High Resolution 4.7 μm Keck/NIRSPEC Spectra of Protostars. I: Ices and Infalling Gas in the Disk of L1489 IRS

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HIGH RESOLUTION 4.7 µm KECK/NIRSPEC SPECTRA OF PROTOTARS. I: ICES AND INFALLING GAS IN THE DISK OF L1489 IRS

A.C.A. Boogert 1, M.R. Hogerheijde 2, G.A. Blake 5

ABSTRACT

We explore the infrared M band (4.7 µm) spectrum of the class I protostar L1489 IRS in the Taurus Molecular Cloud. This is the highest resolution wide coverage spectrum at this wavelength of a low mass protostar observed to date (R = 25,000; Δv = 12 km s⁻¹). A large number of narrow absorption lines of gas phase 12CO, 13CO, and C18O are detected, as well as a prominent band of solid 12CO. The gas phase 12CO lines have red shifted absorption wings (up to 100 km s⁻¹), which likely originate from warm disk material falling toward the central object. Both the isotopes and the extent of the 12CO line wings are successfully fitted with a contracting disk model of this evolutionary transitional object (Hogerheijde 2001). This shows that the inward motions seen in millimeter wave emission lines continue to within ~0.1 AU from the star. The amount of high velocity infalling gas is however overestimated by this model, suggesting that only part of the disk is infalling, e.g. a hot surface layer or hot gas in magnetic field tubes. The colder parts of the disk are traced by the prominent CO ice band. The band profile results from CO in 'polar' ices (CO mixed with H₂O), and CO in 'apolar' ices. At the high spectral resolution, the 'apolar' component is, for the first time, resolved into two distinct components, likely due to pure CO and CO mixed with CO₂, O₂ and/or N₂. The ices have probably experienced thermal processing in the upper disk layer traced by our pencil absorption beam: much of the volatile 'apolar' ices has evaporated, the depletion factor of CO onto grains is remarkably low (~7%), and the CO₂ traced in the CO band profile was possibly formed energetically. This study shows that high spectral resolution 4.7 µm observations provide important and unique information on the dynamics and structure of protostellar disks and the origin and evolution of ices in these disks.

Subject headings: dust, extinction—IrInfrared: ISM—ISM: molecules—stars: formation—stars: individual (L1489 IRS)—planetary systems: protoplanetary disks

1. INTRODUCTION

In the process of low mass star formation, a mixture of gas, dust, and ices accumulates in protostellar envelopes and disks. The fate of this molecular material is diverse. Most of it will fall toward the protostar and dissipate in the inner disk region or stellar photosphere. Some material will be blown away and destroyed by the stellar wind. Some may survive and be the building material for comets and planets. Major aspects of this complicated process are not well understood, and poorly observationally constrained. For example, do the ices that form comets still resemble ices of the original pristine molecular clouds or are new ices of different composition being formed in the envelope or disk? The type of ices being formed depends on the composition of the gas that accretes onto grains. Reducing environments produce H₂O-rich ('polar') ices, while in cold hot environments 'apolar' ices rich in CO, N₂, and O₂ can be formed (Tielens & Hagen 1982). Depending on the composition, ices evaporate between temperatures of 18 and 90 K. Also, heat can change the solid state structure of ices by for example crystallization. Energetic particles (e.g. cosmic rays) and ultraviolet (UV) radiation are able to initiate reactions in ices and form new species. Dynamics and shocks within disks may be able to destroy ices as well.

Clearly, to determine the relative importance of these ice formation and destruction processes, knowledge of the physical conditions and structure of envelopes and disks is crucial. Much theoretical and observational work on this topic has been done over the last ~10 years. Molecular gas was detected in a suite of protostellar disks by millimeter wave observations sensitive to emission over radii of several hundred AU (Dutrey, Guilloteau, & Guelin 1997; Thi et al. 2001). Gas phase abundances were found to be reduced by factors of 5 to several 100, depending on the source and the sublimation temperature of the molecules. Models of disk mid-planes indeed show high depletions because of the formation of icy mantles on grains (Aikawa et al. 1997; Willacy et al. 1998). The predicted depletions were in fact higher than observed and thus desorption mechanisms are needed to explain the millimeter wave observations (Goldsmith, Langer, & Velusamy 1999). It was realized that this mechanism is able to explain the depletion factors of several 100, which is achieved by the influence of the stellar radiation a layer with...
This nominal spectral resolution was verified by measuring the Gaussian width of absorption lines in a variety of astrophysical sources.
High Resolution 4.7 μm Spectroscopy of L1489 IRS

3. RESULTS

The fully reduced echelle spectrum of L1489 IRS shows, in great detail, many deep narrow absorption lines of gas phase $^{12}$CO and $^{13}$CO, and a few weak lines of C$^{18}$O (Fig. 1). These lines were identified, using the line frequencies in the HITRAN catalogue (Rothman et al. 1992). The broad absorption feature between 2122-2149 cm$^{-1}$ can be attributed to the stretching vibration mode of $^{12}$CO in ices along this line of sight.

