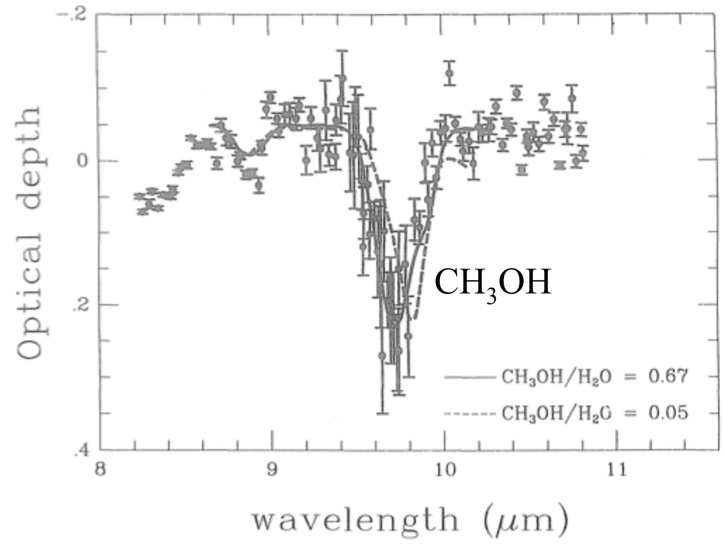


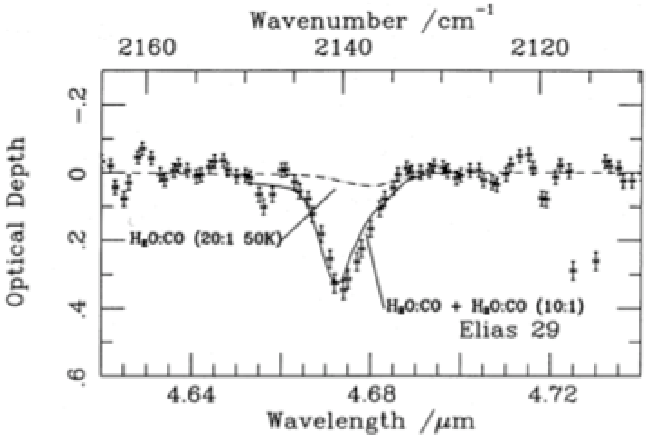
FIG. 3.—Optical depth of the features ascribed to solid methanol, with 1 σ errors. The solid line shows laboratory measurements of the absorption strength of a 2:1 mixture of methanol-ice:water-ice. The dashed line likewise shows laboratory measurements of the absorption strength of a 1:19 mixture of methanol-ice:water-ice.

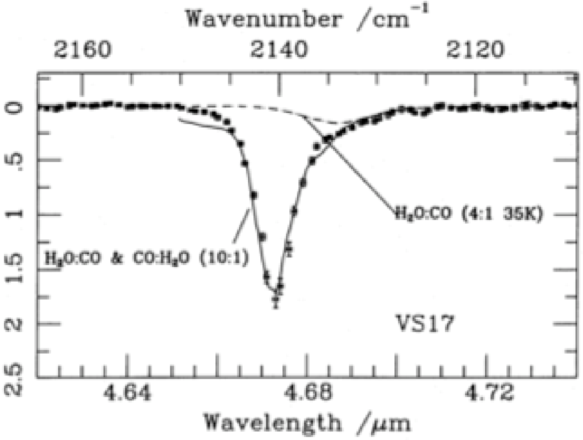
Wavelength ➔ $CH_3OH:H_2O$ > 0.5 Intensity ratio ➔ $CH_3OH/H_2O = 0.1$. Implies that the two species are not mixed.

CO distribution in Ophiucus grain mantles

pure CO or CO in non-polar ice gives narrow profile

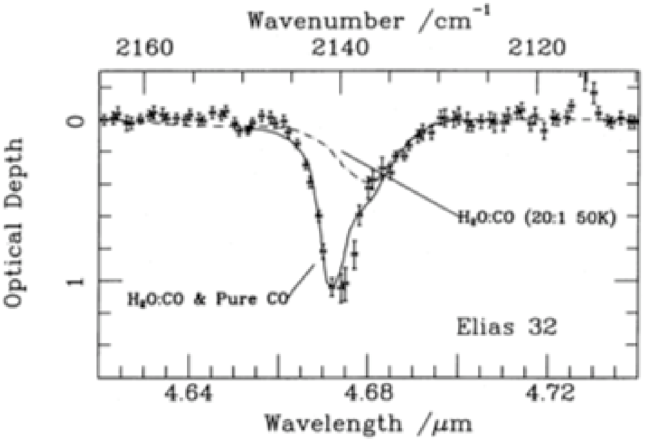
CO in H2O (polar) ice gives broad redshifted profile

