A Study of Absorption Features in the Three Micron Spectra of Molecular Cloud Sources with H$_2$O Ice Bands

T. Y. Brooke$^1$

Jet Propulsion Laboratory, M/S 169-237, 4800 Oak Grove Dr., Pasadena, CA 91109 USA
e-mail: tyb@scn5.jpl.nasa.gov

K. Sellgren$^1$

Department of Astronomy, Ohio State University, 174 West 18th Av., Columbus, OH 43210 USA
e-mail: sellgren@payne.mps.ohio-state.edu

R. G. Smith

Department of Physics, University College, University of New South Wales, Australian Defence Force Academy, 2600 Canberra, Australia
e-mail: r-smith@adfa.edu.au

$^1$Visiting astronomer at Kitt Peak National Observatory
Abstract

New 3.3–3.6 µm spectra were obtained of nine young stellar objects embedded in molecular clouds. An absorption feature at ∼3.47 µm (2880 cm⁻¹) with FWHM ∼0.09 µm (80 cm⁻¹), first identified by Allamandola et al. (1992), was definitively detected toward seven objects, and marginally in the other two. The feature is better correlated with H₂O ice than with the silicate dust optical depth in the data obtained to date. Assuming the feature is due to a C–H stretch absorption, the abundance of the C–H bonds averaged along the lines of sight is closely related to that of H₂O ice. We interpret the correlation with H₂O ice as indicating that the C–H bonds form together with H₂O ice on grain surfaces in the molecular clouds, though other formation mechanisms are not ruled out. A second absorption feature at 3.25 µm (3080 cm⁻¹) was detected toward NGC7538/IRS 1 and S140/IRS 1; this feature was first detected in spectra of MonR2/IRS 3 (Sellgren, Smith, & Brooke 1994; Sellgren et al. 1995). There is as yet insufficient data to tell whether this feature is better correlated with H₂O ice or silicates.

Subject headings: infrared: general — ISM: dust, extinction — stars: pre-main sequence
1. Introduction

The 3.1 µm (3200 cm⁻¹) H₂O ice absorption band seen toward molecular clouds has a long wavelength wing not accounted for by simple models of grains covered only with H₂O ice (e.g. Smith, Sellgren, & Tokunaga 1989). As the wing extends through the 3.2–3.6 µm (3100-2800 cm⁻¹) region characteristic of C–H stretch vibrations, it is a logical place to search for the signatures of solid organics. Spectra of embedded young stellar objects in this region have so far revealed the presence of solid CH₃OH at 3.54 µm (2825 cm⁻¹) and a 3.47 µm (2880 cm⁻¹) absorber along the lines of sight (Grim et al. 1991; Allamandola et al. 1992; Sellgren, Smith & Brooke 1994). Allamandola et al. suggested that the 3.47 µm feature might be due to the C–H stretch absorption of solo hydrogens attached to sp³ bonded carbon clusters, the “diamond”-like form of carbon.

New spectra from 3.3–3.6 µm (3000-2750 cm⁻¹) of nine young stellar objects with H₂O ice features were obtained to determine the prevalence and abundance of the 3.47 µm absorber in molecular cloud dust. Three sources were also observed from 3.0–3.3 µm (3300-3000 cm⁻¹) to investigate a new absorption feature at 3.25 µm (3080 cm⁻¹) recently discovered toward MonR2/IRS 3 (Sellgren, Smith & Brooke 1994; Sellgren et al. 1995). This feature may be due to aromatic hydrocarbons at low temperature. The principal question addressed is whether absorption features are correlated with the H₂O ice or are due to components associated with the refractory dust.

2. Observations

Spectra were obtained at the Kitt Peak National Observatory 2.1-m telescope on 14-19 Oct UT 1994. The facility infrared cryogenic spectrometer (CRSP) equipped with a 256×256 InSb array was used with a 300 lines/mm grating, which provided a spectral resolution λ/Δλ ~ 1300. There were two pixels per resolution element. The wavelength calibration was obtained by observing telluric OH emission lines in second order and is estimated to be accurate to 5 Å.

The slit was 1.7'' × 156'' with the long axis oriented E–W. The spatial resolution was 0.61 ''/pixel. Observations of each source were alternated every 10–20 seconds with
observations of blank sky 30-100" away from the source for background subtraction. The blank sky positions were chosen to minimize the contribution from any nebulosity or additional nearby sources, using K′ images of Hodapp (1994) when available. Five background columns on either side of the flux peak on the array (3-6" away) were fit for additional background subtraction.

