FAR-INFRARED COOLING LINES IN PRE-MS SOURCES

P. Saraceno[1], B. Nisini[1], M. Benedettini[1], A.M. Di Giorgio[1], T. Giannini[1,4], M.J. Kaufman[8], D. Lorenzetti[4], S. Molinari[1,9], S. Pezzuto[1], L. Spinoglio[1], E. Tommasi[10], E. Caux[3], C. Ceccarelli[5], P.E. Clegg[2], J.C. Correia[2], M.J. Griffin[2], S.J. Leeks[2], R. Liseau[6], H.A. Smith[7], & G.J. White[2]

[1]Istituto di Fisica dello Spazio Interplanetario - CNR, Roma, Italy
[2]Queen Mary & Westfield College, Mile End Road, London E1 4NS, UK
[3]CESR, BP4346, F-31028 Toulouse Cedex O4, France
[4]Osservatorio Astronomico di Roma, I-00040 Monteporzio, Italy
[5]Observatoire de Grenoble, BP 53 F-38041, Grenoble, France
[6]Stockholm Observatory, S-133 36 - Saltsjobaden, Sweden
[7]Smithsonian Center for Astrophysics, MA 02138 Cambridge
[8]Dept. of Physics, San Jose State University & NASA/Ames Research Center
[9]IPAC/Caltech, MS 100-22, Pasadena, California (USA)
[10] Agenzia Spaziale Italiana, Roma, Italy

ABSTRACT

We review the results of the observations in the 45–190 μm wavelength range with the ISO Long Wavelength Spectrometer of a sample of Class 0, Class I, Class II pre-Main Sequence objects. We briefly discuss the role of [OI] and of molecular lines in the cooling of these sources.

Key words: Stars: Circumstellar matter; Stars: Pre-main Sequence; Infrared: spectroscopy; Infrared: molecular lines.

1. CHARACTERISTICS OF THE SAMPLE

We used the Long Wavelength Spectrometer (LWS), (Clegg et al. 1996) on the ISO satellite to observe a sample of pre-Main Sequence sources (Class 0, Class I, Class II objects) selected for having a relatively strong submillimeter continuum and for being associated with relatively strong molecular outflows (Saraceno et al. 1996 and 1997).
The youth of the selected objects can also be seen by the ISO FIR colour temperature (Tc) ranging from Tc$\sim$27 K, for the youngest objects, (Class 0), to about 75 K in the most evolved Class II Herbig AeBe stars (see Pezzuto et al. these proceedings).

In Figures 1-2 a few LWS spectra representative of the different groups of objects are presented. Figure 1 shows the youngest objects of the sample: a Class 0 (L1448mm, Tc$\sim$35 K), a low luminosity ($L \lesssim 10^3 L_\odot$) Class I (IC 1396N, Tc$\sim$35 K) and the high luminosity Class I W28 A2 ($L\sim10^5 L_\odot$, Tc$\sim$65 K a very young object with a dynamical time of $\sim$2000 years). Class 0 and low luminosity Class I sources have very rich spectra with several molecular transitions. In these objects (see Table 1) molecules are the major coolants of the gas. On the contrary, in the high luminosity Class I sources atomic lines are the major coolants and the spectra show weak or no molecular lines and have several intermediate ionization lines, as expected from sources with a very strong continuum (tens of kJy) and strong UV field.

Figure 2 presents the more evolved Class II sources: two Herbig AeBe (HAeBe) stars with quite different spectra, RCrA (Tc$\sim$40 K) and MWC 297 (Tc$\sim$75 K), and the TTauri star HL Tau (Tc$\sim$65 K). The HAeBe stars show a relatively large range of temperatures in the FIR colour-colour diagrams (Tc$\sim$ 35-75 K). The coolest objects are generally associated with an embedded cooler companion which probably dominates the FIR colours (in Figure 2 the FIR continuum of RCrA is similar to the one of a Class I); they often show molecular emission (weaker than the one in Class 0/I objects) explained by means of clumpy PDR models (see Giannini et al. 1998 and Giannini et al. these proceedings).
Finally, the observed TTauri stars present only the two fine structure lines ([OI] 63 μm and [CII] 158 μm) with the very important exception of TTauri itself, discussed by Spinoglio et al. in these proceedings.

