TENMICRONSPECTROSCOPY OF YOUNG STARS IN THE \textit{p} OPHEL CLOUD

M.S. Hanner, T.Y. Brooke$^a$

MS 169--237, Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr., Pasadena, CA, 91109

and

A.T. Tokunaga
Institute for Astronomy, University of Hawaii
2680 Woodlawn Dr., Honolulu, HI 96822

$^a$NAS/NRC Resident Research Associate.
ABSTRACT

Spectra in the 10µm region were obtained of 14 young stars associated with the ρ Oph dark cloud. Silicate dust emission and absorption features can be fairly well reproduced with simple models using the emissivity of the silicates in the Orion Trapezium region, believed to be typical of molecular cloud dust. A spectrum of the Trapezium star θ1 Ori D was obtained to define this emissivity more precisely. The emissivity of silicate dust around the late–type giant μ Cep does not improve the fits to the absorption features and provides a poorer match to the emission features. None of the sources display a strong 11.25 µm peak like that seen in comet Halley and attributed to crystalline olivine. A broad shallow feature near 11.25 µm, possibly related to the comet feature, is evident in the emission spectrum of the A star HD 50193. Absorption features toward two of the objects are narrower than would be expected from Trapezium-like silicates, suggesting differences in the composition of the silicates. The relation between the silicate extinction band depth and H2O ice band depths is determined for the deeply embedded objects. One late–type object, Elias14, clearly shows the 11.25 µm aromatic hydrocarbon emission feature, possibly excited by the nearby B star HD147889, though the latter dots not exhibit the feature.
1. INTRODUCTION

Many young stars have silicate dust emission or absorption features at 10 $\mu m$. The spectral shape of the 10 $\mu m$ Si–O band reflects the mineralogy of the silicate.s. Oxygen-rich late-type stars and proto-planetary nebulae show a rich variety of mineralogies indicative of the temperature and pressure conditions in circumstellar regions (e.g. Barlow 1993). It is usually assumed, based on the available spectra, that silicates around young stars have the broad, structureless shape peaking around 9.7 $\mu m$ seen in molecular clouds: the "Trapezium" profile (Gillett et al. 1975; Whittet et al. 1988). The Trapezium emissivity is generally attributed to amorphous silicates (e.g. Day 1974; Dorschner et al. 1988). However, narrower emission features attributed to more crystalline silicates have been reported around a few young stars, such as AB Aur (Cohen and Witteborn 1985).

Silicates in comets, however, appear to have quite different spectral shapes from that of the Trapezium (see Haner et al. 1994 for a review). Comets are believed to have formed in regions of the primitive solar nebula that were cold enough for interstellar grains to have been incorporated directly with little alteration. But a sharp spectral peak at 1 J.2 $\mu m$, attributed to crystalline olivine, has been seen in at least three comets, including P/Halley (Bregman et al. 1987; Campins and Ryan 1989; Haner et al. 1990; Lynch et al. 1992). Could cometary grains have been annealed by heating in the solar nebula during the Sun's T Tauri phase? If so, then one might expect to see evidence of annealing in the silicate dust around young stellar objects. Aitken et al. (1988) reported a weak 11.2 $\mu m$ feature in absorption along the line of sight to Gl 2591 which they attributed to crystalline silicates.
The current generation of infrared array spectrometers makes it possible to determine the spectral shapes of the silicate features of young stars with improved sensitivity and spectral resolution over previous ground-based surveys (e.g. Cohen and Witteborn 1985) and IRAS 1.25RS spectra.

The nearby ρ Ophiuchus cloud contains numerous young stellar objects, including precursors of solar mass stars (e.g. Lada and Wilking 1984), making it an ideal region to conduct a survey. In this paper we report observations of 14 objects in the central core of the ρ Oph cloud, selected from the lists of Elias (1978) and Wilking and Lada (1983). Our primary objective was to determine the spectral shapes of the silicate emission and absorption bands for comparison to cometary silicate emission. We have modelled each spectrum assuming a Trapezium-like emissivity, then search for deviations from this profile. For absorption features, the extinction band depths due to silicates along the line-of-sight were also estimated.

