NEW 3 MICRON SPECTRA OF YOUNG STELLAR OBJECTS WITH H₂O ICE BANDS

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Received 1998 November 17; accepted 1999 January 5

ABSTRACT

We present new ground-based 3 μm spectra of 14 young stellar objects with H₂O ice absorption bands. The broad absorption feature at 3.47 μm was detected toward all objects, and its optical depth is correlated with the optical depth of H₂O ice, strengthening an earlier finding. The broad absorption feature at 3.25 μm was detected toward two more sources, and an upper limit is given for a third source. The optical depths of the 3.25 μm feature obtained to date are better correlated with the optical depth of the refractory silicate dust than with that of H₂O ice. If this trend is confirmed, this would support our proposed identification of the feature as the C-H stretch of aromatic hydrocarbons at low temperature. An absorption feature at 3.53 μm due to solid methanol was detected for the first time toward Mon R2/IRS 2, as well as toward W33A and GL 2136. The wavelengths of the CH₃OH features toward W33A, GL 2136, and NGC 7538/IRS 9 can be fitted by CH₃OH-rich ices, whereas the wavelength of the feature toward Mon R2/IRS 2 suggests an H₂O-rich ice environment. Solid methanol abundances toward GL 2136, NGC 7538/IRS 9, and Mon R2/IRS 2 are 3%-5% relative to H₂O ice. There is an additional narrow absorption feature near 3.47 μm toward W33A. For the object W51/IRS 2, spatially resolved spectra from 2 to 4 μm indicate that the H₂O ice is located predominantly in front of the eastern component and that the H₂O ice extinction is much deeper than previously estimated. For the object RNO 91, spectra from 2 to 4 μm reveal stellar (or circumstellar) CO gas absorption and deeper H₂O ice extinction than previously estimated.

Subject headings: circumstellar matter — infrared: stars — stars: pre-main-sequence

1. INTRODUCTION

Several distinct spectral absorption features have been detected in the long-wavelength wing of the interstellar 3.1 μm H₂O ice absorption band seen toward molecular cloud sources. As the wing extends through the 3.2–3.6 μm region characteristic of C-H stretch vibrations, some or all of these features could be due to organic species in the solid state. Spectra of embedded young stellar objects in this region have so far revealed a broad 3.47 μm feature and a broad 3.25 μm feature, neither of which is securely identified yet, and a feature at 3.53 μm due to solid CH₃OH. There is also a reported detection of a narrow feature near 3.47 μm, attributed to solid H₂CO, toward GL 2136 (Schutte et al. 1996a). The species responsible for the extended long-wavelength wing itself is still not certain.

The broad 3.47 μm feature (FWHM ≈ 0.1 μm) was first noticed in four objects by Allamandola et al. (1992). They suggested that the 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. The feature was present in every molecular cloud source looked at by Brooke, Sellgren, & Smith (1996), with an optical depth that appeared to be correlated with the depth of the H₂O ice band, as opposed to that of the silicates. The feature has also been seen toward Elias 16 (Chiar, Adamson, & Whittet 1996), a star behind the Taurus cloud, so the presence of the feature does not appear to require any heating or radiation processing by an embedded protostar. Graham (1998) detected the feature in two sources in the RCrA association. Under the assumption that the feature is due to C-H bonds, Brooke et al. (1996) interpreted the correlation with H₂O ice as indicating that both C-H bonds and H₂O ice form in step on molecular cloud dust by hydrogen-addition reactions. However, they noted that other identifications of the feature are also possible.

The broad 3.25 μm feature was first noted by Sellgren, Smith, & Brooke (1994) in a spectrum of Mon R2/IRS 3, and later confirmed with better spectra (Sellgren et al. 1995). They speculated that the feature might be due to aromatic hydrocarbons at low temperature. Two more detections were reported (Brooke et al. 1996), but there were insufficient data to determine any correlations with H₂O ice or silicates. The feature falls in a wavelength region where there are strong H₂O and CH₄ absorption lines in the terrestrial atmosphere. It also falls on the steeply sloping edge of the H₂O ice band. Thus reliable detections of the feature are extremely difficult.

Solid methanol has now been seen toward several embedded sources in molecular clouds. Solid CH₃OH was first identified in the interstellar medium by Grim et al. (1991). They observed an absorption feature at 3.53 μm toward...
**TABLE 1**