All sources were observed at the peak of the 3.45 μm (2900 cm\(^{-1}\)) signal. For those sources observed at 3.0–3.3 μm, the telescope was first positioned to the 3.45 μm peak, since surrounding nebulosity could cause the peak position to be a function of wavelength in the strong H\(_2\)O ice absorption band. Spectra from 3.0–3.3 μm were multiplied by a small correction factor to match the flux in the region of overlap with the longer grating setting. This correction was never more than 15%. The flux differences were likely the result of small centering and tracking errors.

The stars used for atmospheric correction were also used for flux calibration. The stars were assumed to be blackbodies. The assumed blackbody temperatures based on spectral type were from Lang (1992) and are given in Table 1. Blackbody functions were normalized to the V magnitude fluxes. The absolute calibrations may be uncertain to 20%. Hydrogen absorption in the Pf δ line at 3.296 μm (3034 cm\(^{-1}\)) in the standard stars was not corrected for and most likely contributes to the Pf δ emission features seen in some of the objects. Based on the spectral types of the standards, we estimate that Pf δ absorption in the standards could contribute all or part of the apparent Pf δ emission features in Elias 18 and NGC 7538/IRS 1, but not contribute significantly to the features in BN and GL961E. Some data points in the strongest telluric absorption features were not well-corrected and were dropped. Other gaps in the spectra are due to occasional bad pixels. Table 1 is a log of the observations. The spectra are shown in Fig. 1.

3. Determination of Spectral Features

The intrinsic spectral shape of the combination of H\(_2\)O ice and the long wavelength wing in molecular cloud sources has not been matched either in theory or experimentally (cf. Smith, Sellgren & Tokunaga 1989). Therefore only an approximate local continuum can be defined. Based on the width of the 3.47 μm and 3.25 μm features identified in W3/IRS 5 (Allamandola et al. 1992) and Mon R2/IRS 3 (Sellgren, Smith & Brooke 1994; Sellgren et al. 1995), the local continuum was defined to be represented by points in the
ranges 3.13-3.17 \( \mu m \) (where available), 3.33-3.37 \( \mu m \), and points longward of 3.61 \( \mu m \). The corresponding wavenumber ranges are 3190-3150 cm\(^{-1}\), 3000-2970 cm\(^{-1}\), and less than 2770 cm\(^{-1}\).

The continuum baselines were estimated using low order polynomial fits to the logarithms of the flux densities of the continuum points. Taking the logarithm enables spectra of the deepest ice band sources to be fit better with low order polynomials, because of the natural concavity of deep ice bands on linear scales. We tested linear, 2nd, and 3rd order polynomials. For those sources observed at 3.0-3.3 \( \mu m \), two separate polynomials of the same order joined together by averaging in the central region of overlap were also tested. We chose as the best fit the one which minimized the deviations in the points held to be continuum, subject to the fit passing over most of the points held to contain a feature. In each case, the best fit was a 3rd order polynomial or the joining of two 3rd order polynomials. In a few cases where there were clearly no strong features, the continuum was allowed to extend down to 3.58 \( \mu m \) (2790 cm\(^{-1}\)) to improve the baseline at the longer wavelengths. The adopted continua are shown in Fig. 1.

The resulting optical depths are shown in Fig. 2. The 3.47 \( \mu m \) and 3.25 \( \mu m \) features were fit with gaussians with the central wavelength, peak depth, and full-width at half-maximum (FWHM) as free parameters. Uncertainties in these parameters were estimated from the standard deviations of the results for fits using all of the baselines that looked reasonable, i.e. that did not dip below the spectra. Table 2 summarizes the results. Individual objects are discussed below. There is no particular significance attached to the use of gaussians; the purpose of the fitting is only to extract the best estimates of the parameters of symmetric features from noisy data, i.e. using all of the points available.

For the weakest 3.47 \( \mu m \) features (S255/IRS 1, Elias 18) the detections are marginal. But for the other objects, the features appear to be real, and the uncertainties simply reflect uncertainties in the baseline.

It is important to note that the actual absorption profiles of the species responsible for the features may extend further up into the long wavelength wing. Since we fit only a local continuum, our technique is sensitive only to the excess absorption at 3.47 \( \mu m \) or 3.25 \( \mu m \) above this continuum, and the derived optical depths may be lower limits to the true contributions of the absorbers.

