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OBSERVATIONS OF THE INTERSTELLAR ICE GRAIN FEATURE IN THE TAURUS MOLECULAR CLOUDS

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1. INTRODUCTION

Although water ice was originally proposed as a major constituent of the interstellar grain population (e.g. Oort and van de Hulst, 1946), the advent of infrared astronomy has shown that the expected absorption due to C-H stretching vibrations at $3\text{ }\mu\text{m}$ is illusive. Observations have in fact revealed that the carrier of this feature is apparently restricted to regions deep within dense molecular clouds (Merrill et al., 1976; Willner et al., 1982). However, the exact carrier of this feature is still controversial, and many questions remain as to the conditions required for its appearance. It is also uncertain whether it is restricted to circumstellar shells, rather than the general cloud medium. Detailed discussion of the $3\text{ }\mu\text{m}$ band properties is given elsewhere in this volume.

The Taurus molecular clouds were selected for observations, in the form of a preliminary survey in the $2\text{--}4\text{ }\mu\text{m}$ window, for several reasons. Firstly, they are among the closest regions of active star formation to the Solar System. In addition, they contain very few sources of ultraviolet radiation, such as OB stars, which could disrupt grain mantles. Finally, observations by Cohen (1975) have revealed that in this region the young object HL Tau has a distinct $3\text{ }\mu\text{m}$ feature (though prior to the observations reported here, this was the only object in the Taurus clouds known to possess such a feature). Sources observed in addition to HL Tau were mostly selected from the survey by Elias (1978). These covered two distinct classes, viz. those objects thought to be embedded at different depths within the clouds (HL Tau, XL Tau and Elias 1) and those suspected to be field stars lying behind the clouds (Elias 3, 6, 9 and 16).

2. THE OBSERVATIONS

Observations were made in November 1981 using the liquid nitrogen cooled spectrophotometer at the $f/35$ focus of the United Kingdom Infrared Telescope on Mauna Kea. Spectral scans with a resolution of ~ 100 in the $2.3\text{--}4.6\text{ }\mu\text{m}$ region were obtained using an InSb detector and circular variable filter. Due to atmospheric absorption, the effective bandpasses are $2.3\text{--}2.6$ and $2.9\text{--}4.1\text{ }\mu\text{m}$. Averaging of several scans ensured the signal to noise was > 20 in each case. Usual techniques were employed, using standard comparison stars, to remove atmospheric extinction and instrumental profile, and to reduce the spectra to relative flux. Calibration of the wavelength scale to $\pm 0.01\text{ }\mu\text{m}$ was achieved by observing the emission line sources HD 44179 and IC418 (Russell et al., 1977).

3. DISCUSSION

Figures 1(a-c) and 2(a-d) show results of the reduced spectrophotometry for the embedded stars, and the field stars,

Fig. 1 (a-c). Infrared ($2.3\text{--}4.1\text{ }\mu\text{m}$) spectra of the embedded sources (a) Xi Tau, (b) HL Tau, (c) Elias 1.

Fig. 2. As Fig. 1 except sources are field stars (a) Elias 9, (b) Elias 3, (c) Elias 6, (d) Elias 16.

respectively. In figure 2(a-d) the spectra are arranged in order of increasing A_V .

Several points are immediately apparent. The most obvious of course is that the feature appears in both groups of objects. This is particularly important, as it suggests that the carrier is not just confined to circumstellar shells, but may be widespread in the cloud medium. In addition, the depth of the feature appears to increase with A_V . Finally, even before comparison spectra are used to derive the precise shape of the extinction curve in this wavelength region, the feature profile for HL Tau can be picked out as being rather different from those of the Elias objects. These latter two impressions will be shown later to be correct.

In order to derive extinction curves, one would ideally like to normalize the extinction in the same way as is generally done for the whole interstellar extinction curve. In that way, no assumptions would be made regarding the actual optical depth at any particular wavelength, and only the form of comparison continuum would be important. In addition, one could tell rather more about the contributions of different grain populations. However, the requirement that the baseline wavelengths should be outside any features, in relatively smooth continuum regions, means the baseline is very short in wavelength. Thus, unfortunately, any slight errors arising from the spectrophotometry or comparison lead to gross errors arising in the feature profile. Extension of observations into the 10 μ m band would be required to render this method more reliable.

Alternatively, one could simply draw in a continuum by eye between regions of assumed stellar continuum either side of the feature, as is in fact normally done. This has several drawbacks, the main one of which is determining the continuum, especially for late type objects such as Elias 3, 6, 9, 16, where molecular features (CO, H₂O etc.) may be apparent in the infrared stellar spectrum. Also, of course, any reasonable grains will tend to increase the extinction toward shorter wavelengths so that it cannot be 'zero' on each side of the feature. For our purposes, the best compromise seems to be to assume that $\tau \sim 0$ at the longest wavelength (4.1 μ m), and then to use comparison continua of as near to the correct spectral type as possible (see Table 1).