**LOG OF OBSERVATIONS**

| Object          | UT      | Telescope | Range (µm) | t' (s) | Standard Star | Spectral Type | T_{bb} b |
|-----------------|---------|-----------|------------|--------|---------------|---------------|----------|
| Mon R2/IRS 2    | 1996 Jan 12 | 2.1 m     | 3.3-3.6    | 180    | e Ori         | B0 I          | 26000    |
| ρ Oph/Elias 29  | 1996 Jun 12 | UKIRT    | 3.1-3.4    | 288    | 49 Lib        | F8 V          | 6200    |
|                 | 1996 Jun 13 | UKIRT    | 3.3-3.6    | 288    | BS 5923       | F6 V          | 6400    |
|                 | 1996 Jul 16 | UKIRT    | 2.9-3.2    | 288    | δ Sco         | B0 IV         | 27000    |
| ρ Oph/WL 6      | 1996 Jun 13 | UKIRT    | 3.1-3.4    | 432    | BS 6469       | F7 V          | 6300    |
|                 | 1996 Jun 13 | UKIRT    | 3.3-3.6    | 432    | BS 6310       | F3 V          | 6700    |
|                 | 1996 Jul 16 | UKIRT    | 2.9-3.2    | 432    | δ Sco         | B0 IV         | 27000    |
| ρ Oph/Elias 21  | 1996 Jun 12 | UKIRT    | 3.1-3.4    | 288    | BS 6310       | F3 V          | 6700    |
|                 | 1996 Jun 12 | UKIRT    | 3.3-3.6    | 288    | BS 6310       | F7 V          | 6700    |
|                 | 1996 Jul 16 | UKIRT    | 2.9-3.2    | 432    | δ Sco         | B0 IV         | 27000    |
| ρ Oph/Elias 33  | 1996 Jun 12 | UKIRT    | 3.1-3.4    | 288    | BS 6310       | F3 V          | 6700    |
|                 | 1996 Jun 12 | UKIRT    | 3.3-3.6    | 288    | BS 6310       | F3 V          | 6700    |
|                 | 1996 Jul 16 | UKIRT    | 2.9-3.2    | 432    | BS 7152       | F0 V          | 7200    |
| RNO 91          | 1996 Jun 06 | 2.1 m     | 2.0-2.4    | 480    | ν Ser         | A2 V          | 9000    |
|                 | 1996 Jun 06 | 2.1 m     | 3.0-3.9    | 240    | ν Ser         | A2 V          | 9000    |
|                 | 1996 Jun 13 | UKIRT    | 3.1-3.4    | 432    | BS 6469       | F7 V          | 6300    |
|                 | 1996 Jun 13 | UKIRT    | 3.3-3.6    | 432    | BS 6012       | F3 V          | 6700    |
|                 | 1996 Jul 16 | UKIRT    | 2.9-3.2    | 432    | δ Sco         | B0 IV         | 27000    |
| W33A            | 1995 Sep 06 | UKIRT    | 2.9-3.6    | 1440   | BS 6469       | F7 V          | 6300    |
| GL 2136         | 1995 Sep 06 | UKIRT    | 2.9-3.6    | 576    | BS 7126       | F5 V          | 6440    |
| Ser/SVS 20      | 1996 Jun 04 | 2.1 m     | 3.3-3.6    | 180    | δ Aql         | F2 IV         | 6890    |
|                 | 1996 Jul 16 | UKIRT    | 2.9-3.2    | 240    | BS 6797       | F5 V          | 6440    |
|                 | 1996 Jul 16 | UKIRT    | 3.1-3.4    | 432    | BS 6797       | F5 V          | 6440    |
| RCrA/IRS 1      | 1996 Jun 12 | UKIRT    | 3.3-3.6    | 288    | BS 7152       | F0 V          | 7200    |
|                 | 1996 Jun 13 | UKIRT    | 3.1-3.4    | 432    | BS 7152       | F0 V          | 7200    |
|                 | 1996 Jul 16 | UKIRT    | 2.9-3.2    | 288    | BS 7152       | F0 V          | 7200    |
| RCrA/IRS 2      | 1996 Jun 13 | UKIRT    | 3.1-3.4    | 432    | BS 7152       | F0 V          | 7200    |
|                 | 1996 Jun 13 | UKIRT    | 3.3-3.6    | 432    | BS 7152       | F0 V          | 7200    |
|                 | 1996 Jul 16 | UKIRT    | 2.9-3.2    | 240    | δ Sco         | B0 IV         | 27000    |
| RCrA/IRS 5      | 1996 Jun 13 | UKIRT    | 3.3-3.6    | 432    | BS 7152       | F0 V          | 7200    |
| W51/IRS 2       | 1996 Jun 06 | 2.1 m     | 2.0-2.4    | 120    | 15 Vul        | A7m           | 7850    |
|                 | 1996 Jun 06 | 2.1 m     | 3.0-3.9    | 320    | 111 Her       | A3 V          | 8720    |
|                 | 1996 Jun 12 | UKIRT    | 3.1-3.4    | 288    | BS 7172       | F8 V          | 6200    |
|                 | 1996 Jun 13 | UKIRT    | 2.9-3.2    | 432    | BS 7550       | F5 V          | 6440    |
| GL 2591         | 1995 Sep 06 | UKIRT    | 2.9-3.6    | 576    | τ Cyg         | F3 IV         | 6700    |

* a Integration time.
* b Assumed blackbody temperature of standard star.

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**Fig. 1.**—Spectra from 2.9 to 3.6 µm with resolution λ/Δλ ≈ 1200 (solid lines). Dashed lines are polynomial fits in local continuum regions (see text). (a) Filled circles are data from Allamandola et al. (1992) scaled to the same flux level. (b) Filled circles are data from Schutte et al. (1996a) scaled to the same flux level. Apparent hydrogen line emission features at 3.04 µm (H1 Pf) and 3.30 µm (H1 Pf) in GL 2136 may be due all or in part to corresponding absorption features in the standard stars, which were not corrected for.

884
Fig. 2.—Spectra from 2.9 to 3.6 \( \mu m \) with effective resolution \( \lambda / \Delta \lambda \approx 1300 \) (1200 for GL 2591) are shown as solid lines. Dashed lines are polynomial fits in local continuum regions (see text). Apparent hydrogen line emission features at 3.04 \( \mu m \) (H\textsc{i} P\textsc{f}v) and 3.30 \( \mu m \) (H\textsc{i} P\textsc{f}d) in Elias 29, SVS 20, RCrA/IRS 1, and RCrA/IRS 2 may be due all or in part to corresponding absorption features in the standard stars, which were not corrected for.
W33A, in good agreement with the \( v_3 \) symmetric CH\(_3\)OH stretch mode in solid CH\(_3\)OH. This feature was subsequently detected toward two other sources, NGC 7538/IRS 9 (Allamandola et al. 1992) and GL 2136 (Schutte et al. 1996a), and has recently been detected toward another, RAFGL 7009S (Dartois et al. 1999). Additional features that can be attributed to solid CH\(_3\)OH have been detected toward GL 2136 at 8.9 and 9.7 \( \mu \)m (Skinner et al. 1992) and toward W33A and RAFGL 7009S at 3.85 and 3.94 \( \mu \)m (Geballe 1991; Allamandola et al. 1992; Dartois et al. 1999). Also, part of the broad 6.8 \( \mu \)m feature seen toward many objects is most likely due to solid CH\(_3\)OH (Schutte et al. 1996b, and references therein). The wavelengths of peak absorption have been used to infer that solid CH\(_3\)OH is found in ice mixtures that are not dominated by \( \text{H}_2\text{O} \) ice (Skinner et al. 1992; Allamandola et al. 1992; Schutte et al. 1996a; Dartois et al. 1999).

As infrared instrumentation continues to improve, it has become possible to detect weak spectral features in an increasing number of young stellar objects. New 3 \( \mu \)m spectra of 14 objects with \( \text{H}_2\text{O} \) ice bands were obtained in 1995 and 1996 with two 256 \times 256 InSb array spectrometers to determine the prevalence and abundance of organics in molecular cloud dust. These were objects with right ascensions 16° \( \leq \alpha \leq 21° \), with the exception of Mon R2/IRS 2. Mon R2/IRS 2 was reobserved to obtain a spectrum of better quality than that shown in Brooke et al. (1996), which suffered from poor cancellation of telluric features.

## 2. Observations

Spectra were obtained at the Kitt Peak National Observatory 2.1 m telescope on 1996 January 12 and 1996 June 4, 6 and at the United Kingdom Infrared Telescope (UKIRT) on 1995 September 6, June 12–13, and 1996 July 16. All dates are UT. Table 1 is a log of the observations. The spectra are shown in Figures 1–4.