Three objects (S140/IRS 1, W3/IRS 5, and NGC7538/IRS 9) were also observed by Allamandola et al. (1992). Our estimates of the 3.47 \( \mu m \) band depths differ somewhat from theirs as described below. We did not observe W33A, the other object studied by Allamandola et al. However, we would interpret their 3.47 \( \mu m \) band depth as a lower limit.
This is because there appears to be a substantial filling in of the bottom of the 3.1 μm H$_2$O ice band in this object, presumably by scattered light near the protostar. This can be seen by comparing the ratio of 3.47 to 3.35 μm optical depths of W33A, 0.84 (Willner et al. 1982) to those of the other ice-band sources for which the ratio has been well-measured, 0.6-0.7 (Smith, Sellgren, & Tokunaga 1989). A better estimate of the 3.47 μm band depth in W33A will require a model of the 3 μm spectrum which includes scattered light.

4. Discussion of Individual Objects

NGC7538/IRS 1—This object appears to have both 3.47 and 3.25 μm features with peak optical depths $\tau \sim 0.05$ and $\tau \sim 0.08$, respectively. No simple continuum was found to fit the entire range. The adopted continuum consists of two third-order polynomials averaged in the central continuum region. Points near 3.3 μm containing Pf $\delta$ emission were deleted from the optical depth plot.

S140/IRS1—This object has a 3.47 μm feature with peak optical depth $\tau \sim 0.03$. The shorter wavelength region suffers from poor sky cancellation but is consistent with a 3.25 μm feature with $\tau \sim 0.04$. The spectrum in Fig. 1 is different from that obtained by Allamandola et al. (1992), from which a 3.47 μm optical depth of 0.14 was estimated. The main difference is at wavelengths shortward of 3.45 μm, where the scatter in the Allamandola et al. spectrum is high. The fluxes in that spectrum are also a factor $\sim 4$ lower than in the present spectrum. Both the absolute flux and the spectral shape of the present spectrum are in agreement with the earlier spectrum of Willner et al. (1982), however.

BN—This object has a 3.47 μm feature with $\tau \sim 0.03$. The sharp feature at 3.10 μm and the broad dip near 3.2 μm are due to the presence of crystalline H$_2$O ice (cf Smith, Sellgren & Tokunaga 1989). Because of this structure, no simple continuum was found to fit the entire range; only the long wavelength segments were fit. The hydrogen emission line in the Humphries series at 3.61 μm, H(20-6), was excluded from the continuum fit. The other emission lines indicated in Fig. 2 were excluded from the feature fit. No firm statement can be made about a 3.25 μm feature; the structure there is due to poor atmospheric cancellation.

W3/IRS 5—This object has a strong 3.47 μm feature with $\tau \sim 0.13$. It was also observed by Allamandola et al. (1992) who derived a 3.47 μm band depth of 0.15 taking into account the maximum possible contribution of solid CH$_3$OH. As there is no clear evidence for the
spectral signature of solid CH$_3$OH at 3.54 µm (2825 cm$^{-1}$) in the present spectrum, we attribute the entire band to the 3.47 µm absorber. Only the long wavelength range was observed.

NGC7538/IRS 9—This object shows absorption by both solid CH$_3$OH at 3.54 µm and the 3.47 µm absorber. As shown by Allamandola et al. (1992), solid CH$_3$OH will also contribute to the absorption at shorter wavelengths. For this reason, no attempt was made to fit the entire feature with a single gaussian. However, using the solid CH$_3$OH absorption profile derived by Allamandola et al. from laboratory spectra, we estimate peak optical depths of $\tau \sim 0.10$ for the 3.47 µm feature and $\tau \sim 0.08$ for CH$_3$OH at 3.54 µm with uncertainties of 0.02. These values are about 60% lower than those derived by Allamandola et al. due to the different continuum adopted.

GL 961E—This object has a strong 3.47 µm feature with $\tau \sim 0.07$. The H(20-6) line was not included in the continuum fit and the other emission lines indicated were not included in the feature fit. Also excluded were points from 3.53-3.57 µm where there appears to be additional absorption. This could be due to solid CH$_3$OH (Grim et al. 1991; Allamandola et al. 1992) with an optical depth at 3.54 µm of roughly 0.04, but the strong hydrogen emission lines make this very difficult to confirm.

MonR2/IRS 2—This object has a 3.47 µm feature with $\tau \sim 0.05$. Two regions with apparent additional absorptions near 3.41 µm and 3.53 µm were excluded from the feature fit. It is not clear whether these features are real or due to incomplete cancellation of telluric features which lie near these wavelengths.

