University of Groningen

The interplay between dust, gas, ice, and protostars
Boogert, Abraham Cornelis Adwin

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
1999

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.
CHAPTER 7

Solid and gas phase inventory of the low mass protostar Elias 29 (\(\rho\) Oph)

To be submitted to Astronomy & Astrophysics by A.C.A. Boogert, C. Ceccarelli, A.G.G.M. Tielens, E.F. van Dishoeck, J.V. Keane, A.M.S. Boonman, D.C.B. Whittet, Th. de Graauw

ABSTRACT. The early phases of star formation are highly obscured, and can only be studied at infrared wavelengths and beyond. With infrared spectroscopy we are able to observe the dust continuum, and the rotation and vibration modes of molecules in absorption and emission. The physical conditions in the star forming region, as well as its geometry and evolutionary stage can thus be determined. We present the full 1-200 \(\mu\)m spectrum of the low luminosity (36 \(L_\odot\)) Class I protostellar object Elias 29 in the \(\rho\) Ophiuchi molecular cloud. It provides a unique amount of information. The continuum shape is remarkably flat. Against the continuum we see hot CO and H\(_2\)O gas at rather high abundances. On the other hand, and in contrast to high mass protostars, the CO, CO\(_2\), H\(_2\)O and “6.8 \(\mu\)m” ice bands show no signs of thermal processing. H I emission lines, probably originating from disk accretion, are also detected. Far-infrared CO lines are found to be in emission. We present a sub-millimeter spectral map of CO \(J = 6 \rightarrow 5\) emission, clearly showing the presence of a molecular outflow. In many aspects, Elias 29 resembles the Herbig Ae star AB Aur, although Elias 29 is less evolved, since it is highly obscured and has a much higher accretion and mass loss rate. Thus, the observations suggest that Elias 29 is a Class I object, with an optically thick disk, in a late accretion phase, approaching the transition to a Class II, Herbig Ae, star. We summarize the possible origins of the observed emission and absorption features, and compare the abundances with sites of high mass star formation.
CHAPTER 7. THE LOW MASS PROTOSTAR ELIAS 29

7.1 Introduction

The general picture of the various stages of low mass star formation has been formed since the 1980’s with the availability of infrared and millimeter wavelength broad band photometry from the ground, and with the IRAS satellite and KAO observatory (e.g., Lada & Wilking 1984; Adams, Lada, & Shu 1987; Hillenbrand et al. 1992; André, Ward-Thompson, & Barsony 1993). A classification scheme was made, where Class 0 and I objects peak in the far-infrared and are deeply embedded in their accreting envelopes. In the Class II phase, the wind of the protostar has cleared its surrounding environment, such that it becomes optically visible, and shows H I emission lines. The continuum emission of these objects peaks in the near-infrared, but there is still significant excess emission above the stellar continuum. They are believed to be surrounded by optically thick dusty disks. Finally, little dust emission remains for Class III objects, when the disk is optically thin, and planetary companions may have been formed.

The state of the material surrounding the protostars at each of these evolutionary stages is at present poorly known. The composition, thermal history, and distribution of gas, dust and ices can only be obtained through infrared and millimeter wavelength spectroscopic observations. The gas phase and solid state (ro-)vibrational bands of various molecules (CO, H$_2$O, CO$_2$, CH$_4$, silicates) in the near and mid-infrared (~2 - 20 µm) provide important information on the abundances and thermal history. The significance of thermal processing was shown by ground-based observations of the 3.07 µm, and 4.67 µm H$_2$O and CO ice bands (e.g. Smith et al. 1989; Tielens et al. 1991; Chiar et al. 1998), as well as for gaseous CO (Mitchell et al. 1991). With the launch of the Infrared Space Observatory in 1995 (Kessler et al. 1996), it became possible to observe all other molecular bands in the near-, mid-, and far-infrared. It was shown that protostellar evolution can be traced in the gas-to-solid abundance ratios (van Dishoeck et al. 1996; van Dishoeck & Blake 1998), and the profiles of the ice bands (Gerakines et al. 1999; Boogert et al. 1999). However, the focus has been on high mass protostars, which are bright and easier to observe. Whether the evolution of the material in the envelope of low mass protostars is similar, is by no means established. Low mass protostars evolve much slower, release less radiative energy, drive less energetic winds, and form disks.

To investigate the influence of low mass protostars on their molecular envelope, we study the low mass protostar Elias 29, also called WL 15 and YLW 7. On a large scale, Elias 29 lies in the south-east corner of the compact CO ridge L 1688, extended over 1 x 2 pc from south-east to north-west in the core of the ρ Ophiuchi cloud, at a distance of ~160 pc from the earth (Wilking & Lada 1983; Whittet 1974). It is the reddest object found in the near-infrared survey of this cloud by Elias (1978), without a counterpart at optical wavelengths. For our observations, we used Elias’s coordinates:

\[ \alpha(1950.0) = 16^h24^m07^s.6, \quad \delta(1950.0) = -24^\circ30'40''. \]

The overall spectrum of Elias 29 is typical for a heavily embedded Class I source, probably in a late accretion phase (Wilking et al. 1989; André & Montmerle 1994;
7.2 Observations

Greene & Lada 1996; Saraceno et al. 1996). The embedded nature is also revealed by its high extinction, and by the cold compact envelope observed at millimeter wavelengths (André & Montmerle 1994; Motte, André, & Neri 1998). Elias 29 is associated with a molecular outflow (Bontemps et al. 1996; Sekimoto et al. 1997). With a bolometric luminosity of \( \sim 36 \, L_\odot \) (Chen et al. 1995), Elias 29 is the most luminous protostar in the \( \rho \) Oph cloud, which makes this source very suitable to be observed with the ISO spectrometers.

This Chapter is structured as follows. Technical details on the ISO infrared and millimeter CO \( J = 6 \rightarrow 5 \) observations are given in Sect. 7.2. All the observed emission and absorption features are discussed in quite some detail in Sect. 7.3. Section 7.3.1 gives a description of the continuum shape, and a comparison to other lines of sight. The ice temperature and composition, and the silicate band depth with inferred extinction and column densities toward Elias 29 are discussed in Sect. 7.3.2. Then, numerous lines of gaseous CO and H\(_2\)O are detected, and modeled to derive gas temperatures and column densities (Sect. 7.3.3). The detected H I emission lines are presented and their origin is discussed in Sect. 7.3.4. Finally, the far-infrared CO emission lines, as well as a map of the CO \( J = 6 \rightarrow 5 \) emission surrounding Elias 29, are analyzed in Sect. 7.3.5. The momentum flux and mass loss rate of the detected molecular outflow are calculated. The molecular abundances and gas-to-solid ratios of Elias 29 are compared to a sample of lines of sight, ranging from dark cloud cores to evolved protostars. A comparison with high mass protostars is made (Sect. 7.4). Section 7.5 discusses the origin of the wealth of observed emission and absorption features and puts them in a geometrical picture, discussing the evidence for an accretion disk. We conclude in Sect. 7.6 with a summary and suggestions for future observations.

7.2 Observations

We have obtained spectra of the low mass protostar Elias 29 in the wavelength range 2.3–195 \( \mu m \). We also mapped the CO \( J = 6 \rightarrow 5 \) emission line in the region surrounding the infrared source.

7.2.1 The 2.3–45 \( \mu m \) spectrum

A low resolution \( (R = \lambda/\Delta\lambda = 400) \), full 2.3–45 \( \mu m \) spectrum of Elias 29 was obtained with the ISO Short Wavelength Spectrometer (ISO–SWS; de Graauw et al. 1996) during revolution 267 (August 10 1996). The ISO-SWS pipeline and calibration files, available in July 1998 at SRON Groningen were applied. The spectrum is generally of good quality, with well-matching up and down scans, and no serious dark current problems, except for band 2C (7–12 \( \mu m \)). Here, we found that the up and down scans deviate over the silicate band. One scan showed excellent agreement with a ground-based spectrum of Hanner, Brooke, & Tokunaga (1995), and
we used this to correct the deviating scan. Standard after-pipeline steps were applied, such as low order flat-fielding, sigma clipping and re-binning (see also Boogert et al. 1998). The twelve sub-spectra in the 2-45 μm range match fairly well at the overlap regions. Small correction factors (<15%) were applied to correct for the band jumps. At selected wavelength ranges (3—3.6, 4—9, and 19.5-28 μm), we also obtained a high resolution (R = 1500) ISO-SWS grating spectrum, in revolution 292 (September 04 1996). These were reduced similarly to the low resolution spectrum. We found that the overall shape of the spectrum near 4–5 μm is quite badly affected by detector memory effects, presumably due to the occurrence of scan breaks (de Graauw et al. 1996). We corrected for this, by applying a wavelength-dependent shift to match the low resolution spectrum. This does not affect our conclusions, since the high resolution spectrum was only used to study narrow features. Also, near 6.9 μm the scans deviate significantly because of memory effects. This problem is reflected in the large systematic error bars given in this Chapter, as they were derived from the difference between the average up and down scans.

### 7.2.2 The 45–190 μm spectrum

Elias 29 was observed during Revolution 484 (March 14 1997) with the ISO Long Wavelength Spectrometer (ISO–LWS; Clegg et al. 1996). We obtained 15 scans covering the range from 43 μm to 197 μm in the low resolution mode (R ~200) for a total of 2611 sec of integration time. The data was reduced using the Off-Line-Processing package (OLP) version 7 and the ISO-Spectral-Analysis-Package (ISAP) version 1.3. The spectra were flux calibrated using Uranus (Swinyard et al. 1996) and the absolute accuracy is estimated to be better than 30%. Finally, the LWS beam size remains roughly constant at all wavelengths, ~ 80'' FWHM (Swinyard et al. 1996).

### 7.2.3 The CO J = 6 → 5 spectral map

The 12CO J = 6 → 5 emission line (691.473 GHz; 433.8564 μm) was mapped in a 5×5 grid, spaced by 7'', covering a 20''×20'' field centered on the infrared source Elias 29. The observations were done with the “RxG” receiver on the James Clerk Maxwell Telescope (JCMT) on Mauna Kea during April 1995. The technical performance of this configuration is described in Harris et al. (1994). The spectral resolution was 0.61 km s⁻¹ per channel. The JCMT’s beam is composed of a 7'' FWHM Gaussian, containing 55% of the power, and an 18'' FWHM Gaussian with the remaining power. The data were converted from $T_A^*$ to $T_R$ scale, applying an efficiency factor $\eta_{is}=0.27$, which corrects for all instrumental scattering and loss terms (Kutner & Ulich 1981). The weather conditions were excellent, with a transmission at zenith of 0.6 at the CO J = 6 → 5 frequency. The sky background
emission was subtracted by switching frequently to a reference position. Due to the strong variability of sky emission at 690 GHz, a large position switch to a region in the ρ Ophiuchi cloud free of CO $J = 6 \rightarrow 5$ emission is not feasible. Instead, we used the beam switch mode, with the maximum possible chop throw. The reference position alternates between $+120''$ and $-120''$ in Azimuth. For each spatial point, these so-called “A” and “B” spectra were averaged to obtain the final spectrum. The difference between the A and B spectra indicates that in the NW and SE corners of our map, the reference position B was slightly contaminated by CO $J = 6 \rightarrow 5$ emission. The effective integration time on each position was 1 minute, yielding an RMS noise level of $T_R = 2.8$. Additionally, the $^{13}$CO $J = 6 \rightarrow 5$ line (661.067 GHz) was observed on the central position, as well as at one position at the edge of the $^{12}$CO map (ΔRA, ΔDec=–14″, +14″). The effective integration time was 4 and 8 minutes, yielding RMS noise levels of 1.8 and 1.0 K respectively. These observations are presented in Sect. 7.3.5.