At Kitt Peak, the infrared cryogenic spectrometer CRSP was used. The pixels were 0′61 wide and oriented north-south for Mon R2/IRS 2 and east-west for the others. Background subtraction for Mon R2/IRS 2 was done by nodding the telescope 10° south along the slit. For the other objects, the telescope was nodded 160° east (west for Serpens SVS 20). The spectra were sampled every 1/2 of a resolution element. Observations of Mon R2/IRS 2 and Serpens SVS 20 in the 3.5 \( \mu \)m region were taken with the 300 lines mm\(^{-1} \) grating (grating 1), which provided a spectral resolution \( \lambda/\Delta \lambda \approx 1300 \) at 3.5 \( \mu \)m. The spectra of SVS 20 were smoothed to an effective resolution of \( \approx 800 \) to improve the signal to noise. Observations of W51/IRS 2 and RNO 91 were taken with the 150 lines mm\(^{-1} \) grating (grating 3), which provided \( \lambda/\Delta \lambda \approx 530 \) in the 3.4–3.9 \( \mu \)m region and \( \approx 700 \) in the 2.2 \( \mu \)m region. The spectrum of RNO 91 was smoothed to an effective resolution of \( \approx 200 \) in the 3.6–3.9 \( \mu \)m region and \( \approx 400 \) in the 2.2 \( \mu \)m region.

At UKIRT, the facility spectrometer CGS 4 was used. The pixels were 1′2 across. A 1′2 wide slit was oriented east-west. The sources were nodded \( \sim 12° \) along the slit for background subtraction. The spectra were sampled every 1/3 of a resolution element. Spectra in 1995 September were obtained with the 75 lines mm\(^{-1} \) grating that provided a spectral resolution of \( \approx 1200 \). The rest of the spectra were obtained with the 150 lines mm\(^{-1} \) grating that provided a spectral resolution of \( \approx 2400 \). They were smoothed to an effective resolution of \( \approx 1300 \).

For those sources observed at 2.2 \( \mu \)m, the telescope was first positioned to the 3.5 \( \mu \)m peak, since surrounding nebulosity could cause the peak position to be a function of wavelength.

The stars used for atmospheric correction were also used for flux calibration. The stars were assumed to be black-bodies. The assumed blackbody temperatures based on spectral type are given in Table 1. The absolute flux calibration may be uncertain by 20%. Where possible, Kitt Peak spectra were scaled to the flux level of the UKIRT spectra, which we consider more reliable. The scaling factors were less than 20%.

Hydrogen absorption lines in the standard stars were not removed. This means that apparent emission features at 3.04 \( \mu \)m (H i Pf\( \epsilon \)) and 3.30 \( \mu \)m (H i Pf\( \delta \)) in the data for Elias 29, GL 2136, SVS 20, RCrA/IRS 1, and RCrA/IRS 2 may be due all or in part to corresponding absorption features in the standards. In the case of RNO 91, the standard star used to correct the K (2.2 \( \mu \)m) and 3.7 \( \mu \)m regions observed at Kitt Peak was an A2 V star with strong hydrogen absorptions at Br\( \gamma \) (2.17 \( \mu \)m) and Pf\( \gamma \) (3.74 \( \mu \)m), so these regions...
For W51/IRS 2(E), spectral resolution was $\approx 700$ in the 2.2 $\mu$m region, $\approx 1300$ in the 2.9–3.4 $\mu$m region, and $\approx 530$ in the 3.4–3.9 $\mu$m region. Long-dashed line is estimated continuum. A scaled blackbody (dash-dotted line) indicates the approximate color temperature. Short-dashed line is the local continuum for the 3.47 $\mu$m feature. Wavelengths of the indicated lines are (in microns): 2.059 ($\text{He I} 2p^5 3S^1 - 2p^4 3P^0$), 2.113 ($\text{He I} 4s^3 3S - 4p^3 3P^0$), 2.122 ($\text{H}_2 [v = 1–0 \text{ Si}]$), 2.166 ($\text{H I} \text{Br}$), 3.039 ($\text{H I} \text{Pf}$), 3.297 ($\text{H I} \text{Pd}$), 3.741 ($\text{H I} \text{Pf}$). After correction for hydrogen absorption in the standard stars, the line flux ratios (Wm$^{-2}$) relative to Br$\gamma$ of the indicated lines are (in increasing wavelength order): 0.63, 0.04, 0.03, 1.0, 0.38, 0.91, 5.21.

For RNO 91 the effective spectral resolution was $\approx 400$ in the 2.2 $\mu$m region, $\approx 1300$ in the 2.9–3.6 $\mu$m region, and $\approx 200$ in the 3.6–3.9 $\mu$m region. Long-dashed line is estimated continuum. Short-dashed line is the local continuum for the 3.47 $\mu$m feature. The wavelengths of the CO band heads are (in microns): 2.293 (2–0), 2.323 (3–1), 2.352 (4–2), 2.383 (5–3).
Fig. 5.—Derived H$_2$O ice band profiles from the continua indicated in Fig. 4. Wavelengths of the hydrogen emission lines are given in Fig. 4.
Fig. 6—Derived 3.47 μm feature optical depth profiles from continua indicated in Figs. 2–3. Dashed lines are Gaussian fits. A representative ±1 σ error bar is offset lower right.
were deleted. The emission lines in the data of W51/IRS 2(E) are predominantly intrinsic to the source.

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. Error bars are omitted in the flux plots for clarity, but representative error bars are shown in the plots of optical depth that follow.

3. 2–4 μm SPECTRA

Two young stellar objects were observed from 2 to 4 μm in order to obtain improved estimates of the H₂O ice band optical depth. These spectra are shown in Figure 4 and discussed in this section. Our goal was not an in-depth study of the 2 μm spectra of these objects, but some interesting aspects of the spectra are noted.

3.1. W51/IRS 2

W51/IRS 2 is an infrared source that contains an embedded H II region. It has a 3 μm H₂O ice absorption band previously estimated to have an optical depth τ ≈ 0.8 (Soifer, Russell, & Merrill 1976; Joyce & Simon 1982). These ice band observations were taken with aperture diameters of 17″ and 11″, respectively. The source was shown to be double in the mid-infrared by Genzel et al. (1982). The eastern source, which is brighter over the 2.2 to 20 μm range, has a 10 μm silicate absorption feature, but the western source ≈ 5″ away has no detectable silicate feature. Goldader & Wynn-Williams (1994) showed that W51/IRS 2(E) has a 3 μm ice absorption band but that W51/IRS 2(W) does not. Our spectra show that the ice band toward W51/IRS 2(E) is deeper than the previous estimate.