2. OBSERVATIONS

The spectra of the ρ Oph objects were obtained at the United Kingdom Infrared Telescope (UKIRT) on UT 29 May 1991 and 23, 24 June 1992. The 32-element grating spectrometer CGS3 was used in the low resolution mode, giving a spectral resolution of approximately 85. Data were obtained through a 5.5" aperture, usually at two grating positions approximately 1/2 resolution element apart. The sky chopping throw was 15" EW in 1991 and 20" EW in 1992. Wavelength calibration
was determined by observing the emission lines in the planetary nebula NGC 6572; we estimate the uncertainty to be ± 0.03 μm.

Sources were observed at airmass 1.4–2.0. Repeated spectra of β Oph (K2 III) were used to define an atmospheric extinction correction at each wavelength and each source spectrum was corrected to unit airmass. The flux standard was α Ly, assumed to be a 9600 K blackbody with flux $1.17 \times 10^{-11}\text{W m}^{-2}\mu\text{m}^{-1}$ at 10.1 μm (Rieke et al. 1985).

On UT 4 Nov 1993, a spectrum of the Orion Trapezium star $\theta^1$ Ori D was obtained with CGS3 at the same resolution. A 9.4" aperture was used. This region contains extended 10 μm emission (e.g. Gehrz et al. 1975). The sky chopping throw was set to 90° EW to minimize contamination in the reference beam. The airmass standard was α Tau; the flux standard was α CMa, assumed to be a 10000 K blackbody with flux $4.33 \times 10^{-12}\text{W m}^{-2}\mu\text{m}^{-1}$ at 10.1 μm.

The sources are listed in Table 1 and their spectra are plotted in Figs. 1-4. An additional object, W 16, is described in Hanner, Tokunaga, and Geballe (1992). For objects with fluxes $< 10^{-13}\text{W m}^{-2}\mu\text{m}^{-1}$ the spectra were smoothed with a triangle function of FWHM = 0.2 μm to improve the signal-to-noise ratio. The effective resolution of these spectra is $\approx 0.28\mu\text{m}$.

3. A NEW TRAPEZIUM EMISSIVITY SPECTRUM

Interstellar silicate features are often compared to the "Trapezium" emissivity obtained from a spectrum of the strong silicate emission feature in the Orion Trapezium region by assuming optically thin emission at a single temperature,
250 K (Forrest et al. 1975; Gillett et al. 1975). To define this emissivity more precisely, we observed the Trapezium star \( \theta^1 \) Ori as described above. The data are shown in Fig. 1a.

The overall shape of the \( \theta^1 \) Ori spectrum matches the Forrest et al. data reasonably well. However, forbidden lines of Ar III at 8.99 pm, S IV at 10.51 \( \mu \)m and Ne II at 12.81 pm, and an emission feature at 11.25 \( \mu \)m can be seen in our spectrum at spectral resolution \( R \sim 55 \). A spectrum of this feature taken with CGS3 at a resolution of \( \sim 190 \) shows it to have the characteristic width and shape of the 11.25 \( \mu \)m aromatic hydrocarbon emission feature. We removed the forbidden lines by linear interpolation. To remove the contribution of the hydrocarbon bands at 7.7, 8.6, and 11.25 \( \mu \)m, we assumed that their spectral shape was the same as that seen in the Orion bar (Bregman et al. 1989; Roche et al. 1989), scaled to fit the Trapezium flux near 11.25 pm, as shown in Fig. 1a.

The resulting relative emissivity obtained by subtracting the features and dividing by a 250 K blackbody is shown in Fig. 1b. This profile is similar to the broad, structureless silicate emission feature given by Gillett et al. (1975). Possible structure between 9.7 and 10 \( \mu \)m is uncertain due to the possibility of incomplete correction for the strong telluric ozone absorption in this region. We compare the new Trapezium emissivity to the spectra of the \( \rho \) Oph objects, in the following section.

4. MODEL FITS TO THE SPECTRA

Determining the spectral emissivity of the silicates from observations requires knowing the optical depths of all of the dust components which contribute to the 10
\(\mu m\) spectrum. This is a difficult challenge, beyond the scope of this paper, requiring knowledge of the densities, temperatures, and dust geometries (e.g. disks or spherical envelopes) around each object. It is clear, for example, that the silicate emission features of Fig. 2 are not due solely to optically thin emission from Trapezium-like silicates, since the feature contrasts are lower than that of Fig. 1b. Dilution by featureless emission or optical depth effects could account for the lower contrast.

