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LWS observations of the protostar IRAS16293-2422

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Abstract. We report ISO-LWS observations toward the low mass star IRAS16293-2422 between $43\mu m$ - $197\mu m$. The CO, H_2O and OH rotational lines and the OI($63\mu m$) fine-structure line dominate the spectrum. Combining the CO J_{up}=14 to 25 observations with previous J_{up}=6 measurements, we derive stringent limits on the density ($\sim 3 \cdot 10^4 cm^{-3}$), temperature (~1500 K), and column density ($\sim 1.5 \cdot 10^{20} cm^{-2}$) of the emitting gas. We show that this warm gas is associated with the outflow and that a low velocity, C-type shock can account for the characteristics of the CO spectrum. The H_2O and OH abundances derived from the observed line fluxes are $[H_2O] / [H_2] \sim 2 \cdot 10^{-5}$ and $[OH] / [H_2] \sim 5 \cdot 10^{-6}$ respectively.

Finally, we speculate that the OI($63\mu m$) line emission originates in the collapsing envelope that surrounds the central object.

1. Introduction

IRAS16293-2422, at 160pc in a fairly isolated and cold molecular cloud core in the ρ Ophiuchus complex, is one of the best studied protobinary systems (Wootten 1989), and one in which infall has been claimed to occur simultaneously with outflow (Zhou 1995). CO low J transitions trace the presence of an outflow emanating from one component of the protobinary system, 1629A, and possibly another outflow originating in the second component, 1629B (Walker et al 1993). Previous observations with the Kuiper Airborne Observatory (KAO)

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showed OI(63μm) line emission associated with the outflow (Ceccarelli et al 1997a).

2. Observations

Long Wavelength Spectrometer (LWS) grating spectra covering the range from 43μm to 197μm were obtained during February 1996 toward IRAS16293-2422, at the position α_{1950}=16^{h}29^{m}20^s.9, δ_{1950}=–24°22′13″ The spectra were flux calibrated against Uranus (Swinyard et al. 1996) and the absolute accuracy is estimated to be better than 30%. The LWS beam size is ~ 80" (Swinyard et al. 1996). The observed line spectrum is shown in Fig. 1.

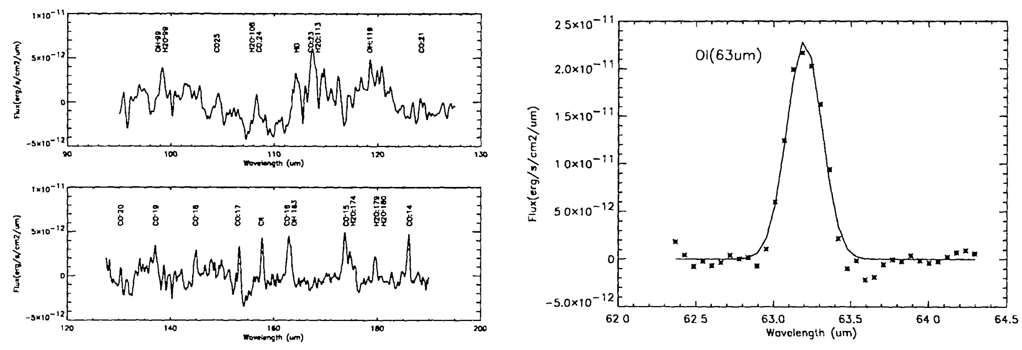

Figure 1. Right: continuum subtracted line spectrum. Left: OI(63 μm) line, where the solid line shows the gaussian fit.

3. DISCUSSION

3.1. The molecular emission

The LWS spectrum shows CO rotational transitions from J_{up} of 14 through to 25, and rotational transitions of H_2O and OH, as marked in Fig. 1.