S255/IRS1—This source appeared double at 3.3–3.6 µm. The sources were separated by 2.4" E–W. The eastern source was 30% brighter and had a redder slope, presumably due to a deeper H$_2$O ice band. Its spectrum is used here. It may have a weak 3.47 µm feature with $\tau \sim 0.02$. The western source has at best only a weak 3.47 µm feature; the 2σ upper limit is $\tau \leq 0.03$.

Elias 18—Although the spectrum does not have high signal-to-noise, this object appears to have a weak 3.47 µm feature with $\tau \sim 0.02$.

5. Discussion
The 3.47 μm Feature

The 3.47 μm feature was detected in 7 of 9 young stellar objects observed, and marginally detected in the remaining two (S255/IRS 1 and Elias 18). The absorber is clearly a widespread component towards molecular cloud sources, as suggested by Allamandola et al. (1992). For the 10 young stellar objects observed here and by Sellgren, Smith, & Brooke (1994), the average central wavelength is $\lambda_0 = 3.469 \pm 0.002$ μm ($\nu_0 = 2883 \pm 2$ cm$^{-1}$) and the average FWHM is $\Delta\lambda = 0.092 \pm 0.005$ μm ($\Delta\nu = 76 \pm 4$ cm$^{-1}$). The uncertainties above are the 1σ standard deviations of the means of all the measurements. The total spreads in position and width are 0.023 μm (19 cm$^{-1}$) and 0.049 μm (39 cm$^{-1}$), respectively.

To determine whether the 3.47 μm feature is due to a refractory dust component, the peak optical depths are compared to the 9.7 μm silicate dust absorption band depths in Fig. 3. There is some uncertainty in the silicate band depths due to the unknown amount of intrinsic silicate emission in the sources. All of the 9.7 μm band depths except that of Elias 18 assume intrinsic silicate emission in the source (see Willner et al. 1982).

There is not a strong correlation between the optical depths of the 3.47 μm feature and the silicate band (correlation coefficient $r = 0.55$). Note that NGC 7538/IRS 9, with a strong 3.47 μm feature, has about the same silicate band depth as S140/IRS 1 and MonR2/IRS 3, which have much weaker 3.47 μm features. The lack of correlation is in contrast to the C–H stretch absorption features of aliphatic hydrocarbons seen in the diffuse interstellar medium towards galactic center sources, which correlate with the silicates (Sandford, Pendleton, & Allamandola 1995).

There is a better correlation between the 3.47 μm absorber and the 3.1 μm H$_2$O ice band ($r = 0.89$) as shown in Fig. 4. The best linear fit, exclusive of the upper limit, is

$$\tau(3.47) = (0.035 \pm 0.003) \tau(3.1) - (0.014 \pm 0.006)$$

which passes near the origin. Thus the abundance of the 3.47 μm absorber is closely related to that of H$_2$O ice.

The optical depth of the 3.47 μm feature is also well-correlated with the optical depth of the long wavelength absorption wing of the H$_2$O ice band at 3.5 μm ($r = 0.84$) as shown in Fig. 5. The optical depth of the long wavelength wing was estimated from low resolution spectra by fitting blackbody curves to data at 2.5 and 3.8 μm (see Willner et al. 1982; Smith, Sellgren, & Tokunaga 1989). A linear fit gives

$$\tau(3.47) = (0.17 \pm 0.02) \tau_{wing}(3.5) - (0.015 \pm 0.001).$$
In both Eqs. 1 and 2, the uncertainties are the formal ones derived from the measurement uncertainties; the true uncertainties can better be gauged by noting the deviations of the points from the straight lines. Figs. 4 and 5 also demonstrate that the wing is fairly well correlated with the peak optical depth in the ice band toward protostars, a result which has been shown to hold for the Taurus dark cloud medium (Smith, Sellgren, & Brooke 1993).

The 3.47 \( \mu m \) feature may be simply structure on the long wavelength wing, the overall profile of which is similar in many young stellar objects as indicated in Fig. 6 of Smith, Sellgren, & Tokunaga (1989). The wing is believed to be due to overlapping absorptions of C–H groups, though some kind of hydrate with H\(_2\)O has not been completely ruled out. Even if the absorption profile of the species responsible for 3.47 \( \mu m \) feature extends into the wing, the correlation with H\(_2\)O ice should still hold, since the wing as a whole correlates fairly well with H\(_2\)O ice. The correlation breaks down only in the worst case scenario: a) the 3.47 \( \mu m \) feature extends into the wing; b) it extends by different amounts relative to the rest of the wing in different sources; and c) some other absorber fills in the rest of the wing so as to mimic a correlation with H\(_2\)O ice. We consider this an unlikely possibility, though it can’t be ruled out.