The 2–4 μm spectrum of W51/IRS 2(E) is shown in Figure 4a. The measured fluxes for W51/IRS 2(E) are within 20% of those of Goldader & Wynn-Williams (1994). The slits were oriented east-west and centered on W51/IRS 2(E). With this orientation, we also obtained a spectrum of a bright region about 2″ south of the position given for W51/IRS 2(W) by Goldader & Wynn-Williams. Emission lines of H I, He I, and H₂ were detected toward both regions. The detected lines are indicated in the figure for W51/IRS 2(E) (Fig. 4a). The equivalent width of the H I Brγ line (corrected for absorption in the standard star) in the region 2″ south of IRS 2(W), W( Brγ) ≈ 540 Å, is very close to the theoretical value for emission by thermal electrons at T = 10,000 K in an H II region (≈ 590 Å, Wynn-Williams et al. 1978), but in W51/IRS 2(E) it is lower [W( Brγ) ≈ 140 Å], indicating that the 2 μm continuum of W51/IRS 2(E) contains starlight, scattered light, and/or dust thermal emission. This is in agreement with the conclusion of Goldader & Wynn-Williams (1994) from spectrophotometric imaging. Line ratios are given in the legend to Figure 4a.

W51/IRS 2(E) exhibits a strong H₂O ice band. There was no evidence for any H₂O ice absorption in the western

Fig. 7.—Derived 3.25 and 3.47 μm feature optical depth profiles from continua indicated in Fig. 2. Dashed lines are Gaussian fits. Some ± 1σ error bars are indicated.
Fig. 8.—Optical depths for the 3.47 μm feature vs. (a) silicates and (b) H₂O ice. Solid line is the best weighted linear fit. Dashed line is best unweighted linear fit. Open circles are from Sellgren et al. (1994) and Brooke et al. (1996); crosses from Chiar et al. (1996); filled circles from this work.
Fig. 9.—Optical depths for the 3.25 \( \mu \text{m} \) feature vs. (a) silicates and (b) H\(_2\)O ice. Open circles are from Sellgren et al. (1994) and Brooke et al. (1996); filled circles from this work.
**TABLE 2**

| Object          | $\lambda_0$ (µm) | $\Delta\lambda$ (µm) | $\tau$       |
|-----------------|-------------------|----------------------|--------------|
| Mon R2/IRS 2    | 3.460 (0.006)     | 0.103 (0.007)        | 0.083 (0.013) |
| $\rho$ Oph/Elias 29 | 3.490 (0.006)     | 0.113 (0.009)        | 0.089 (0.007) |
| $\rho$ Oph/WL 6  | 3.472 (0.003)     | 0.111 (0.009)        | 0.062 (0.012) |
| $\rho$ Oph/Elias 21 | 3.464 (0.003)     | 0.104 (0.012)        | 0.042 (0.012) |
| $\rho$ Oph/Elias 33 | 3.457 (0.009)     | 0.120 (0.007)        | 0.024 (0.006) |
| RNO 91          | 3.469 (0.003)     | 0.118 (0.012)        | 0.085 (0.015) |
| W33A            | 3.477 (0.010)     | 0.099 (0.012)        | 0.290 (0.040) |
| GL 2136         | 3.471 (0.010)     | 0.118 (0.005)        | 0.137 (0.020) |
| Ser/SVS 20      | 3.463 (0.011)     | 0.111 (0.009)        | 0.030 (0.009) |
| RCra/IRS 1      | 3.469 (0.012)     | 0.122 (0.016)        | 0.041 (0.005) |
| RCra/IRS 2      | 3.472 (0.005)     | 0.092 (0.005)        | 0.041 (0.011) |
| RCra/IRS 5      | 3.470 (0.006)     | 0.111 (0.005)        | 0.090 (0.019) |
| W51/IRS 2(E)    | 3.471 (0.003)     | 0.094 (0.005)        | 0.143 (0.012) |
| GL 2591         | 3.464 (0.005)     | 0.131 (0.007)        | 0.045 (0.005) |
| NGC 7538/IRS 9  | 3.485 (0.003)     | 0.118 (0.024)        | 0.130 (0.017) |

* Central wavelengths, full widths at half-maximum, and peak optical depths of absorption features from Gaussian fits.

* Entries in parentheses are 1σ uncertainties obtained from standard deviations of results using several different baselines (see text).

* Interpreted as a lower limit (see text).

**TABLE 3**

| Object          | $\lambda_0$ (µm) | $\Delta\lambda$ (µm) | $\tau$       |
|-----------------|-------------------|----------------------|--------------|
| Ser/SVS 20      | 3.245 (0.003)     | 0.061 (0.007)        | 0.021 (0.003) |
| RCra/IRS 1      | 3.239 (0.003)     | 0.059 (0.012)        | 0.032 (0.010) |
| $\rho$ Oph/Elias 29 | ... ... ... ...   | ... ... ... ...     | ... <0.03*    |

* Central wavelengths, full widths at half-maximum, and peak optical depths of absorption features from Gaussian fits.

* Entries in parentheses are 1σ uncertainties obtained from standard deviations of results using several different baselines (see text).

* 3σ upper limit.
3.2. RNO 91

RNO 91, in the L43 dark cloud, is a young stellar object that illuminates a reflection nebula. It has a 3 \( \mu \)m \( \text{H}_2\text{O} \) ice absorption band previously estimated to have an optical depth \( \tau = 1.29 \) from a 2.8–3.8 \( \mu \)m spectrum (Weintraub et al. 1994). The \( K \) (2.2 \( \mu \)m) band flux is extended in two lobes (Weintraub et al. 1994). All of our spectra were taken at the peak 3.5 \( \mu \)m position, presumably the exciting star. The \( K \)-band spectrum (Fig. 4b) shows hot CO gas overtone absorption longward of 2.3 \( \mu \)m.

To estimate the ice band depth, a third-order polynomial (in the log) was drawn between 2.1–2.3 and 3.8–3.9 \( \mu \)m, avoiding the CO absorption (Fig. 4b). The derived ice band optical depth profile is shown in Figure 5b. The \( \text{H}_2\text{O} \) ice toward this source is mostly amorphous. The derived optical depth is \( \tau(3.1) = 2.1 \pm 0.2 \), higher than the estimate of Weintraub et al. (1994). Our optical depth is probably a better estimate since the 2 \( \mu \)m spectral continuum was included.