Accordingly, we have taken the approach of applying simple models to test how well each spectrum can be reproduced by assuming that the grains producing the feature have the Trapezium emissivity, \(e_1(\lambda)\), given in Fig. 1b. We modeled the spectra in four limiting cases described below. The underlying continuum emission in each source was assumed to follow a power law in wavelength. The use of power laws rather than single-temperature blackbodies is motivated by the success of models which include grains at a range of temperatures to match the spectral energy distributions of young stars (e.g. Adams et al. 1987; Hillenbrand et al. 1993). The models given here do not incorporate any specific geometries for the dust; more detailed modeling of the entire spectral energy distributions would be required to constrain the dust spatial distributions. The goal here is to see whether some simple modeling can reproduce the observed range of 8–13 \(\mu m\) spectra with a given emissivity.

Emission features were modelled with cases 1–3 and absorption features with cases 3 and 4, described below. For each spectrum, a least squares minimization was performed to determine best-fit values for the parameters: i.e. the optical depths, spectral indices, and normalization factors.
Case 1 -- Variable optical depth (after Cohen and Witteborn 1985)

$$\lambda F_\lambda = a_0(\frac{\lambda}{9.7})^m (1 - e^{-\tau_{9.7}})$$  \hspace{1cm} (1)

With $\epsilon_1(\lambda)$ normalized at 9.7 $\mu$m, the parameter $a_1$ is the total silicate optical depth at 9.7 $\mu$m, $\tau_{9.7}$. This slab model approximates a dusty envelope, which both emits and absorbs at 10 $\mu$m.

Case 2 -- Two component: Optically thick + optically thin emission

$$\lambda F_\lambda = a_0(\frac{\lambda}{9.7})^m + a_2(\frac{\lambda}{9.7})^m \epsilon_1(\lambda)$$  \hspace{1cm} (2)

The quantity $f = a_2/(a_0 + a_2)$ is the relative contribution of the optically thin grains to the flux at 9.7 $\mu$m. This model might apply, for example, to an optically thin envelope and an optically thick disk (or the star itself), both of which both contribute to the flux at 10 $\mu$m. The optically thick component could alternatively represent emission from featureless dust.

Case 3 -- Optically thin with line of sight extinction (after Gillett et al. 1975)

$$\lambda F_\lambda = a_0(\frac{\lambda}{9.7})^m \epsilon_1(\lambda)e^{-\tau_{9.7}(\lambda)}$$  \hspace{1cm} (3)

The parameter $a_1$ is equal to the total line of sight extinction at 9.7 pm, $\tau_{9.7}$. Note,
that both the emitting and the absorbing groins are assumed to have the Trapezium emissivity. This equation might apply to an optically thin circumstellar envelope obscured by cold dust along the line of sight.

Case 4 - Optically thick with line of sight extinction

\[ \lambda F_\lambda = a_0 (\frac{\lambda}{9.7})^\alpha e^{-a_1 \tau_\lambda} \]  

The parameter \( a_1 \) is the total line of sight extinction at 9.7 \( \mu \text{m}, \tau_{9.7} \). This equation might apply to an optically thick disk or envelope (or the star itself) obscured by cold dust.

The best-fit parameters for each case are given in Tables 2 and 3 and the fits plotted in Figs. 2 and 3. Fits to the emission features with case 3 were very similar to those of case 1 and are not plotted.

The silicate optical depths derived under case 3 refer to the extinction by cold (non-emitting) dust along the line of sight. If the extinction is interstellar, so that the extinction of the star and the dust envelope are the same, then it is likely that the derived optical depths are too high, given the estimated visual extinctions, \( A_v \), to these stars. For an extinction law typical of dust in the solar neighborhood, \( A_v/\tau_{9.7} = 18.5 \) (Roche and Aitken 1984), the required \( A_v \) values for \( \text{IIID}150193, \text{IIias} \) 28, and \( \text{IIias13} \) under case 3 would be 9.6, 13, and 19, respectively, compared to previously estimated values of 1.8, 4.5, and 2.2 (Iillenbrand et al. 1993; Cohen and Kuhi 1979; Bouvier and Appenzeller 1992). Although the extinction laws to
These stars are not known precisely, this tends to favor either model 1 or 2 to explain the observed emission features. For model 1 to avoid the same objection as model 3, the geometry must be such that the extinction of the star is only a small fraction of the extinction in the dust envelope.