2. [OI] EMISSION: PDRs AND SHOCKS

The [OI] 63 μm emission line is the strongest FIR line observed in YSOs. It is mainly originated by two physical processes: the excitation from photoionised and photodissociated regions (PDR, Tielens and Hollenbach 1985) and the shock excitation produced by the interaction of supersonic winds with the ambient medium.

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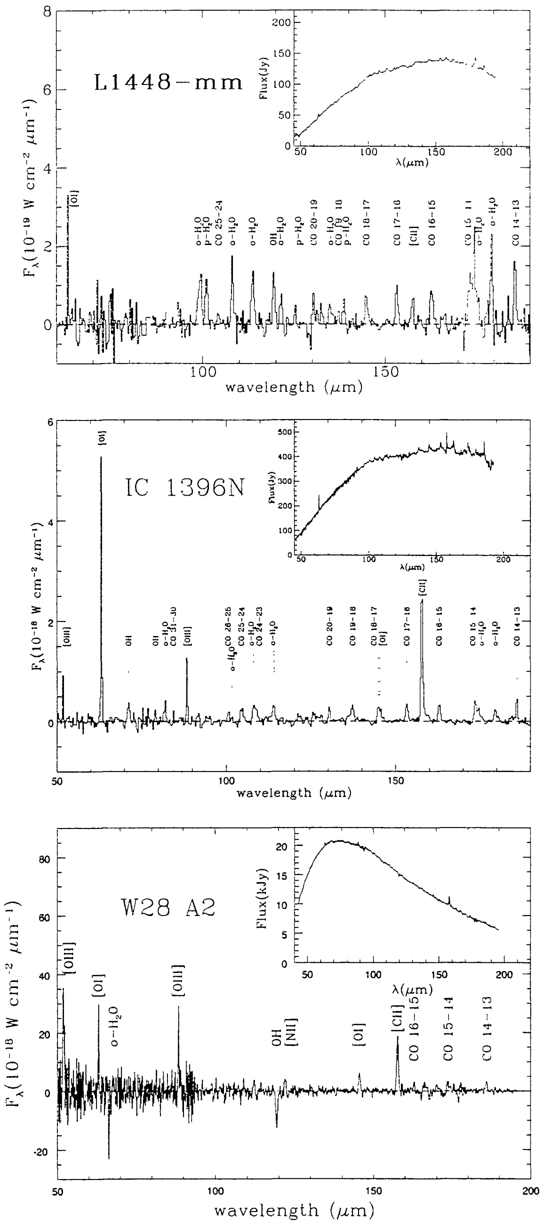

Figure 1. Spectra of the youngest objects: a Class 0 (L1448mm), a low luminosity Class I (IC 1396N) and a high luminosity Class I (W28 A2).