An LVG model, applied to a slab geometry, was used to interpret the observed CO line intensities. This model considers the first 50 rotational levels, with the collisional excitation rates taken from McKee et al (1982) and an adopted value for [CO] / [H_2] = 10^{-4} (van Dishoeck et al 1995). Additionally, the linewidth is assumed to be 10 km s^{-1} (as suggested by the CO J=6→5 observations of Ceccarelli et al 1997b). The model has four other free parameters: the density and the temperature of the gas, the angular extent of the emitting region and the depth of the slab (multiplied by the linewidth). The last two parameters, the angular extent and slab depth, are independent only if the lines are optically thick, otherwise the emission is proportional to their product.

Comparison of the observed 14→13 to 21→20 ratio with theoretical values clearly demonstrates that the CO lines observed by the LWS cannot uniquely constrain the parameters of this model, and only put a lower limit to the gas temperature $\geq$ 150K. The emission could, in principle, be explained as either originating in a dense ($\sim 10^7$cm^{-3}), compact ($\sim 8 \cdot 10^{15}$ cm) and warm ($\sim$ 150 K) gas, *or* to arise in less dense ($\sim 10^4$cm^{-3}), more diffuse ($\sim 10^{17}$cm) and hotter ($\sim$ 2000 K) gas. However, the denser and colder hypothesis seems to be unlikely, since in this case the gas and dust will be thermally coupled and a 30 $L_\odot$ source would only heat the dust (and consequently, the gas) up to $\leq$ 50 K at $r \sim 10^{16}$cm. It seems unlikely that CO line emission would escape self-absorption by colder gas, lying further out in the surrounding envelope. In fact, detailed model computations of CO emission lines from collapsing envelopes predict a very high opacity for the high J CO lines, and, consequently, a much lower flux (Ceccarelli et al. 1996).

Additional support for the hot diffuse hypothesis is provided by observations made in the CO J=6→5 transition toward IRAS16293-2422 (Ceccarelli et al 1997b). The observed CO J=6→5 emission is has a size about 14"x80" and both the broadened line profiles and the spatial distribution suggest that the CO J=6→5 emission originates in the outflowing gas. Assuming that the high J CO emission observed comes from the same region, we can set stringent limits to constrain inputs to the LVG model. The J=6→5 to J=25→24 CO lines are fitted by gas with a density between $3 \cdot 10^4$ cm^{-3} and $4 \cdot 10^4$ cm^{-3}, a temperature between 1000 K and 1700 K, and a slab depth $\sim 5 \cdot 10^{15}$ cm. The CO column density of this warm gas is then $\sim 1.5 \cdot 10^{16}$ cm^{-2} and the total gas mass is $\sim 2 \cdot 10^{-3}$ $M_\odot$. The total CO line observed luminosity in this case amounts to 0.04 $L_\odot$, i.e. 10^{-3} of the bolometric luminosity of the source. The fitted spectrum is shown in Fig. 2.

We also used an LVG code to interpret the H_2O and OH line intensities, by solving the transfer equations for 48 and 44 levels respectively. The spontaneous emission coefficients are taken from the HITRAN database (Rothman et al. 1987), the H_2O collisional coefficients from Green et al. (1993) and the OH rates from Offer et al. (1994). Assuming that the water lines originate in the same hot gas where the CO lines originate, then $[H_2O]/[H_2] = 2 \cdot 10^{-5}$. We emphasise that it is *not* possible to exclude a different origin for these lines, given the detection of only a few water lines. Finally, assuming that the observed OH line emission also originates from the hot gas responsible for the CO emission, the $[OH]/[H_2] \sim 5 \cdot 10^{-6}$, i.e. the OH abundance is only 4 times lower than the H_2O abundance.

3.2. The C-shock associated with the outflow

As already mentioned, the observed CO J=6→5 to J=25→24 line emission seems to originate in the outflow. It is natural to think that it comes from material associated with the interaction of the stellar wind emanating from the central star with the ambient medium. The observed high molecular luminosity (with respect to the OI(63μm) luminosity), the relatively high temperature ($\sim$ 1500 K) and low density ($\sim 3 \cdot 10^4$ cm^{-3}) of the emitting gas lead to the hypothesis that this interaction will be better described by a C-shock (Draine 1980) than a J-shock (Hollenbach and McKee 1989) (see also the more detailed discussion in Ceccarelli et al. 1998).