In order to analyze these gas and solid state absorption features, a shallow, second order polynomial continuum was applied to derive the optical depth spectrum. The solid CO band was then analyzed using available laboratory experiments (§3.2). The derivation of physical parameters from the gas phase lines is highly model dependent. First, we will derive temperatures and column densities using the standard curve of growth and rotation diagram techniques (§3.1). Then, we will independently test an astrophysically relevant power law model in §4.1. This information is combined in §4.3 to discuss the origin and thermal history of the solid CO seen in this line of sight.

3.1. Gas Phase CO

The $^{12}$CO lines have a complicated profile. Deep lines are present at a velocity of +43 km s$^{-1}$ with respect to
Then, we find that all isotopes are best fit simultaneously to unresolved lines at the observed peak optical depth. Equivalent widths in Table 1 with 40%, which corresponds sides. As a first order correction we lowered the $^{12}$C$^0$ by gas not seen in lsCO, both on the blue and red shifted above, the main $^{12}$CO component is clearly contaminated by gas not seen in lsCO, as evidenced by the high signal-to-noise average line profile (Fig. 2). We derived equivalent widths for the isotopes and $^{12}$CO components (Table 1), and applied a standard curve of growth technique to calculate column densities for each $J$ level. The comparison of equal $J$ levels of C$^{18}$O, $^{13}$CO, and main $^{12}$CO component provides a handle on the intrinsic line width $b_D$ (=FWHM/2/$\sqrt{\ln 2}$), in the assumption that all material absorbs at the same velocity (however, see §4.1). One also has to assume that the isotope ratios are constant along the line of sight ($^{12}$CO/$^{13}$CO=80 and $^{12}$CO/C$^{18}$O=560; Wilson & Rood 1994). The equivalent widths of C$^{18}$O and $^{13}$CO are then simultaneously fit at $b_D$=0.8 km s$^{-1}$. Lower $b_D$ significantly (> 3$\sigma$) underestimates the $^{13}$CO lines, with respect to C$^{18}$O. As mentioned above, the main $^{12}$CO component is clearly contaminated by gas not seen in $^{12}$CO, both on the blue and red shifted sides. As a first order correction we lowered the $^{12}$CO equivalent widths in Table 1 with 40%, which corresponds to unresolved lines at the observed peak optical depth. Then, we find that all isotopes are best fit simultaneously at $b_D$=1.4±0.1 km s$^{-1}$. This would be an upper limit if the correction for contamination of the $^{12}$CO lines were too small. Hence, this curve of growth analysis of the CO isotopes shows that, in the assumption that all gas absorbs at the same velocity, $b_D$ is limited to 0.8$c$b$<1.5$ km s$^{-1}$.

With the column densities per $J$ level at hand, a rotation diagram was constructed for the $^{13}$CO lines (Fig. 3) to derive the total column density and temperature at a number of allowed $b_D$ values (Table 2). Clearly, the rotation diagram shows a double temperature structure, much resembling that of high mass objects (Mitchell et al. 1990): cold ($T$ $\sim$ 15 K), and warm gas ($T$ $\sim$ 250 K) are present along the same line of sight. The column density of the cold component toward L1489 IRS is a particularly strong function of $b_D$, increasing by an order of magnitude from 0.7 to 1.3 km s$^{-1}$. An independent CO column of 1.4x10$^{19}$ cm$^{-2}$ can be estimated from $A_V=29$ (Myers et al. 1987), assuming the dust and gas are co-spatial. This would suggest $b_D$ is in the 1.0-1.3 km s$^{-1}$ range.
significant amount of warm gas ($T \sim 250$ K) are present within $\sim 3$ km s$^{-1}$ of the systemic velocity (Table 2). The $^{12}$CO lines show that warm gas at $T \sim 250$ K is also present at highly red shifted velocities ($20 - 100$ km s$^{-1}$), but at a factor 10 lower column. A small amount of warm gas is present at low red and blue shifted velocities as well (within 10 km s$^{-1}$). As further described in §4.1, the gas components at the red shifted and systemic velocities can be fitted within the same physical model of a contracting disk, but the origin of the warm gas at low blue shifted velocities is more difficult to explain.