The main issue is that all of the silicate features can be fairly well matched by the Trapezium emissivity using one or more models, with some possible deviations noted below. For the emission features, adoption of a variable optical depth (e.g., Cohen and Witteborn 1985) is not necessarily required. Such a model does reproduce the III 1S0193 spectrum well, but a two-component model provides a comparably good fit to Elias 28. Thus, the observed contrast in the silicate emission feature does not necessarily provide a direct measure of the silicate optical depth, since an optically thick component will lower the contrast.

For the absorption features, the optically thick model with extinction (case 4) reproduced the data fairly well. Optically thin emission with extinction (case 3) improves the fit at the bottom of the band in all cases (especially W1 12, Elias 21) but requires the flux to drop sharply at 8 μm, which is not consistent with the data. This is because the exponential extinction affects the wavelengths near the peak of the band more strongly than the wings. Gillett et al. (1975) found that including optically thin emission did improve the fits to the silicate absorption features toward deeply embedded II regions.

We also investigated whether the narrower, more symmetric, silicate emissivity seen around the late-type giant μ Cep (Roche and Aitken 1984) would provide better fits to the young stars. Roche and Aitken suggested that silicate dust in the
diffuse interstellar medium is more consistent with the \( \mu \) Cep emissivity. We found that the agreement was never better than the Trapezium models. For the strong emission features in \( \text{HD} \) 150193 and \( \text{Elias} \) 28, models with the \( \mu \) Cep profile were significantly worse. (e.g. Fig. 5a). For the absorption features, no reasonable fits could be found using the \( \mu \) Cep profile. with case 3; fits using case 4 were generally of comparable quality to those obtained with the Trapezium emissivity (e.g. Fig. 5b). Whittet et al. (1988) found that the Trapezium gave a better match than \( \mu \) Cep to silicate emission and absorption features in the region of the Taurus dark cloud.

Thus the silicates along the lines of sight to these young stars in the \( \rho \) Oph cloud generally appear to be similar to Trapezium silicates. With the possible exceptions discussed below, there does not appear to be structure, in the silicate spectra in particular, none of the spectra show a prominent 11.2 \( \mu \)m feature similar to that observed in Comet Halley and attributed to crystalline olivine (Bregman et al. 1987; Campins and Ryan 1989). This implies either that substantial thermal annealing of the silicates has not yet occurred in the cloud, that, if thermal annealing has taken place close to the stars, the annealed grains are concealed by optically thick shells.

5. DEVIATIONS FROM THE TRAPEZIUM EMISSIVITY

5.1 \( \text{HD} \) 150193

Although none of cmr sources display a strong 11.2 \( \mu \)m peak like that seen in Comet Halley, excess emission near 11.25 \( \mu \)m at the 10 percent level is evident on the wing of the strong emission feature in the Ae star \( \text{HD} \) 150193. A similar emission feature at 11.25 \( \mu \)m may be present in \( \text{Elias} \) 28 and \( \text{Elias} \) 13 but the lower
signal/noise. in these spectra makes its reality uncertain. For 1111150193, the feature appears to be broader than the typical aromatic hydrocarbon emission band at 11.25 μm (FWHM - 0.2 - 0.4 μm; Witteborn et al. 1989; Roche et al. 1991) and there is no evidence of emission from the related hydrocarbon 8.6 μm feature or the wing of the 7.7 μm feature. Yet HD150193 is a Herbig Ae/Be star (Finkenzeller and Mundt 1984) and it is not unusual for such stars to exhibit emission from the hydrocarbon bands (Brooke et al. 1993). Brooke et al. (1993) did not detect the aromatic 3.29 μm feature in HD 150193 and placed an upper limit to the 3.29 μm feature flux of 0.8 x 10^{-15} W m^{-2}. Based on a typical flux ratio of the 11.25/3.29 bands of -2.4 (Puget and Leger 1989), the 11.25 μm aromatic emission could contribute, at most, only about half of the excess flux at 11.25 μm, although this flux ratio varies substantially from object to object (Cohen et al. 1989). Observations at higher spectral resolution are needed to clarify the possible contribution of aromatics and better define any new silicate feature in HD 150193.