From the peak wavelength of the 3.47 \( \mu m \) feature, Allamandola et al. (1992), proposed that single hydrogens attached to \( sp^3 \) bonded carbon clusters might be responsible for the feature. Assuming the feature to be due to C–H bonds, Fig. 4 indicates that averaged along the lines of sight, the ratio of abundances of the C–H bonds and H\(_2\)O ice is roughly similar.

The lack of a correlation with silicates suggests that the C–H bonds are not associated with the refractory dust cores. Some other plausible origins for the C–H bonds are: direct condensation of hydrocarbons from the gas, ultraviolet or thermal processing of carbon-containing ices as demonstrated in the laboratory (e.g. Allamandola, Sandford, & Valero 1988; Schutte, Allamandola, & Sandford 1993), or surface reactions on the grains.

One fact worth noting is that the 3.47 \( \mu m \) feature is nearly as strong relative to H\(_2\)O ice in NGC7538/IRS 9 as it is in W3/IRS 5, though NGC7538/IRS 9 has enhanced ratios of solid CO and CH\(_3\)OH relative to H\(_2\)O compared to W3/IRS 5 (Allamandola et al. 1992). Thus the abundance of the C–H bonds does not appear to correlate with solid CO, which may primarily condense from the gas (d’Hendecourt, Allamandola, & Greenberg 1985; Brown and Charnley 1990). Nor does the growth of the 3.47 \( \mu m \) feature appear to come at the expense of CO (or CH\(_3\)OH) by ultraviolet processing (assuming that both clouds began with the same complement of ices) as has recently been suggested for the 2166 cm\(^{-1} \) “X–CN” band (Tegler et al. 1995). This does not strictly rule out an ultraviolet or thermal processing origin for the 3.47 \( \mu m \) feature, though it suggests that different initial abundances, parents or processes would have to occur in different clouds, or in different
regimes along the lines of sight.

Theoretical calculations suggest that H$_2$O ice in molecular clouds forms primarily by surface reactions on grains rather than condensation from the gas (Jones & Williams 1984; d’Hendecourt, Allamandola, & Greenberg 1985; Brown & Charnley 1990). If we assume that the C–H bonds also form by surface reactions, then we are led to interpret the correlation of the 3.47 μm feature with H$_2$O ice as indicating that the C–H bonds form together with H$_2$O ice on grain surfaces in molecular clouds.

Duley and Williams (1995) have recently proposed that H$_2$O ice and hydrogenated amorphous carbon (proposed to account for the long wavelength wing) both form by surface reactions on the grains with the formation of $sp^3$ bonded carbon being necessary for the retention of an H$_2$O ice mantle. The correlation of the 3.47 μm feature with H$_2$O ice provides support for such a scenario, if in fact the feature is due to C–H groups on carbon clusters. However, the observed correlation does not necessarily require the C–H bonds and H$_2$O ice to form on the same grains, or for the C–H bonds to form first as Duley and Williams propose.

Under the assumption that the 3.47 μm feature is due to C–H groups on carbon, the required column densities (Table 3) were estimated from $N = \tau \Delta \nu / A$, where $\tau$ is the peak optical depth, $\Delta \nu$ the FWHM in cm$^{-1}$, and $A$ the integrated absorbance, taken to be $4.0 \times 10^{-18}$ cm per C–H bond (Allamandola et al. 1992). With $A = 2.0 \times 10^{-16}$ cm for the 3.1 μm H$_2$O ice band (Allamandola, Sandford, & Valero 1988), the linear relation of Fig. 4 gives $N_{C–H} / N_{H_2O} \approx 0.42$ or roughly one C–H bond for every two H$_2$O molecules.

It is difficult to say with certainty at this time whether the 3.47 μm is the signature of solo C–H bonds on $sp^3$ bonded carbon clusters as proposed by Allamandola et al. (1992). There has been much work recently on characterizing amorphous and diamond-like carbon films in the laboratory. Assignments for the monohydride stretch in these films vary from 3.42 μm (2920 cm$^{-1}$) to 3.53 μm (2830 cm$^{-1}$) (Dischler, Bubenzer, & Koidl 1983; Chin et al. 1992). These bracket the observed feature, so the Allamandola et al. identification is plausible. Relevant experiments at low temperatures would be useful to test whether material can be created with a band at the correct position and width under interstellar conditions.