7.3 Results

7.3.1 The spectral energy distribution (SED)

Elias 29 is only visible at wavelengths larger than ~1.5 μm (Fig. 7.1; Greene & Lada 1996; Elias 1978). The continuum emission rises steeply between 2–3 μm, reaches a maximum of $\lambda F_{\lambda}=15 \times 10^{-16}$ W cm$^{-2}$ at $\lambda \sim 5$ μm, and is remarkably flat with $\lambda F_{\lambda} \sim 8 \times 10^{-16}$ W cm$^{-2}$ between 20 and 100 μm. The emission has dropped to $\lambda F_{\lambda} \sim 4 \times 10^{-16}$ W cm$^{-2}$ at 200 μm, and by four orders of magnitude at 1300 μm. Our near-infrared spectral continuum fluxes are in excellent agreement with broad band fluxes from ground-based observations (Elias 1978). Also the ground-based narrow beam 10 and 20 μm observations, as well as the large beam 12 and 25 μm IRAS fluxes, match the ISO–SWS observation well, thus indicating that at these wavelengths the emission is extended less than 8″ (Fig. 7.1; Lada & Wilking 1984; Young, Lada, & Wilking 1986). At larger wavelengths, the emission still peaks at the near-infrared position of Elias 29, but is more extended (> 80″ in diameter). In particular, the IRAS 100 μm flux is a factor of 2.4 larger compared to that found with ISO–LWS, while it was observed in a 5.5 times larger beam.

The observed SED of Elias 29 is very different from that of massive protostars such as GL 2591, and GL 7009S, which peak in the far-infrared (Fig. 7.2). The shape of SEDs is determined by the total dust column density along the line of sight, rather than the luminosity of the central object. Then, Elias 29 would have a column density corresponding to $A_V \sim 10$, and GL 2591, and GL 7009S a factor of 10 larger than this (Ivezic & Elitzur 1997). This seems reasonable for GL 7009S, since its 9.7 μm silicate band is much deeper (actually saturated) compared to Elias 29 (Fig. 7.2). However, the silicate band in GL 2591 is only a factor of 2 deeper, and
CHAPTER 7. THE LOW MASS PROTOSTAR ELIAS 29

FIGURE 7.1—Spectral energy distribution of Elias 29, consisting of ground-based observations ($\lambda < 2.4 \, \mu m$; Greene & Lada 1996), an ISO-SWS spectrum ($\lambda = 2.4–45 \, \mu m$), and an ISO-LWS spectrum ($\lambda = 45–195 \, \mu m$). The data point at 1300 $\mu m$ is taken from André & Montmerle (1994), which we have connected with a dashed straight line to the ISO-LWS spectrum, to guide the eye. The dotted line is the adopted continuum, as determined by blackbody fits and by hand. The open circles are far infrared ground-based and IRAS observations (see text). The top inset shows a magnification of the 10-200 $\mu m$ region.
7.3 Results

FIGURE 7.2— Spectral energy distribution of various sources. From bottom to top: the high mass protostars GL 7009S (Dartois et al. 1998b), and GL 2591, the low mass protostar Elias 29 as observed, and extinction corrected assuming $A_V = 30$ and 60 respectively. The top spectrum is a compilation of continuum observations of the Herbig Ae star AB Aur taken from Mannings (1994), and is further discussed in Sect. 7.5. All filled dots indicate continuum observations. The dotted line on top indicates the spectral slope expected for an optically thick circumstellar accretion disk (e.g. Hillenbrand et al. 1992). All spectra have been arbitrarily shifted along the flux axis, except for Elias 29.
thus a lower column density alone cannot explain the very different SED of Elias 29. Other parameters, such as grain composition, and density distribution can affect the SED as well. We discuss the effect of geometry on the SED, such as the presence and orientation of a circumstellar disk, in Sect. 7.5.

7.3.2 Ice and dust absorption bands

Numerous absorption bands due to ices and silicates are superposed on the infrared continuum of Elias 29 (Fig. 7.3). We identify each band, derive column densities, and, when possible, determine the ice mantle composition and temperature. The full spectrum also allows us to determine upper limits of abundances for undetected, though astrophysically relevant molecules.

\( H_2O \) ice

The infrared spectrum of Elias 29 shows all the vibration modes of \( H_2O \) ice in absorption (Fig. 7.4). We see the O–H stretching mode at 3.0 \( \mu \)m ("\( \nu_1 \), \( \nu_3 \)" in spectroscopic notation), the O–H bending mode at 6.0 \( \mu \)m ("\( \nu_2 \)"), the libration or hindered rotation mode at \( \sim 12 \) \( \mu \)m ("\( \nu_4 \)"), the combination mode at 4.5 \( \mu \)m ("3\( \nu_1 \)" or "\( \nu_2 + \nu_1 \)"), and the lattice mode at \( \sim 45 \) \( \mu \)m. The continuum determination is...
complicated by the large width of all these bands. The ‘easiest’ cases are the 3.0 and 6.0 μm bands. In accordance with other studies (Smith et al. 1989; Schutte et al. 1996), we fitted blackbodies to determine the continuum. Single blackbodies fit the continuum only locally, directly adjacent to the absorption bands. This is due to a combination of reasons. First, the spectral shape of the continuum emission is distorted by wavelength dependent extinction (e.g. Fig. 7.2). Second, the continuum emission is composed by dust radiating at a range of temperatures along the line of sight. However, the emission becomes optically thick at different wavelengths at different depths in the envelope (i.e. at different $T$), and the spectrum cannot be simply treated as a sum of blackbodies. And third, the dust radiation deviates from a blackbody, depending on the grain size and its optical properties. In order to find the continuum over large infrared wavelength ranges, the object needs to be modeled, taking into account the temperature structure, the geometry and the dust grain properties (e.g. Dartois et al. 1998a). Here, we determine local continua and find that for the 3 μm H$_2$O band a blackbody at $T = 740$ K fits the continuum on both sides, while for the 6 μm band $T = 655$ K suffices. Instead, when fitting modified blackbodies with a power law emissivity of index $-1$, we find that the best fitting temperature decreases ($T = 630$ K and $505$ K resp.), but not the shape of the actual continuum on such a short wavelength scale. For the 6 μm band we took into account that laboratory spectra of the bending mode of H$_2$O ice show a prominent wing on the long wavelength side (e.g. Hudgins et al. 1993, Maldoni et al. 1998). We simultaneously fitted a blackbody continuum, normalized at 5.1 μm, and a laboratory ice spectrum to fit the observed flux at 8 μm and the shape of the 6.0 μm feature (Fig. 7.5).

The shape of the 6.0 μm H$_2$O bending mode is particularly sensitive to the ice temperature (e.g. Maldoni et al. 1998). In the laboratory it is composed of a feature at 6.0 μm and a prominent long wavelength wing extending up to 8 μm. At higher $T$, the strength of the 6.0 μm component decreases at the expense of more absorption in the long wavelength wing. In the spectrum of Elias 29, the wing cannot be seen as a separate feature, since at 8 μm it blends with the very deep silicate band. However, the observed 6.0 μm band is relatively sharp, it can only be fitted with H$_2$O ice at $T < 80$ K, with a best fit at $T = 40$ K (Fig. 7.5). The excellent fit to the 6.0 μm band in Elias 29 indicates that this source does not have the 5.83, and 6.25 μm excess absorptions seen in several massive protostars and attributed to the carbonyl stretch in formic acid (HCOOH) and PAHs respectively (Schutte et al. 1996, 1998; Keane et al., in prep.). After subtraction of the H$_2$O ice band and a correction for the gas phase H$_2$O lines, our spectra indicate upper limits to the 5.83 and 6.25 μm features of $\tau < 0.03$ (Fig. 7.8). This is significantly lower than the peak depths of $\tau (5.83 \mu m)=0.12$ and $\tau (6.25 \mu m)=0.05$ that would be expected if the 6.0 μm band had the same shape as toward the massive protostar NGC 7538 : IRS9 (Schutte et al. 1996).

The observed peak position of the stretching mode of H$_2$O ice toward Elias 29 is 3.07±0.01 μm. For a proper analysis of this band, effects of particle size need to be taken into account. Light scattering by large ice grains leads to extra extinction on the long wavelength wing of this band (e.g. Léger et al. 1983; Smith et al.
CHAPTER 7. THE LOW MASS PROTOSTAR ELIAS 29

Figure 7.4— Optical depth spectrum of Elias 29, assuming the continuum indicated in Figs. 7.1 and 7.3. The light, thick line is a laboratory spectrum of H$_2$O ice at $T=10$ K (Hudgins et al. 1993). All five H$_2$O ice vibration bands can be discerned: the O–H stretch (3.0 $\mu$m), the combination band (4.5 $\mu$m), the O–H bend (6.0 $\mu$m), the libration band (12 $\mu$m), and (perhaps) the lattice mode at $\sim$45 $\mu$m.

Figure 7.5— Optical depth spectrum of Elias 29 of the 3.0 $\mu$m absorption band (left panel). The thick line is a laboratory spectrum of pure H$_2$O ice at $T=40$ K, the best fit to the H$_2$O bending mode (as given in right panel). The dotted line gives a calculated band profile of a spherical silicate grain with radius 0.5 $\mu$m, coated with a 0.13 $\mu$m thick ice mantle at $T=40$ K. The right panel shows the 5–8 $\mu$m spectrum, with laboratory spectra of pure H$_2$O ice at $T=40$ K (light, thick line), and at $T=100$ K (thin, solid line), showing that only low temperatures provide good fits to Elias 29. The dashed line shows the assumed blackbody continuum. The narrow absorption lines in the observed spectrum originate from H$_2$O vapor (Sect. 7.3.3).
7.3 Results

This effect is unimportant for the 6.0 \(\mu m\) band since it is much weaker, and the grains are much smaller compared to the wavelength. In order to fit the peak position of the 3.07 \(\mu m\) band with amorphous \(H_2O\) ice at the same temperature as derived from the 6.0 \(\mu m\) band \((T = 40 \text{ K})\), we calculate the extinction cross section for large spherical silicate grains coated with ice mantles, using the optical constants of Draine \& Lee (1984) and Hudgins et al. (1993). We find that a core+mantle radius of \(\sim 0.6 \mu m\) is needed to fit Elias 29. The relative size of core and mantle is unimportant to the band profile. In reality, there is a distribution of grain sizes such as the MRN power law \((\text{number of grains at radius } r \text{ proportional to } r^{-3.5}; \text{Mathis, Rumpl, \& Nordsieck 1977})\). Then, for an ice mantle thickness independent of grain size \((\text{Draine 1985})\), and upper and lower limits to the grain size of 0.005 and 0.300 \(\mu m\) respectively, as found in the diffuse medium \((\text{MRN})\), small grains dominate the ice volume. Taking into account the silicate volume along the line of sight \((\text{derived from the 9.7 \(\mu m\) band})\), only very thin ice layers \((\sim 0.01 \mu m)\) would be possible, and the effect of scattering on the band profile is negligible. Better fits to the observed 3.07 \(\mu m\) band can only be obtained with an ice at \(T = 40 \text{ K}\) if the bulk of the ice along the line of sight is primarily present on large grains. For example, assuming an upper limit of 0.800 \(\mu m\) \((\text{as in Pendleton et al. 1990})\) for the silicate grains, an MRN power law size distribution, and taking into account the observed silicate and \(H_2O\) ice column along the line of sight, we find that a lower limit to the silicate grain radius of 0.350 \(\mu m\), and an ice mantle thickness of 0.13 \(\mu m\) are needed. Such large grain sizes have also been inferred from the 3.0 \(\mu m\) ice band in other lines of sight, such as the BN/KL nebula \((\text{Le\'ger et al. 1983; Pendleton et al. 1990; Smith, Sellgren \& Tokunaga 1989})\). As noted by Le\'ger et al. \(1983)\), scattering by large grains not only shifts the peak of the \(H_2O\) ice band to longer wavelengths, it can also explain the long wavelength shoulder \((\text{Fig. 7.5})\). Furthermore, continuum extinction observations toward \(\rho\) Ophiuchi \((\text{in which Elias 29 is located})\) have revealed that the grains are indeed larger compared to the diffuse medium \((\text{e.g. Martin \& Whittet 1990})\). On the other hand, invoking such large grains would put significant constraints on other observables, such as continuum extinction and polarization of the \(H_2O\) ice band which one is not able to satisfy at the same time \((\text{e.g. Smith, Sellgren, \& Brooke 1993; Tielens 1982})\). Alternative absorbers at the long wavelength wing have been proposed, such as \(NH_3.H_2O\) bondings and hydrocarbons. Each of these candidates are discussed below. Detailed fitting of the 3.0 \(\mu m\) band also reveals the presence of extinction at 2.8–2.9 \(\mu m\) \((\text{Fig. 7.5}; \text{Smith et al. 1989})\) which is not due to absorption or scattering by \(H_2O\) ice mantles along the line of sight. However, scattering by large grains in a reflection nebula can explain this feature \((\text{Pendleton et al. 1990})\). Indeed, 2 \(\mu m\) continuum observations show evidence for such a reflection nebula toward Elias 29 \((\text{Sect. 7.5})\). To summarize, we find that the 3.07 and 6.0 \(\mu m\) bands toward Elias 29 can both be well fitted with a pure amorphous \(H_2O\) ice at \(T = 40 \text{ K}\), provided that a significant fraction of the grains along the line of sight is large \((\geq 0.6 \mu m))\).