There is a dip near 9.8 μm in the spectrum of 111>150193, producing an apparent maximum in the silicate emissivity at around 9.4 μm. No strong aromatic features lie in this region. The dip occurs in the region of strong telluric ozone absorption but, if real, the peak at 9.4 μm could indicate a compositional difference in the silicates around this star.

5.2 Absorption Features

There appear to be significant deviations from the Trapezium emissivity in two of the absorption sources; both L[ia]s2.1 and W] 12 require a silicate emissivity that
is narrower than that of the Trapezium. To illustrate this, the parameters for the Case 4 fits were used to invert the data and obtain new relative emissivity profiles. This procedure is valid as long as the true emissivities do not differ greatly from the Trapezium emissivity and the model assumptions are correct. The derived emissivities normalized roughly to the ir peaks are shown with the Trapezium emissivity normalized in the same way in Fig. 6. Elias 2.1 and WL 12 have similar profiles that are lower than the Trapezium on the long wavelength side. This narrower profile could indicate differences in the composition of the silicates. These two objects have the coolest dust continuum emission of any sources in our sample. The wavelength of maximum and the width of the central part of the feature are similar to the μCep emissivity although the wings differ.

Cohen & Witteborn (1985) concluded that a few young stars, such as the Herbig Ae/Be star AB Aur, had silicate emission features narrower than expected from the Trapezium emissivity; they attributed this to more crystalline silicates. In contrast to Elias 21 and WJ, 12, AB Aur matches the Trapezium on the long wavelength side, but requires a narrower emissivity on the short wavelength side, so different materials appear to be involved.

Both crystalline and amorphous silicates can differ in the width and the wavelength of maximum of their 10 μm spectral feature. (see discussion in Hanner et al. 1994). Amorphous olivine (e.g. Stephens and Russell 1979) and amorphous pyroxenes (e.g. Dorschner et al. 1988) have both been suggested as plausible candidates to explain the Trapezium emissivity, the pyroxenes tending to peak at shorter wavelengths compared to olivine (see also Day 1979; Krätschmer and
Numbe of the samples measured in these papers displays a 10 μm feature wide enough to explain the Trapezium emissivity by itself, assuming grain radii < 0.5 μm. Some of the amorphous materials do have features wide enough to match a narrower feature like those seen toward Elias 21, W1, 12 or AB Aur, though we have not found a precise spectral match. Koike and Hayasegawa (1987) suggest that the width of the 10 μm feature in amorphous silicates is correlated with the SiO₂ content, with higher SiO₂ content leading to progressively narrower features peaking at shorter wavelengths. Thus compositional differences within amorphous silicates may be sufficient to explain the deviations from the Trapezium emissivity seen in a few young stars, without the need for invoking a higher degree of crystallinity.

A change in the mean particle size can also affect the width of the 10 μm silicate feature; larger particles cause the feature to broaden on the long wavelength side. This effect is significant for particles with radii ≥ 0.75 pm, larger than the canonical value for interstellar grains (Draine and Lee 1984). Note also that the grains in the Trapezium would have to be the larger ones.

6. SILICATE ANI> H₂O ICE BAND DEPTHS

Our models provide estimates of the extinction due to silicate grains toward the young stars in the ρ Oph cloud under different assumptions. The extinction due to silicates can be compared to the extinction at other wavelengths to determine the broad optical properties of the grains along the line of sight. Values of the total visual extinction, A_v, are difficult to estimate for the deeply embedded objects.
These objects do exhibit $3\mu m$ $\text{H}_2\text{O ice}$ absorption bands, however. Thus we limit the discussion to a comparison of the silicate and $\text{H}_2\text{O ice}$ band depths.

A major uncertainty in the estimation of the silicate band extinction depths towards the embedded sources is the possibility of intrinsic silicate emission in the sources. Our two models give good upper and lower limits to the extinction, in the limit that the intrinsic emission is optically thin (case 3), the derived optical depths are greater by -2, compared to the optically thick model (case 4). As discussed above, the model which included optically thin emission did not in general provide better fits to the spectra compared to the model with extinction only, (see Fig. 2 and Table 3). Also, if there were optically thin emission, the extinction were interstellar (so that the star suffers the same extinction as the emitting dust), and the extinction law were similar to that in the solar neighborhood, $A_V/\tau_{9.7} = 18.5$ (Roche and Aitken 1984), then the implied $A_V$ values for the visible stars Elias 22, Elias 30, Elias 16, and 111>147889 would be extremely high: 31, 44, 27, and 42 mag, respectively, compared to previously estimated values for these stars of 6.6, 5.0, 6.2, and 4.6 mag (Bouvier and Appenzeller 1992; Adams et al. 1987; Elias 1978). The implied $A_V$ values for the optically thick case are closer to the literature values, though only upper limits can be obtained for Elias 22 and Elias 16. For these reasons, we will assume in this section that there is no significant silicate emission in the embedded sources.