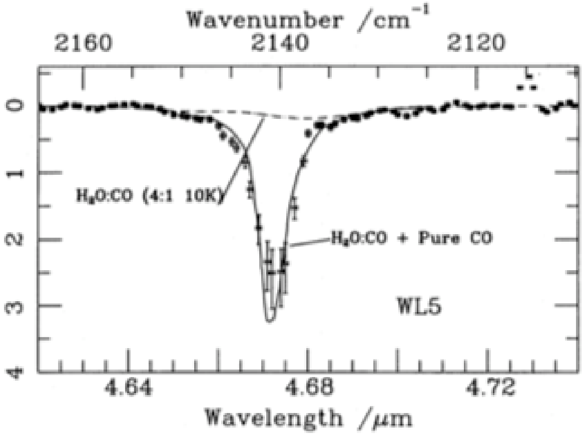


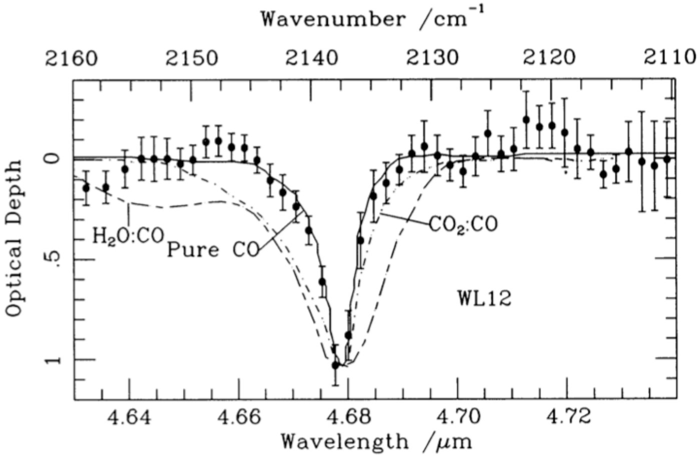


Data reveal
various mixtures of nearly pure CO ice
and CO heavily diluted in water ice

Various degrees of segregation
demonstrate effects of different
freeze-out temperatures
and range of formation conditions

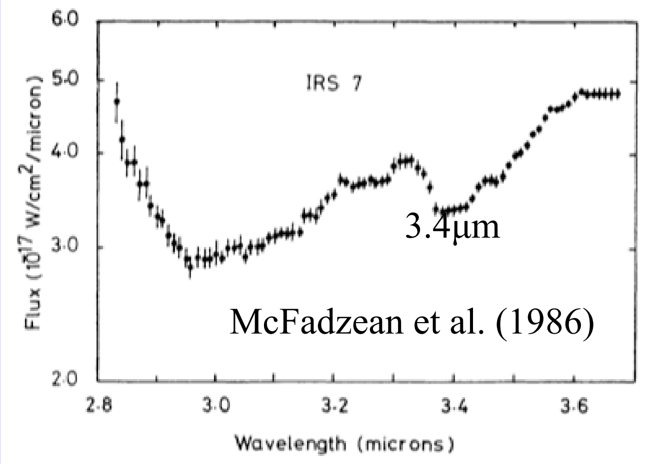






Kerr, Adamson, & Whittet
(1991, 1993)
CGS2 and CGS4

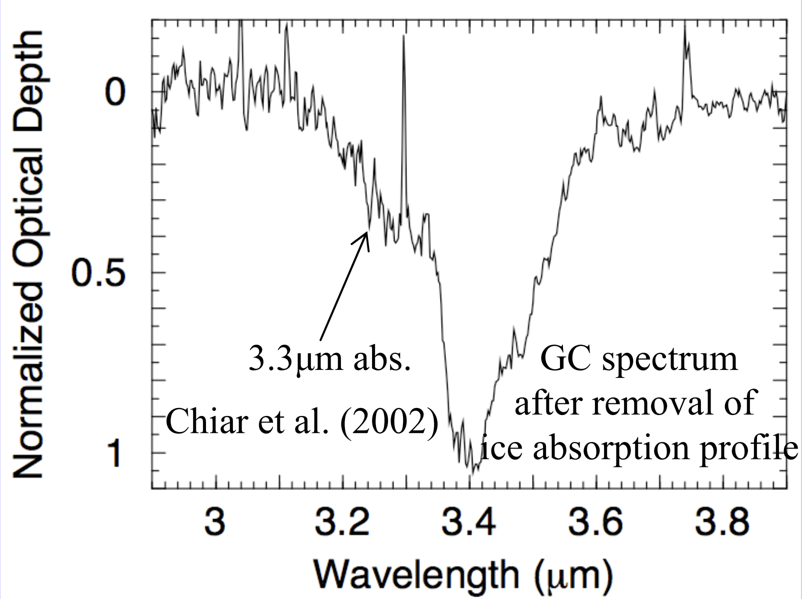
Dust in Diffuse Clouds



3.4µm

McFadzean et al. (1986)

