IDENTIFICATION OF THE EMISSION FEATURES NEAR 3.5 MICRONS IN THE
PRE-MAIN-SEQUENCE STAR HD 97048

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ABSTRACT

The spectrum of HD 97048 has been measured with a resolving power of 450 between 3.37 and
3.64 μm. The prominent feature near 3.5 μm, discovered by Blades and Whittet, is well resolved, with
a peak at 3.53 μm and a wing extending to shorter wavelength. The weaker feature near 3.4 μm
is found to peak at 3.43 μm, in contrast to the 3.40 μm feature seen in other astronomical objects.
The observed spectrum strongly resembles laboratory spectra of mixtures of monomeric and dimeric
formaldehyde embedded in low-temperature solids. Of various possible excitation mechanisms,
ultraviolet pumped infrared fluorescence of formaldehyde in interstellar grains provides the best
explanation for the observed spectrum of HD 97048.

Subject headings: infrared: spectra — interstellar: molecules — stars: individual —
stars: pre-main-sequence

I. INTRODUCTION

Attention was drawn to HD 97048, a likely pre-main-
sequence star in the Chamaeleon T Association, by Blades
and Whittet (1980), who measured its 3–4 μm spectrum
at a resolving power of ∼50 and discovered a bright and
broad emission feature near 3.5 μm. Although many
astronomical objects display mid-infrared emission
features, probably due to vibrational bands of molecules
bound in grains (see review by Aitken 1981), the 3.5 μm
emission feature appears to be quite rare. Allen et al.
(1982) have made a survey of 56 emission-line stars and
stellar planetary nebulae and have detected 3.5 μm
emission only from HD 97048 and Elias 1.

HD 97048 has a spectral type of B9–A0 Ve and
illuminates a reflection nebula in the Chamaeleon dark
cloud at a distance of ∼150 pc from the Sun. Variable
hydrogen line emission (Irvine and Houk 1977) and an
infrared excess (Grasdalen et al. 1975) both indicate that
it is losing mass. In addition to the unusual 3.5 μm
feature, HD 97048 shows emission features near 3.3, 3.4,
and 11.3 μm (Blades and Whittet 1980; Aitken and
Roche 1981), which are among those seen in other
astronomical objects. The 3.3 and 11.3 μm features have
an intensity ratio like that seen elsewhere, but whereas
other objects have a weak 3.4 μm feature associated with
that at 3.3 μm, the intensity ratio of these features is
reversed in HD 97048. This suggests an additional
contribution near 3.4 μm, perhaps from the same species
which is responsible for the 3.5 μm feature.

Blades and Whittet suggested that the 3.4 and 3.5 μm
features in HD 97048 could be due to formaldehyde
(H₂CO) or polyoxymethylene (n-H₂CO). Aitken and
Roche showed that the ultraviolet fluorescence
mechanism of Allamandola and Norman (1978) could
explain the 3.4 and 3.5 μm emission if 20% of the ultra-
 violet photons emitted by the star shortward of 200 nm
resulted in fluorescence in these bands. They were able to
rule out polyoxymethylene, however, because of the lack
of an expected strong feature near 9 μm, and on this basis
condemned the 3.4 and 3.5 μm bands “to join the ranks
of the unidentified.”

In this paper, we present new spectroscopic observa-
tions of HD 97048 which resolve the 3.4 and 3.5 μm
features. Comparison of these observations with
laboratory spectra lends further support to their identifi-
cation with H₂CO. We also show that the existence of
these features in this particular object is better explained
by the ultraviolet-pumped fluorescence model of
Allamandola and Norman (1978) than by the bimodal
grain size model of Dwé et al. (1980).

