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
Ice mantles and the anomalous ultraviolet extinction of HD 29647

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Summary. HD 29647, a reddened early-type star in the Taurus dark cloud, was shown by Snow & Sahu to have anomalously weak absorption in the 2.2300 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.

An early portent of the important contributions of UKIRT in interstellar infrared spectroscopy...
Some Highlights of IR Spectroscopy of the ISM

- $\text{H}_2$ and the physics of shock waves in molecular clouds
- Fluorescent $\text{H}_2$
- Dust in dense clouds
- Dust in diffuse clouds
- $\text{H}_3^+$ in the ISM
REVIEW OF H₂

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) \( A_{1-0} S(1)^{-1} \approx 1 \) 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\textsubscript{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\textsubscript{2}

We also can learn from observing shocked H\textsubscript{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\textsubscript{2} survive the shock?

H\textsubscript{2} – H\textsubscript{2} collisions at more than 20 km/s dissociate

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

OMC1 – Peak 1
H\textsubscript{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.

Conclusion: C shocks in which the H₂ 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
$\sim$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.
DIRECT EVIDENCE THAT PRECURSORS EXIST
(Graham, Wright, et al. 1991)

Precursor

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

EXPANSION DIRECTION

T=2200 K

H$_2$ lines
UKT9

$\text{H} \alpha$

$\text{[O III]}$

$\text{H}_2$
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 H₂, 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.

**H₂ line emission was likely to be very extended and low surface brightness – not well suited to standard techniques of IR astronomy in 1970s and 1980s.**
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 H₂
Now detected in numerous PDRs, H II regions (galactic and extragalactic), planetary nebulae, proto-planetary

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.
CHEMICAL 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

Water ice in Taurus Dark Cloud: $A_v > 3$ mag

Water ice in Ophiucus Dark Cloud: $A_v > 6$ mag

CO ice in Taurus $A_v > 6$ mag

Chiar, Whittet, Kerr & Adamson 1995

Whittet et al. 1983 Nature
New detections from UKIRT

Wavelength \( \frac{\text{CH}_3\text{OH}}{\text{H}_2\text{O}} > 0.5 \)  
Intensity ratio \( \frac{\text{CH}_3\text{OH}}{\text{H}_2\text{O}} = 0.1 \). Implies that the two species are not mixed.

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

Skinner, Tielens, Barlow & Justannont (1992) CGS3
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 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.

Toward the Galactic center

3.3μm absorption profile (Chiar et al. 2002)

After removal of water ice absorption profile

Mason et al. 2004)
Dispelling a myth about the 3.4μm absorption feature.

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

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

UKIRT discovery spectra (1996)
Oka & Geballe
Lots of $\text{H}_3^+$ in Diffuse Clouds!

Expect little $\text{H}_3^+$ in diffuse clouds because much higher concentration of $e^-$

Instead found $N_{\text{diffuse}}(\text{H}_3^+) = n(\text{H}_3^+)L$ same as in dense clouds

but $n(\text{H}_3^+)$ should be $\sim 1000$ times less in diffuse clouds

Does this imply $L_{\text{diffuse}}$ is $\sim 1000$ times longer than $L_{\text{dense}}$?
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 H$_2$ 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.