Toward the Galactic center

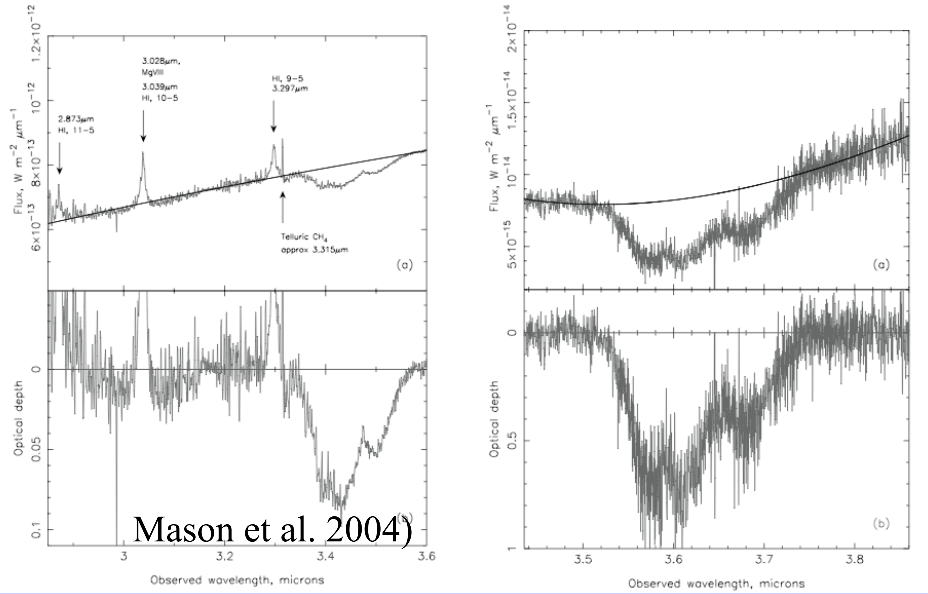


3.3µm abs.

Chiar et al. (2002)

GC spectrum after removal of ice absorption profile

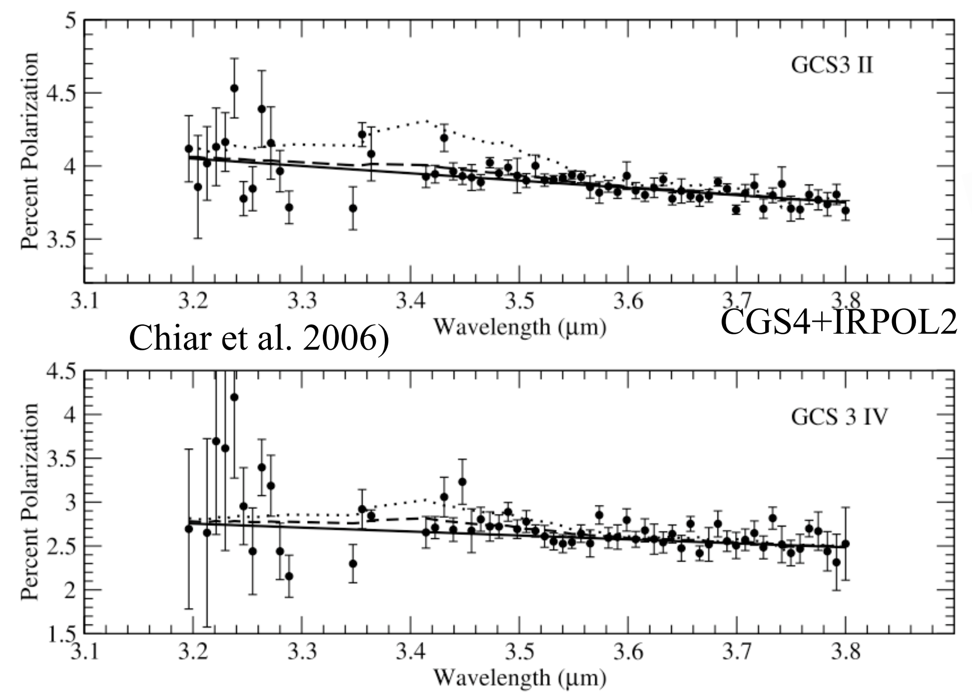
After removal of water ice absorption profile



Mason et al. 2004)

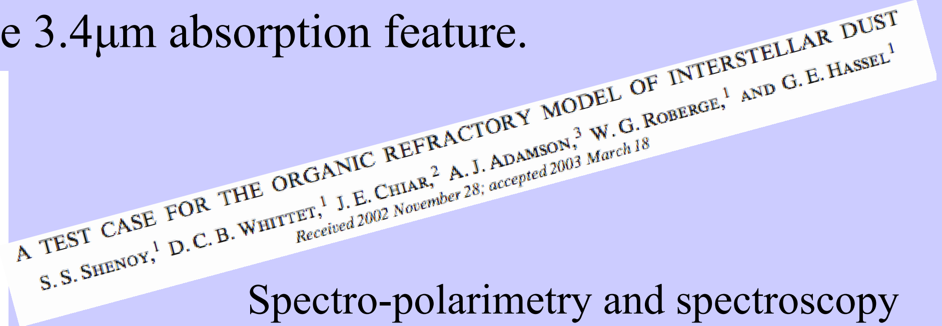
3.4µm feature discovered in other galaxies as well (Wright, Bridger, et al.) implying a significant diffuse ISM component near their nuclei, and diagnostic of dominant AGN

Dispelling a myth about the 3.4μm absorption feature.