The peak optical depth of the 3.0 \(\mu m\) band is 1.85\(\pm0.08\), which is in excellent agreement with the study of Tanaka et al. \(1990)\). We derive a column density of \(N(H_2O)= 3.0\pm0.5 \times 10^{18} \text{ cm}^{-2}\) by fitting the laboratory spectra of Hudgins

\[ \text{N(H}_2\text{O)} = 3.0 \pm 0.5 \times 10^{18} \text{ cm}^{-2} \]
et al. (1993) to the 3.0 \( \mu m \) band, where we used an integrated band strength \( A = 2.0 \times 10^{-16} \text{ cm molecule}^{-1}. \) Since the band strength varies with temperature (a 10% increase when heated from 10 to 100 K; Gerakines et al. 1995), the uncertainty of the \( \text{H}_2\text{O} \) ice column density is larger than expected from the good data quality. Note that a column density determination from the 6.0 \( \mu m \) bending mode is more uncertain due to the unreliable continuum on the long wavelength side (Fig. 7.5).

At this column density of \( \text{H}_2\text{O} \) ice, the depth of the remaining vibrational modes is in good agreement with the observed spectrum of Elias 29 (Fig. 7.4). Due to its intrinsic weakness, combined with instrumental systematic errors due to detector memory effects, the combination band at 4.5 \( \mu m \) does not allow an accurate profile analysis, although the overall profile and depth are well fitted with laboratory spectra. Furthermore, at longer wavelengths there is good evidence that the libration (\( \sim \)12 \( \mu m \)) and lattice (\( \sim \)45 \( \mu m \)) modes are present. In both cases the profile analysis is complicated by the uncertain continuum. The libration mode is blended with the stretching (\( \sim \)9.7 \( \mu m \)) and bending (\( \sim \)18 \( \mu m \)) modes of silicate dust (Figs. 7.3 and 7.4). Taking a linear continuum between 8 and 30 \( \mu m \) (Fig. 7.3), gives a good match of the strength with respect to the other \( \text{H}_2\text{O} \) ice bands. The structure seen between 30–90 \( \mu m \) is also in reasonable agreement with laboratory experiments, although the spectral shape does not match exactly with the lattice mode in a pure \( \text{H}_2\text{O} \) ice at \( T = 10 \text{ K} \) (Fig. 7.4). This could be due to several reasons. First, a smooth continuum was determined by hand, and thus is subjective and it would be preferable to model the dust emission and its transfer through the cloud. Second, the feature extends over a wavelength region observed by two different spectrometers. The ISO–LWS beam is a factor of 10 larger than the ISO–SWS beam, and thus long-ward of 45 \( \mu m \) we may have an extended, probably cold, dust component in the beam which may for example give rise to the observed increase in the continuum at \( \sim \)100 \( \mu m \). Finally, part of the lattice mode of \( \text{H}_2\text{O} \) ice may be seen in emission, thus filling-in the absorption, e.g. in the ISO–LWS spectrum near \( \sim \)55 \( \mu m \) (Fig. 7.4). For a proper analysis of the lattice mode of \( \text{H}_2\text{O} \) ice the radiative transfer through the molecular material surrounding the protostar needs to be calculated (Dartois et al. 1998a).

**CO ice**

The CO ice band at 4.67 \( \mu m \) in Elias 29 is contaminated by gas phase CO lines from low \( J \) levels (Figs. 7.6 and 7.9). In particular, the P(1) line lies in the center of the ice band at 4.674 \( \mu m \). To study the band profile, we subtracted a model for the gaseous lines at \( T = 750 \text{ K}, N = 5 \times 10^{18} \text{ cm}^{-2}, \) and \( b_D=5 \text{ km s}^{-1} \) (Sect. 7.3.3). This increases the ice band width by 0.9 cm\(^{-1}\), to FWHM=4.40 cm\(^{-1}\) (0.010 \( \mu m \)). With a peak position of 4.673 \( \mu m \) (2140.1 cm\(^{-1}\)), the CO ice band profile observed toward Elias 29 and the luminous protostar NGC 7538 : IRS9 are very similar (Fig. 7.6; Tielens et al. 1991; Chiar et al. 1998). The main, narrow component at 4.673 \( \mu m \) is attributed to pure solid CO, or CO embedded in an environment of apolar molecules. In particular, mixtures with \( \text{O}_2 \), at an \( \text{O}_2/\text{CO} \) ratio of as much as 5 (Elsila et al. 1997; Chiar et al. 1998) do provide good fits to the narrow profile. Mixtures of CO with
7.3 Results

FIGURE 7.6—The CO ice band on optical depth scale observed toward Elias 29 (thin solid line). The thick line is the spectrum with a gas phase CO model subtracted (see text). The dotted line shows the spectrum of the high mass protostar NGC 7538 : IRS9 (divided by 7.5; Tielens et al. 1991) showing the similarity of the band profiles.

CO$_2$ are generally too broad (Ehrenfreund et al. 1997). While the apolar, volatile component dominates the spectrum, both Elias 29 and NGC 7538 : IRS9 show evidence for a wing on the long wavelength side. This is attributed to CO diluted in a mixture of polar molecules such as H$_2$O, and CH$_3$OH (Chiar et al. 1998; Tielens et al. 1991). Assuming a band strength $A = 1.1 \times 10^{17}$ cm molecule$^{-1}$ for both the polar and apolar components (Gerakines et al. 1995), we derive $N$(CO ice)$=1.7 \times 10^{17}$ cm$^{-2}$ with an apolar/polar ratio of ~8, comparable to NGC 7538 : IRS9. These results are in good agreement with the ground-based study of Kerr et al. (1993). Although NGC 7538 : IRS9 seems to have a larger polar CO component in Fig. 7.6, this difference can be entirely attributed to uncertainties in the continuum subtraction, and the fact that the NGC 7538 : IRS9 spectrum is not corrected for gas phase CO lines.

CO$_2$ ice

The absorption bands of CO$_2$ ice are prominently present in the infrared spectrum of Elias 29 (Fig. 7.3). We see the stretching and bending modes at 4.27 and 15.2 $\mu$m respectively. Not visible in this spectrum is the stretching mode of solid $^{13}$CO$_2$ at 4.38 $\mu$m, although the high resolution spectrum (Fig. 7.9) shows a hint of its presence. A very sensitive observation is presented elsewhere (Chapt. 4), and allows to analyze the band profile. The $^{12}$CO$_2$ bending mode and the $^{13}$CO$_2$ stretching mode have proven to be very sensitive to ice mantle composition and heating history. Unfortunately, the quality and resolution of the $^{13}$CO$_2$ bending mode in Elias 29 is too low for an accurate band profile fitting (Gerakines et al. 1999). The $^{13}$CO$_2$ ice band does not show the separate narrow peak at 2282 cm$^{-1}$ (4.382 $\mu$m), seen in many other protostars, and attributed to heated polar CO$_2$ ices (Chapt. 4). As for the CO ice band (Fig. 7.6), the width and peak position of the $^{13}$CO$_2$ band very much resemble that of the luminous protostar NGC 7538 : IRS9. Thus, the CO$_2$ ice toward Elias 29 is mixed in with polar molecules, and is not much affected by heating. The
CHAPTER 7. THE LOW MASS PROTOSTAR ELIAS 29

**FIGURE 7.7**— Spectral structure in the long wavelength wing of the 3.0 \( \mu m \) feature. **Top panel:** The merged high \(( R = 1500)\) and low \(( R = 400)\) resolution spectra and the assumed polynomial continuum (dotted line). **Bottom panel:** Optical depth plot of the detected 3.47 \( \mu m \) feature. The light, thick line represents the laboratory spectrum \( \text{H}_2\text{O}:\text{CH}_3\text{OH}:\text{NH}_3:\text{CO}=100:10:1:1 \) at \( T = 40 \) K showing the C–H stretch mode of solid \( \text{CH}_3\text{OH} \) at 3.54 \( \mu m \). The spectrum of Elias 29 does not show this feature, with an upper limit as indicated here \(( \tau = 0.03)\). To allow a better comparison, we have shifted the laboratory spectrum down by 0.035 on optical depth scale.

\( ^{12}\text{CO}_2 \) column density is 22\( \pm \)4\% relative to \( \text{H}_2\text{O} \) ice, which is comparable to the values reported for high mass protostars \((\text{Gerakines et al. 1999})\). Finally, we derive an isotope ratio of \( ^{12}\text{CO}_2/^{13}\text{CO}_2=81\pm11 \) in the ice toward Elias 29, which is well within the range found for the local ISM \((\text{Chapt. 4})\).

**The 3.47 \( \mu m \) band**

The long wavelength wing of the deep 3.0 \( \mu m \) absorption band shows a change of slope at 3.38 \( \mu m \), indicative of a shallow absorption feature ((Fig. 7.7)). The long wavelength wing of this feature is not so well determined. Fitting a smooth 6-th order polynomial to local continuum points between 3.20–3.37 \( \mu m \) and 3.7–4.1 \( \mu m \) results in an absorption band centered on 3.49\( \pm \)0.03 \( \mu m \) with a peak optical depth of \( \tau = 0.06 \) (Fig. 7.7). The width is FWHM=120\( \pm \)40 cm\(^{-1}\), where the uncertainty includes the poorly constrained continuum on the long wavelength side. Features of similar width and peak position have been detected in several massive protostellar objects \((\text{Allamandola et al. 1992})\) and in low mass objects and the quiescent molecular cloud material \((\text{Chiar et al. 1996})\). A likely candidate for this 3.47 \( \mu m \) band is the C–H stretching mode of hydrocarbons. From the correlation of peak optical depths of this feature and the 3.0 \( \mu m \) ice band, it is concluded that the carrier for the
There are several high mass protostars where the 3.47 μm band is blended with a narrower feature centered on 3.54 μm (Allamandola et al. 1992). This feature is ascribed to the C–H stretching mode of solid CH$_3$OH. No such feature is observed in Elias 29, with an upper limit to the peak optical depth of τ(3.54 μm)<0.03 (Fig. 7.7). Using a band strength $A$(3.54 μm)=7.5 $10^{18}$ cm molecule$^{-1}$ and a typical width of 30 cm$^{-1}$ (Chiar et al. 1996), this results in an upper limit to the CH$_3$OH ice column density $N$(CH$_3$OH ice)<1.2 $10^{17}$ cm$^{-2}$, or less than 4% of H$_2$O ice (Table 7.4). The other modes of CH$_3$OH ice are either much weaker, or are severely blended with the strong H$_2$O and silicate bands (e.g. the C–O stretching mode at 9.7 μm; Schutte et al. 1991) and thus cannot be used to further constrain the CH$_3$OH ice column density. Toward other low mass objects, and the quiescent medium, low upper limits have been set to the CH$_3$OH ice abundance as well. The CH$_3$OH ice abundance found in massive protostars is generally of the same magnitude (Chiar et al. 1998), or for some objects larger (Dartois et al. 1999), than these upper limits.