Figure 7 shows the $\text{H}_2\text{O ice}$ band optical depth, $\tau_{3.08}$ from Tanaka et al. (1990), plotted against the silicate band optical depth for the $p$ Oph sources in which both
features were detected. There is rough correlation, though with considerable scatter; a formal weighted fit gives:

\[ \tau_{3.08} = 1.06 \pm 0.04(\tau_{9.7} - 0.004 \pm 0.021). \]  \hspace{1cm} (5)

It would be useful to compare this relation to the results for embedded young stars in other clouds. The slope is a measure of the extent of ice mantling on grains; a negative, intercept could indicate an extinction threshold above which \( \text{H}_2\text{O} \) ice is shielded from destruction by the interstellar or circumstellar radiation field (cf Whitten et al. 1988). Whitten et al. obtained ice and silicate optical depths for four embedded young stars in the Taurus cloud assuming no intrinsic silicate emission in the sources, but the data show too much scatter to define any clear relation at this time. They also obtained data for field stars behind the Taurus cloud, but there is at this time insufficient data to say definitively whether the \( \tau_{3.08} \) vs. \( \tau_{9.7} \) relation for the \( \rho \) Oph embedded objects is significantly different from the relation for the Taurus field stars.

Note that even a small amount of intrinsic emission would tend to shift the points to the right on Fig. 7, rendering conclusions about the slope and threshold of the \( \tau_{3.08} \) vs. \( \tau_{9.7} \) relation somewhat uncertain. Further progress in the determination of this relation for the \( \rho \) Oph cloud will come from better observations of the absorption band depths in background stars free of circumstellar dust.
7. AROMATIC HYDROCARBON EMISSION FEATURES IN ELIAS14

The spectrum of Elias14 is plotted in Fig. 4. An emission peak at 11.25 µm is clearly visible, with a width ~ 0.4 µm, consistent with the 11.25 µm aromatic hydrocarbon feature (see, e.g., Roche et al. 1991). The rising slope near 8 µm is consistent with the presence of the '7.7 µm feature, but the expected 8.6 µm feature, if present at all, is weak. Elias14 is the second young stellar object with strong aromatic emission features we have found in the p Oph cloud; the first was WL 16 (Hanner et al. 1992). Both sources exhibit plateau emission longward of the 11.25 µm feature, but there is no clear evidence for the 12.7 µm feature seen in WL 16 in the Elias 14 spectrum.

The presence of aromatic hydrocarbon emission features in Elias14 is surprising since the spectral type of this object is estimated to be KO (Bouvier and Appenzeller 1993), and the family of aromatic emission features is usually seen in regions of high ultraviolet flux (for a recent review, see Sellgren 1990). Furthermore, the star does not show a significant dust excess in ground-based photometry; the infrared colors up to 10 µm are consistent with a reddened photosphere (Lada and Wilking 1984). However, Elias 14 lies only about 10' away (projected distance 0.5 pc for a distance \( d = 160 \) pc) from the B2 V star HD 147889, and in the region of extended IRAS 12 µm emission excited by this star (Greene and Young 1989). So it seems plausible that the B star excites the feature in the dust around Elias14. Interestingly, HD 147889 itself does not show any evidence of the 11.25 µm feature (Fig. 2), perhaps due to destruction or dehydrogenation of the aromatics near the star.
Two stars with silicate absorption features (Elias 23 and Elias 30) also appear to have some excess emission at 11.25 μm, though the cancellation of the sky background is poor in each case. Elias 23 also lies in the region of strong 12 μm emission around 1 ID 147889 (as does Elias 21); Elias 30 lies just outside this region. Both are classified as KO (Bouvier and Appenzeller 1993; Chini 1981).

