*Star Formation with the Infrared Space Observatory*
*ASP Conference Series, Vol. 132, 1998*
*J. L. Yun, and R. Liseau, eds.*

# High-J CO lines from YSOs driving molecular outflows

B. Nisini, T. Giannini, S. Molinari, P. Saraceno

*IFSI-CNR, I-00044 Frascati, Italy*

E. Caux

*CESR, BP4346, F-31028 Toulouse Cedex 04, France*

C. Ceccarelli

*Observatoire de Grenoble, BP 53, F-38041 Grenoble, France*

R. Liseau

*Stockholm Observatory, S-133 36 - Saltsjöbaden, Sweden*

D. Lorenzetti

*Osservatorio di Roma, I-00040 Monteporzio, Italy*

E. Tommasi

*ISO-SOC, Villafranca, P.O. Box 50727, 28080 Madrid, Spain*

G.J. White

*Queen Mary & Westfield College, Mile End Road, London E1 4NS, UK*

**Abstract.** LWS observations towards molecular outflows driving sources show that their FIR spectrum is often dominated by the emission of CO rotational lines. Model fits to these lines show that they originate from a dense and compact gas component with temperatures ranging from few hundred up to 1600 K. An analysis of their emission suggests that non-dissociative shocks are the main excitation mechanism, although in few cases other contributions may also be present. We discuss the origin of this shocked emission and how it relates to the large scale properties of the molecular outflows.

## 1. Introduction

Line emission from carbon monoxide is one of the main diagnostic tools used to investigate the physical properties of star forming regions and the outflow activity from Young Stellar Objects (YSOs) in particular. Low-$J$ rotational transitions of CO and its isotopomers, which are easily excited at very low temperatures, are extensively used to detect and map molecular outflows. The CO transitions which fall in the LWS spectral range ($J_{up} > 14$) probe warmer (T>100 K ) and denser gas arising mainly from shocked regions, where a collimated wind (or jet), which drives the large scale outflow, interacts with the ambient medium. These transitions could in principle also be excited in Photo-Dominated-Regions (PDRs) when there is a significant diffuse FUV field, or they could be originated in collapsing envelopes surrounding protostars. LWS offers the possibility to observe many CO transitions simultaneously, together with other molecular or atomic species excited in the same region; all this information can be used to discriminate between different excitation mechanisms and to study how the derived physical conditions compare with current models for outflow activity.

## 2. ISO-LWS observations

As part of the LWS guaranteed time program on pre main sequence evolution, about 20 YSOs have been observed to date and their outflows mapped with LWS in the grating mode (R~200, FOV~80 ", Clegg et al. 1996). We detected CO emission in about half of them, but we here discuss only the six sources, namely B335 FIR , IRAS16293-2422, HH54B, IRAS12496-7650, R CrA and IC1396 N, in which at least four transitions are detected at a level of confidence to allow comparison with models and to estimate the excitation conditions. Details on how the observations have been carried out for each source are separately given by Ceccarelli et al. and Giannini et al. in this volume, by Nisini et al. (1996,1997) and by Saraceno et al. (1996).

## 3. CO line emission fitting

The CO data have been modelled by using a Large Velocity Gradient (LVG) code with a plane-parallel geometry. Collisional downward rates for levels with $J_{up} <$ 60 and T > 100 K were calculated using the $\gamma_{J0}$ coefficients taken from McKee et al. (1982). Upwards rates are computed using the principle of detailed balance. Radiative decays rates were taken from Chackerian & Tipping (1983). The model depends on several free parameters (gas temperature, density, intrinsic linewidth, CO column density and filling factor), some of them related together. The linewidth has been taken equal to the maximum velocity observed in the extended CO outflow. Since we checked a posteriori that the lines are optically thin in the majority of the model fits, the results only marginally depend on the $\Delta$v choice. The shape of the flux intensity as a function of $J_{up}$ has been used to derive a range of possible gas temperatures and densities. In general, a rough estimate of column density and filling factor can be given by assuming that the linear dimension of the region is comparable to its depth. In this way we can use the absolute flux level ( proportional to $N_{CO} \cdot \theta^2$) and the estimated total gas density ( equal to $N_{H_2}/dl$) to independently derive both $N_{CO}$ and the size of the region where the emission originates, assuming X(CO)=$10^{-4}$. In HH54B and IC1396 N the observation of water lines and the assumption that they arise from the same region which emits the CO lines, allow to define uniquely a model for the emission (see Liseau et al. 1996 and Molinari et al. this volume). In

IRAS16293 a further constraint is provided by ground-based observations of the CO 6-5 line , which has been used to better constrain the density, temperature and measure the size of the emitting region (Ceccarelli et al., this volume). In Fig.1 we show some of the line fitting results while Table 1 summarizes the physical parameters derived from the model. Despite for some sources there is a significant spread in density and temperature, the model fits always indicate that the emission comes from relatively dense and compact regions.