However, given the high temperature ($\sim$ 1500K) of the emitting gas, "standard" chemical models predict that all the oxygen (not in CO) will be locked into water molecules, as the endothermic reaction $O + H_2 \rightarrow OH + H$ followed

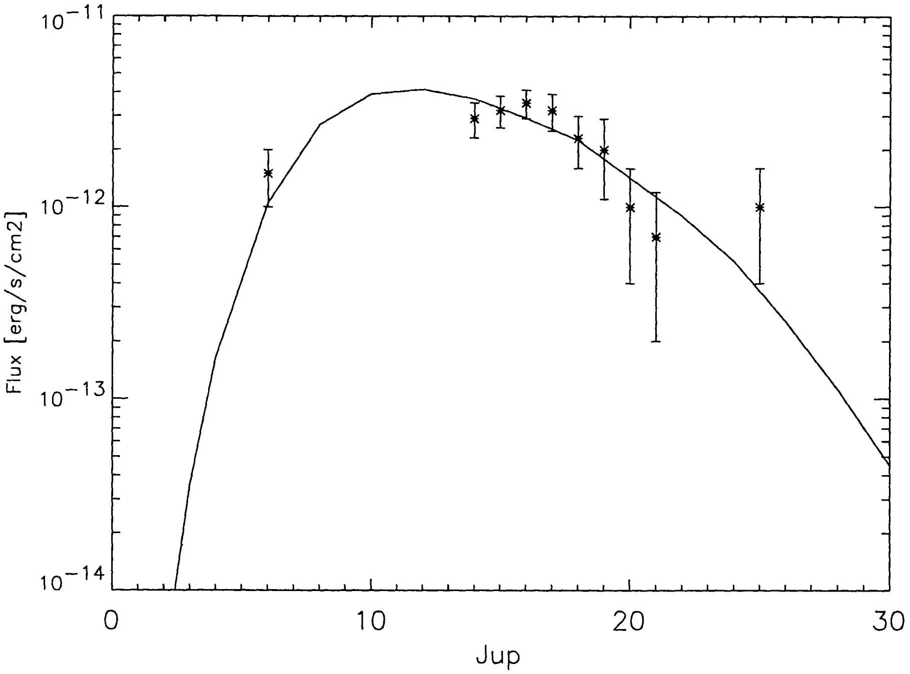

Figure 2. The best fit of the CO line spectrum. The ISO-LWS points with $J_{up} \geq 14$ are presented in this work, while the J=6→5 line is from Ceccarelli et al. (1997b). The solid line shows the emission of a slab of gas at a temperature of 1500 K and with a volume density of $3 \cdot 10^4$ cm^{-3}. The depth of the slab for this calculation is $5 \cdot 10^{15}$ cm.

by $OH + H_2 \rightarrow H_2O + H$ would efficiently incorporate the atomic oxygen into water molecules (Graff and Dalgarno 1987).

On the other hand, we only see $[H_2O]/[H_2] \sim 2 \cdot 10^{-5}$ (this can also be considered as an upper limit to the water vapour in this C-shock, if actually water emission does not originate in the same region of the CO emission). This means that either a relevant fraction of the gas-phase oxygen is in other forms than water, or that it is locked into the the icy mantles of grains, or both. The OI(63μm) on-source line intensity would require an atomic oxygen abundance $[OI]/[H_2] \sim 2.5 \cdot 10^{-5}$ if it originated in the same region as the CO (the OI(63μm) line results optically thin under these conditions). So even assuming that not all of the gas-phase oxygen is locked into water, a large fraction of oxygen must be in other molecules, such as O_2 (for which is difficult to obtain stringent upper limits on the abundance). In principle, if the pre-shock gas is not fully molecular but mainly atomic, as some protostellar wind models predict (see for example Glassgold, Mammon and Huggins 1991), the timescale for conversion of all the oxygen into water may exceed the "outflow dynamical time" (see for example the time dependent computation of Graff and Dalgarno 1987). Indeed the observed high OH abundance with respect to the H_2O abundance provides support to this hypothesis.