The 6.8 μm band

Elias 29 is the first low mass protostar in which the 6.8 μm absorption band is detected (Fig. 7.5). After subtraction of the H$_2$O ice band and the gas phase H$_2$O lines (Fig. 7.8), we find that it has a peak optical depth of $\tau$~0.07 and an integrated optical depth $\tau_{int} = 7.8 \pm 1.6$ cm$^{-1}$. When scaled to the H$_2$O ice column density, the strength of the 6.8 μm band toward Elias 29 is similar to high mass
proto-stars (Keane et al., in prep.). The band profile, e.g., the sharp edge at 6.60 μm, also agrees very well with several high mass objects tracing ‘cold’ gas and dust (NGC 7538 : IRS9, W 33A, GL 989), and clearly deviates from warmer lines of sight (GL 2136, Mon R2 : IRS3). Given the low upper limits to the CH3OH ice column density toward Elias 29, only a fraction of the band, as in high mass objects can be explained by the C–H bending mode of CH3OH ices (Schutte et al. 1996). For a detailed band profile analysis and a discussion on the origin of the 6.8 μm band, we refer to Keane et al. (1999; in prep.).

Upper limits to solid CH4, NH3, OCS, and ‘XCN’

Several solid state species were detected toward luminous protostars, but are absent toward Elias 29. The deformation mode of solid CH4 was detected toward protostars, with a peak position at 1303 cm⁻¹ (7.67 μm), and a width FWHM=11 cm⁻¹ (Boogert et al. 1996; Dartois et al. 1998b). For Elias 29 we can exclude this band to a peak optical depth of τ <0.03 (3-sigma), corresponding to N(CH4)/N(H2O)<1.5%. This upper limit is comparable to the detection in NGC 7538 : IRS9 (Boogert et al. 1996; Table 7.4).

Solid NH3 was recently detected by its 9.10 μm inversion mode toward NGC-7538 : IRS9 at 10% of H2O ice (Lacy et al. 1998). We do not detect this band in Elias 29, with a peak optical depth τ <0.1. This corresponds to a column density of N(NH3)< 2.7 10¹⁷ cm⁻², i.e. N(NH3)/N(H2O)<10%. Since this feature is heavily blended with the silicate stretching mode, an accurate modeling of the silicate band (see e.g. Hanner et al. 1995) will possibly reduce the upper limit. This is also the case for the N–H stretching mode at 2.90 μm which is blended with the H2O ice band. Another useful band is the N–H deformation mode at 6.16 μm. When subtracting water ice and vapor absorption, a weak band with an optical depth of τ =0.03 remains perhaps present (Fig. 7.8). It has been detected in several lines of sight (Schutte et al. 1996; 1998), and has been ascribed to absorption by carbonaceous dust. However, if we ascribe it fully to the deformation mode of NH3, it would correspond to 10% of H2O ice, comparable to the NH3 detection in NGC 7538 : IRS9 (Lacy et al. 1998).

An absorption feature has been detected at 2042±4 cm⁻¹ (4.90 μm) in lines of sight toward several massive protostars (Palumbo et al. 1997). With a width FWHM=23±6 cm⁻¹, it has been ascribed to absorption by solid OCS. For Elias 29 this feature is not detected with a peak optical depth τ <0.01 (3-σ), corresponding to N(OCS)< 1.5 10¹⁵ cm⁻² or < 0.05% of H2O ice. This upper limit is of the same order of magnitude as the detections in W 33A and Mon R2 : IRS2 (Palumbo et al. 1997).

Finally, toward several high and low mass protostars a feature has been detected at ~2166 cm⁻¹ (4.62 μm) with a width FWHM~20 cm⁻¹ (Lacy et al. 1984; Tegler et al. 1995). This feature is absent in Elias 29, with a peak optical depth τ <0.01 (3-σ). If this feature is caused by the C≡N stretching mode in ‘XCN’, this corresponds to a column density N(XCN)< 6.7 10¹⁵ cm⁻², or less than 0.2% of H2O ice (applying A = 3 10⁻¹⁷ cm molecule⁻¹; Tegler et al. 1995). This is considerably less than the
7.3 Results

detections made toward high mass objects (e.g., W 33A) and several low mass objects (Elias 18; L 1551 : IRS5; Tegler et al. 1995). This feature has not been detected in the quiescent medium toward the Taurus molecular cloud (Elias 16; Table 7.4). For a more elaborate discussion on this feature, and the proposed carriers, we refer to Pendleton et al. (1999).

Silicates

The absorption bands of the Si–O stretching and bending modes of silicate dust are prominently present at 9.7 μm and 18 μm (Fig. 7.3). We derive a peak absorption optical depth of the 9.7 μm band $\tau_{9.7} = 1.38$ (Fig. 7.4), which is in excellent agreement with the ground-based study of Hanner et al. (1995). It is likely that this is a lower limit, since the absorption bands have been partly filled in with silicate emission from hot dust near the protostar. Modeling of the 9.7 μm silicate band toward Elias 29, including emission and absorption, shows that $\tau_{9.7}$ ranges between 1.51 and 3.38 for optically thick and thin emission respectively (Hanner et al. 1995). A better fit is obtained for optically thick emission. In contrast, for luminous protostars optically thin emission has been generally assumed. Using the relation $\tau_{9.7} = 1.4 \tau_{9.7}(\text{obs}) + 1.6$ (Gillet et al. 1975; Willner et al. 1982), yields $\tau_{9.7} = 3.53$ for Elias 29.

For these values of $\tau_{9.7}$, the visual extinction $A_V$ ranges between 28 and 65, assuming the standard relation $A_V/\tau_{9.7}=18.5$ (Roche & Aitken 1984). However, these limits are likely overestimated (30-50%), because of the anomalous extinction curve due to larger grains in the ρ Oph molecular cloud (Bohlin, Savage, & Drake 1978; Martin & Whittet 1990). Independent extinction determinations, such as $A_V < 48$ from the H–K broad band color and $A_V < 80$ from $^{18}$O observations (Wilking & Lada 1983), do not help to solve this issue. A recently determined upper limit $A_V < 29$ from the J–H color (Greene, priv. comm.), suggests a relatively low value.

The total hydrogen column density $N_{\text{HI}} = N(\text{H I})+2N(\text{H}_2)$ is closely related to $\tau_{9.7}$, and, in contrast to the derivation of $A_V$, the derived $N_{\text{HI}}$ is not strongly affected by the large grain size in ρ Oph. Applying standard conversion factors for the diffuse ISM (Bohlin et al. 1978; Roche & Aitken 1984), we find $N_{\text{HI}} = 0.5 - 1.2 \cdot 10^{23} \text{ cm}^{-2}$, depending on the applied $\tau_{9.7}$. To be consistent with studies of high mass protostars, we will assume in this Chapter the value corresponding to optically thin silicate emission, i.e. the high limit $N_{\text{HI}} = 1.2 \cdot 10^{23} \text{ cm}^{-2}$ (Table 7.4).

7.3.3 Gas phase absorption lines

The high resolution 4.00–8.50 μm spectrum of Elias 29 shows a large number of narrow absorption lines of gaseous CO and H$_2$O (Figs. 7.5 and 7.9). We determined local continuum points by hand and connected these with a smooth curve, using a cubic spline interpolation. Then the data were converted to optical depth scale, and the absorption lines were modeled, using the ro-vibrational spectra of gaseous CO and H$_2$O described in Helmich (1996). These models assume the gas is in Local
Thermodynamic Equilibrium (LTE), and is at a single excitation temperature $T_{\text{ex}}$. The absorption lines have a Voigt profile, and are Doppler broadened to a width $b_D$ ($=\text{FWHM}/2\sqrt{\ln 2}$). The line oscillator strengths are calculated from the HITRAN database (Rothmann et al. 1992). Finally, the spectrum is convolved with a Gaussian to the resolution of our observations ($R = 1500 - 2000$). Thus, three parameters are varied to fit the observed absorption lines: the column density $N$, the Doppler parameter $b_D$, and the excitation temperature $T_{\text{ex}}$. Reliable column densities can only be derived if $b_D$ is a priori known, which in many studies (like ours) is not the case, since the lines are unresolved. At low values of $b_D$, the lines become easily optically thick, and much larger column densities are needed to fit the observed lines, compared to models with high $b_D$ values, and optically thin lines. Some guidance to reasonable lower limits to $b_D$ is given by the width of (sub-) millimeters emission lines (see below; van der Tak et al. 1999).

We do emphasize that our assumptions of collisional excitation, LTE and a single $T_{\text{ex}}$ need not be valid. Gas clouds at different temperatures may be present along one line of sight. The LTE assumption may not apply for the high rotational levels, which have high critical densities. Also, the energy levels may be pumped by infrared photons, rather than being collisionally excited. We will not address these uncertainties in much detail here, and focus on deriving CO and H$_2$O gas column densities and temperatures using the LTE models.

**CO gas**

The 4.4–5.0 $\mu$m region shows an impressive number of absorption lines due to gas phase $^{12}$CO (Fig. 7.9). The central frequency of each line is in excellent agreement with the CO line list of Goorvitch (1994). Lines are detected up to rotational quantum number $J_{\text{low}}=33$ in the R-branch, and $J_{\text{low}}=36$ in the P-branch. The P(1), P(2) and R(0) lines are blended with the CO ice band at 4.67 $\mu$m and the H I Pf $\beta$ emission line at 4.653 $\mu$m. For all other absorption lines we determined equivalent widths to construct a rotation diagram. A rotation diagram gives a first impression of the temperature and column density of the absorbing gas. However, one has to make the probably unrealistic assumption that the lines are optically thin, and the column densities derived in this way are actually lower limits. For technical details on constructing such a diagram we refer to Mitchell et al. (1990), Dartois et al. (1998b) and Boogert et al. (1998; Chapt. 3). The equivalent widths were converted to column densities, using the oscillator strengths of Goorvitch (1994). A straight line in a rotation diagram indicates a single rotational temperature. For $^{12}$CO (Fig. 7.10), we find two regimes with very different slopes, corresponding to temperatures $T_{\text{rot}} = 90 \pm 45$ K and $T_{\text{rot}} = 1100 \pm 300$ K respectively (with 3-$\sigma$ errors). However, the slopes of the R- and P-branch lines are different (Fig. 7.10), resulting in $T_{\text{rot}} = 1700 \pm 420$ K when fitting to the P-branch lines only. At present, we have no satisfactory explanation for this difference. Possible explanations, such as errors in the continuum determination, non-LTE effects, or excitation by radiative pumping rather than collisions, need to be investigated in more detail.
7.3 Results

The gaseous CO column densities that we derive from the abscissa in the rotation diagram are \( N(\text{CO}) > 1.7 \times 10^{17} \) and \( N(\text{CO}) > 3.5 \times 10^{17} \) cm\(^{-2}\) for the cold and hot components respectively. To better constrain the column densities and derive more reliable temperatures, one has to take into account optical depth effects. For this, we used LTE model spectra of Helmich (1996) to fit the observed CO lines. As described above, the line optical thickness depends strongly on the poorly constrained velocity broadened line width \( b_D \). We chose to fit to the frequency range 2170–2290 cm\(^{-1}\) (\( J_{\text{low}} > 7 \) in R-branch), thus minimizing the contribution from the cold CO component and contamination by \(^{13}\text{CO}\) lines (see below). We find that good fits to these high R-branch lines are obtained only for line widths \( b_D > 3 \) km s\(^{-1}\). Sub-millimeter emission line studies indicate \( b_D = 3.6 \) km s\(^{-1}\) for CO \( J = 6 \rightarrow 5 \) (Sect. 7.3.5), but much lower values of \( b_D = 1.2 \) km s\(^{-1}\) for \(^{18}\text{O} J = 1 \rightarrow 0\) and CS \( J = 5 \rightarrow 4 \) (Boogert et al., in prep.). Indeed, studies of other sources have shown that, as a rule, infrared absorption lines are broader than sub-millimeter emission lines (van der Tak et al. 1999). Figure 7.10 shows the \( \chi^2 \) contour diagram of temperature versus column density for two values of the line width \( b_D = 5 \), and \( b_D = 10 \) km s\(^{-1}\). We only show values of \( \chi^2 \leq 4 \), since higher values clearly do not fit the data. The best fitting models have temperatures \( T = 1100 \pm 400 \) K, in good agreement with the rotation diagram. At \( b_D = 10 \) km s\(^{-1}\) the column density is well
CHAPTER 7. THE LOW MASS PROTOSTAR ELIAS 29

Figure 7.10—Left panel: Rotation diagram of the $^{12}$CO lines detected toward Elias 29 showing the presence of hot and cold gas along the line of sight of Elias 29 by the different slopes at high and low rotational levels. Right panel: $\chi^2$ contour diagram of model fits to the observed ro-vibrational spectrum of the R-branch of gaseous CO toward Elias 29. $\chi^2$ values are shown for the temperature $T$ versus CO column density $N$ at constant velocity broadenings $b_D$ of 5 km s$^{-1}$ (dotted) and 10 km s$^{-1}$ (solid). We only show models that provide acceptable fits to the data, i.e. $\chi^2 < 4$. This contour plot shows that the velocity broadening is an essential, but at present observationally poorly constrained, parameter to determine the gas phase CO column density, and to a lesser degree the temperature.