II. OBSERVATIONS AND RESULTS

In order to better determine the profiles of the infrared
emission features in HD 97048, we observed the source
at higher spectral resolution than has been reported to
date. The observations were carried out on the 2.5 μm
du Pont telescope at Las Campanas Observatory, using
the 1–5 μm grating spectrometer described by Persson,
Geballe, and Baas (1982). The instrument was set up to
give a spectral resolving power of 450 at 3.5 μm; this
corresponds to a resolution of 6.3 cm⁻¹ or 0.0078 μm.
Standard infrared chopping and beam-switching

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techniques were used; the entrance aperture was 8" in diameter, and the throw was 60". HD 97048 was observed in 1981 April and again in 1982 May. It was observed on several nights in 1981; the best pair of spectra are presented here. Two pairs of scans were measured in 1982. In order to correct for atmospheric absorption and to divide out the system response, we have ratioed the observed spectrum of HD 97048 to that of the nearby star γ Cha (M0 III) which was observed through a similar air mass. At our spectral resolution, the atmospheric features in the γ Cha spectrum are between 15% and 25% deep, so we expect uncertainties due to residual atmospheric features to be no greater than 5%.

The spectra of HD 97048, ratioed to those of γ Cha, are shown in Figure 1. Other than an apparent overall decrease in flux in 1982, which is within our calibration uncertainties, the two spectra are virtually identical. The peaks of the two emission features occur at 3.53 μm and 3.43 μm. The brighter feature at 3.53 μm has a full width at half-maximum of about 0.035 μm and an asymmetric profile with a tail extending to shorter wavelengths. The dropoff from the peak to longer wavelengths is steep but resolved. The shorter wavelength feature is centered at 3.42 μm, and has distinct peaks at 3.41 μm and 3.43 μm. The 3.4 μm feature was identified by Blades and Whittet with the 3.4 μm feature seen in NGC 7027 and other sources. Aitken and Roche called attention to the unusual strength of the 3.4 μm feature in HD 97048, however; it is considerably brighter than the 3.3 μm feature—a situation reversed from that observed elsewhere, for example in NGC 7027. In addition, both grating spectra (Grasdalen and Joyce 1976b) and FTS spectra (Tokunaga and Young 1980) obtained at resolutions comparable to ours (10 cm⁻¹ and 4 cm⁻¹, respectively, compared to our 6.3 cm⁻¹) show clearly that the feature in NGC 7027 is centered at 3.40 μm, and has no peak at 3.43 μm. It appears that the 3.40 μm feature, seen in conjunction with a 3.28 μm feature in many objects, contributes only a small part of the flux near 3.4 μm in HD 97048. A weak shoulder does appear at 3.40 μm in Figure 1; this may be the usual 3.40 μm feature.

Comparison of the spectra in Figure 1 with that published by Aitken and Roche (1981) reveals two interesting anomalies (see Table 1). First, the equivalent widths of both features are higher in the Aitken and Roche data than in ours. Second, the ratio of the strength of the 3.4 μm feature to that of the 3.5 μm feature is considerably larger in the Aitken and Roche data. It would appear that the intensities of these features varied between 1980 January and 1981 April. However, the equivalent widths in Blades and Whittet’s spectrum agree well with our results, and we observed no change in the equivalent widths between 1981 and 1982. We also made spatial scans of HD 97048 in 1982 to test whether extended emission could cause the equivalent widths to be aperture dependent. No evidence of extension was seen, limiting the source size to less than 2° FWHM. Although we cannot be sure of the explanation for the discrepancy in measured equivalent widths, we note that there are six strong atmospheric absorption features

![Graph](image)

**FIG. 1.—** The 3.37 to 3.64 μm spectrum of HD 97048 ratioed to that of γ Cha, as observed with a spectral resolution Δλ of 0.0078 μm (λ/Δλ = 450). The 1981 spectrum was sampled at 0.002 μm intervals, the 1982 spectrum at 0.004 μm intervals.