This is the first published 2 \( \mu \)m spectrum of this object to our knowledge. Because the goal was simply to define the continuum, the integration time was short and the signal-to-noise ratio low. However CO gas overtone absorptions can clearly be seen. Many young stellar objects show strong CO overtone absorption, comparable to late-type giants, although they have low total luminosities (Casali & Eiroa 1996; Greene & Lada 1996). The combined equivalent width of the CO 2–0 and 4–2 bands at 2.29 and 2.35 \( \mu \)m in RNO 91, defined as in Greene & Lada (1996), is \( \sim 15 \) \AA. Two other photospheric features, the atomic Na and Ca lines at 2.21 and 2.26 \( \mu \)m, are weak, with equivalent widths \( \lesssim 2 \) \AA. With these line strengths, RNO 91 falls between main-sequence dwarf and giant photospheres, as do several young stellar objects in the \( \rho \) Oph cloud (Greene & Lada 1996). As the bolometric luminosity of RNO 91 is low (\( \lesssim 3.7 \) \( L_\odot \); Chen et al. 1995), the observations are consistent with photospheric absorption by a young star characterized by low surface gravity. Higher resolution spectra of this object should be able to confirm whether the CO absorption bands are in fact photospheric or due to a circumstellar disk.

4. DETERMINATION OF SPECTRAL FEATURES

The method of defining the local continuum in order to extract the 3.25 and 3.47 \( \mu \)m features is discussed in Sellgren et al. (1994, 1995) and Brooke et al. (1996). To summarize the standard case, the local continuum was defined to be represented by points in the ranges 3.13–3.17 and 3.33–3.37 \( \mu \)m and points longward of 3.61 \( \mu \)m. The continua were
estimated using low-order polynomial fits to the logarithms of the flux densities of the continuum points, with the constraint that the best fit fall above those points held to contain features and look “reasonable” to the eye. In most cases, the best fit was a single third-order polynomial in the log or the joining of two third-order polynomials. In cases where there were clearly no strong broad 3.47 \( \mu \text{m} \) or solid CH\(_3\)OH features, the continuum was allowed to extend down to 3.58 \( \mu \text{m} \) to improve the baseline at the longer wavelengths. The adopted continua are shown in Figures 1-4.

An exception to this standard case was made when the 3.53 \( \mu \text{m} \) absorption feature of solid CH\(_3\)OH was clearly present: W33A, GL 2136, and Mon R2/IRS 2. The C-H stretch bands of solid CH\(_3\)OH absorb strongly between approximately 3.33 and 3.65 \( \mu \text{m} \) (Hudgins et al. 1993). For the sources with solid CH\(_3\)OH, only points near 3.33 \( \mu \text{m} \) were used to define the continuum in that region. At the long-wavelength end, our spectra lacked sufficient wavelength coverage. We used data from previously published spectra to help define the continuum, after first scaling the earlier spectra to the appropriate flux level. The earlier spectra were from Allamandola et al. (1992) for W33A, Schutte et al. (1996a) for GL 2136, and Smith, Sellgren, & Tokunaga (1989) for Mon R2/IRS 2. The data taken from these spectra are indicated in Figures 1a, 1h, and 3a. The points used to define the continuum were from 3.65 to 3.70 \( \mu \text{m} \).

The resulting optical depths for sources with no detected CH\(_3\)OH are shown in Figures 6 and 7. The 3.47 \( \mu \text{m} \) feature and the 3.25 \( \mu \text{m} \) feature (where detected) were fitted with Gaussians with the central wavelength, peak optical 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 other baselines that looked reasonable. These are larger than the formal statistical uncertainties associated with the point-to-point scatter. The results are shown in Table 2 and 3. There is no particular significance attached to the use of Gaussians; the purpose of the fitting is only to extract reasonable estimates of the parameters of symmetric features. For W33A, GL 2136, and Mon R2/IRS 2, the fits in the 3.47 \( \mu \text{m} \) region consisted of the sum of a Gaussian and a CH\(_3\)OH ice template, as discussed below.

Although a local continuum could be drawn in the 3.25 \( \mu \text{m} \) region in most cases by our technique, the cancellation of telluric features was often insufficient to put any useful constraints on a 3.25 \( \mu \text{m} \) feature. One exception was Elias 29. No feature was detected but a 3 \( \sigma \) limit of \( \tau(3.25) < 0.03 \) was estimated (Fig. 7c).

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 fitted only a local continuum, our technique is sensitive only to the excess absorption at 3.47 or 3.25 \( \mu \text{m} \) below this continuum, and the derived optical depths may be lower limits to the true contributions of the absorbers.

### 5. Notes on Some Individual Sources

**W33A.**—Our estimate of the optical depth of the 3.47 \( \mu \text{m} \) feature is 0.29 \( \pm \) 0.04, considerably higher than the value of 0.15 estimated by Allamandola et al. (1992). This is because the points we held to be continuum at the long-wavelength end were at longer wavelengths to take into account the presence of solid CH\(_3\)OH. We continue to consider this value to be a lower limit to the true line-of-sight value, as the shape of the 3.1 \( \mu \text{m} \) H\(_2\)O ice band suggests that light suffering less ice extinction, possibly scattered light near the source or unresolved sources, is filling in this region to some extent (Brooke et al. 1996). The 3.25 \( \mu \text{m} \) region was too faint to fit due to the deep H\(_2\)O ice band.

**GL 2136.**—The H\(_2\)O ice band optical depth toward this source has been recently measured to be \( \tau(3.1) = 3.2 \pm 0.2 \) (Kastner & Weintraub 1996). The H\(_2\)O ice is partially crystalline (Fig. 1b). The crystalline ice inflection at 3.20 \( \mu \text{m} \) precludes an accurate test for the 3.25 \( \mu \text{m} \) feature with our current technique.

**SVS 20.**—SVS 20 is a double source in the Serpens cloud, with a mostly north-south separation of 1.6 (Eiroa et al. 1987). Our observations are of SVS 20(S), which is 3 times brighter at 3.6 \( \mu \text{m} \) (Huard, Weintraub, & Kastner 1997). Both objects exhibit H\(_2\)O ice absorption bands (Eiroa & Leinert 1987; Huard et al. 1997).

**RCrA/IRS 1.**—Graham (1998) estimated a 3.47 \( \mu \text{m} \) feature optical depth of \( \approx 0.06 \). Our value is 0.041 \( \pm \) 0.005, not remarkably different.

**RCrA/IRS 2.**—Graham (1998) also estimated a 3.47 \( \mu \text{m} \) feature optical depth of \( \approx 0.06 \) for this source (TS 13.1). Our value is 0.041 \( \pm \) 0.011, not remarkably different.

**GL 2591.**—Although this source is relatively bright, our spectrum suffers from a poor cancellation of telluric features. No attempt was made to fit a continuum to the 3.25 \( \mu \text{m} \) region.