The presence of $^{13}$CO lines also indicates that the $^{12}$CO lines are severely optically thick. Several $^{13}$CO lines can be seen in between the $^{12}$CO P-branch lines (Fig. 7.12). At the resolution of our observations, the blending with the $^{12}$CO lines hinders analyzing the much weaker $^{13}$CO lines. But for lines in between the $^{12}$CO lines we were able to construct a rotation diagram (Fig. 7.13). We find that they result from a cold gas at $T_{\text{rot}} = 85 \pm 57$ K (3-$\sigma$ error), in good agreement with the cold $^{12}$CO gas temperature. The column density of this cold component is $N(^{13}{\text{CO}})=1.1 \pm 0.2 \times 10^{17} \text{ cm}^{-2}$. Using the isotope abundance ratio $^{12}$CO/$^{13}$CO=80 (Chapt. 4), the inferred cold $^{12}$CO column density is thus $N(^{12}{\text{CO}})=90 \pm 20 \times 10^{17} \text{ cm}^{-2}$. There is also evidence for $^{12}$CO lines of warm gas ($f_{\text{low}} > 9$), but at low significance ($\leq 2\sigma$) and no reliable temperature or column density could be derived. The detected $^{13}$CO lines could still be optically thick. Therefore, we also modeled the $^{13}$CO spectrum, and determine the $\chi^2$ after subtraction of a good fitting hot $^{12}$CO gas model (Figs. 7.13 and 7.12). In the optically thick case, such as for constrained to $N(\text{CO})=1.3\pm 0.5 \times 10^{18} \text{ cm}^{-2}$, which is a factor of 3 larger compared to that derived from the rotation diagram. Thus at $b_D=10$ km s$^{-1}$ the lines are still somewhat optically thick. At a lower $b_D=5$ km s$^{-1}$, the lines become very optically thick, and the column density is poorly constrained. Although the best fits with $\chi^2 < 3$ have $N(\text{CO})=8 \pm 4 \times 10^{18} \text{ cm}^{-2}$ at $T = 650 \pm 150$ K (Fig. 7.11), reasonable fits are obtained at any $N(\text{CO})> 2 \times 10^{18} \text{ cm}^{-2}$ for this hot CO gas.

The presence of $^{13}$CO lines also indicates that the $^{12}$CO lines are severely optically thick. Several $^{13}$CO lines can be seen in between the $^{12}$CO P-branch lines (Fig. 7.12). At the resolution of our observations, the blending with the $^{12}$CO lines hinders analyzing the much weaker $^{13}$CO lines. But for lines in between the $^{12}$CO lines we were able to construct a rotation diagram (Fig. 7.13). We find that they result from a cold gas at $T_{\text{rot}} = 85 \pm 57$ K (3-$\sigma$ error), in good agreement with the cold $^{12}$CO gas temperature. The column density of this cold component is $N(^{13}\text{CO})=1.1 \pm 0.2 \times 10^{17} \text{ cm}^{-2}$. Using the isotope abundance ratio $^{12}\text{CO}/^{13}\text{CO}=80$ (Chapt. 4), the inferred cold $^{12}\text{CO}$ column density is thus $N(^{12}\text{CO})=90 \pm 20 \times 10^{17} \text{ cm}^{-2}$. There is also evidence for $^{12}\text{CO}$ lines of warm gas ($f_{\text{low}} > 9$), but at low significance ($\leq 2\sigma$) and no reliable temperature or column density could be derived. The detected $^{13}\text{CO}$ lines could still be optically thick. Therefore, we also modeled the $^{13}\text{CO}$ spectrum, and determine the $\chi^2$ after subtraction of a good fitting hot $^{12}\text{CO}$ gas model (Figs. 7.13 and 7.12). In the optically thick case, such as for
7.3 Results

**FIGURE 7.11** — The R branch of gas phase CO observed in Elias 29 (top) compared with a well fitting gas model at $T = 750$ K (middle). The bottom panel shows the residual after subtraction of the gas model, with observational error bars indicated.

**FIGURE 7.12** — The P branch of gas phase CO observed in Elias 29 (top) compared with a well fitting $^{12}$CO gas model at $T = 750$ K (middle). The bottom panel shows that the residual after subtraction of the $^{12}$CO gas model, contains lines of cold $^{13}$CO gas.
CHAPTER 7. THE LOW MASS PROTOSTAR ELIAS 29

Figure 7.13—Left panel: Rotation diagram of the $^{13}$CO lines detected toward Elias 29 showing the presence of cold gas along the line of sight of Elias 29. Circles are P-branch lines, and triangles are R-branch lines. Open symbols of each kind refer to $^{13}$CO lines heavily blended with $^{12}$CO lines, and are not used to determine the physical parameters. The straight line indicates the best fit, with a gas temperature $T = 85 \pm 57$ K, and a column density $N( ^{13}\text{CO}) = 1.1 \pm 0.2 \times 10^{17}$ cm$^{-2}$. Lines from higher energy levels ($E_J/k > 200$ K) are below our detection limit, and thus $^{13}$CO cannot be used to confirm the presence of hot gas. Right panel: $\chi^2$ contour diagram of model fits to the observed ro-vibrational spectrum of gaseous $^{13}$CO toward Elias 29. $\chi^2$ values are shown for the temperature $T$ versus CO column density $N$ for constant velocity broadenings $b_D=2.5$ km s$^{-1}$ (solid line) and $b_D=10$ km s$^{-1}$ (dotted line). Only acceptable fits to the data, having $\chi^2 < 3.5$, are shown.

$b_D=2.5$ km s$^{-1}$, the column density can be in the wide range of $N( ^{13}\text{CO}) = 2 \pm 1.3 \times 10^{17}$ cm$^{-2}$ (i.e., $N( ^{12}\text{CO}) = 1.6 \pm 1.0 \times 10^{16}$ cm$^{-2}$).

We conclude that the CO gas along the line of sight consists of two temperature components, $T_{\text{rot}} = 90 \pm 45$ K and $T_{\text{rot}} = 1100 \pm 300$ K. The column density of both components depends highly on the assumed line optical thickness (Table 7.1). Until the intrinsic line width is directly observed by very high spectral resolution observations, we can only give a lower limit of $N(\text{CO–hot}) > 2 \times 10^{18}$ cm$^{-2}$, while $N(\text{CO–cold})$ is not well constrained, i.e. $16 \pm 10 \times 10^{18}$ cm$^{-2}$. Given that $N_{\text{H}_2} = 1.2 \times 10^{23}$ cm$^{-2}$ toward Elias 29, a total gas phase CO column density $N(\text{CO}) = 1.2 \times 10^{19}$ cm$^{-2}$ is expected, assuming that most of the gas along the line of sight is molecular and the

Table 7.1—Gas phase $^{12}$CO column densities, assuming various line widths for $^{12}$CO, and $^{13}$CO, and applying $N( ^{12}\text{CO})/N( ^{13}\text{CO})=80$ (Chapt. 4).

<table>
<thead>
<tr>
<th>Method</th>
<th>$N( ^{12}\text{CO–cold})$</th>
<th>$N( ^{12}\text{CO–hot})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$CO—rotation diagram</td>
<td>1.7</td>
<td>3.5</td>
</tr>
<tr>
<td>$^{12}$CO—LTE model, $b_D=10$ km s$^{-1}$</td>
<td>–</td>
<td>13$\pm$5</td>
</tr>
<tr>
<td>$^{12}$CO—LTE model, $b_D=5$ km s$^{-1}$</td>
<td>–</td>
<td>&gt;20</td>
</tr>
<tr>
<td>$^{13}$CO—rotation diagram</td>
<td>90$\pm$20</td>
<td>–</td>
</tr>
<tr>
<td>$^{13}$CO—LTE model, $b_D=2.5$ km s$^{-1}$</td>
<td>160$\pm$100</td>
<td>–</td>
</tr>
</tbody>
</table>
conversion factor $N(\text{H}_2)/N(\text{CO})=5000$ applies (Lacy et al. 1994). Then, the ratio of hot to cold CO gas along the line of sight must be at least 0.22.

$\text{H}_2\text{O}$ gas

We compare the numerous narrow absorption lines detected in the 5-7.3 $\mu$m spectral region of Elias 29 with model spectra of H$_2$O vapor at various physical conditions (Fig. 7.14). Clearly, the lines observed at wavelengths longer than $\sim$6.55 $\mu$m are explained by H$_2$O vapor at a high temperature ($T > 100$ K). These models also indicate that the low depth of the lines observed at 6.55-6.65 $\mu$m, relative to the lines at $\lambda > 6.65 \mu$m, imposes a strict upper limit to the temperature of this hot gas ($T < 1000$ K). To further constrain the gas temperature, and the H$_2$O vapor column density, we determined the $\chi^2$ for a large number of models. First, we fitted the regions 5.5–5.8 and 6.55–7.3 $\mu$m. These wavelength regions do not contain lines from the lowest rotational levels (Helmich et al. 1996; Dartois et al. 1998b) and thus are particularly sensitive to warm H$_2$O vapor along the line of sight. Assuming a noise level $\Delta \tau = 0.01$, we find that acceptable fits have $\chi^2 < 2.5$. The excitation temperature of the gas is $T = 500 \pm 300$ K (Fig. 7.15). Due to optical thickness of the lines, the column density of this hot gas, like for CO, depends strongly on the

![Figure 7.14](image-url)
CHAPTER 7. THE LOW MASS PROTOSTAR ELIAS 29

**FIGURE 7.15**—\( \chi^2 \) contour diagram of model fits to the observed ro-vibrational spectrum of gaseous H\(_2\)O toward Elias 29. \( \chi^2 \) values are shown for the temperature \( T \) versus H\(_2\)O column density \( N \) at constant velocity broadenings \( b_\text{D} \) of 2.5 km s\(^{-1}\)(dotted) and 5 km s\(^{-1}\)(solid). The left panel shows model fits to the wavelength regions 5.5–5.8 and 6.55–7.3 \( \mu \)m, excluding the lowest rotational levels, and thus tracing the warm H\(_2\)O gas along the line of sight. We only show models that provide acceptable fits to the data, i.e. \( \chi^2 < 2.5 \). The right panel shows a fit composed of a good fitting hot gas model (\( T = 500 \) K, \( N = 5 \times 10^{17} \) cm\(^{-2}\), \( b_\text{D} = 2.5 \) km s\(^{-1}\)) added to a variable second model to fit the complete 5.5–7.3 \( \mu \)m spectrum. This shows that also a significant cold H\(_2\)O gas component may be present along the Elias 29 line of sight.