**TABLE 1**

<table>
<thead>
<tr>
<th>Date</th>
<th>w₃ (3.4) (μm)</th>
<th>w₃ (3.5) (μm)</th>
<th>w₄ (3.4)/w₄ (3.5)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979 Mar</td>
<td>0.06</td>
<td>0.10</td>
<td>0.6</td>
<td>Blades and Whittet</td>
</tr>
<tr>
<td>1980 Jan</td>
<td>0.12</td>
<td>0.145</td>
<td>0.8</td>
<td>Aitken and Roche</td>
</tr>
<tr>
<td>1981 Apr</td>
<td>0.06</td>
<td>0.115</td>
<td>0.5</td>
<td>This paper</td>
</tr>
</tbody>
</table>
across the 3.4 µm feature and none near 3.5 µm. If a part of the 3.4 µm feature were due to a narrow emission line, it could vary in intensity with the hydrogen lines or could move in and out of an atmospheric absorption feature with the Earth’s motion or with atmospheric variations.

III. IDENTIFICATION OF THE FEATURES

On the basis of the wavelength coincidence alone, Blades and Whittet (1980) suggested that the 3.4 and 3.5 µm features in HD 97048 could be due to formaldehyde bound to grains. The higher resolution spectra presented here allow a more detailed comparison with laboratory spectra. Because the 3 µm vibrational bands of H₂CO bound in a solid show similar infrared and Raman spectra, either type of spectrum can be used for comparison with the astronomical observations. Raman spectra of the ν₁ and ν₄ functional modes of H₂CO (symmetric and antisymmetric C–H stretch, respectively) embedded in argon and nitrogen matrices at 22 K have been obtained by Khoshkhou and Nixon (1973). Two representative spectra are shown in Figure 2. The peaks labeled M and D are due to formaldehyde monomers and dimers, respectively, and vary in relative intensity with the formaldehyde concentration in the samples. The laboratory spectra are very similar to those of HD 97048, supporting the identification of the 3.5 and 3.4 µm features with H₂CO. If this identification is correct, the wing on the blue side of the 3.5 µm feature would be due to dimers and possibly other complexes of H₂CO. The structure in the 3.4 µm peak could also be due to monomeric and dimeric H₂CO.

Laboratory absorption studies by one of us (L. J. A.) have failed to find any other astrophysically plausible molecule with a pair of bands near 3.4 and 3.5 µm. C–H stretching bands of non-aldheydic molecules generally occur at shorter wavelengths. It is also significant that infrared spectra of frozen mixtures of H₂O, CO, CH₄, and NH₃ in the laboratory (by L. J. A. and F. B.) after photolysis by vacuum ultraviolet light have shown that a significant fraction (up to 10%) of the original mixture was converted into H₂CO and that the H₂CO was not readily photodissociated. These facts, coupled with the relative simplicity and known astrophysical presence of H₂CO, further support our identification of the features in HD 97048.

Two differences between the laboratory and astronomical spectra are apparent and must be explained. First, both features are seen at higher frequency in the astronomical spectra; the stronger feature is shifted by 33 cm⁻¹. This shift is relatively small (1% of the band energy) and could be due to interaction of the H₂CO molecule with adjacent molecules in the grain. Observations of a shift of about one-half the required amount as a result of hydrogen bonding to H₂O (see Table 2) indicate that a 33 cm⁻¹ shift is not unreasonable. The ν₁ and ν₄ bands of associated H₂CO are in fact shifted by almost the required amount (Harvey and Ogilvie 1962; see Table 2) from those of gaseous H₂CO.

We note here a distinction between polymerized formaldehyde (polyoxyethylene or n-H₂CO) and associated formaldehyde. Polymerization of formalde-
TABLE 2
H₂CO BAND FREQUENCIES IN SOLIDS

<table>
<thead>
<tr>
<th>MONOMER⁺</th>
<th>H₂CO: H₂O⁻</th>
<th>DIMER⁺</th>
<th>ASSOCIATED⁻</th>
<th>HD 97048⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>Ar</td>
<td>N₂</td>
<td>Ar</td>
<td>Ar</td>
</tr>
<tr>
<td>2782</td>
<td>2797</td>
<td>2800</td>
<td>2817</td>
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<tr>
<td>2843</td>
<td>2865</td>
<td>2884</td>
<td>2873</td>
<td>2885</td>
</tr>
</tbody>
</table>