When comparing the total CO line luminosity with the luminosity derived for the other species observed in the LWS spectrum (Table 1 of Saraceno et al., this volume), we see that CO cooling always dominates over the other observed molecules and in most cases it is also greater than the cooling due to [OI].

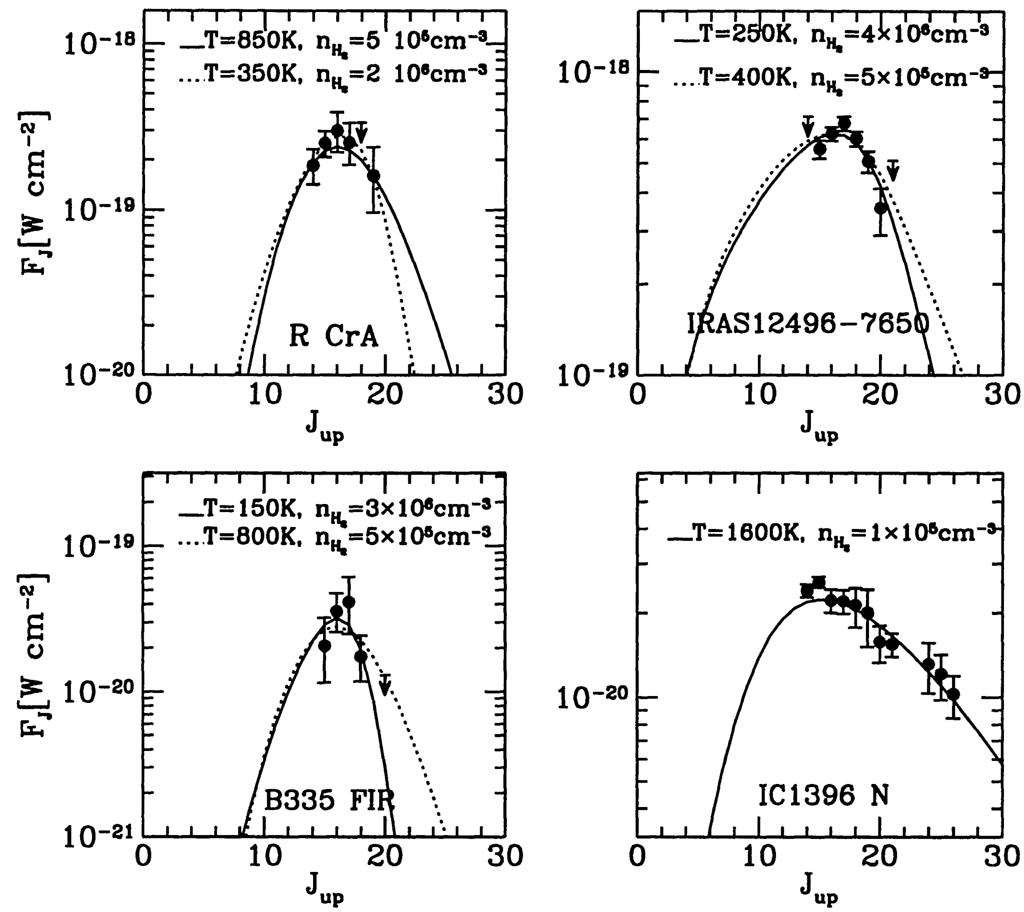


Figure 1. The CO line fluxes observed by the ISO-LWS are plotted as a function of the rotational quantum number $J_{up}$ for four of the YSOs discussed. For each source, the solid and dotted lines indicate the range of possible model fits.