When comparing the best fitting models of this selective wavelength region to the full observed spectrum, we find that a somewhat ‘cooler’ gas is needed to provide a good fit (\( T \sim 300 \) K). At higher temperature (\( T \geq 500 \) K), the observed line depth in the 6.0–6.5 \( \mu \)m region are underestimated. Since this region contains lines from the lowest rotational levels, we conclude that the line of sight also may contain cold H\(_2\)O vapor. To determine the temperature and column density of this possible cold component, we fitted the sum of a good fitting hot gas model (\( T = 500 \) K, \( N = 5 \times 10^{17} \) cm\(^{-2}\), \( b_\text{D} = 2.5 \) km s\(^{-1}\)) and a grid of models at a wide range of physical conditions to the spectrum of Elias 29. Thus, here we assume that the lines of the hot and cold gas have different radial velocities and the optical depth spectra can simply be added. We find that indeed a significant amount of ‘cold’ H\(_2\)O vapor, at \( T < 300 \) K may be present along the Elias 29 line of sight (Figs. 7.14 and 7.15).

At \( T < 200 \) K the column density exceeds the assumed hot H\(_2\)O column density of \( N = 5 \times 10^{17} \) cm\(^{-2}\). For a line width of \( b_\text{D} = 5.0 \) km s\(^{-1}\), we find that \( N < 5 \times 10^{18} \) cm\(^{-2}\). At \( b_\text{D} = 2.5 \) km s\(^{-1}\), the column density of this cold H\(_2\)O gas cannot be constrained.

To summarize, the lines in the 5–7.3 \( \mu \)m range are reasonably fitted with H\(_2\)O models at \( T \sim 350 \pm 200 \) K, and \( N = 7 \pm 4 \times 10^{17} \) cm\(^{-2}\) at low line optical depths. For narrower lines (\( b_\text{D} < 5 \) km s\(^{-1}\)), the column density can be an order of magnitude
7.3 Results

A number of emission lines are present in the spectrum of Elias 29, all originating from atomic hydrogen: Br $\alpha$, Br $\beta$, Pf $\alpha$, Pf $\beta$, Pf $\gamma$, and Hu $\beta$ (Fig. 7.16). Previous ground-based observations already revealed the presence of Br $\gamma$ emission (Greene & Lada 1996). We determined the line flux, and applied an extinction correction using a visual extinction $A_V = 29$ (Sect. 7.3.2), a total-to-selective extinction ratio for the $\rho$ Ophiuchi cloud $R = 4.0$ (Bohlin et al. 1978) and the analytic expression for the mean Galactic extinction curve provided by Howarth (1983). Then we calculated extinction corrected line ratios and total line luminosities, assuming a distance of 160 pc (Whittet 1974; Tables 7.2 and 7.3).

The Br $\alpha$/Br $\gamma$ and Br $\alpha$/Pf $\gamma$ line ratios and luminosities observed toward Elias 29 are similar to the values for other low mass pre-main-sequence objects (Evans et al. 1987). In particular, the values match very well with the A0e star AB Aur, which also has a similar luminosity as Elias 29 ($\sim 40 L_\odot$). However, this object has a much lower mass loss rate ($< 10^{-8} M_\odot$ yr$^{-1}$; derived from CO gas) and is, like most other sources in the sample of Evans et al. (1987), optically vis-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7_16.png}
\caption{\textbf{FIGURE 7.16}— H I emission lines detected with ISO-SWS toward Elias 29. The Br $\gamma$ line was observed from the ground (Greene & Lada 1996).}
\end{figure}
necessary and thus likely more evolved than the deeply embedded object Elias 29. Furthermore, we find that the Br \( \alpha \) line in our observations is resolved (Fig. 7.17). If the emission is fully extended, this corresponds to a deconvolved line width FWHM=240 km s\(^{-1}\), or FWHM=310 km s\(^{-1}\) for point source emission. This is comparable to the high Br \( \gamma \) line width observed in other low mass objects (Najita, Carr, \& Tokunaga 1996).

The line ratios differ significantly from the ratios expected from an optically thin, photo-ionized H II region ('case B'; Evans et al. 1987; Table 7.3). The origin of infrared H I emission lines has been extensively debated in literature. They could arise in stellar winds. Model calculations show that in this case the line luminosity depends on the mass loss rate, the gas temperature, and the stellar temperature (Natta, Giovanardi, \& Palla 1988; Giovanardi et al. 1991). Given a mass loss rate of \( 5 \times 10^{-7} \) M\(_{\odot}\) yr\(^{-1}\) derived from CO observations (Sect. 7.3.5), a wind gas temperature of \( T_g \sim 7000 \) K can explain the observed Br \( \alpha \), Br \( \gamma \), and Pf \( \gamma \) luminosities toward Elias 29. This corresponds to a relatively cold and neutral atomic wind, where the ionization is primarily due to photo-ionization from excited levels. It has been suggested that this represents a common phase of the pre-main-sequence evolution of low-mass stars (Giovanardi et al. 1991).

An alternative view on the origin of infrared H I emission lines has been reinforced by high resolution Br \( \gamma \) line profile studies (Najita, Carr, \& Tokunaga 1996). These observations show the absence of noticeable blue-shifted absorption features in the Br \( \gamma \) spectra, as was predicted by the outflow models (Giovanardi et al. 1991). The line profile is better explained by infalling, rather than outflowing gas. The gas originates from the disk and accretes along magnetic field lines onto the stellar surface. This regulates stellar angular momentum and generates an energetic wind (i.e. the CO outflow, Sect. 7.3.5).
### Table 7.2 — HI emission line fluxes observed and corrected for extinction toward Elias 29

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Br α</td>
<td>4.053</td>
<td>0.59</td>
<td>19.1 (1.6)</td>
<td>32.9 (2.8)</td>
<td>24.01</td>
</tr>
<tr>
<td>Br β</td>
<td>2.632</td>
<td>1.48</td>
<td>31.0 (5.0)</td>
<td>121.2 (19.5)</td>
<td>24.57</td>
</tr>
<tr>
<td>Br γ</td>
<td>2.165</td>
<td>2.20</td>
<td>4.2 (0.6)</td>
<td>31.2 (4.6)</td>
<td>23.98</td>
</tr>
<tr>
<td>Pf α</td>
<td>7.458</td>
<td>0.14</td>
<td>3.0 (0.3)</td>
<td>3.4 (0.3)</td>
<td>23.02</td>
</tr>
<tr>
<td>Pf γ</td>
<td>3.740</td>
<td>0.70</td>
<td>5.4 (1.0)</td>
<td>10.3 (1.9)</td>
<td>23.50</td>
</tr>
<tr>
<td>Hu β</td>
<td>7.505</td>
<td>0.13</td>
<td>4.3 (1.1)</td>
<td>4.8 (1.2)</td>
<td>23.17</td>
</tr>
</tbody>
</table>

[^a]: extinction in magnitudes (see text)
[^b]: extinction corrected line flux
[^c]: total luminosity assuming distance d = 160 pc

### Table 7.3 — HI emission line ratios toward Elias 29

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Obs[^e]</th>
<th>Ext. Corr[^f]</th>
<th>Case B[^g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Br α / Br β</td>
<td>0.62 (0.12)</td>
<td>0.28 (0.05)</td>
<td>1.74</td>
</tr>
<tr>
<td>Br α / Br γ</td>
<td>4.53 (0.74)</td>
<td>1.05 (0.18)</td>
<td>2.83</td>
</tr>
<tr>
<td>Br α / Pf α</td>
<td>6.30 (0.82)</td>
<td>9.68 (1.18)</td>
<td>3.17</td>
</tr>
<tr>
<td>Br α / Pf γ</td>
<td>3.53 (0.71)</td>
<td>3.19 (0.65)</td>
<td>7.47</td>
</tr>
<tr>
<td>Br γ / Pf γ</td>
<td>0.79 (0.18)</td>
<td>3.03 (0.72)</td>
<td>1.74</td>
</tr>
<tr>
<td>Pf α / Pf γ</td>
<td>0.56 (0.12)</td>
<td>0.33 (0.07)</td>
<td>2.36</td>
</tr>
<tr>
<td>Br γ / Hu β</td>
<td>0.98 (0.29)</td>
<td>6.50 (1.89)</td>
<td>2.79</td>
</tr>
</tbody>
</table>

[^e]: observed line ratio
[^f]: extinction corrected line ratio
[^g]: Case B recombination (Sect. 7.3.4)
FIGURE 7.18— CO $J = 6 \rightarrow 5$ map, centered on the infrared source Elias 29. Each panel gives the average of the spectra obtained with respect to the A and B sky background positions, i.e. “(A+B)/2” (top; Sect. 7.2.3), as well as the difference between these A and B spectra, “(A−B)/2”, which was shifted by −20 K for clarity (bottom). Any signal in the difference spectrum is due to contamination by the A or B sky background positions. The velocity scale extent is $v_{\text{lsr}} = -20$ to $+30$ km s$^{-1}$, and the intensity scale extent $T_A^K = -25$ to $+25$ K.

7.3.5 Pure rotational CO emission lines

The ISO–LWS spectrum of Elias 29 reveals five pure rotational CO emission lines, from $J = 15 \rightarrow 14$ up to $J = 20 \rightarrow 19$ (Ceccarelli et al., in prep). These are observed in a large beam (~80”). Spatial information is obtained from our ground-based CO $J = 6 \rightarrow 5$ spectra (Sect. 7.2.3). These $J = 6 \rightarrow 5$ and higher $J$ lines do not necessarily have to originate from the same region around the protostar. This is discussed in Sect. 7.5; here we focus on the CO $J = 6 \rightarrow 5$ emission line profiles, and their spatial extent.

The CO $J = 6 \rightarrow 5$ line was detected at the infrared position, and is extended to the South-East (SE) and North-West (NW; Fig. 7.18). The line is still bright at the edge of our map, i.e. extends beyond 20” (~3300 AU) from the center. The line is broadest in the map center, with FWHM~ 10 km s$^{-1}$. It has two peaks, with the red-shifted peak somewhat brighter (Fig. 7.21). Toward the NW the line is double peaked, with also a dip at $+3.3$ km s$^{-1}$, but here the blue peak is brightest, while toward the SE only the red peak is present and shows a prominent wing (Fig. 7.21). A contour map of the wing emission is shown in Fig. 7.19. These spectra thus indicate the presence of a high velocity molecular outflow emanating from Elias 29, oriented in the NW–SE direction, with the NW lobe directed toward us. The outflow is unresolved in the perpendicular direction. The fact that the emission
7.3 Results

Figure 7.19.— Contour map of the integrated CO $J = 6 \rightarrow 5$ emission toward Elias 29, showing the presence of a bipolar molecular outflow. The solid lines show the blue lobe in the north-west, with the emission integrated between $v_{\text{lsr}} = -10$ and $0$ km s$^{-1}$, while the dotted lines show the red lobe in the east-south-east, for emission in the interval $+7$ to $+17$ km s$^{-1}$. Levels of $5, 10, 15, 20, 25,$ and $30$ K km s$^{-1}$ are shown.

is resolved in the NW–SE direction indicates that we see the outflow under an angle (see also the discussion in Sect. 7.5). The outflow traced by our CO $J = 6 \rightarrow 5$ observations agrees well with that seen in the $J = 2 \rightarrow 1$ line (Bontemps et al. 1996), and shows even better a characteristic bipolar shape. The correspondence is less clear compared to the $J = 2 \rightarrow 1$ map of Sekimoto et al. (1997), due to their large beam ($34''$ against our $\sim 12''$). The morphology of the outflow is better defined in the $J = 6 \rightarrow 5$ than the $J = 2 \rightarrow 1$ line, probably because the $J = 6 \rightarrow 5$ line traces warmer gas and is less contaminated by material belonging to the cloud itself. The average line profile of the $J = 2 \rightarrow 1$ (Bontemps et al. 1996) and $J = 6 \rightarrow 5$ lines shows that there is a larger fraction of $J = 6 \rightarrow 5$ emission at high velocities (Fig. 7.20). This is particularly evident in the blue wings, and in this sense the $J = 6 \rightarrow 5$ line traces faster material than the $J = 2 \rightarrow 1$ line.