5.2. The 3.25 μm Feature
A 3.25 µm feature similar to that identified in Mon R2/IRS 3 (Sellgren, Smith, & Brooke 1994; Sellgren et al. 1995) was detected in NGC 7538/IRS1 and S140/IRS 1. The telluric atmosphere contains strong features at this wavelength; however the present observations add to the evidence that there is a real absorption feature here. The wavelength of the 3.25 µm feature is near the range expected for hydrogens attached to aromatic hydrocarbons at low temperatures. This feature is discussed further by Sellgren et al. (1995).

The 3.25/3.47 optical depth ratios are roughly comparable in all three objects. However, there is as yet insufficient data to tell whether the 3.25 µm feature is better coupled to H₂O ice or silicate dust. Further searches for the 3.25 µm feature and determination of possible correlations are planned.

6. Conclusions

A distinct absorption feature at \(\sim 3.47 \mu m\) (2880 cm\(^{-1}\)) with FWHM\(\sim 0.09 \mu m\) (80 cm\(^{-1}\)), first identified by Allamandola et al. (1992), is extremely common toward young stellar objects with H₂O ice bands. The feature may be structure on the broad long wavelength wing of the ice band that remains after the absorption by pure H₂O ice has been removed. The 3.47 µm feature, like the long wavelength wing, is better correlated with H₂O ice than with the silicate dust optical depth in the data obtained to date. If the feature is due to a C–H stretch absorption, such as the solo hydrogens on \(sp^3\) bonded carbon clusters suggested by Allamandola et al., then we interpret the correlation with H₂O as indicating that the C–H bonds form together with H₂O ice on grains in the molecular cloud, with roughly one C–H bond forming for every two H₂O molecules, though other formation mechanisms are not ruled out.

There are now three detections of a second distinct absorption feature at 3.25 µm (3080 cm\(^{-1}\)) toward young stellar objects; this feature may be due to aromatic hydrocarbons at low temperature along the lines of sight. There is as yet insufficient data to determine whether this feature is correlated with H₂O ice or not.
We thank R. Joyce (NOAO) for assistance with the instrument and T. Mailloux (OSU) for help with the observations. K. Hodapp (U. Hawaii) provided digital images of some of the objects from his $K'$ survey.
Notes to Table 1:

\(^{a}\) Integration time

\(^{b}\) Assumed blackbody temperature of standard star.
Table 1: Log of Observations

| Object            | UT (Oct 1994) | Range (µm) | t<sup>a</sup> (sec) | Standard Star | Spectral Type | $T_{bb}$<sup>b</sup> (K) |
|-------------------|--------------|------------|----------------------|---------------|---------------|-------------------|
| W3/IRS5           | 14.3         | 3.29-3.63  | 120                  | BS 1035       | B9Ia          | 10255             |
| Elias 18          | 14.5         | 3.29-3.63  | 360                  | BS 1497       | B3V           | 18700             |
| BN                | 19.5         | 3.29-3.63  | 64                   | BS 1673       | F2V           | 6890              |
| Mon R2/IRS2       | 14.5         | 3.29-3.63  | 360                  | BS 1931       | O9.5V         | 32000             |
| S255/IRS1         | 19.5         | 3.29-3.63  | 128                  | BS 2484       | F5V           | 6440              |
| GL961E            | 17.5         | 3.29-3.63  | 320                  | BS 1412       | A7III         | 7650              |
| S140/IRS1         | 19.2         | 3.29-3.63  | 240                  | δ Cep         | F5Iab         | 6000              |
| NGC 7538/IRS1     | 18.2         | 3.29-3.63  | 320                  | β Cas         | F2IV          | 6870              |
|                   | 17.2         | 3.02-3.38  | 256                  |               |               |                   |
| NGC 7538/IRS 9    | 18.4         | 3.29-3.63  | 240                  | β Cas         | F2IV          | 6870              |

<sup>a</sup> t = time

<sup>b</sup> $T_{bb}$ = Blackbody Temperature
Notes to Table 2:

\(^a\) Central wavelengths (frequencies), full widths at half maximum, and peak optical depths of absorption features from gaussian fits.