Chiar et al. 2006)

CGS4+IRPOL2

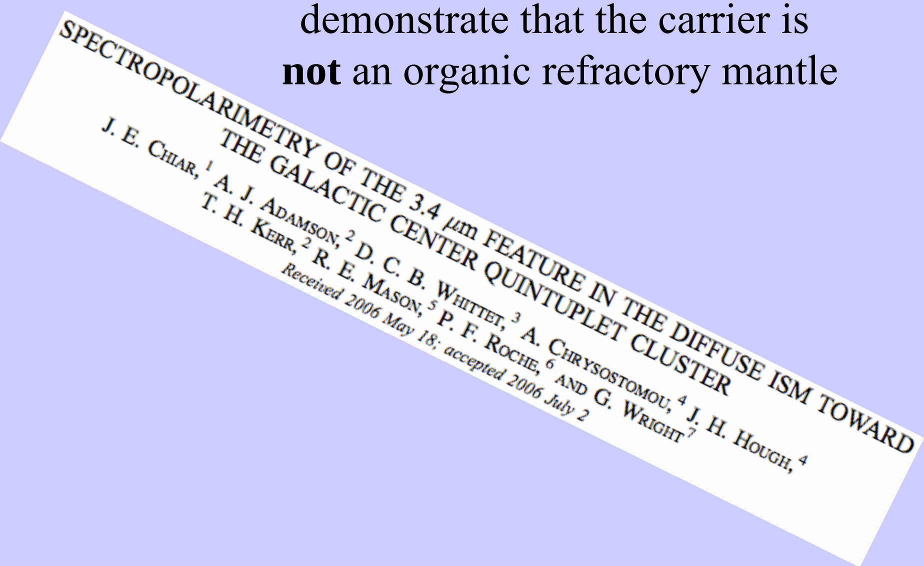


A TEST CASE FOR THE ORGANIC REFRACTORY MODEL OF INTERSTELLAR DUST

S. S. Shenoy,[1] D. C. B. Whittet,[1] J. E. Chiar,[2] A. J. Adamson,[3] W. G. Roberge,[1] and G. E. Hassel[1]

Received 2002 November 28; accepted 2003 March 18

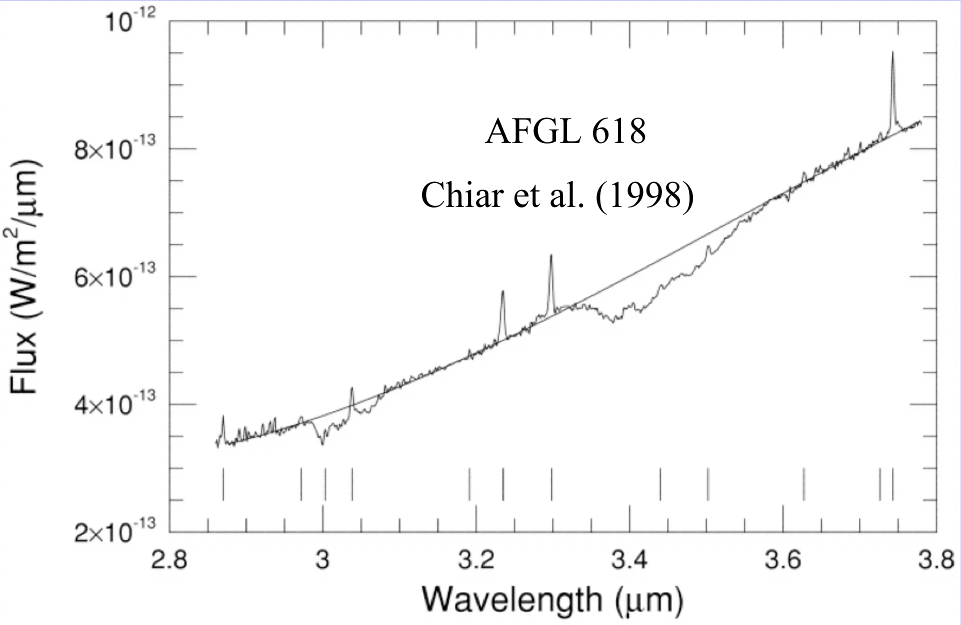
Spectro-polarimetry and spectroscopy demonstrate that the carrier is **not** an organic refractory mantle



SPECTROPOLARIMETRY OF THE 3.4 μm FEATURE IN THE DIFFUSE ISM TOWARD THE GALACTIC CENTER QUINTUPLET CLUSTER

J. E. Chiar,[1] A. J. Adamson,[2] D. C. B. Whittet,[3] A. Chrysostomou,[4] J. H. Hough,[4] T. H. Kerr,[2] R. E. Mason,[5] P. F. Roche,[6] and G. Wright[7]