### 3.2. Solid CO

The broad absorption feature between 2122-2149 cm$^{-1}$ (Fig. 1) can be entirely attributed to the stretching vibration mode of $^{12}$CO in circumstellar ices (§4.3). The high spectral resolution allows, for the first time, to unambiguously separate the gas phase CO lines from the solid state absorption and study the solid CO band profile in great detail. In accordance with previous, low resolution studies (Chiar et al. 1998; Teixeira et al. 1998), a distinct narrow feature is seen at 2140 cm$^{-1}$, and a significantly broader component at longer wavelengths. Our data however, indicates the presence of a new, third component on the blue side, separate from the narrow 2140 cm$^{-1}$ feature, most notable by a change of the blue slope at 2142 cm$^{-1}$ (Fig. 1).

In order to explain the shape of this CO absorption profile, we have taken laboratory experiments of solid CO from the literature (Sandford et al. 1988; Schmitt, Green-

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### TABLE 1

**Equivalent Widths**

<table>
<thead>
<tr>
<th>transition $^{12}$CO</th>
<th>$W_{v}$</th>
<th>transition $^{13}$CO</th>
<th>$W_{v}$</th>
<th>transition $^{13}$C$^{18}$O</th>
<th>$W_{v}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R(5) 88 (11)</td>
<td>70 (22)</td>
<td>R(17) 65 (2)</td>
<td>&lt; 3</td>
<td>R(6) 6 (2)</td>
<td>&lt;3</td>
</tr>
<tr>
<td>R(4) 84 (10)</td>
<td>54 (17)</td>
<td>R(16) 5 (2)</td>
<td>&lt; 5</td>
<td>R(5) 6 (2)</td>
<td>...</td>
</tr>
<tr>
<td>R(3) 67 (9)</td>
<td>55 (18)</td>
<td>R(15) 5 (2)</td>
<td>&lt; 4</td>
<td>R(4) 6 (2)</td>
<td>...</td>
</tr>
<tr>
<td>R(2) 73 (10)</td>
<td>64 (20)</td>
<td>R(14) ...</td>
<td>R(3)</td>
<td>&lt; 5</td>
<td>...</td>
</tr>
<tr>
<td>R(1) 70 (9)</td>
<td>39 (12)</td>
<td>R(13) ...</td>
<td>R(2)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>R(0) 68 (9)</td>
<td>41 (14)</td>
<td>R(12) ...</td>
<td>R(1)</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>P(1) 65 (9)</td>
<td>11 (4)</td>
<td>R(11) 6 (2)</td>
<td>P(1)</td>
<td>&lt; 3</td>
<td>...</td>
</tr>
<tr>
<td>P(2) 72 (10)</td>
<td>30 (10)</td>
<td>R(10) 6 (2)</td>
<td>P(2)</td>
<td>&lt; 3</td>
<td>...</td>
</tr>
<tr>
<td>P(3) 80 (11)</td>
<td>21 (7)</td>
<td>R(9) 7 (2)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>P(4) 69 (9)</td>
<td>82 (26)</td>
<td>R(8) ...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>P(5) 84 (11)</td>
<td>73 (25)</td>
<td>R(7) 12 (3)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>P(6) 85 (10)</td>
<td>65 (20)</td>
<td>R(6) 13 (2)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>P(7) 85 (10)</td>
<td>90 (28)</td>
<td>R(5) 19 (2)</td>
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<td>...</td>
<td>...</td>
</tr>
<tr>
<td>P(8) 85 (11)</td>
<td>71 (22)</td>
<td>R(4) 17 (2)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
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<td>69 (21)</td>
<td>R(3) 21 (2)</td>
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<td>...</td>
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<tr>
<td>P(10) 86 (10)</td>
<td>84 (26)</td>
<td>R(2) 17 (2)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>P(11) 79 (10)</td>
<td>61 (18)</td>
<td>R(1) ...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>P(12) 79 (11)</td>
<td>56 (17)</td>
<td>R(0) 24 (2)</td>
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<td>...</td>
<td>...</td>
</tr>
<tr>
<td>P(13) 88 (12)</td>
<td>43 (13)</td>
<td>P(1) 22 (2)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>P(14) 69 (9)</td>
<td>64 (19)</td>
<td>P(2) 25 (2)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>P(15) 72 (10)</td>
<td>53 (16)</td>
<td>P(3) 18 (2)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>P(16) ...</td>
<td>...</td>
<td>P(4) 15 (2)</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