Using this approach, the maximum optical depth in the feature ($\tau_{\max}$) was calculated for each source. Figure 3 shows the results plotted against A_V . The upper limit on $\tau_{\max}$ in HD 29647 is from Whittet et al. (1981). From figure 3 it can be seen that, as expected, after a given threshold, $\tau_{\max}$ increases with A_V . Indeed, taking the Elias

Table 1 Observed stars

Star	Spectral type ^{(a)(b)}	Comparison used ^{(c)(d)}	$\tau_{\max}$	A_V ^{(a)(b)}
Elias 1	Ae + 1500 K dust	1500K bb	0.51	8-10
Elias 3	K2III	4460K bb	0.61	8.1
Elias 6	M8III	M8	0.27	5.9
Elias 9	M4III	M3.1I	0.10	4.5
Elias 16	K1II-I	4580K bb	1.60	20.6
HL Tau	T Tau	1100K bb	0.85	~6
XL Tau	T Tau	-	0.05	~3

^(a)Cohen (1975); ^(b)Elias (1978); ^(c)Johnson (1976); and ^(d)Merrill and Stein (1976)

Fig. 3. Plot of derived peak optical depth in the $3\ \mu\text{m}$ feature (τ_{max}) against visual extinction (A_v). The best fit straight line for the Elias sources is shown.

sources alone (for reasons given below), the linear fit is exceptionally good, giving

$$\tau_{\text{max}} \begin{cases} = 0 & A_v < (A_v)_0 \\ = \alpha (A_v - (A_v)_0) & A_v \geq (A_v)_0 \end{cases}$$

where $\alpha = 0.1$, and the threshold $(A_v)_0 = 3$. Conservatively, we might ascribe the actual threshold of detectability to be $A_v \geq 5$. This latter value is still very small compared to that found in the Ophiuchus cloud ($(A_v)_0 \sim 20$) using data from Whittet and Blades (1980) and Harris et al. (1978). In fact, such a low threshold appears to be unprecedented. The linearity of the fit also suggests that our assumption of a non-circumstellar origin of the feature is correct. We may note that earlier eye fits of the continuum produced far more scatter in this diagram.

Fig. 4. Observed feature profiles for (a) HL Tau and (b) Elias 16 compared to theoretical extinction curves for silicate core/amorphous water ice mantle grains (solid curves). Insets show difference curves illustrating the long wavelength wing. The discrepancy between model and observations for Elias 16 at short wavelengths is due to CO absorption not accounted for in the comparison spectrum.

In figures 4(a) and 4(b), the reduced feature profiles for HL Tau and Elias 16 are shown, the latter being representative of the profiles of all the Elias sources. Solid lines are the derived profiles from Mie theory computations using silicate cores (radius $a_0 = 0.2 \mu\text{m}$ and wavelength independent refractive index $m = 1.6 + 0.00i$) with amorphous water ice mantles (outer radius a , $a/a_0 = 1.1$, refractive indices from Lager et al., 1979).

For HL Tau, the fit is particularly good in the 2.9-3.1 μm region where even the asymmetry of the profile is reproduced. For Elias 16, the fit is much poorer, mainly because the profile is more symmetric, and λ_{max} is shifted to shorter wavelengths. The mismatch in the 2.3-2.5 μm region is due to CO absorption not accounted for in the comparison star spectrum. In both profiles, the long wavelength (3.2-3.8 μm) wing is left as a residual. Many combinations of grain sizes and core-mantle ratios were tried, as were crystalline ice

mantles, to alleviate these discrepancies, but without improving the fit.

There are several ways in which HL Tau differs from the Elias objects. Firstly, it is spatially well separated from them, being approximately 8° away. Secondly, as we have seen, its feature profile is rather different. Finally, it lies well above the Elias objects on the $A_V - \tau_{\text{max}}$ diagram. Cohen (1983) has suggested that the ice feature in HL Tau actually arises from grains in the circumstellar shell of this young object. If so, one might expect the grains to have undergone a different recent thermal history from their interstellar cousins. In this context it is interesting to note that Lager's amorphous ice measurements were made at $T = 77$ K. Hagen et al. (1983) found that warming amorphous ice deposited initially at 10 K through this temperature narrowed the absorption band, made it less symmetric, and shifted its peak to longer wavelengths. We note that in the general cloud medium one might expect $T < 30$ K, whereas Cohen (1983) finds $40 \text{ K} < T < 130 \text{ K}$ for grains in the "ice zone" of the circumstellar disc of HL Tau. An alternative (though less well defined) explanation is that the chemistry of the cloud may vary spatially, leading to variations in mantle composition for different regions.

The long wavelength wing to the ice feature has always been puzzling and has never been matched satisfactorily using pure ice grains. However, recent work, using water ice mantles with impurities containing C-H bonds, has produced rather better fits to the data (see elsewhere in this volume).

In addition to a marked $3 \mu\text{m}$ feature, the spectrum of Elias 1 shows emission features at 3.29, 3.42 and $3.52 \mu\text{m}$ (figure 1(c)). Whittet et al. (1983) have discussed these and other similar unidentified features as observed in several early type emission line objects.

4. CONCLUSIONS

The carrier of the $3 \mu\text{m}$ absorption feature appears to reside in the general cloud medium of the Taurus molecular clouds, with the possible exception of HL Tau. This carrier is probably amorphous water ice situated as mantles on refractory grain cores. The residual long wavelength wing may be explained in terms of impurities in the mantle material. Differences in feature profile between objects are due either to the different thermal histories, or chemical compositions, of the mantles.

The threshold of shielding from the ambient ultraviolet radiation field for stable ice mantles to be detectable appears to be very low ($A_V \geq 5$). Thereafter, the $3 \mu\text{m}$ feature depth depends linearly on A_V (for the Elias sources). This low threshold is unprecedented, but may be due to the small number of early type stars in this region.

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