Received 2006 May 18; accepted 2006 July 2



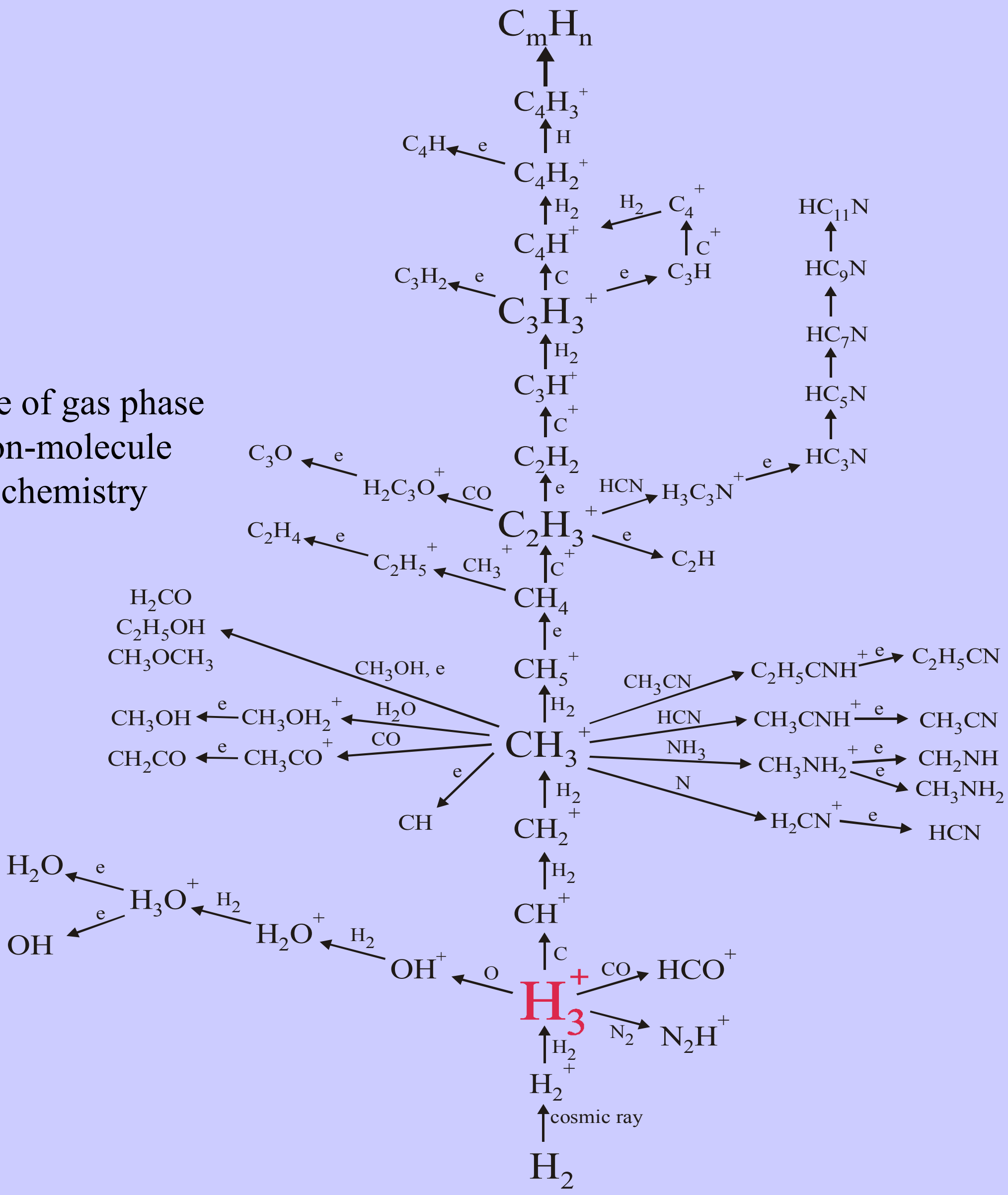
Likely origin:
The carrier of the 3.4μm feature is deposited in the ISM by the mass-loss winds of carbon-rich PPNe.

Lequeux & Jourdain de Muizon (1990) – CGS2

(improved spectrum by Chiar et al. 1998) – CGS4

H_3^+ in the ISM

Main significance is not the discovery (it had to be there) – but its value as a tool and what it has revealed about the physical conditions in the ISM



Tree of gas phase ion-molecule chemistry

$$H_2 \xrightarrow{\text{cosmic ray}} H_2^+ \xrightarrow{H_2} H_3^+ \xrightarrow{C} CH^+ \xrightarrow{H_2} CH_2^+ \xrightarrow{H_2} CH_3^+ \xrightarrow{H_2} CH_5^+ \xrightarrow{e} CH_4 \xrightarrow{C^+} C_2H_3^+ \xrightarrow{e} C_2H_2 \xrightarrow{C^+} C_3H^+ \xrightarrow{H_2} C_3H_3^+ \xrightarrow{C} C_4H^+ \xrightarrow{H_2} C_4H_2^+ \xrightarrow{H} C_4H_3^+ \rightarrow C_mH_n$$

$$H_3^+ \xrightarrow{O} OH^+ \xrightarrow{H_2} H_2O^+ \xrightarrow{H_2} H_3O^+ \xrightarrow{e} H_2O$$