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### TABLE 2

**Physical Parameters From Curve of Growth and Rotation Diagram**

<table>
<thead>
<tr>
<th>$T_{\text{rot}}$</th>
<th>$b_{D}$</th>
<th>$N(^{12}$CO)$^{a}$</th>
<th>$v_{\text{lsr}}$</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>19$^{+5}_{-5}$</td>
<td>1.6</td>
<td>6</td>
<td>5±3</td>
<td>circumstellar disk+foreground; from $^{13}$CO</td>
</tr>
<tr>
<td>15$^{+5}_{-5}$</td>
<td>1.3</td>
<td>10</td>
<td>5±3</td>
<td>as above, but alternative $b_{D}$</td>
</tr>
<tr>
<td>13$^{+5}_{-5}$</td>
<td>1.0</td>
<td>19</td>
<td>5±3</td>
<td>as above, but alternative $b_{D}$</td>
</tr>
<tr>
<td>11$^{+5}_{-5}$</td>
<td>0.7</td>
<td>96</td>
<td>5±3</td>
<td>as above, but alternative $b_{D}$</td>
</tr>
<tr>
<td>300$^{+300}_{-150}$</td>
<td>1.3</td>
<td>2.4</td>
<td>5±3</td>
<td>disk; from $^{13}$CO</td>
</tr>
<tr>
<td>250$^{+150}_{-100}$</td>
<td>1.0/0.7</td>
<td>2.8</td>
<td>5±3</td>
<td>as above, but alternative $b_{D}$</td>
</tr>
<tr>
<td>250$^{+500}_{-100}$</td>
<td>&lt;32</td>
<td>0.20±0.03$^{b}$</td>
<td>28±6</td>
<td>$^{12}$CO red wing</td>
</tr>
<tr>
<td>500±250</td>
<td>&lt;12</td>
<td>0.06$^{b}$</td>
<td>-5/15</td>
<td>blue and red wings resolved $^{12}$CO main</td>
</tr>
</tbody>
</table>

$^{a}$ assuming $N(^{12}$CO)/$N(^{13}$CO)=80

$^{b}$ assuming optically thin absorption
do not induce strong particle shape effects and therefore pure CO does not provide a good fit to L1489 IRS for any particle shape.

Broadening of the laboratory profile, in order to fit the 2140 cm\(^{-1}\) feature in L1489 IRS, is also achieved by adding a small amount of CO\(_2\), O\(_2\), or H\(_2\)O molecules. To avoid a too large broadening, and minimize aforementioned particle shape effects, this mixture needs to be diluted in N\(_2\). This astrophysically relevant molecule does not broaden the feature, and gives a small blue shift (Ehrenfreund et al. 1997; Elsila et al. 1997), required to fit the 2140 cm\(^{-1}\) feature in L1489 IRS. Thus, both this mixture, as well as ellipsoidally shaped pure CO ice grains, provide good fits to the central 2140 cm\(^{-1}\) feature.

Now, the width significantly increases, and the peak shifts to longer wavelengths by diluting CO in a mixture of molecules with large dipole moments such as H\(_2\)O or CH\(_3\)OH (Sandford et al. 1988; Tielens et al. 1991). This particular behavior is needed to fit the broad long wavelength wing seen toward L1489 IRS. Solid CH\(_3\)OH has an abundance less than a few percent of solid H\(_2\)O toward low mass objects (Chiar, Adamson, & Whittet 1996). H\(_2\)O seems the best dilutant, because of its large interstellar abundance. The use of H\(_2\)O:CO mixtures requires interesting additional constraints. Although a low temperature, unprocessed H\(_2\)O–rich ice does provide a good fit to the red wing, it can be excluded based on the presence of a prominent second absorption at \(~2150\) cm\(^{-1}\) in the laboratory, which is clearly absent toward L1489 IRS. This second peak is caused by CO molecules located in pockets in an amorphous ice. These CO molecules are weakly bound, and the \(~2150\) cm\(^{-1}\) peak disappears rapidly at higher \(T\) or as a result of cosmic ray hits (Sandford et al. 1988). Thus, the H\(_2\)O ice responsible for the long wavelength wing toward L1489 IRS must be thermally (\(T > 50\) K) or energetically processed.