**Table 1: Parameters for the FIR-CO emission**

| Source | $T_{kin}$ (K) | $n_{H2}$ ($cm^{-3}$) | $N_{CO}$ ($cm^{-2}$) | size ($''$) | size (pc) | $L_{CO}$ ($L_\odot$) |
|---|---|---|---|---|---|---|
| IC1396 N | 1600 | $1.2 \cdot 10^5$ | $1.8 \cdot 10^{17}$ | 7 | 0.025 | 0.63 |
| IRAS16293-2422 | 1500 | $3 \cdot 10^4$ | $1.5 \cdot 10^{16}$ | 14x80 | 0.01x0.29 | 0.04 |
| HH54B | 330 | $3 \cdot 10^5$ | $4 \cdot 10^{16}$ | 25 | 0.03 | 0.01 |
| B335 FIR[a] | 150 | $4 \cdot 10^6$ | $4 \cdot 10^{18}$ | 2 | 0.002 | 0.003 |
| | 800 | $5 \cdot 10^5$ | $1 \cdot 10^{17}$ | 1 | 0.001 | 0.005 |
| R CrA[a] | 350 | $2 \cdot 10^6$ | $2 \cdot 10^{18}$ | 4.6 | 0.0033 | 0.032 |
| | 850 | $5 \cdot 10^5$ | $6 \cdot 10^{16}$ | 15 | 0.01 | 0.034 |
| IRAS12496-7650[a] | 250 | $4 \cdot 10^6$ | $2.5 \cdot 10^{18}$ | 2 | 0.003 | 0.006 |
| | 400 | $5 \cdot 10^5$ | $1.4 \cdot 10^{18}$ | 3 | 0.003 | 0.009 |

[a] the two different lines give the limiting values of the derived parameters.

## 4. Discussion

### 4.1. Excitation mechanisms

Since we are considering sources driving molecular outflows, shock excitation seems to be the most natural origin for the emission of the observed warm and dense gas. Contributions by PDRs cannot be in principle excluded in those sources showing evidence of an enhanced UV field, particularly IC1396 N and R CrA (Molinari et al. and Giannini et al., this volume). However, the observed CO cooling in these sources, compared with the [OI] luminosity, is much larger than that expected from models of dense PDRs (Burton et al. 1990); in such models, moreover, the CO temperature never reaches the values derived from our fits, since these lines are predicted to originate deeply into the region, where the temperature is already dropped below 100 K.

There is evidence in all the cases considered here to favour a non-dissociative C-type shock (Draine et al, 1983) rather then a J-type shock (Hollenbach & McKee, 1989). This interpretation is supported by the fact that the total luminosity of the CO lines always exceeds the luminosity of the [OI] 63$\mu$m line observed in the same objects: J-shocks models predict that [OI] will be the main coolant whereas in C-shocks the molecular emission should always dominate. Moreover, the CO emission as a function of $J_{up}$ is also consistent with the prediction of C-shock models with velocities below 25 km $s^{-1}$ (Kaufman & Neufeld, 1996).

Table 2 shows a comparison between the observed emission and these models; here we also give the total luminosity of the shock ($L_{rad} = 1/2\ v_s^3 \cdot \rho_s \cdot A_{eff}$, where $v_s$ is the shock velocity, $\rho_s$ the pre-shock density and $A_{eff}$ the shock effective area) and the expected cooling due to $H_2$ pure rotational and ro-vibrational lines. We can see that the cooling observed in FIR lines often accounts for almost all the luminosity irradiated by the shock, being the expected contribution from $H_2$ lines significant only for the higher velocity models.

**Table 2: derived C-shock parameters**

| Source | $V_s$ (km $s^{-1}$) | $n_o$ ($cm^{-3}$) | $L_{rad}$[a] ($L_\odot$) | $L_{H_2}$[b] ($L_\odot$) | $L_{obs}$[c] ($L_\odot$) | $L_{kin}$[d] ($L_\odot$) |
|---|---|---|---|---|---|---|
| IC1396 N | 25 | $1 \cdot 10^5$ | 2.8 | 0.9 | 0.9 | 0.02 |
| IRAS16293-2422 | 25 | $1 \cdot 10^4$ | 0.29 | 0.1 | 0.05 | 0.18 |
| HH54B | 10 | $1 \cdot 10^4$ | 0.025 | 0.006 | 0.039 | 0.033 |
| B335 FIR | 10 | $3 \cdot 10^5$ | 0.005 | $2 \cdot 10^{-4}$ | 0.006 | 0.04 |
| R CrA | 15 | $3 \cdot 10^5$ | 0.31 | 0.01 | 0.078 | 0.1 |
| IRAS12496-7650 | 15 | $3 \cdot 10^5$ | 0.016 | 0.006 | 0.013 | ... |

[a] $L_{rad} = 1/2\ v_s^3 \cdot \rho_s \cdot A_{eff}$.
[b] $L_{H_2}$ is the $H_2$ cooling predicted by the model.
[c] $L_{obs}$ is the total cooling in the FIR lines observed by LWS.
[d] $L_{kin}$ is the kinetic energy of the associated outflow.