$$H_3O^+ \xrightarrow{e} OH$$

$$H_3^+ \xrightarrow{CO} HCO^+$$

$$H_3^+ \xrightarrow{N_2} N_2H^+$$

$$CH_3^+ \xrightarrow{e} CH$$

$$CH_3^+ \xrightarrow{CO} CH_3CO^+ \xrightarrow{e} CH_2CO$$

$$CH_3^+ \xrightarrow{H_2O} CH_3OH_2^+ \xrightarrow{e} CH_3OH$$

$$CH_3^+ \xrightarrow{CH_3OH,\ e} H_2CO,\ C_2H_5OH,\ CH_3OCH_3$$

$$CH_3^+ \xrightarrow{CH_3CN} C_2H_5CNH^+ \xrightarrow{e} C_2H_5CN$$

$$CH_3^+ \xrightarrow{HCN} CH_3CNH^+ \xrightarrow{e} CH_3CN$$

$$CH_3^+ \xrightarrow{NH_3} CH_3NH_2^+ \xrightarrow{e} CH_2NH$$

$$CH_3NH_2^+ \xrightarrow{e} CH_3NH_2$$

$$CH_3^+ \xrightarrow{N} H_2CN^+ \xrightarrow{e} HCN$$

$$CH_4 \xrightarrow{CH_3^+} C_2H_5^+ \xrightarrow{e} C_2H_4$$

$$C_2H_3^+ \xrightarrow{CO} H_2C_3O^+ \xrightarrow{e} C_3O$$

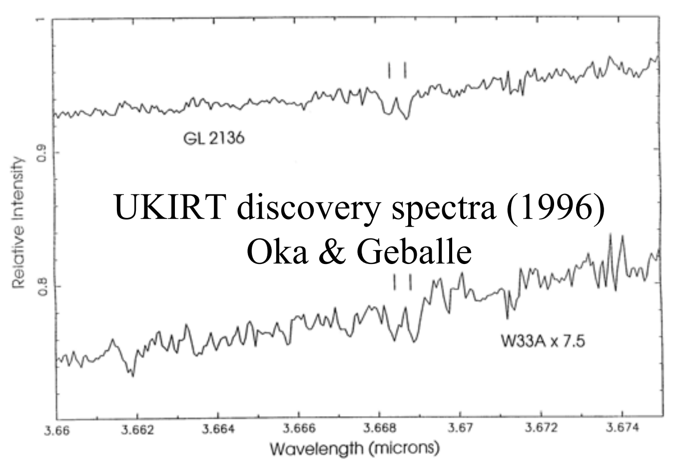
$$C_2H_3^+ \xrightarrow{HCN} H_3C_3N^+ \xrightarrow{e} HC_3N \rightarrow HC_5N \rightarrow HC_7N \rightarrow HC_9N \rightarrow HC_{11}N$$

$$C_2H_3^+ \xrightarrow{e} C_2H$$

$$C_3H_3^+ \xrightarrow{e} C_3H_2$$

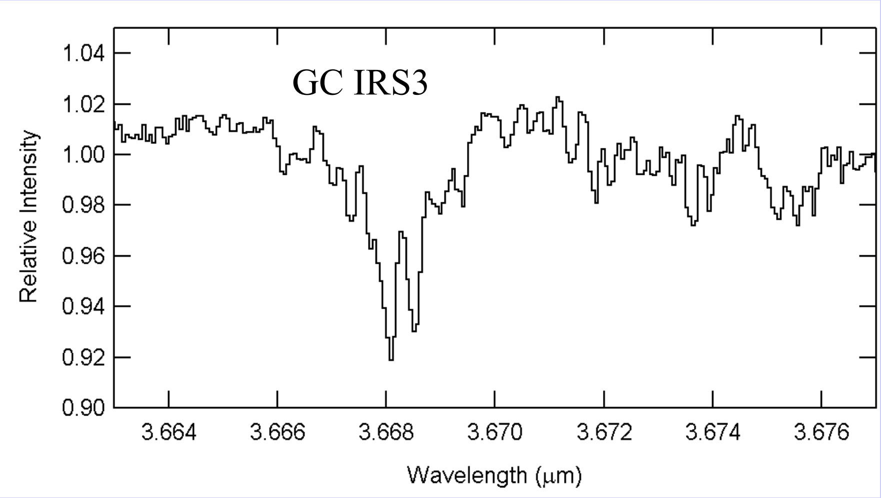
$$C_3H_3^+ \xrightarrow{e} C_3H \xrightarrow{C^+} C_4^+ \xrightarrow{H_2} C_4H^+$$

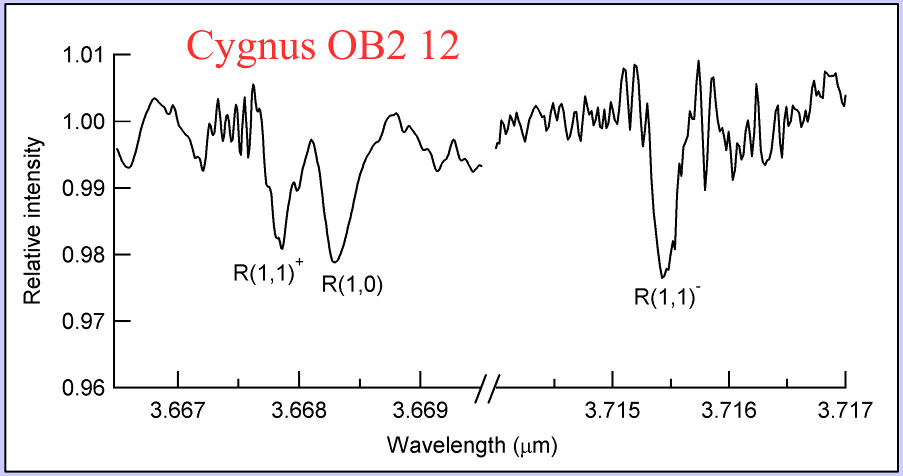
$$C_4H_2^+ \xrightarrow{e} C_4H$$



UKIRT discovery spectra (1996)
Oka & Geballe

Lots of H_3^+ in Diffuse Clouds!