8. CONCLUSIONS

1. Silicate emission and absorption features toward young stars in the ρ Oph cloud can be fairly well represented by the Trapezium silicate dust emissivity common in molecular clouds using simple models. This indicates that substantial thermal annealing of the silicates along the lines of sight has not occurred. If thermal annealing has taken place close to the stars, spectral signatures of the annealed grains are masked by optically thick shells. The emissivity of the dust around the late-type giant υ Cep does not provide significantly better fits to the absorption sources and provides a poorer match to the emission sources.

2. There are possible deviations from the Trapezium emissivity in some objects, which could indicate differences in silicate composition. The strong silicate emission feature in the Herbig Ae/Be star HD1 50193 shows deviations at the 10% level from the Trapezium emissivity at 9.4–10 μm and near 11.25 μm. Narrower silicate features are seen in absorption toward two objects, Elias 21 and W1-12.

3. Silicate extinction band depths were estimated for the deeply embedded sources. The slope of the $\tau_{3.08}$ vs. $\tau_{9.7}$ relation was estimated (assuming no intrinsic silicate emission in the sources).
4. At least one KO star in the cloud Elias 14, shows the 11.25 μm emission feature due to aromatic hydrocarbons, probably excited by the nearby B2 V star, HD 147889.

ACKNOWLEDGEMENTS

We thank the staff of the [JK11{1'1' and Joint Astronomy Centre for their support. UKIRT] is operated by the Royal Observatory Edinburgh on behalf of the U.K. Science and Engineering Research Council. A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration. A. Tokunaga acknowledges support of NASA Grant NAGW–2278. T. Brooke acknowledges a postdoctoral fellowship from the National Research Council.
REFERENCES


FIGURE CAPTIONS

Fig. 1 – (a) Spectra of the Orion Trapezium star $\theta^1$ Ori D obtained with the UKIRT CGS3 low resolution grating through a 9.4” aperture. Dashed line is the scaled Orion bar aromatic hydrocarbon spectrum. (b) Relative emissivity found by linearly interpolating under the emission features, subtracting the component due to aromatic hydrocarbons, and dividing by a 250 K blackbody. The relative emissivity has been smoothed by a triangle function of $FWHM = 0.2 \mu m$ and normalized at 9.7 $\mu m$.

Fig. 2(a – c) – Spectra of $\rho$ Oph sources with silicate emission features obtained with the UKIRT CGS3 low resolution grating through a 5.5” aperture. Model fits are described in the text.

Fig. 3(a – j) – Spectra of $\rho$ Oph sources with silicate absorption features obtained with the UKIRT CGS3 low resolution grating through a 5.5” aperture. Model fits are described in the text.

Fig. 4 – Spectrum of Elias 14 in the $\rho$ Oph cloud obtained with the UKIRT CGS3 low resolution grating in 1992 through a 5.5” aperture.

Fig. 5– (a) Fits to HD 150193 using the $\mu$ Cep emissivity profile. (b) Fit to Elias 21 using the $\mu$ Cep emissivity profile.

Fig. 6– Resulting emissivities of Elias 21 and WI, 12 after inverting a fit with extinction only (case 4). The emissivities have been normalized roughly to their peaks.

Fig. 7– $H_2O$ ice band optical depths from Tanaka et al. (1990) plotted against silicate absorption band depths for deeply embedded $\rho$ Oph sources, assuming no intrinsic silicate emission. Dashed line is the best least squares fit.
### TABLE 1

Log of the Observations

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<td>Two component</td>
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<td>(0.06)</td>
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<tr>
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<td>(0.1)</td>
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*Errors in parentheses.

$^b$Units are $10^{-3}$ Wm$^{-2}$. 
TABLE 3
Fit Parameters for $\rho$ Oph Absorption Features

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*Units are $10^{-5}$ Wm$^{-2}$. 
Elias 13

Flux (10^{-13} \text{ W m}^{-2} \text{ \mu m}^{-1})

Wavelength (\mu m)

Fig. 2c
Fig. 3d
Wavelength (pm)

Flux (10^{-13} Wm^{-2}\mu m^{-1})

Elias 14
**HD 150193**

- Case 1 - Variable
- Case 2 - Two components

**μ Cep Profile**

**Elias 21**

- Case 4 - Thick with ext.
Fig. 6

Elias 21

W.L 12

Trapezium

Relative emissivity

wavelength (μm)