The blue wing seen at \(~2143\) cm\(^{-1}\) toward L1489 IRS can only be explained by an apolar ice. Adding a significant amount of CO\(_2\) to a CO ice (CO\(_2\)/CO\(> 1\)) results in the blue shift and broadening required to fit the observed wing. Somewhat less CO\(_2\) is needed (CO\(_2\)/CO\(~ 0.5\)) when a large amount of O\(_2\) is present. N\(_2\) may be added as well, but is not essential except as a dilutant to reduce the effects of particle shape. A good fit is obtained by the mixture N\(_2\):O\(_2\):CO\(_2\):CO=1.5:0.5:1, as proposed in Elsila et al. (1997). If CO\(_2\)/CO\(~ 0.5\) the band peaks at too high wavelength. In CO–rich ices this problem can however be overcome by particle shape effects (Fig. 4). In view of this effect it is not possible to constrain the relative molecular abundances of this interstellar component in more detail, but it is clear that an apolar CO\(_2\) or O\(_2\) ice is needed, different from the distinct 2140 cm\(^{-1}\) feature.

A three component fit to the entire CO ice band of L1489 IRS is shown in Fig. 5. Although this is not a unique fit, it does obey the global trends that we identified in the laboratory experiments.

Finally, the solid CO column density is derived by dividing the integrated optical depth over the band strength \(A\). We take \(A = 1.1 \times 10^{-17}\) cm molecule\(^{-1}\) independent of ice composition (Gerakines et al. 1998), and thus find \(N(\text{solid CO}) = \text{6.5} \times 10^{17} \text{ cm}^{-2}\). The main source of uncertainty here is in \(A\), which is about 10%. CO in polar ices
4. DISCUSSION

4.1. An Infalling Disk

The astrophysical meaning of the apparent two component temperature structure seen in the \(^{13}\)CO rotation diagram (Fig. 3) requires further investigation. For high mass protostars it was found that similar rotation diagrams can be 'mimicked' by power law models of spherical envelopes (van der Tak et al. 2000).

For L1489 IRS, the detection of molecular gas at a range of temperatures and red shifted velocities could indicate the presence of infalling gas at a range of radii from the protostar. Indeed, a 2000 AU radius contracting, disk-like structure was found in millimeter wave interferometer data (Hogerheijde & Sandell 2000). In a detailed follow-up study, Hogerheijde (2001) adopts a flared-disk model based on Chiang & Goldreich (1997) with a radial power-law distribution for the temperature

\[ T = 34(R/1000\text{ AU})^{-0.4} \text{ K}, \]

and a density distribution that has a power-law drop-off with radius and a vertical exponential drop-off with scale height \( h \)

\[ \rho(R, z) = \rho_0(R/1000\text{ AU})^{-1.5} \exp(-z^2/h^2) \text{ kg cm}^{-3}. \]

The scale-height \( h \) is assumed to be a simple function of \( R \), \( h = R/2 \). An inward-directed radial velocity field described as

\[ V_{in} = 1.3(R/100\text{ AU})^{-0.5} \text{ km s}^{-1} \]

is inferred, in addition to Keplerian rotation around a 0.65 \( M_\odot \) central star.

Can this contracting disk model, based on (sub-) millimeter emission observations with angular resolution of 4-8", reproduce the observed infrared CO absorption line profiles measured along a pencil beam? The absorption lines are modeled with the radiative transfer code of Hogerheijde & van der Tak (2000); the high densities in the disk ensure LTE excitation for the lines involved, and line trapping is neglected in the excitation calculation. The model spectra include dust opacity at a standard gas/dust ratio, as well as a \( N(\text{CO}) = 1 \times 10^{18} \text{ cm}^{-2} \) column of cold foreground material (15 K; Hogerheijde 2001); both factors do not affect the spectra in any significant way. The calculated spectrum is convolved with a Gaussian of FWHM=12 km s\(^{-1} \), which is the NIRSPEC instrumental resolution.

We find that, while keeping all other parameters the same as in Hogerheijde (2001), the assumed density profile sensitively influences the wings of the \(^{12}\)CO lines. This is enhanced by the fact that we are observing the flared disk of L1489 IRS at an inclination between 60° and < 90° (cf., Padgett et al. 1999), and the pencil beam crosses the disk at a few scale heights. Small changes in the density profile, for example induced by the thermal structure, have a large effect on the absorption line profile. In the model of Hogerheijde (2001) the scale height increases linearly with distance from the star, and thus the density \( \rho(l) \) along the line of sight \( l \) follows the density in the mid-plane (Eq. 2) reduced by a factor \( e^{-l/\tan^2(a)} \), with \( a \) being the inclination. Here, we include the effect of density variations, or deviations from the adopted scale height \( h = R/2 \), by relaxing the values of the density along the line of sight \( l \) by fitting \( \rho(l) = \rho_0(l/1000 \text{ AU})^{-p} \) to the data.