⁻ Nelander 1980.
⁻⁺ Harvey and Ogilvie 1962.
⁴ This paper.

monomeric H₂CO (Khoshkoo and Nixon). This evidence is not conclusive, however, as an 8.6 μm feature is seen in other objects which lack the 3.53 and 3.43 μm features. A better test of the proposed identification with H₂CO would be observation of the ν₂ C=O stretch band at 5.75 μm, although a nondetection would not necessarily imply the absence of H₂CO if mode-sensitive nonradiative processes play a role in de-excitation of the molecules.

A second difference between the laboratory and astronomical spectra is that the observed spacing between the two peaks in HD 97048 is 80 cm⁻¹, compared with the laboratory splitting of 65 cm⁻¹. Interactions with adjacent grain molecules may also explain this discrepancy, since the different vibrational modes could respond differently to interactions which constrain the formaldehyde molecule. The ν₂ band does shift more than the ν₁ band in being frozen in a matrix (Khoshkoo and Nixon), although the splitting does not change in going from an argon to a nitrogen matrix or to the hydrogen bonded system of H₂O: H₂CO in argon. Alternatively, the 3.4 μm feature in HD 97048 may be due to more than one species. It could, for example, be due to a 3.4 μm feature associated with the 3.28 μm band, a 3.45 μm feature due to H₂CO, and perhaps a third feature centered near 3.43 μm.

The identification of the 3.43 and 3.53 μm features as due to H₂CO would seem unlikely if a 3.5 μm feature which appeared for a short time in two novae (Grasdalen and Joyce 1976a; R. R. Joyce, private communication) were caused by the same species; it is unlikely that the grains flowing out from a nova could be sufficiently cold to allow H₂CO to condense. The spectral resolving power of the Nova Cyg data is high enough, however (Δλ/Δλ ~ 45), that the 3.4 μm feature should have been seen easily; it should have looked much like that in Blades and Whitet’s HD 97048 spectrum taken at a resolving power of 50. There is no evidence for any 3.4 μm feature in the nova spectra, however, indicating that the 3.5 μm feature seen there probably has a different origin from that seen in HD 97048.

IV. EXCITATION MECHANISMS

Two models appear most promising to explain the infrared emission bands generally; the ultraviolet-pumped infrared fluorescence model of Allamandola and Norman (1978) and the bimodal grain size model of Dwek et al. (1980). In the Allamandola and Norman model, ultraviolet light is absorbed by molecules bound in the grains, leaving the molecules vibrationally excited. Some of the vibrationally excited molecules then radiatively decay before the vibrational energy can be distributed among other modes of the grains. Dwek et al. argue that there are not enough ultraviolet photons to account for all of the infrared features, particularly those at the longer wavelengths, ~ 10 μm, which are observed from most astronomical sources showing these emission features. They instead suggest that two grain populations exist. Large, cool grains would account for the infrared absorption bands, whereas small hot grains would account for the emission features. The small grains could absorb ultraviolet radiation efficiently, but would be relatively inefficient at emitting infrared radiation except at resonant frequencies of bound molecules. This hypothesis for the excitation mechanism for the unidentified emission features has recently been criticized by Olofsson (1982), who argues that the observed emission at 3.28 μm in two well studied sources implies a much higher flux in the 10 μm region than has been observed, unless the resonant emitters possess abnormally strong intrinsic band strengths.