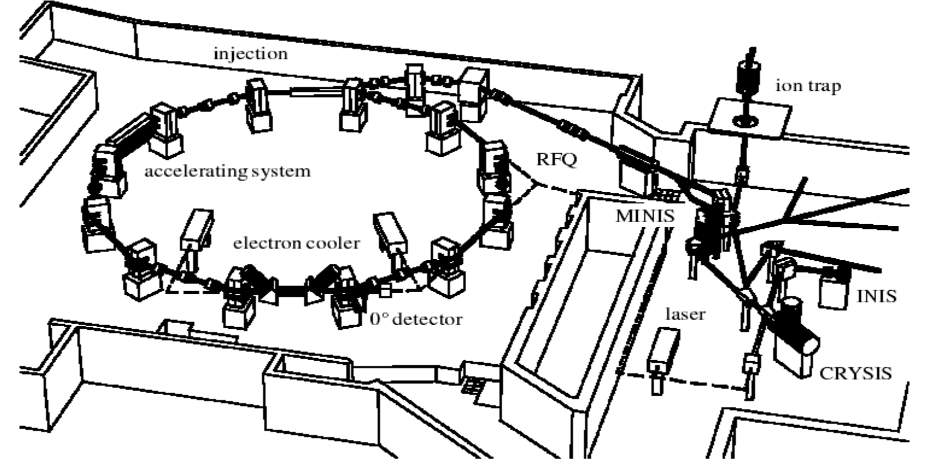


Expect little H_3^+ in diffuse clouds because much higher concentration of e^-

Instead found $N_{diffuse}(H_3^+) = n(H_3^+)L$ same as in dense clouds

but $n(H_3^+)$ should be ~ 1000 times less in diffuse clouds

Does this imply L_{diffus}e is ~ 1000 times longer than L_{dense}?

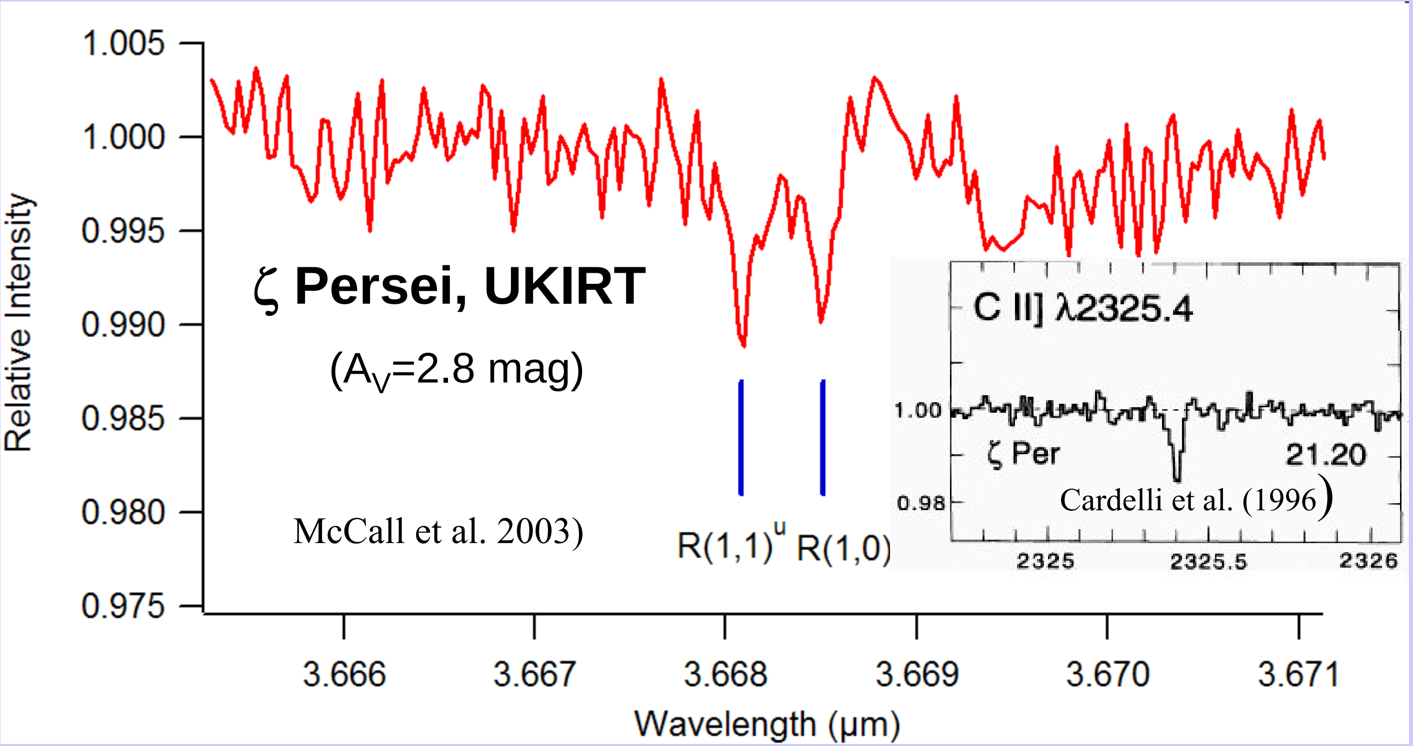


CRYRING (Sweden)