This initial model successfully fits the peak velocity and depth of both high and low \( J \) \(^{12}\)CO lines (Fig. 6). Its rotation diagram is quite different from that of the curve of growth analysis (Fig. 3), showing that rotation diagrams must be interpreted with great care. Our model also matches the range of velocities observed in the red wings of the \(^{12}\)CO lines, when taking \( p = 0.55 \pm 0.15 \). This is a much shallower density profile compared to that derived from millimeter wave data (\( p = 1.5 \); Eq. 2) and indicates that the scale height increases more than linear, i.e. the disk flares more than assumed in Hogerheijde (2001). With this result, it is possible to determine the important relation of disk scale height \( h(R) = a.e^{-\left(R\right)} \) as a function of \( R \), but only if the disk inclination is \textit{a priori} known. Unfortunately the inclination is not better constrained than within the range of 60° and < 90° imposed by near-infrared data (Padgett et al. 1999). We can therefore not distinguish between low and high values of \( a \) and corresponding high and low inclinations respectively. In either case, the total \(^{12}\)CO column along the pencil beam is \( 1.2 \times 10^{19} \text{ cm}^{-2} \), with 58% of the CO mass at a temperature of \( T = 20 - 60 \text{ K} \), 15% at \( 60 - 90 \text{ K} \), and 27% at \( 60 - 90 \text{ K} \). This result is of importance in §4.3 in the interpretation of the solid CO observations, and in particular in assessing the thermal history of ices. The total column of our model is in good agreement with the column derived from the visual extinction (\( 1.4 \times 10^{19} \text{ cm}^{-2} \), §3.1). It is also of the same order of magnitude as the total column through the mid-plane, calculated from dust and line emission (\( N(\text{CO}) = 6 \times 10^{18} \text{ cm}^{-2} \), Hogerheijde 2001), and confirms the relatively edge-on orientation of the disk.
However, apart from these successes, the $^{12}$CO lines show that our infalling disk model produces too much warm gas at high velocities (Fig. 6). The $^{12}$CO lines are a factor of 2.5 deeper, and, in contrast to $^{13}$CO, they peak at a too high velocity (+10 km s$^{-1}$) with respect to the observations. In principle, one could make the $^{12}$CO lines less deep by assuming that $\sim 1\%$ of the original, unextincted continuum flux (corresponding to 30\% of the extincted continuum) reaches the slit without passing through the disk, by scattering on large grains. The shift in peak velocity however requires a solution of a more fundamental origin. Perhaps the infall velocity function is shallower, and the disk is more rotationally supported at lower radii. The amount of warm gas at high velocities can also be lowered by assuming that only part of the disk participates in the high velocity inflow, such as a thin hot surface layer, or gas accelerated in magnetic field tubes directed from the inner disk to the stellar photosphere. Such a two component model is consistent with the rotation diagram derived from the curve of growth (Fig. 3), and also with the low observed mass accretion rate. If we take the inflow at face value, and assume that the entire disk participates, the mass accretion rate would be $10^{-6} M_\odot$, generating 7 $L_\odot$ in accretion luminosity. The star's $L_{bol}$ is estimated at 3.7 $L_\odot$ which also contains the stellar luminosity. It is therefore indeed likely that the mass accretion onto the star is significantly lower, as is also traced through the lack of the hydrogen Pf$\beta$ emission line in our spectrum (2148.8 cm$^{-1}$; Fig. 1) and the weakness of Br$\gamma$ emission (Mueller, Hartmann, & Calvet 1998).

4.2. Binarity?

An entirely different explanation for the line profiles may lie in the possibility that L1489 IRS is a protobinary system. A protobinary nature of L1489 IRS is suggested by various pieces of evidence (Lucas, Blundell, & Roche 2000; Wood et al. 2001 and references therein). The presence of a quadrupolar outflow system is inferred from K band polarization images, C$^{18}$O emission line profiles, Herbig-Haro knots that are scattered throughout the L1489 IRS environment, and a very complex near infrared scattered light pattern. Three dimensional models, in which the axisymmetry of the infalling circumstellar envelope is broken by multiple outflow cavities that are perpendicular to each other, are able to account for the observed morphology.