### 6. The 3.47 \( \mu \text{m} \) Feature

Using all of the available data, the best estimates of the central wavelength and width of this feature are \( \lambda_0 = 3.469 \pm 0.002 \mu \text{m} \) (2883 cm\(^{-1}\)) and FWHM = 0.105 \( \pm \) 0.004 \( \mu \text{m} \) (87 cm\(^{-1}\)). Table 4 summarizes all of the detections of the feature to date. Figures 8a and 8b demonstrate that the 3.47 \( \mu \text{m} \) absorber is better correlated with the 3.1 \( \mu \text{m} \) H\(_2\)O ice band depth than with the 9.7 \( \mu \text{m} \) silicate absorption band depth. References for the H\(_2\)O ice and silicate optical depths are given in Table 4. This is the same comparison done by Brooke et al. (1996), but the number of data points is now roughly doubled. The best weighted linear fit, exclusive of the upper limit, is

\[
\tau(3.47) = (0.033 \pm 0.002) \tau(3.1) - (0.004 \pm 0.004),
\]

which passes near the origin. These coefficients are consistent with the values derived by Brooke, Sellgren, & Smith from the more limited data. The linear correlation coefficient is \( r = 0.88 \). The weighted fit is especially sensitive to the optical depth of GL 961E [open circle at \( \tau(3.1) = 2.46 \) in Fig. 8b], since its error as estimated by Brooke, Sellgren, & Smith is significantly lower than the points around it. In the event that there may be some as yet undetermined systematic effects that affect the error determinations, we also give the unweighted fit

\[
\tau(3.47) = 0.042\tau(3.1) - 0.010.
\]

In any case, the abundance of the 3.47 \( \mu \text{m} \) absorber is closely related to that of H\(_2\)O ice over a wide range in ice extinction.

If in fact the 3.47 \( \mu \text{m} \) feature is due to the stretching vibration of sp\(^3\) C-H bonds, the linear relation of Figure 8b corresponds to roughly one C-H bond for every two H\(_2\)O molecules, and a possible explanation for the correlation is...
The C-H stretch absorption band of aromatic hydrocarbons should be accompanied by absorption counterparts of the well-known aromatic emission features near 6.2, 7.7, 8.6, and 11.3 μm. A possible absorption feature at 6.25 μm toward the young stellar object NGC 7538/IRS 9 has been suggested to be the C-C stretching mode of aromatic hydrocarbons (Schutte et al. 1996b). However, the identification and optical depth are still uncertain due to the presence of other absorbers. There are as yet no published high-sensitivity spectra of this object in the 3.25 μm region.

A test of the possible correlation of the 3.25 μm feature with the refractory dust would be the clear detection of the feature along a line of sight with heavy dust extinction but little H₂O ice, as can be found in the diffuse interstellar medium (ISM). Such a detection has not yet been made. Previous searches for the aromatic C-H stretch absorption in the diffuse ISM have been made near 3.29 μm, the wavelength of the aromatic emission feature. Pendleton et al. (1994) discussed a possible absorption feature at 3.28 μm, perhaps due to aromatic hydrocarbons, toward three Galactic center sources whose extinction is believed to be dominated by dust in the diffuse ISM. But the definition of the continua was difficult, so they placed upper limits of \( \tau(3.28) \leq 0.02 \) on this feature. Schutte et al. (1998) also placed an upper limit of \( \tau(3.3) \leq 0.02 \) toward one Wolf-Rayet star in their sample of diffuse ISM sources. Sellgren et al. (1995) proposed that the 3.25 μm feature observed in
absorption in molecular clouds may be due to the same aromatic hydrocarbons responsible for the 3.29 μm emission feature but shifted to a shorter wavelength due to a difference in temperature between cold absorbers and hot emitters. High-sensitivity spectra of diffuse ISM sources in the 3.25 μm region are needed to test this proposal.

However, an absorption feature at 6.2 μm identified as the aromatic C-C stretch has recently been identified toward five Wolf-Rayet stars and two Galactic center sources in Infrared Space Observatory (ISO) spectra (Schutte et al. 1998). The extinction to all of these objects is believed to come primarily from the diffuse ISM. The optical depth of the 6.2 μm feature is well correlated with the 9.7 μm silicate absorption optical depth toward these sources. In Figure 10, we compare the relationships of the possible aromatic absorptions at 6.2 and 3.25 μm and silicate absorption. For this comparison, we multiplied the τ(6.2) values of Schutte et al. (1998) by 0.25, the factor needed to bring the best-fit linear slopes into agreement. Figure 10 suggests that the apparent relationship between τ(3.25) and τ(9.7) is consistent with the linear correlation of τ(6.2) versus τ(9.7), after correcting by a scale factor. This agreement is what one would expect if the abundance of aromatic hydrocarbons relative to silicates, and the relative strengths of C-H stretch absorptions at 3.25 and 6.2 μm (2829 cm⁻¹) are in Table 4. In the weak ISM mix, it occurs at 3.530 μm (2833 cm⁻¹).

In order to fit the spectra, local continua similar to those used for the observations were applied to the CH₃OH laboratory data. Each of the spectra in Figure 11 were simultaneously fitted with a Gaussian for the 3.47 μm feature and a CH₃OH ice template. Optical depths are quoted for the 3.53 μm feature alone. An additional narrow absorption feature near 3.47 μm in W33A discussed below was deleted from the fit for this object.

The features in GL 2136 and NGC 7538/IRS 9 occur at 3.536 μm (2828 cm⁻¹), in good agreement with pure CH₃OH ice. In W33A, the feature occurs at 3.534 μm (2830 cm⁻¹). We have fitted this feature with a mix of the two samples described above, as indicated in Table 6.

The feature in Mon R2/IRS 2 occurs at 3.528 μm (2834 cm⁻¹). This is too short a wavelength to be consistent with pure CH₃OH. The weak ISM mix provides a better, although still not exact, fit with τ(3.53) ≈ 0.033 ± 0.010. Presumably an even more water-rich mix would improve the fit. It would be desirable to have laboratory spectra of such mixtures.

Previous studies indicated that the solid methanol toward W33A, GL 2136, and NGC 7538/IRS 9 is in a CH₃OH-rich phase with CH₃OH/H₂O ≳ 0.5 (Skinner et al. 1992; Allamandola et al. 1992; Schutte et al. 1996a; Dartois et al. 1999), and our fits confirm this. The 3.53 μm feature in W33A is consistent with pure CH₃OH, and the weak ISM mix provides a better fit. In GL 2136, the feature at 3.536 μm is due to pure CH₃OH, while the feature at 3.534 μm is due to a mix of pure CH₃OH and a weak ISM mix.

In Table 5, we summarize the results of our fits. The optical depth of the 3.53 μm absorption feature, 1 σ error in parentheses. References for τ(3.25) are in Table 4.