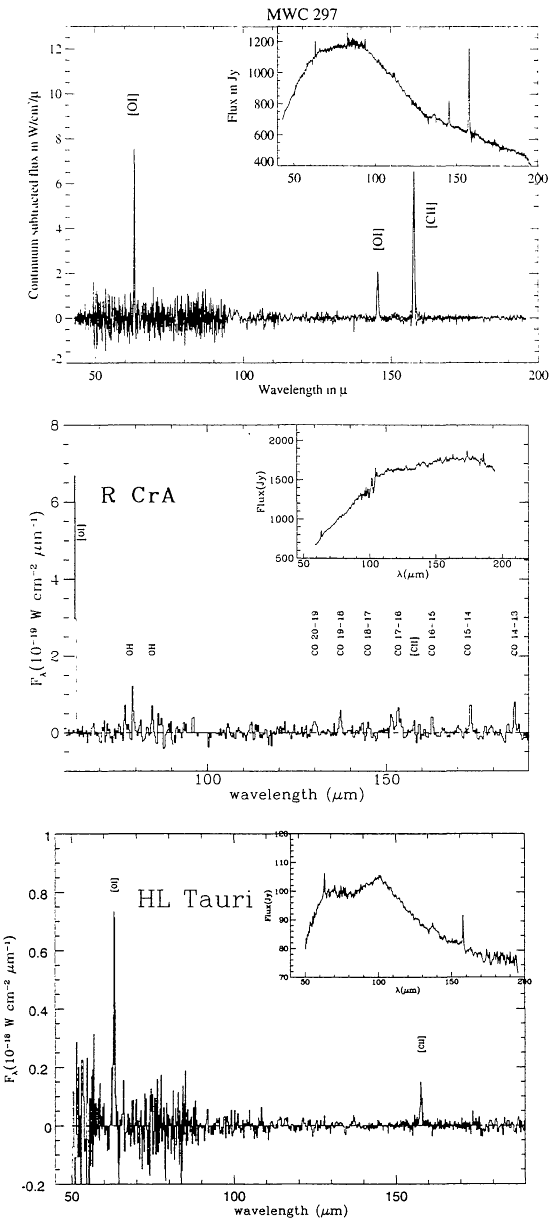

Figure 2. Spectra of Class II objects: 2 HAeBe stars (MWC 297 and RCrA) and a TTauri star (HL Tauri).

There are two kinds of shocks: dissociative "J" shocks (Hollenbach and McKee 1989), in which the temperature is relatively high, all molecules are dissociated and atomic lines are the dominant coolants of the gas and non-dissociative "C" shocks (Kaufman & Neufeld 1996; Draine 1983), in which molecules are the dominant coolants. [OI] 63 μm is the main coolant in dissociative "J" shocks; therefore Hollenbach (1985) suggested that the wind mass loss rate ($\dot{M}_{wind}$) should be proportional to the [OI] 63 μm line luminosity. $\dot{M}_{wind}$ can also be derived from the molecular mass loss ($\dot{M}_{mol}$) and its velocity (V_{mol}); therefore, assuming momentum conservation in the wind-molecular flow interaction, the following relation is valid: $\dot{M}_{wind}V_{wind} = \dot{M}_{mol}V_{mol}$. In the case of "J" shocks, the two $\dot{M}_{wind}$ determinations should be equal. Liseau et al. (1997) showed this equivalence for the [OI] detected in Herbig Haro (HH) objects.

This equivalence holds also for other objects of our sample, as shown in the upper panel of Figure 3, where the mass loss rate derived from the [OI] intensity is plotted versus the one obtained from the mole-

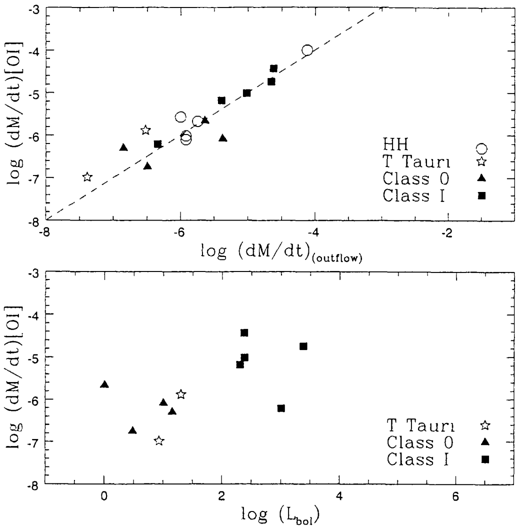

Figure 3. [OI] and molecular outflow mass loss rates determinations (upper panel) for Class 0, low luminosity Class I and TTauri stars; [OI] mass loss rate vs bolometric luminosity (lower panel) for the same objects.

cular flow observations. The dashed line represents equal values of the two mass loss rate determinations, as expected in "J" shocks. This figure contains the objects that lie on this line. They are all the HH objects, and all the Class 0 and low luminosity Class I (for TTauri stars the statistics is not conclusive).