The putative binary itself, however, has not been resolved so far. An upper limit on the projected separation has been set at $< 20$ AU from near infrared images (Padgett et al. 1999). If the CO absorption line profile is in any way related to a binary system, then the large observed velocities ($\sim 23$ km s$^{-1}$; §3.1) may indeed favor a close binary system. The line profile is then expected to vary on a time scale of a few months, which can easily be tested. In this case, much of the observed warm gas might
be present in two small circumstellar disks, which are in a close orbit around each other. Some of the warm gas may also be present at low density in the central cavity created by the binary. The large column of cold gas may originate in the circumbinary disk. The binary extracts momentum from the 2000 AU circumbinary disk, setting up the inward motion seen in millimeter wave emission lines. We leave further investigation of this topic for future studies.

4.3. The Origin and Evolution of Ices

In order to establish if the solid CO observed toward L1489 IRS originates in foreground clouds or in a circumstellar (or binary) disk, it is worth to compare with ices observed in lines of sight not affected by star formation. Observations of field stars obscured by intervening quiescent material of the Taurus Molecular Cloud have revealed that solid CO is not present when the extinction $A_V \lesssim 5$ (e.g. Teixeira & Emerson 1999). The solid CO toward L1489 IRS can therefore not be associated with foreground clouds, which have a gas column of $N(^{12}\text{CO}) = 1 \times 10^{18}$ cm$^{-2}$ (Hogerheijde 2001), corresponding to $A_V \sim 2$.

Thus, the solid CO must be present in the disk of L1489 IRS. The absorption profile is intriguingly different from that seen in quiescent clouds. The broad red wing has a depth of ~30% with respect to the narrow 2140 cm$^{-1}$ peak, which is significantly more than toward all measured background stars (10%; Chiar et al. 1995). This may well be an effect of thermal processing along the L1489 IRS line of sight, because the sublimation temperatures of polar and apolar ices, causing the broad and narrow features respectively, are very different (90 versus 18 K). However, a chemical origin of an increased abundance of polar ices in disks cannot be excluded, because the apparently edge-on system Elias 18 in the Taurus Molecular Cloud has an extremely large CO depletion factor ($\text{solid}/[\text{gas+solid}] \sim 100\%$ versus 7% for L1489 IRS), but a deep red 'polar' CO wing is present as well (Shuping et al. 2001; Chiar et al. 1998). On the other hand, energetic processing may take place even in the cold disk of Elias 18 (Whittet et al. 2001). Clearly, it is necessary to observationally characterize the ices in circumstellar disks in much more detail.

If for now we assume the sublimation scenario, we can do some general extrapations which can be compared with the results of our gas phase study (§4.1). By scaling the long wavelength wing of solid CO of background field stars to that of L1489 IRS, we find that a column of $6 \times 10^{17}$ cm$^{-2}$ of CO has evaporated from the apolar ice component in the part of the L1489 IRS disk along the pencil absorption beam where $T < 90$ K (the sublimation temperature of polar ices). Then the column of solid CO that went from the quiescent cloud into building this part of the disk is $1.25 \times 10^{17}$ cm$^{-2}$. Extrapolating this further, we use the observed CO depletion factor of 30% toward field stars behind the Taurus Molecular Cloud (Chiar et al. 1995) to calculate that the original quiescent gas column must have been of the order of $3 \times 10^{18}$ cm$^{-2}$. Adding the evaporated column, the expected present day gas column at $T < 90$ K is $3.6 \times 10^{18}$ cm$^{-2}$. This is of the same order of magnitude as the CO column below 90 K in our collapsing disk model ($N(\text{CO})=8.7 \times 10^{18}$ cm$^{-2}$), which may indicate that no chemical change in the apolar/polar CO ice ratio and no significant additional depletion has occurred in the evolution from quiescent Taurus Molecular Cloud material to the formation of the L1489 IRS disk. This contrasts strongly with the very large depletions found in the (older) disks of T Tauri stars (Dutrey et al. 1997). The low CO depletion along the pencil beam toward L1489 IRS (7%) and the supposed signs of thermal processing (see below) may be due to the fact that our line of sight does not cross the disk mid-plane, i.e. the system is not exactly edge-on. The ice processing we see takes place higher in the disk atmosphere, perhaps in the warm layer below the super-heated dust layer responsible for millimeter wave line emission (van Zadelhoff et al. 2001). It must be noted that in the model of Hogerheijde (2001) the gas temperatures are larger than 25 K, prohibiting the formation of apolar ices and large CO depletions anywhere in the disk. The observed presence of apolar CO ices thus indicates that, as already suggested in §4.1, the line of sight may cross the cold, rotationally supported disk interior not traced in the observations and infall model of Hogerheijde (2001).