### Table 5

| Object         | τ(3.25)  | N(C-H)  | N(H)  | [C-H]/H |
|----------------|---------|---------|-------|---------|
|                | (0.007) | (10⁸ cm⁻²) | (10²³ cm⁻²) | (10⁻⁵) |
| Mon R2/IRS 3   | 0.049   | 2.1     | 1.5   | 1.4     |
| Elias 29       | <0.03   | <1.3    | 0.53  | <2.4    |
| SVS 20         | 0.021   | 0.91    | 0.70  | 1.3     |
| RCrA/IRS 1     | 0.032   | 1.4     | 0.42  | 3.3     |
| SI40/IRS 1     | 0.036   | 1.6     | 1.4   | 1.1     |
| NGC 7538/IRS 1 | 0.078   | 3.4     | 2.2   | 1.5     |

|                | (10⁻⁵) |
|----------------|-------|
| Mon R2/IRS 3   | 0.2    |
| Elias 29       | 0.1    |
| SVS 20         | 0.1    |
| RCrA/IRS 1     | 0.1    |
| SI40/IRS 1     | 0.1    |
| NGC 7538/IRS 1 | 0.3    |

* Optical depth of 3.25 μm absorption feature. 1 σ error in parentheses. References for τ(3.25) are in Table 4.

b Column density of aromatic C-H bonds calculated from N(C-H) = τ(3.25)Δν/ΔA with A = 1.7 × 10⁻¹⁸ cm/C-H bond (Sellgren et al. 1995) and Δν = 74 cm⁻¹. 1 σ error in parentheses.

c Column density of hydrogen gas estimated from N(H) = 3.5 × 10²² × τ(9.7) cm⁻² (Tielens et al. 1991). References for τ(9.7) are in Table 4.

A Abundance of aromatic C-H bonds relative to hydrogen gas. 1 σ error in parentheses.
Mon R2/IRS 2 suggests that solid methanol can also be found within H$_2$O-rich ice having CH$_3$OH/H$_2$O $\leq 0.1$.

An additional indicator of CH$_3$OH in H$_2$O-rich environments would be the presence of two weak features that appear at 3.38 and 3.41 $\mu$m (Schutte et al. 1996a). These can be seen in the laboratory data in Figure 11. The present signal to noise is not high enough to constrain the presence of these features in any of the sources.

Column densities and CH$_3$OH abundances are listed in Table 6. For W33A, the column density of H$_2$O ice is uncertain. The range given results from converting the observed optical depths of the 3.1 and 6.0 $\mu$m features to column densities. But, as discussed above, the 3.1 $\mu$m band is most likely filled in by light that undergoes less ice extinction. On the other hand, the 6.0 $\mu$m band may contain other absorbers (Schutte et al. 1996b). The range given should bracket the true line-of-sight column density. It should be noted that the CH$_3$OH column density may be an underestimate if the filling-in noted above is also important at 3.53 $\mu$m.

In the other three sources, the CH$_3$OH/H$_2$O ice abundance derived from the 3.53 $\mu$m band ranges from 3% to 5%. The derived value of the abundance for GL 2136 is in agreement with that derived by Schutte et al. (1996a) from the same band. The derived values for W33A and NGC 7538/IRS 9 are roughly a factor 3 lower than those of Allamandola et al. (1992), due to the use of different band strengths, different adopted continua, and different assumed contributions of the 3.47 $\mu$m feature. Our abundance range for W33A, 3%–16%, is in reasonable agreement with that of Dartois et al. (1999), 5%–22%.

Upper limits to the CH$_3$OH/H$_2$O ice ratio toward other sources have been estimated (Chiar et al. 1996; Dartois et al. 1999). The most stringent is that for W3/IRS 5, for which the upper limit is of order 1%. In contrast, Dartois et al. (1999) estimate a very high abundance of 30% for RAFGL 7009S. Thus solid CH$_3$OH is common along molecular cloud lines of sight with H$_2$O ice, with a typical abundance of a few percent, but its abundance definitely varies.

There are two notable aspects about the methanol abundances. First, the typical values (1%–5% relative to H$_2$O) of the CH$_3$OH abundance are very similar to the values in comets, which are derived from the same band in gas-phase fluorescence (Hoban et al. 1991; Bockelée-Morvan, Brooke, & Crovisier 1995; DiSanti et al. 1995). This provides some supporting evidence for the direct incorporation of interstellar ice grains into comets.

Second, the CH$_3$OH/H$_2$O ice ratio toward NGC 7538/IRS 9 is similar to the ratios toward GL 2136 and Mon R2/IRS 2, but the relative abundance of solid CO trapped in nonpolar ices toward this source is ≥5 times higher (Tielens et al. 1991; Chiar et al. 1998). Thus the abundance of solid CH$_3$OH is not tightly coupled to this CO component, which is believed to form in dense regions of molecular clouds where most of the hydrogen is molecular (Tielens et al. 1991). This favors theories that postulate the formation of solid CH$_3$OH by hydrogen-addition reactions in regions where atomic hydrogen predominates, as has also been proposed for H$_2$O ice (e.g., d’Hendecourt, Allamandola, & Greenberg 1985). The abundance of solid CO trapped in polar ices (presumably H$_2$O) is also similar in all three sources (2%–3%, Tielens et al. 1991) and this CO component may form under similar conditions.

### Table 6

| Object          | $\tau$(3.53)$^a$ | Fit Type$^b$ | $N$(CH$_3$OH)$^e$ | $N$(H$_2$O)$^f$ | [CH$_3$OH/H$_2$O]$^i$ |
|-----------------|-----------------|--------------|-------------------|-----------------|-----------------------|
| Mon R2/IRS 2    | 0.033 (0.010)   | Weak ISM mix | 1.3 (0.4)         | 0.42$^e$        | 0.031 (0.009)         |
| W33A           | 0.27 (0.05)     | Pure CH$_3$OH (+) | 11.9 (2.2)     | 0.9–4.2$^f$    | 0.03–0.16             |
|                 | 0.07 (0.02)     | Weak ISM mix | 2.7 (0.8)         | ...            | ...                   |
| GL 2136        | 0.060 (0.010)   | Pure CH$_3$OH | 2.6 (0.4)         | 0.50$^g$        | 0.052 (0.009)         |
| NGC 7538/IRS 9 | 0.070 (0.01)    | Pure CH$_3$OH | 3.0 (0.4)         | 0.7$^i$         | 0.043 (0.006)         |

$^a$ Optical depth of 3.53 $\mu$m absorption feature. 1 $\sigma$ error in parentheses.

$^b$ For the weak ISM mix, a FWHM $\Delta v = 29$ cm$^{-1}$ and absorbance $A = 7.5 \times 10^{-18}$ cm molecule$^{-1}$ (Hudgins et al. 1993) were assumed. For pure CH$_3$OH, a FWHM $\Delta v = 29$ cm$^{-1}$ and absorbance $A = 6.6 \times 10^{-18}$ cm molecule$^{-1}$ (Schutte et al. 1996a) were assumed.