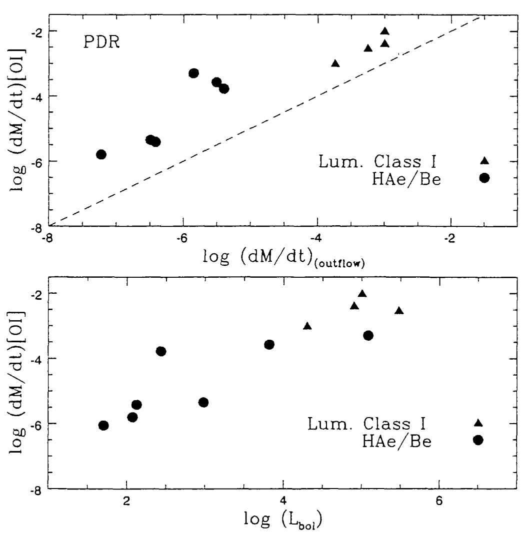

Figure 4. Same as Figure 3 but for Class I and HAeBe.

In the upper panel of Figure 4 the objects that do not lie on the line of equivalence are shown: they have an [OI] emission in excess of that predicted by "J" shock models. This means that a second and dominant component is added to the shock component, due to the presence of HII regions and PDRs, as expected for the objects in Figure 4: HAeBe stars, in which the [OI] emission is accounted for by PDR excitation (Lorenzetti et al. 1998), and high luminosity Class I sources ($L>10^4 L_\odot$), which are embedded in HII regions and PDRs. The correlation shown by these objects is explained by the fact that, in HII regions and PDRs, the [OI] luminosity is proportional to the bolometric luminosity L_{bol}: in fact, for luminous young objects, L_{bol} is proportional to $\dot{M}_{mol}$, while for Class 0 and low luminosity Class I this proportionality does not exist (Saraceno et al. 1996). This is clearly shown in the lower panels of Figures 3 and 4 where the mass loss derived from [OI] is shown as a function of L_{bol}. The objects of Figure 3 show a high dispersion while those of Figure 4 correlate. The effect is even more strong if we consider the distribution of the different classes of objects (Class 0, Class I, HAeBe) separately.

3. MOLECULAR LINE COOLING

Table 1 lists the objects of the sample for which it was possible to compute the molecular line intensities. Molecular lines have been detected in 2 HH objects out of a sample of 18, in 3 HAeBe stars out of a sample of 11 (Lorenzetti et al. 1998) and in one TTauri object out of a sample of 4. For the three categories listed above the table is statistically representative of the relevance of molecular lines. This is not the case of Class 0 and Class I sources: we observed about 20 objects and more than a half of them show molecular lines but at the present level of data analysis only for the 5 listed objects was it possible to compute the line cooling.

The table shows the importance of molecular cooling in Class 0 and Class I sources and the minor role that H_2O plays in the cooling of the shocked gas (with the exception of L1448mm). This is unexpected, because H_2O was foreseen to be the dominant FIR coolant of the gas around pre-MS objects. Water is produced by two processes: sublimation from grains, at T>100 K (van Dishoeck & Blake 1998), and gas-phase reactions ($O+H_2$)(Graff & Dalgarno 1987), which are very efficient when the gas reaches the threshold temperature of 300 K and all the oxygen not locked in CO is transformed into H_2O. These temperatures can be reached either by radiative heating close to the star, or in shocked regions, in particular by means of low velocity non dissociative "C" shocks (Kaufman & Neufeld 1996; Draine 1983). The fact that we find $L_{H_2O}/L_{CO} < 1$ for most of the sources seems to exclude very efficient gas phase reactions and implies a gas temperature $T \lesssim 300$ K. From the fit of the CO lines we can estimate the temperature of the gas and (with the exception of L1448mm and IC 1396N) the models fit agrees quite well with $T_{CO} \approx 200$ K (Saraceno et al. 1998).