\(^b\) Entries in parentheses are 1\(\sigma\) uncertainties obtained from standard deviations of results using several different baselines (see text).
| Object               | $\lambda_0$ (µm) | $\nu_0$ (cm$^{-1}$) | $\Delta \lambda$ (µm) | $\Delta \nu$ (cm$^{-1}$) | $\tau$ |
|---------------------|------------------|----------------------|------------------------|-------------------------|--------|
| 3.47 µm (2880 cm$^{-1}$) feature |                  |                      |                        |                         |        |
| W3/IRS5             | 3.461            | 2889                 | 0.114                  | 95                      | 0.133  |
|                     | (0.003)          | (3)                  | (0.010)                | (8)                     | (0.019) |
| Elias 18            | 3.469            | 2883                 | 0.117                  | 98                      | 0.022  |
|                     | (0.008)          | (7)                  | (0.066)                | (54)                    | (0.007) |
| BN                  | 3.459            | 2891                 | 0.093                  | 78                      | 0.034  |
|                     | (0.003)          | (3)                  | (0.021)                | (18)                    | (0.010) |
| Mon R2/IRS2         | 3.476            | 2877                 | 0.095                  | 79                      | 0.046  |
|                     | (0.004)          | (3)                  | (0.014)                | (12)                    | (0.009) |
| S255/IRS1           | 3.467            | 2885                 | 0.068                  | 56                      | 0.024  |
|                     | (0.006)          | (5)                  | (0.028)                | (24)                    | (0.018) |
| GL961E              | 3.463            | 2888                 | 0.099                  | 82                      | 0.068  |
|                     | (0.003)          | (3)                  | (0.006)                | (5)                     | (0.004) |
| S140/IRS1           | 3.473            | 2879                 | 0.072                  | 60                      | 0.027  |
|                     | (0.007)          | (6)                  | (0.032)                | (26)                    | (0.007) |
| NGC 7538/IRS1       | 3.464            | 2887                 | 0.092                  | 77                      | 0.052  |
|                     | (0.004)          | (3)                  | (0.019)                | (16)                    | (0.014) |
| NGC 7538/IRS 9      | 3.48             | 2880                 | 0.08                   | 70                      | 0.10   |
|                     | (0.01)           | (10)                 | (0.02)                 | (16)                    | (0.02)  |
Table 2–continued

| Object           | $\lambda_0$ | $\nu_0$ | $\Delta \lambda$ | $\Delta \nu$ | $\tau$ |
|------------------|--------------|---------|-------------------|--------------|--------|
|                  | (\(\mu m\)) | (cm\(^{-1}\)) | (\(\mu m\)) | (cm\(^{-1}\)) |        |
| 3.25 \(\mu m\) (3080 cm\(^{-1}\)) feature |              |         |                  |              |        |
| S140/IRS1        | 3.255        | 3072    | 0.073             | 69           | 0.036  |
|                  | (0.004)      | (4)     | (0.005)           | (5)          | (0.007)|
| NGC 7538/IRS1    | 3.263        | 3065    | 0.091             | 85           | 0.078  |
|                  | (0.008)      | (8)     | (0.006)           | (6)          | (0.013)|
Notes to Table 3: The optical depths given in the table are for silicates at 9.7 $\mu$m, $\tau(9.7)$; H$_2$O ice at 3.08 $\mu$m, $\tau(3.1)$; the long wavelength wing of the ice band at 3.47 $\mu$m, $\tau_{\text{wing}}(3.5)$; and features at 3.47 and 3.25 $\mu$m. $N_{\text{C–H}(3.47)}$ is the column density of C–H bonds required to give the 3.47 $\mu$m feature assuming an absorbance $A=4.0 \times 10^{-18}$ cm per C–H bond (see text).

References—(a) Willner et al. 1982; (b) Whittet et al. 1988. (c) Smith, Sellgren, & Tokunaga 1989; (d) Sellgren, Smith & Brooke 1994;

Notes—

(1) Optical depth from Allamandola et al. (1992) interpreted as an lower limit.