The $^{13}\text{CO} J = 6 \rightarrow 5$ line at the central position peaks at $v_{\text{lsr}} \sim 5$ km s$^{-1}$, clearly not coincident with the $3.3$ km s$^{-1}$ dip in the $^{12}\text{CO}$ line (Fig. 7.21). Perhaps the $^{13}\text{CO}$ line is also absorbed at $3.3$ km s$^{-1}$. The absorbing gas could be a cool foreground cloud, not part of the collapsing core. This cloud is extended, as the same absorption appears in the NW border of the map. Here, the $^{13}\text{CO} J = 6 \rightarrow 5$ emission is marginally detected ($T_R \sim 3$ K). The much larger $^{13}\text{CO}$ emission toward the center indicates a larger column density of warm gas. Part of this gas ($\sim 20\%$; Sect. 7.5) is radiatively excited near the central core.

Protostellar outflows can be usefully characterized by their momentum flux,
CHAPTER 7. THE LOW MASS PROTOSTAR ELIAS 29

FIGURE 7.20— Average spectra of the $J = 2 \rightarrow 1$ (thin line) and $J = 6 \rightarrow 5$ (thick) lines. The $J = 6 \rightarrow 5$ spectrum was multiplied with a factor of 1.5 to match the $J = 2 \rightarrow 1$ peak, and better show the different wing extent. The dotted lines show the velocity interval taken by Bontemps et al. (1996) to derive their outflow map of Elias 29. The beam size of both observations is $\sim 12''$.

FIGURE 7.21— From top to bottom are shown the $^{12}$CO and $^{13}$CO $J = 6 \rightarrow 5$ spectra observed toward the infrared position of Elias 29, the $^{12}$CO spectrum to the SE of this, and the $^{12}$CO and $^{13}$CO spectra to the NW. This clearly demonstrates that a large fraction of the CO $J = 6 \rightarrow 5$ emission originates from a high velocity outflow. The vertical dashed lines at 3.3 and 5.0 km s$^{-1}$ are given to facilitate the comparison of the profiles.
7.4 Discussion: gas and solid state abundances

or “force” (e.g., Bontemps et al. 1996). It allows to compare the molecular outflows of many objects, and determine their evolutionary stage. The momentum flux \( F(v_r, r, \Delta r) \) of a gas at velocity \( v_r \) is calculated by dividing the momentum in an annulus with radius \( r \) and width \( \Delta r \) over the crossing time \( \Delta r/v_r \):

\[
F(v_r, r, \Delta r) = \frac{m(v_r, r, \Delta r)}{\Delta r/v_r} \tag{7.1}
\]

The mass \( m(v_r, r, \Delta r) \) within the annulus is derived from the line intensity, and the momentum flux \( F(r) \) is obtained by integrating over the high velocity wings. The resulting expression is independent of the annulus width:

\[
F(r) = \int_{\text{wings}} 2\pi r v_r^2 C(T_{\text{ex}}, J_{\text{up}}, \tau) \frac{\tau}{T_{\text{ex}}} \, dv_r \tag{7.2}
\]

Here, \( C(T_{\text{ex}}, J_{\text{up}}, \tau) \) is the conversion factor between the observed intensity in one detector channel \( T_{\text{ex}}^0 \, dv_r \), averaged over the annulus, and the hydrogen column density \( N_{\text{H}_2} \). Assuming LTE, it depends straightforwardly on the excitation temperature \( T_{\text{ex}} \), the quantum number of the upper rotational level \( J_{\text{up}} \), and the line optical depth \( \tau \). At present, we do not take into account departures from LTE, but note that these can be significant, depending on the assumed gas temperature and density (Ceccarelli et al., in prep.). For Elias 29, we calculate the momentum flux from CO \( J = 6 \rightarrow 5 \) by integrating over the blue and red wings (Fig. 7.20). Since the outflow is very weak in \(^{13}\)CO \( J = 6 \rightarrow 5 \), we assume the \(^{12}\)CO wings are optically thin. Then, assuming the gas is hot, \( T_{\text{ex}} = 1500 \) K, we find a momentum flux \( 6.8 \times 10^{-6} M_\odot \, \text{km s}^{-1} \text{yr}^{-1} \), in reasonable agreement with the value obtained for CO \( J = 2 \rightarrow 1 \) (Bontemps et al. 1996; Sekimoto et al. 1997). With a highest observed outflow velocity of \( \sim 10 \) km s\(^{-1} \), the inferred mass loss rate is \( \sim 7 \times 10^{-7} M_\odot \) yr. This value increases with a factor of \( \sim 4 \) when a colder gas of \( T_{\text{ex}} = 50 \) K is assumed, but decreases when we would take into account departures from LTE. The momentum flux and mass loss rate will also significantly increase when inclination corrections are made. We refer to Ceccarelli et al. (in prep.), where these effects are discussed in more detail. A similar momentum flux for \( J = 6 \rightarrow 5 \) and \( J = 2 \rightarrow 1 \) would imply conservation of momentum between the inner, warmer parts (traced by \( J = 6 \rightarrow 5 \)) and the cooler outer layers of the outflow (traced by \( J = 2 \rightarrow 1 \)). The momentum flux of Elias 29 is relatively low compared to other YSO’s, even more when correcting for its relatively high luminosity, thus indicating that Elias 29 is a rather evolved Class I protostar (Bontemps et al. 1996).

7.4 Discussion: gas and solid state abundances

We have calculated line of sight averaged gas and solid state abundances toward Elias 29, by dividing the column densities presented in this Chapter over the total hydrogen column density \( N_{\text{H}_2} = 1.2 \times 10^{23} \) cm\(^{-2} \) (Sect. 7.3.2). We compare these abundances with a sample of sight-lines, spanning the range from dark cloud core
to fairly evolved protostars (Table 7.4). As a tracer of quiescent dark cloud material, we chose the object Elias 16, an evolved star by chance located behind the Taurus molecular cloud (e.g. Whittet et al. 1998). The least evolved protostar in our comparison sample is NGC 7538 : IRS9. The infrared spectrum of this deeply embedded object is characterized by cold ice (Whittet et al. 1996; Chapt. 4), and the gas phase temperatures and abundances indicate a very modest hot core (Mitchell et al. 1990; van Dishoeck et al. 1996). W 33A is even more embedded than NGC 7538 : IRS9, but does have a significant amount of warm gas along the line of sight (Mitchell et al. 1991), and has a lower abundance of volatile ices (Tielens et al. 1992). The most evolved object in our sample is GL 2591. It is a typical high mass hot core source, with low ice abundances and high gas temperatures. NGC 7538 : IRS9, GL 2591, and Elias 29, are all associated with infrared reflection nebulae, and have well developed high velocity molecular outflows. A notable exception is W 33A (Mitchell et al. 1991). Although radio continuum observations do indicate the presence of an ionized wind, it has an unusually low mass loss rate (5 \(10^{-7}\) M\(_{\odot}\) yr\(^{-1}\); Rengarajan & Ho 1996). Finally, all these comparison protostars are at least three orders of magnitude more luminous than Elias 29, thus allowing an investigation of the effect of low and high mass star formation on the abundances.

The H\(_2\)O and CO ice abundances decrease for the sequence of objects Elias 16,
NGC 7538 : IRS9, W 33A to GL 2591 (Table 7.4). At the same time, the gas phase H$_2$O abundance, the gas phase CO and H$_2$O temperatures, as well as the gas-to-solid ratios (Table 7.5), increase for these objects. The H$_2$O gas may originate from evaporation of ice mantles, or may be newly formed by reactions of atomic O and H$_2$ in warm conditions (T $\gtrsim$ 200 K) in the central hot core or in shocks created by the outflow (e.g., van Dishoeck & Blake 1998). The total (gas plus ice) H$_2$O abundance decreases for the more evolved objects, indicating that H$_2$O is destroyed rather than being newly formed (van Dishoeck 1998). In this heating sequence, Elias 29 is placed after W 33A, and before GL 2591. Thus, despite its much lower luminosity, Elias 29 fits well in this hot core trend, and heating of molecular envelopes by protostars seems to be scale invariant (Ivezic & Elitzur 1997). The various ice band profiles (H$_2$O, CO, CO$_2$, and 6.8 $\mu$m), however, indicate a low ice temperature toward Elias 29, and a high fraction of apolar ice, resembling very much NGC 7538 : IRS9, rather than W 33A or GL 2591. The combination of high gas phase abundances and temperatures, together with low ice temperatures, as seen in Elias 29, is remarkable and is not seen in the high mass protostars. Thus, although thermal processing is important for the evolution of the surrounding material of both high and low mass protostars, the effects seem to be different in low mass objects. Geometry, such as the presence of a circumstellar disk, or a layer of cold foreground material, not physically connected to the protostar, may play a more important role here. Also, shock heating by the molecular outflow may have a larger influence in low mass objects (Sect. 7.5).

Whereas thermal processing is very important for species such as H$_2$O, CO, and CO$_2$, other mechanisms are needed to explain the variations of solid CH$_3$OH, and XCN abundances for the sources in our sample (Table 7.4). To date, no CH$_3$OH ice has been found in low mass protostars or dark clouds. For XCN, energetic processing by the far-ultraviolet radiation of the star, or produced by cosmic rays, as well as particle bombardment have been considered (e.g. Lacy et al. 1984, Grim et al. 1987, Allamandola et al. 1988). These processes apparently are of less importance in low mass protostellar systems.

### Table 7.5 — Gas-to-solid state column density ratios of Elias 29 compared to other lines of sight. Values taken from Table 7.4 and van Dishoeck et al. (1997). Elias 29 seems to resemble the more evolved hot core sources.

<table>
<thead>
<tr>
<th>Object</th>
<th>CO</th>
<th>H$_2$O</th>
<th>$T_{\text{warm}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elias 16</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NGC 7538 : IRS9</td>
<td>12</td>
<td>0.02</td>
<td>180</td>
</tr>
<tr>
<td>W 33A</td>
<td>45</td>
<td>0.02</td>
<td>120</td>
</tr>
<tr>
<td>Elias 29</td>
<td>&gt;53</td>
<td>&gt;0.26</td>
<td>200-1000</td>
</tr>
<tr>
<td>GL 2136</td>
<td>200</td>
<td>0.4</td>
<td>580</td>
</tr>
<tr>
<td>GL 2591</td>
<td>&gt;400</td>
<td>0.8</td>
<td>200-1000</td>
</tr>
<tr>
<td>GL 4176</td>
<td>&gt;400</td>
<td>~2</td>
<td>200-1000</td>
</tr>
</tbody>
</table>

7.5 Discussion: the structure of Elias 29

The variety of dust, gas and ice absorption and emission components presen-
ted in this Chapter, and in the Literature, allows us to construct an overall view of Elias 29. We discuss each of these components here, with reference to the sketches in Figs. 7.22 and 7.23. The most direct view on the geometry has been provided by lunar occultation observations. A central object with diameter of ~1 AU emits 90% of the 2.2 μm continuum emission (Simon et al. 1987). This is emission from hot dust directly surrounding the protostar, or perhaps the inner parts of a circumstellar disk. The remaining 10% of the emission comes primarily from an object of 60 AU in diameter. This could be the hottest part of a disk (T ~ 1000 K), which must have an inclination less than 45° (i.e. close to pole-on), otherwise it would be difficult to detect.

Independent evidence for the presence of a disk surrounding Elias 29 comes from the SED. We compare the SED with that of Herbig AeBe stars, since, given its luminosity (~ 36 L☉), Elias 29 might well be a (progenitor) Herbig Ae star. Herbig AeBe stars have been classified according to the spectral slope between 3.5 and 10.6 μm (Hillenbrand et al. 1992). Group I objects have λFλ ~ λ−4/3, generally assigned to an optically thick circumstellar accretion disk. Group II objects have flatter, or even rising, SEDs, which may be stars or star/disk systems embedded in an extended envelope, not confined to a disk. Finally, group III objects have steeply falling spectra in the infrared, indicative of little circumstellar dust. Within this classification, Elias 29 is a group I or II object. Its slope does not drop as steeply as λ−4/3 (Fig. 7.2), and the continuum drops sharply short-ward of ~ 2 μm, similar to the group II object R CrA of Hillenbrand et al. (1992). On the other hand, the SED of Elias 29 also very much resembles that of the typical group I object AB Aur (Fig. 7.2). High spatial resolution radio continuum and emission line observations provide strong evidence for the presence of a circumstellar disk around this object (Mannings & Sargent 1997). The flatness of the SED in AB Aur indicates that the disk is optically thick up to 100 μm, and becomes optically thin at longer wavelengths where the SED drops steeply (e.g. van den Ancker et al. 1999). It is worth to notice that also the luminosity of this object is very similar to Elias 29 (~40 L☉). Its spectral type is A0e, with stellar mass 2.5 M☉ (Mannings & Sargent 1997). Thus, Elias 29 may be a (progenitor) Herbig Ae star, with a stellar disk, but in contrast to typical Herbig stars, heavily extincted (A_v = 20 ~ 60).