Is this scenario consistent with shock models ? Figure 5 shows the objects of Table 1 plotted in a L_{H_2O}/L_{CO} vs $L_{[OI]}/L_{CO}$ diagram together with "J" and "C" shocks models predictions. The "C" shock models foresee that between 10 and 20 km s^{-1} the threshold temperature for H_2O formation is reached (see Figure 3 of Kaufman & Neufeld 1996).

The observed spread in the distribution of the cooling luminosity ratios in Figure 5 shows that our sources must be close to the threshold temperature

Table 1. Line cooling

Source	Class	L_{bol}	$L_{[OI]}$	L_{CO}	L_{H_2O}	L_{OH}	L_{lines}	$\frac{L(mol)}{L([OI])}$	$\frac{L(lines)}{L(bol)}$
		Luminosities expressed in $L_\odot$							
B335 FIR	0	3	0.002	0.004	<0.001	...	0.006	2	2 E-3
IRAS16293	0	27	0.005	0.04	0.003	0.003	0.05	9.2	1.8 E-3
L1448mm	0	10	0 008	0.03	0.045	...	0.083	9.3	8 E-3
HH25mm	0	5	0.024	0.03	0.015	...	0.07	1.9	1.3 E-2
IC1396 N	I	235	0.1	0.63	0.17	...	0.9	8	3.8 E-3
TTau	II	28	0.013	0.01	0.01	0.02	0.05	6.6	2.0 E-3
R CrA	II	132	0.038	0.03	<0.002	0.01	0.078	1.05	5.9 E-4
IRAS12496	II	50	0.005	0.008	<0.001	...	0.013	1.6	2.6 E-4
LkHα234	II	270	1.68	0.5	...	...	2.18	0.3	8 E-3
HH54B	HH	-	0.026	0.01	0.002	0.001	0.039	0.5	...
HH26C	HH	-	0.022	0.025	0.02	...	0.067	2.04	...

for water formation and thus the factor 100 in the L_{H_2O}/L_{CO} ratio is fitted by an unlikely small range of velocities (12-16 km s^{-1} for the Draine models of Figure 5). Some model efforts are therefore needed to understand if it is possible to obtain lower temperatures allowing an higher range of velocities, by changing other parameters (as magnetic field and preshock densities).

The other hypothesis to explain at least those sources with the lower L_{H_2O}/L_{CO}, is that H_2O is mainly produced by sublimation of grain mantles (with a gas temperature below 300 K for not having efficient H_2O gas phase production). This hypothesis is supported by the fact that all the objects of Table 1 (except HHs) have only on-source H_2O detections, with inferred emitting regions of few hundreds of AU. If such a region is circumstellar the temperature necessary for grain sublimation can be easily reached. The sublimation of H_2O from grain mantles has been also suggested to explain the CO, H_2O, CO_2, and CH_4 abundances detected toward high luminosity sources, where the grains could be, at T$\lesssim$100 K, not fully thermalized with the gas (van Dishoeck 1998).

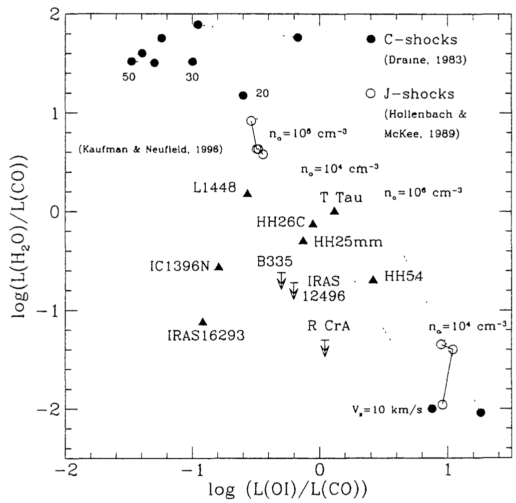

Figure 5. Cooling luminosity ratios for our sources with the predictions of shock models (Kaufman & Neufeld predictions are shown with a horizontal dashed line, since the [OI] line intensity is not given). Notice that "C" shocks models predict a jump in water cooling luminosity of 3 order of magnitude changing the velocity from 10 to 20 km s^{-1}

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