(2) Estimated from Whittet et al. 1988.
Table 3: Dust Feature Optical Depths

| Object            | $\tau(9.7)$ | $\tau(3.1)$ | $\tau_{wing}(3.5)$ | $\tau(3.47)$ | $\tau(3.25)$ | $N_{C-H}(3.47)$ |
|-------------------|-------------|-------------|---------------------|-------------|-------------|-----------------|
| W3/IRS5           | 7.64$^a$    | 3.48$^c$   | 0.71$^c$            | 0.133       | –           | 3.2 $^{(10^{18}\text{ cm}^{-2})}$ |
| Elias 18          | 0.43$^b$    | 0.80$^b$   | 0.13$^{2}$          | 0.022       | –           | 0.54            |
| BN                | 3.28$^a$    | 1.78$^c$   | 0.22$^c$            | 0.034       | –           | 0.66            |
| Mon R2/IRS2       | –           | 2.54$^c$   | 0.46$^c$            | 0.046       | –           | 0.91            |
| Mon R2/IRS3       | 4.30$^a$    | 1.14$^c$   | 0.39$^c$            | 0.036$^d$   | 0.049$^d$   | 0.68            |
| S255/IRS1         | 5.11$^a$    | 1.48$^c$   | 0.26$^c$            | 0.024       | –           | 0.34            |
| GL961E            | 2.11$^a$    | 2.46$^c$   | 0.36$^c$            | 0.068       | –           | 1.4             |
| W33A              | 7.84$^a$    | >5.4$^a$   | 2.53$^a$            | >0.15$^l$   | –           | >3.0            |
| S140/IRS1         | 3.97$^a$    | 1.28$^a$   | 0.46$^a$            | 0.027       | 0.036       | 0.40            |
| NGC 7538/IRS1     | 6.38$^a$    | 1.29$^a$   | 0.42$^a$            | 0.052       | 0.078       | 1.0             |
| NGC 7538/IRS 9    | 4.46$^a$    | 3.28$^a$   | 0.64$^a$            | 0.10        | –           | 1.8             |
REFERENCES

Allamandola, L. J., Sandford, S. A., Tielens, A. G. G. M., & Herbst, T. M. 1992, ApJ, 399, 134
Allamandola, L. J., Sandford, S. A., & Valero, G.J. 1988, Icarus, 76, 225
Brown, P.D. & Charnley, S.B. 1990, MNRAS, 244, 432
Chin, R.P., Huang, J.Y., Shen, Y.R., Chuang, T.J., Seki, H., & Buck, M. 1992, Phys. Rev. B, 45, 1992
d’Hendecourt, L.B., Allamandola, L.J., & Greenberg, J.M. 1985, A&A, 152, 130
Dischler, B., Bubenzer, A., & Koidl, P. 1983, Sol. State Comm., 48, 105
Duley, W. W. & Williams, D. A. 1995, MNRAS, 272, 442
Grim, R. J. A., Baas, F., Geballe, T. R., Greenberg, J. M., & Schutte, W. 1991, A&A, 243, 473
Hodapp, K.-W. 1994, ApJS, 94, 615
Jones, A.P., & Williams, D.A. 1984, MNRAS, 209, 955
Lang, K. R. 1992, Astrophysical Data: Planets and Stars, (New York: Springer Verlag), 137.
Sandford, S. A., Pendleton, Y. J., & Allamandola, L. J. 1995, ApJ, 440, 697
Schutte, W., Allamandola, L. J., & Sandford, S. A. 1993, Icarus, 104, 118
Sellgren, K., Brooke, T.Y., Smith, R.G., & Geballe, T.R. 1995, ApJ, 449, L69, 1995.
Sellgren, K., Smith, R. G., & Brooke, T. Y. 1994, ApJ, 433, 179
Smith, R.G., Sellgren, K.S., & Brooke, T.Y. 1993, MNRAS, 263, 749
Smith, R. G., Sellgren, K., & Tokunaga, A. T. 1989, ApJ, 344, 413
Tegler, S.C, Weintraub, D.A., Rettig, T.W., Pendleton, Y.J., Whittet, D.C.B., and Kulesa, C.A. 1995, ApJ, 439, 279
Whittet, D. C. B., Bode, M. F., Longmore, A. J., Adamson, A. J., McFadzean, A. D., Aitken, D. K. & Roche, P. F. 1988, MNRAS, 233, 321
Willner, S. P., et al. 1982, ApJ, 253, 174

This manuscript was prepared with the AAS L\LaTeX macros v3.0.
Figure Captions

**Figure 1(a-c)** — Spectra with resolution $\lambda/\Delta\lambda \sim 1300$. Error bars are $\pm1$-$\sigma$. Solid lines are polynomial fits to the observations in local continuum regions (see text).

**Figure 2(a-c)** — Optical depths from the continuum fits in Fig. 1. Solid lines are gaussian fits to features. Hydrogen emission lines marked in BN and GL961E were excluded from the fits.

**Figure 3** — 3.47 $\mu$m feature optical depths vs. silicate optical depths. Error bars correspond to $1\sigma$ uncertainties obtained from the standard deviations of fits using several different baselines (see text).

**Figure 4** — 3.47 $\mu$m feature optical depths vs. $\text{H}_2\text{O}$ ice optical depths. Solid line is best linear fit.

**Figure 5** — 3.47 $\mu$m feature optical depths vs. long wavelength wing optical depths. Solid line is best linear fit. Refer to Fig. 4 for identification of points.