$^c$ Column density of solid CH$_3$OH calculated from $N$(CH$_3$OH) = $\tau$(3.53)$\Delta v$ (Allamandola et al. 1992). 1 $\sigma$ error in parentheses.

$^d$ Column density of H$_2$O ice.

$^e$ Abundance of solid CH$_3$OH relative to H$_2$O ice. 1 $\sigma$ error in parentheses.

$^f$ Estimated from the 3.1 $\mu$m band measured by Smith et al. 1989.

$^g$ Estimated from the 3.1 and 6.0 $\mu$m bands by Allamandola et al. 1992.

$^h$ Estimated from the 3.1 $\mu$m band measured by Schutte et al. 1996a.

$^i$ Estimated from the 3.1 $\mu$m band by Allamandola et al. 1992.

### 9. ADDITIONAL NARROW ABSORPTION NEAR 3.47 $\mu$m

There is an additional narrow absorption feature near 3.47 $\mu$m (2882 cm$^{-1}$) in the spectrum of W33A (Fig. 11). This region was excluded from the fit with the 3.47 $\mu$m Gaussian plus solid methanol for W33A. It is unlikely to be simply structure within the broad 3.47 $\mu$m feature as it does not appear at the same level in well-measured 3.47 $\mu$m features like those toward Mon R2/IRS 3 (Sellgren et al. 1995) and W3/IRS 5 (Brooke et al. 1996). The feature is detected at the 3 $\sigma$ level. A similar absorption feature was noted by Dartois et al. (1999).

Before examining the feature toward W33A, we discuss the spectrum of GL 2136 in this region. Schutte et al. (1996a) proposed that a feature at 3.473 $\mu$m (2879 cm$^{-1}$) with FWHM $\approx 25$ cm$^{-1}$ was present in GL 2136 with an optical depth $\tau \approx 0.01$. They identified the feature as the $v_5$ band of solid H$_2$CO in a mixture with H$_2$O and CH$_3$OH. Our spectrum of GL 2136 does not show the same structure that led Schutte et al. (1996a) to claim the presence of a feature, and the current spectrum has higher signal to noise.
In our spectrum, this region resembles the peak of a broad 3.47 μm absorption feature like that seen in other sources. However, due to uncertainties in baselines we cannot rule out some contribution from solid H₂CO at the bottom of the band. Our 3σ upper limit is τ < 0.01, i.e., comparable to the claimed detection, which corresponds to a solid H₂CO column density of ≲3 × 10⁻¹⁷ cm⁻² and an abundance of ≲6% relative to H₂O using the same bandwidth and strength adopted by Schutte et al. (1996a). If this much H₂CO were present, part of the 3.53 μm band would be due to the ν₁ H₂CO band and the solid CH₃OH abundance would be roughly 9% lower. But as we see no evidence for solid H₂CO, we prefer attributing all of the 3.53 μm band to solid CH₃OH.

The narrow 3.47 μm feature in W33A falls at a wavelength consistent with solid H₂CO in various mixtures with CH₃OH and H₂O (Schutte et al. 1996a), but the feature appears asymmetric, unlike H₂CO. If the excess absorption is interpreted as entirely due to the ν₁ band of H₂CO, the peak optical depth of τ ≳ 0.06 would imply a column density of 1.8 × 10¹⁷ cm⁻². As discussed above, the H₂O ice column density to W33A is uncertain, but this upper limit to the optical depth corresponds to a solid H₂CO abundance of ≲4%–20% relative to H₂O. If this feature were due to H₂CO, the ν₁ H₂CO band would contribute to the 3.53 μm band and methanol abundances would be ≲12% lower.

Another possible contributor to the narrow 3.47 μm feature is solid ethane, C₂H₆, which has a narrow (FWHM ≈ 6 cm⁻¹) band at 3.472 μm (2880 cm⁻¹) (Boudin, Schutte, & Greenberg 1998). A stronger C₂H₆ band occurs at 3.365 μm (2972 cm⁻¹) and the optical depth of this feature should be 2–3 times higher. The present data for W33A would be consistent with a 3σ optical depth upper limit of approximately 0.06 for this feature. Thus up to about half of the apparent narrow 3.47 μm feature could be due to solid C₂H₆. This would correspond to a solid C₂H₆ column density of 3.0 × 10¹⁷ cm⁻² or 0.1%–0.3% relative to H₂O ice. This is near the abundance of C₂H₆ in comets C/1996 B₂ Hyakutake and C/1995 O₁ Hale-Bopp of ~0.4% relative to H₂O (Mumma et al. 1996; Weaver et al. 1999). Future, higher signal-to-noise spectra of W33A in this region should be able to distinguish possible contributions of solid H₂CO and C₂H₆.

10. CONCLUSIONS

1. The optical depth of the broad absorption feature at 3.47 μm seen on the long-wavelength wing of molecular cloud H₂O ice bands is correlated with the optical depth of H₂O ice, in agreement with an earlier conclusion based on a smaller data set. If the feature is due to C-H bonds, the abundance of the C-H bonds must be closely related to that of H₂O ice.

2. The broad absorption feature at 3.25 μm was detected toward two more young stellar objects. There are insufficient data to draw any firm conclusions, but the optical depths measured to date correlate better with the refractory silicates than with H₂O ice, providing evidence that supports an identification with aromatic hydrocarbons at low temperature.

3. The 3.53 μm solid CH₃OH features toward W33A, GL 2136, and NGC 7538/IRS 9 can be fitted by CH₃OH-rich ices, whereas the wavelength of the feature toward Mon R2/IRS 2 suggests an H₂O-rich ice environment. Solid methanol abundances toward GL 2136, NGC 7538/IRS 9, and Mon R2/IRS 2 are 3%–5% relative to H₂O ice, similar to cometary abundances.

4. There is an additional narrow absorption feature near 3.47 μm toward W33A. Possible contributors are solid H₂CO and solid C₂H₆.

5. The H₂O ice toward W51/IRS 2 is located primarily in front of the eastern component, is partially crystalline, and has an optical depth τ(3.1) = 2.4 ± 0.2. Spectra of RNO 91 from 2 to 4 μm reveal stellar (or circumstellar) CO gas absorption and an H₂O ice band optical depth τ(3.1) = 2.1 ± 0.2.

The spectra from 1995 September were obtained through the UKIRT Service Programme. R. Joyce (NOAO) obtained and reduced the spectrum of Mon R2/IRS 2 for us. We thank D. Crisp (JPL) for making computer resources available.

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