Strong evidence for the presence of accretion disks in protostellar systems is provided by the presence of emission or absorption by the vibrational overtone band heads of CO (e.g. Carr 1989; Najita et al. 1996). The bands are excited only in a hot (2500–4500 K), dense (> 10¹¹ cm⁻³) gas, and thus trace the inner disks close to the central objects (<1 AU). The 2.0–2.5 μm spectrum of Elias 29 does show a regular structure (Greene & Lada 1996), but it is much weaker than the CO overtone bands seen in several other protostars, such as another ρ Oph protostar, WL 16. Furthermore, the structure at 2.0–2.5 μm does not coincide with the expected wavelength of the CO band heads. The absence of the CO overtone bands in Elias 29 does however not prove the absence of an (inner) disk (Calvet et al. 1991). The Herbig Ae star AB Aur, which does have a disk, and resembles Elias 29 in many aspects, also has no detected CO overtone bands in emission or absorption.
The H I emission lines in Elias 29 may be indicative for an accretion disk. Although they might as well originate from a relatively cold (7000 K), neutral wind, an origin in disk matter accreted along magnetic field lines onto the stellar surface seems more plausible (see Sect. 7.3.4 for a discussion). The magnetic field in protostellar systems is strong enough to hold off the disk before it reaches the stellar surface. It disrupts the inner disk and channels the accreting material to fall onto the star in accretion rings or spots. The accretion energy dissipates and heats the photosphere enough to ionize hydrogen \( (T \sim 10^4 \text{ K}) \), when the rapidly moving magnetospheric gas shocks at the stellar surface (e.g. Hartmann 1998). Again, the \( \text{Br}\alpha/\text{Br}\gamma \) and \( \text{Br}\alpha/\text{Pf}\gamma \) line ratios and luminosities are very similar to that of the object Herbig Ae object AB Aur. This is somewhat surprising since both the mass loss and accreting rates are (at least) a factor of 50 larger in Elias 29. We have to stress, however, that this similarity may not be real, since the uncertainties in the extinction correction for the H I lines in Elias 29 are large.

The inclination of the possible disk with respect to the line of sight is uncertain. If the disk were edge-on, a higher absorbing column, perhaps an order of magnitude larger than the observed \( N_H \sim 1.2 \times 10^{23} \text{ cm}^{-2} \) (Sect. 7.3.2) would be expected.
An independent measure for \( N_{\text{H}} \) and the disk inclination is provided by the hard X-ray flux and spectrum, arising from a hot gas in the magnetosphere. For Elias 29, a high \( N_{\text{H}} \sim 2 \times 10^{23} \text{ cm}^{-2} \) is observed during X-ray flares, but \( N_{\text{H}} \) is a factor of 5 lower in quiescent phases (Kamata et al. 1997). Perhaps the X-ray flares are formed low in the magnetosphere, and in an edge-on configuration trace higher column densities compared to X-rays formed in quiescent phases higher in the magnetosphere. We can at present not discriminate between these contradictory views. It has also been suggested that in disk systems, deep silicate bands indicate an edge-on orientation (Kenyon et al. 1993). However, in the case of Elias 29, the silicate absorption may also originate in a dense envelope (see discussion further below). On the other hand, in the models of Kenyon et al., edge-on systems give SEDs that peak in the far-infrared, in contrast to what is observed for Elias 29.

Accretion disks are unavoidably associated with outflows through the poles of the system. For Elias 29, the blue and red lobes of the detected CO \( J = 6 \rightarrow 5 \) outflow do not overlap in our projection, and thus we do not see the disk pole-on. The molecular outflow is oriented NW-SE, extended to at least 3300 AU, in projection, from the infrared source. Extended 2.2 \( \mu \text{m} \) continuum emission is seen to radii of 150-300 AU (1-2 \( '' \); Zinnecker et al. 1987) or even 1200 AU (8 \( '' \); Elias 1978). This may be the reflection nebula on the inner side of the outflow lobes, illuminated by the central star through the cavity created by the outflow. Evidently, the reflection nebula must be seen under an angle, confirming that the outflow and disk are tilted with respect to our line of sight, i.e. the system is not pole-on.

Millimeter wave continuum observations, tracing the coldest dust, indicate an extended envelope, centrally concentrated on the infrared source (FWHM=17\( '' \); 2600 AU; André & Montmerle 1994). The emission is fairly symmetric in the map of André & Montmerle, but appears extended in the NE-SW direction, perpendicular to the outflow, in a recent study of Motte et al. (1998). The outflow, extending to over 3300 AU, likely has removed part of this envelope in its flow direction. The envelope is found to have a mass of \( \sim 0.10 M_\odot \), and temperature \( T = 35 \text{ K} \). The spatially extended deep absorption at \( v_{\text{lsr}} = 3.3 \text{ km s}^{-1} \) in the \(^{12}\text{CO} \ J = 6 \rightarrow 5 \) emission line may arise in this circumstellar envelope, or in extended foreground cloud material, which is clearly present (Motte et al. 1998).

The detected ices toward Elias 29 could be present in the foreground cloud, the extended envelope, and, in the edge-on case, the circumstellar disk. The low \( \text{H}_2\text{O} \) ice temperature (40 K in the laboratory), the particularly low CO ice abundance, which all is in the volatile, apolar phase, and the profiles of the \(^{13}\text{CO} \) and 6.8 \( \mu \text{m} \) bands, all indicate that currently no regions around the warm central core exist where ices are strongly heated (\( \sim 70-90 \text{ K} \)). The particularly low abundance of CO ice is explained by the temperature of the envelope (35 K), exceeding the sublimation temperature of 20 K. The detected apolar CO ice can thus only be present in the outer layers of the envelope, the foreground cloud, or the most shielded regions of the disk, if seen edge-on. The abundances of the less volatile \( \text{H}_2\text{O} \) and CO2 ices are higher, and may be present also in the envelope.

The abundant hot CO and \( \text{H}_2\text{O} \) gas is seen in absorption against the continuum
7.5 Discussion: the structure of Elias 29

Figure 7.23— Schematic overview of a possible geometry in the central core of Elias 29. The location of various observed species have been indicated. The components are not drawn to scale. This Figure is adapted after Hartmann (1998)
CHAPTER 7. THE LOW MASS PROTOSTAR ELIAS 29

of the central heating source, or the heated disk. The gas may have been heated by radiation from the central object, or by shocks from the outflow. Radiative heating to such high temperatures (∼500 K) would locate the gas in a hot core, surrounding the central object. The gas could be concentrated in a high density layer above the circumstellar disk. To sufficiently heat it, the disk needs to flare outwards, rather than being flat (e.g. Chiang & Goldreich 1997). The gas could also be present more uniformly in the hot core, at lower densities (∼ 10⁶ cm⁻³). It might then also be partly heated by shocks from the outflow. Shock heating may also locate the hot gas at much larger distances from the central source (> 1000 AU).

The scale on which the hot gas is present can be constrained when one assumes that the pure rotational CO emission lines (Ceccarelli et al., in prep.) are emitted by the same hot gas. With the temperature and column density derived from the CO absorption lines, the line emission can be calculated, assuming spontaneous, and optically thin emission from an LTE level distribution. The observed line emission is then fitted by adjusting the size of the emitting region. For the range of column densities and temperatures of the hot component found to fit the CO absorption lines (Fig. 7.10), we find diameters in the range 85–225 AU. Thus indeed, the observed hot CO gas may be present in a hot core region with the size of a circumstellar disk. More detailed modeling of the CO emission lines, including departures from LTE, optical thickness corrections, and taking into account excitation by radiative pumping, will provide firmer conclusions on the location of the gas phase CO and H₂O components, e.g. whether there is also a component associated with the transition region between the hot core and the dense envelope (Ceccarelli et al., in prep.). In any case, it is clear that the far-infrared CO emission fills only a small fraction of the ISO–LWS beam (∼12000 AU), and is not associated with the molecular outflow far away from the central core. In contrast, and in the same physical model, only ∼20% of the CO J = 6 → 5 flux within the 1800 AU beam on the central position can be explained by the hot gas. Most of the flux originates from the shock of the outflow, as is also indicated by the large width of the CO J = 6 → 5 line.

7.6 Summary and conclusions

A full 1.2–195 μm spectrum has been presented for the low mass protostellar object Elias 29 in the ρ Ophiuchi molecular cloud. The SED — in the Log(λ) vs. Log(∆Fλ) plane — rises steeply to a maximum near 5 μm, is remarkably flat up to 100 μm, and drops steeply at longer wavelengths. Superposed on the continuum is a wealth of absorption lines of gas and solid state molecules. Hot CO and H₂O gas are detected (T ∼500 K) at rather high abundances, as well as cold CO and perhaps cold H₂O gas. This indicates that the central core of Elias 29 has been significantly heated. This is supported by the relatively low ice abundances. In this respect, Elias 29 resembles luminous protostars with well developed hot cores, such as GL 2591. However, none of the many ice bands that are detected, i.e. from H₂O, CO, CO₂, and the 6.8 μm band, shows outspoken signs of thermal pro-
cessing. Again in comparison with luminous protostars, Elias 29 more resembles less evolved objects, such as NGC 7538 : IRS9. Perhaps geometric effects play a more important role in low mass protostars. The cold ices may originate in cold foreground clouds, not directly associated with the collapsing envelope, or these ices have been shielded from the radiation of the central source by the presence of a circumstellar disk.

We construct a picture of the geometry and evolutionary status of Elias 29. In many aspects, Elias 29 resembles the Herbig A0e star AB Aur. The luminosity of the objects are similar (~40 $L_\odot$), as well as several indicators for a circumstellar disk, such as the shape of the SED, and the strength and ratios of H I emission lines. Since AB Aur’s disk has been spatially resolved, it seems likely that Elias 29 has a disk as well. However, the disk of Elias 29 must be in an earlier evolutionary stage, since this source has a factor of 50 larger accretion (and mass loss) rate, and the spectrum does not show the many dust (silicates, PAH) emission features seen in AB Aur (van den Ancker et al., in prep.). Furthermore, Elias 29 has a massive circumstellar envelope, and suffers from a large extinction. Thus, Elias 29 is a rather evolved Class I protostar, having a deeply embedded, optically thick accretion disk, and approaches the transition to the Class II, Herbig Ae, phase. This is further supported by the relatively low momentum flux and mass loss rate ($\sim 7 \times 10^{-7} M_\odot \text{yr}^{-1}$), as derived from the molecular outflow.

If we assume that the hot CO absorption lines and the detected far-infrared CO emission lines originate from the same gas, we calculate that it is present on a scale of 85–225 AU, i.e. the typical size of circumstellar disks. The hot CO and H$_2$O gas is perhaps present in the photosphere of the disk, which must then be flared, to be sufficiently heated by the central object. The observed CO $J = 6 \rightarrow 5$ emission, however, must have been excited by shocks from the molecular outflow, as is also evident from the high velocity wings. More detailed modeling of the CO and H$_2$O absorption and emission lines is necessary to further constrain the location of the gas, i.e. the distance from the central heating source, height above the disk, distribution over the hot core, and association with the molecular outflow. The importance of heating by the outflow can be further investigated by observing other species, such as SiO and SO.

The inclination of the disk/outflow with respect to the line of sight is very uncertain. It is an important question, to be answered by future high spatial resolution infrared (HST) or millimeter continuum and line observations. It will clarify whether the large extinction and ice bands arise from the (edge-on) disk, or a dense envelope.

### 7.7 Acknowledgments

We thank Tom Greene for providing us the 1.1–2.4 $\mu$m spectrum of Elias 29.