However, there is also a simpler explanation for the relatively low observed water abundance. Although the gas is heated by the shock, the same does not necessarily apply to the dust grains, whose temperature may well be less than the ice evaporation limit of ~ 100 K. Hence, a simple explanation for the relatively low water abundance is that the oxygen may be locked into grain mantles.

Anyway, this would not explain the high [OH]/[H_2O] observed ratio which clearly demonstrates that the conversion of OH onto H_2O has not yet been completed, and that the chemical timescale exceeds the outflow dynamical scale. This also implies that the pre-shock gas is not fully molecular.

In conclusion, the observed molecular emission agrees with the general characteristics predicted by C-shock models. Such mild shocks may be result of the oblique impact of a wind with the edges of the cavity wall created by the wind itself, or they may represent the tails of a bow shock, or finally they may trace the entrainment of the ambient material by the wind. Model computations by Lizano and Giovannardi (1995), although explicitly "tuned" for the L1551 outflow, predict that the mixing layers of the material entrained along the cavities of an outflow would attain temperatures of up to several thousand degrees.

3.3. The On-source OI(63μm) Line Emission and the Infall

Finally, we would like to explore the possibility that the OI(63μm) line emission observed at the on-source position originates in the collapsing envelope surrounding IRAS16293-2422. Recently Ceccarelli et al. (1996) modeled the infalling protostellar envelopes, computing self-consistently the evolution of their chemical and thermal structure and the emitted line spectrum. The computed OI(63μm) line luminosity only depends on the accretion shock radius and the mass accretion rate.

We show in Fig. 3 the predictions of this model for a source of 30 $L_\odot$ as a

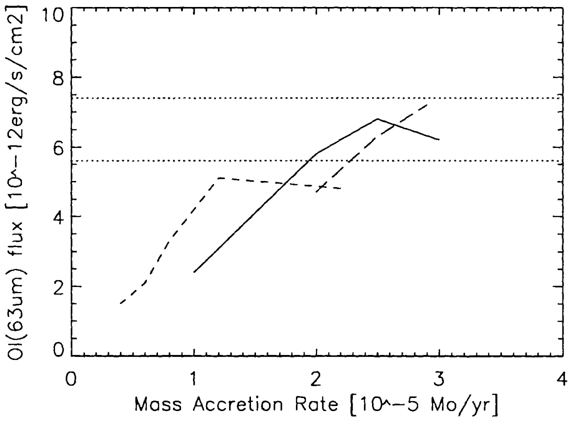

Figure 3. OI(63μm) line flux versus mass accretion rate. The short dashed line refers to an accretion shock radius equal to the protostar radius (following to Stahler 1988), the solid line assumes that the accretion shock radius is 3 times the protostar radius, and finally the long dashed line assumes that the accretion shock radius is ~ 0.4 AU. The dotted lines show the range of the observational limits, taking into account a 30% uncertainty.

function of the mass accretion rate for three different values of accretion shock radius. The agreement with the observed value is striking: the model predictions are consistent with the observed OI(63μm) emission for the mass accretion rates $\geq 2 \cdot 10^{-5}$ M$_{\odot}$yr^{-1} and accretion shock radii larger than 3 times the protostar radius. We are conscious that this interpretation is still speculative and that high spectral resolution observations of the OI(63μm) line are needed to assess if the origin of this line is in gas associated with the collapsing envelope or from the outflow. However, the point at $3 \cdot 10^{-5}$ M$_{\odot}$yr^{-1} and accretion shock radii equal to 0.4 AU corresponds to the model which also fits the observed CS line profiles (Zhou 1995).

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