Apart from evaporation of apolar ices, other hints of thermal processing include the aforementioned absence of the 2150 cm$^{-1}$ absorption (§3.2), which occurs in cold unprocessed polar CO ices but disappears at temperatures $T > 50$ K. Also, the blue apolar wing may be a consequence of thermal processing. If the central 2140 cm$^{-1}$ peak is due to a mixture of O$_2$, N$_2$ and CO instead of pure CO (spectroscopically these cannot be distinguished), thermal or energetic processing (UV radiation from the ISRF, UV induced by H$_2$ cosmic ray collisions, or direct hits of cosmic rays) could efficiently produce CO$_2$. This could cause the band to broaden and shift to the position of the observed blue wing. Chemical models indicate that energetic processing of molecules in disks takes place on a time scale of 10$^8$ yrs (Aikawa et al. 1999), which is somewhat longer than the age of the disk of L1489 IRS ($\sim 5 \times 10^5$ yrs). This however applies to the disk mid-plane, and the time scale may well be shorter in the lower density higher disk layers that our observations of L1489 IRS trace. A possible problem with the energetic processing interpretation is the absence of a feature adjacent to the short wavelength side of the CO ice band, usually attributed to energetically produced C≡N bondings (Whittet et al. 2001). Another spectroscopic tracer of thermal processing is the signature of crystallization in the band profiles of H$_2$O and CO$_2$ ices. Our infalling disk model predicts that only 15% of the gas is within the temperature range at which ices crystallize (60–90 K), and thus crystallization is not expected to play a significant role in the disk of L1489 IRS. This model prediction can be tested with future high quality H$_2$O and CO$_2$ spectra of L1489 IRS.

In summary, several pieces of evidence indicate that the CO ices in the disk of L1489 IRS have experienced thermal or energetic processing. The strongest arguments are the low depletion factor and the low ratio of apolar to polar ices with respect to the quiescent Taurus Molecular Cloud material. This may be explained by the fact that the disk of L1489 IRS is seen under an angle, and our pencil absorption beam traces the warm upper disk layers.
5. SUMMARY AND FUTURE WORK

We have shown that valuable and unique information is obtained from high resolution spectroscopy of the CO fundamental at 4.7 μm toward the low mass class I protostar L1489 IRS in the Taurus Molecular Cloud. At a resolution of $R = 25,000$ (12 km s$^{-1}$) this object shows a multitude of deep ro-vibrational absorption lines of $^{12}$CO, as well as $^{13}$CO and C$^{18}$O. The isotopes trace large columns of warm and cold gas in the circumstellar disk at or within 3 km s$^{-1}$ of the systemic velocity, while the $^{12}$CO line profiles show warm gas that is red shifted at a range of velocities of up to 100 km s$^{-1}$. Both the line depth of the isotopes and the extent of the red shifted warm gas seen in $^{12}$CO are well explained by an infalling flared disk model with power laws for the temperature, infall velocity, and density (a small column of blue shifted gas seen in the $^{12}$CO line wing however remains unexplained). These observations show that the inward motions inferred on scales of several hundred AU through millimeter wave interferometry continue to within 0.1 AU of the star, where the velocity model of Hogerheijde (2001) predicts inward velocities exceeding several tens of km s$^{-1}$. A detailed comparison of our power law infall model however overestimates the amount of warm, high velocity infalling gas. Much of this gas must therefore be rotationally supported, and only a thin disk surface layer is infalling, or gas is accelerated along magnetic fields in the inner parts of the disk. High spatial resolution millimeter wave observations (with ALMA) are needed to test our model, e.g. to refine the determination of the velocity field in the inner disk parts and the dependence of the disk scale height on radius $h(R)$. Finally, high spatial resolution infrared interferometer observations would be able to see if L1489 IRS is a close binary system (< 20 AU), which is essential to assess the importance of magnetic fields in the inner parts of the disk. The present work shows that high spectral resolution 4.7 μm observations are a great tool to better understand protostellar disks, which define the initial conditions of planet and comet formation, both in the solid and gas phase. This is an exploratory study and needs to be followed up by observing a larger sample of protostellar disks at 4.7 μm to investigate the influence of parameters such as foreground contribution, disk inclination, age, and binarity on gas and ice band profiles.

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