### 4.2. Origin of the shocks and comparison with the large scale outflow

Although in most of the sources we obtained spectra towards the outflow lobes, the strongest molecular emission was always detected towards the on-source position. On the other hand, [OI]63$\mu$m emission is observed in any position of the outflow in which deep integrations were made. One possible interpretation could be that we are observing different shock excitation mechanisms along the outflow, with a low-velocity non-dissociative component close to the exciting source and a dissociative shock at the apex of the flow, traced by the [OI] emission.

If a wide-angle collimated wind is driving the outflow (Shu et al. 1995), we could indeed have slower shocks closer to the source, where the wind obliquely impacts on the ambient medium, and higher velocity shocks at the apex of the wind, where it strikes the medium at the maximum velocity.

On the other hand, this two shock scenario is less clearly represented by jet-driven outflow models (Raga & Cabrit, 1993). These models predict the formation of bow shocks at the head of the jet, having different and spatially separated excitation conditions moving from the head of the bow to its wings; however, the entire bow-shock structure will be encompassed by the large LWS beam, and we should observe both the high and low velocity shock components simultaneously.

Another possible explanation for the observations, is that we do not see molecular emission on the outflow lobes because the column density of the shocked material is lower than close to the star, preventing the detection of the weaker lines; indeed, the [OI] emission is always weaker along the outflow in all the sources reported here. It is therefore likely that close to the source we observe shocked material denser than on the outflow lobes, probably originating at the base of the flow, where the jet or collimated wind plough into the dense core within which the YSO is still embedded.

If the shock traced by the CO lines is accelerating the ambient medium into the molecular outflow, we would expect to see a definite correlation between the luminosity radiated away by the shock and the mechanical luminosity of the outflow (Davis & Eislöffel, 1995). In this case the rate of mass accumulated through the shock is $\dot{M} \sim \rho_a \cdot v_s \cdot A_{eff}$, and the outflow mechanical luminosity will be given by

$$L_{out} = \frac{1}{2} \cdot v_{out}^2 \dot{M} \sim \frac{v_s}{v_{out}} \cdot L_{rad}. \tag{1}$$

Assuming that the outflow and shock velocities are similar, then their kinetic luminosities should also be comparable. In Table 2 we list the total luminosity estimated for the species observed with LWS ([OI], CO, $H_2O$ and OH), together with the kinetic luminosity of the outflows. We can see that if we also add at the observed line cooling the contribution of the expected $H_2$ cooling, we obtain values comparable to the kinetic luminosity in most of the cases. The striking exception is IC1396 N where the shock luminosity is about 40 times greater than the kinetic luminosity of the outflow. Explanations for this result could be that the outflow parameters are badly defined, leading to an inaccurate estimate of $L_{kin}$, that not all the momentum carried out by the shock is transferred to the outflow or that the an additional contribution of shock emission not associated to the outflow, needs to be taken into account (see also Molinari et al. , this volume).

**Acknowledgments.** We are grateful to M. Kaufman for having provided us with his C-shock code results.

## References

Burton, M.G., Hollenbach, D.J., Tielens, A.G.G.M. 1990, ApJ, 365, 620

Chackerian, C. & Tipping, R.H. 1983, J. of Molecular Spectroscopy, 99,431

Clegg, P.E., et al. 1996, A&A, 315, L38

Davis, C.J. & Eislöffel 1995, , 300, 851

Draine, B.T., Roberge, W.G., Dalgarno, A. 1983, ApJ, 264, 485

Kaufman, M.J. & Neufeld, D.A. 1996, ApJ, 456, 611

Hollenbach, D.J. & McKee, C.F. 1989, ApJ, 342, 306

Liseau R., et al. 1996, A&A, 315, L181

McKee, C.F., Storey, J.W.V., Watson, D.M., Green, S. 1982, ApJ, 259,647

Shu, F.H., Najita, J., Ostriker, E., Shang, S. 1995, ApJ, 455,L155

Raga, A. & Cabrit S. 1993,A&A , 278, 627

Nisini B., et al. 1996, A&A, 315, L321

Nisini B., et al. 1997, in preparation

Saraceno P., et al. 1996, A&A, 315, L293

# Part 7

## Circumstellar Environments