Ion storage ring

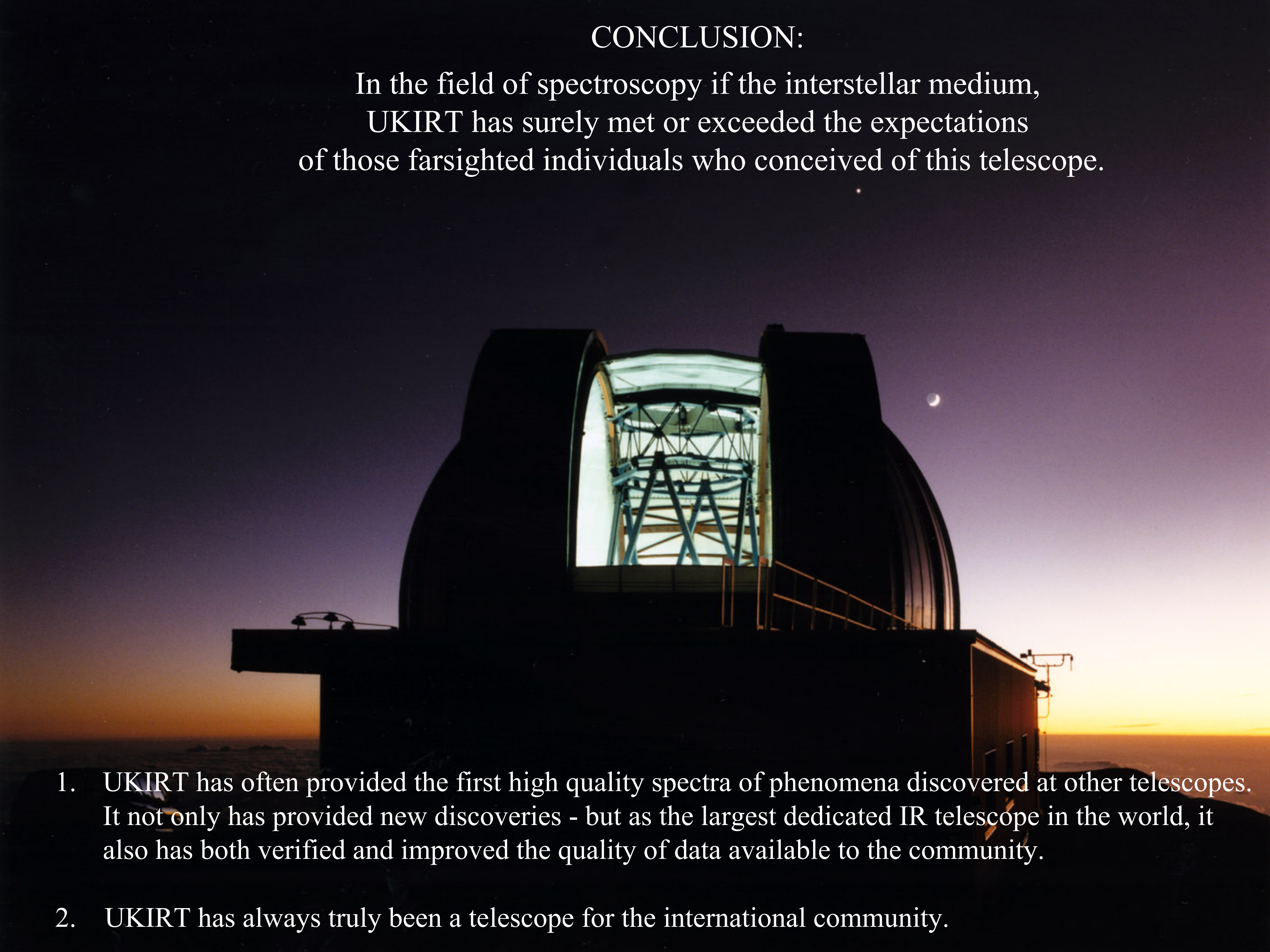
Inject rotationally cold H_3^+

$k_e \sim 2.6 \times 10^{-7}$ cm^3 s^{-1} at 23 K



Conclusion – cosmic ray ionization rate is >10 times higher in diffuse clouds than dense clouds

Most likely explanation – a previously unsuspected large population of low energy cosmic rays that dominate the ionization of H2 in diffuse clouds, but only affect the surfaces of dark clouds.



CONCLUSION:

In the field of spectroscopy if the interstellar medium,
UKIRT has surely met or exceeded the expectations
of those farsighted individuals who conceived of this telescope.

1. UKIRT has often provided the first high quality spectra of phenomena discovered at other telescopes. It not only has provided new discoveries - but as the largest dedicated IR telescope in the world, it also has both verified and improved the quality of data available to the community.

2. UKIRT has always truly been a telescope for the international community.