Dwek et al. argue that because the 3.5 μm feature is so often associated with the other features it must be excited in the same way. These arguments probably do not apply to the particular case of HD 97048, however. The 3.5 μm feature is nearly unique to this object, so it need not be excited in the same way as the other features. In addition, other aspects of the spectrum of HD 97048 make it difficult to explain the 3.5 μm feature by thermal emission from grains. The infrared excess from HD 97048 is apparently dominated by grains with temperatures of about ~ 800 to 1200 K (Grasdalen et al. 1975; Glass 1979). A considerably cooler grain component is required for the 3.5 μm feature, however, as H₂CO evaporates quickly at ~ 200 K. Since the cool grains which could emit the 3.5 μm feature contribute very little of the 3.5 μm continuum radiation, the feature would have to have an unreasonably large equivalent width in the cool grains.

The ultraviolet-pumped fluorescence model can in principle have the required high quantum yields for conversion of ultraviolet photons into infrared photons, provided that the excited vibrational states do not quickly decay into the phonon modes of the grains. The efficiency of this mechanism is therefore critically dependent on the lifetimes of the excited states. These
lifetimes depend on the strength of the coupling of each mode to the lattice and decrease as the temperature of the grains increases. In this model, mode-dependent nonradiative relaxation processes can account for the weakness of the 9 μm band while the 3.5 μm band remains strong.

The ultraviolet radiation from HD 97048 can be converted efficiently into infrared emission from frozen H₂CO since the radiation from this A0 star peaks near 300 nm while solid H₂CO absorbs over a broad band shortward of 360 nm (McQuigg and Calvert 1969). The total flux emitted shortward of 360 nm is ~1 × 10⁻¹⁴ W cm⁻², a factor of 5 larger than calculated by Aitken and Roche who included only wavelengths shortward of 200 nm. Consequently, the energy conversion factor per H₂CO molecule can be as low as 3 × 10⁻³ to account for the observed 3.4 and 3.5 μm fluxes.

Although the low grain temperatures which are required for H₂CO to remain frozen in grain mantles point to the reflection nebula around HD 97048 as the source of the 3.4 and 3.5 μm emission, our spatial scans of the source at the peak of the 3.5 μm emission feature argue against this interpretation. The emission was observed to be extended over no more than 2', which corresponds to 300 AU, or 1.5 × 10⁻³ pc. To obtain an adequate number of grains in a column of length 300 AU (assuming the emitting column to be no longer than it is wide) would require a cloud density of ≥10⁵ cm⁻³, for a normal gas to dust ratio, and a band oscillator strength of f ≤ 1. As HD 97048 is clearly not embedded in a dense molecular cloud it appears that the emitting grains must be of circumstellar origin. These grains could either have formed in the gas flowing out from the star or be contained in remnant protostellar material. In either case the grains would probably have to be contained within dense condensations in order to be sufficiently cool to allow H₂CO to be bound within their mantles. With no shielding from the stellar radiation, grains at 300 AU from an A0 V star would have temperatures between ~70 and 300 K, depending on their absorption and emission properties. The combined requirements of low grain temperatures and sufficient ultraviolet radiation to excite the H₂CO indicate that emission of the 3.5 μm features must be a temporary phenomenon. Although we know of no unambiguous way to choose among the various origins of the grains, the possibility of dense condensations within a protostellar nebula seems particularly interesting as a likely stage in the formation of a planetary system. Such a short-lived phase would also provide a natural explanation for the rarity of the 3.5 μm feature.

V. CONCLUSION

The 3.4 and 3.5 μm emission features in HD 97048 have been remeasured with a spectral resolving power of 450. The feature profiles, which are now resolved, support the assignment to H₂CO. This assignment and the observed fluxes are difficult to reconcile with the thermally induced resonance radiation model of Dwek et al. On the other hand, it does appear possible to explain the observations by ultraviolet-stimulated infrared emission from H₂CO frozen on grains. This model requires inefficient conversion of vibrational excitation into thermal modes of the grains. Laboratory experiments are now in progress to measure the relative rates of radiative and nonradiative deexcitation of H₂CO and other molecules frozen in solids. The small observed angular extent and required low grain temperatures suggest that the emitting grains are in condensations in circumstellar, and possibly protostellar, material.

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