

FAR-IR SPECTROPHOTOMETRY OF HH FLOWS WITH THE ISO LONG-WAVELENGTH SPECTROMETER

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Abstract. Full ISO-LWS spectral scans between about 45 to 190 μm of 17 individual HH objects in 7 star forming regions have revealed essentially only [O I] 63 μm line emission, implying that the FIR cooling of these objects is totally dominated by this line alone. In this case, J-shock models can be used to determine the mass loss rates of the HH exciting sources. These mass loss rates are in reasonably good agreement with those estimated for the accompanying CO flows, providing first observational evidence that HH and molecular flows are driven by the same agent. The $L_{\text{mech}} - L_{\text{bol}}$ relation, based on our results with the LWS, implies that young stellar objects of lower mass are losing mass at relatively higher rates than their more massive counterparts.

1. Introduction

Herbig-Haro objects (HH) have commonly been identified on the basis of observations in the *visual* spectral region. As such, the known objects are, when viewed against dark clouds, surface phenomena in regions of stellar formation. Recent advances in detector array development have opened the near infrared (NIR) for the observational study of HH flows and a growing body of $2\ \mu\text{m}$ -data is now becoming available also for cloud embedded flows (cf. article by J. Eislöffel). At NIR-wavelengths, extinction of radiation by dust can still present a problem, particularly in regions of high column density ($A_K \sim 0.1 A_V$), and HH flows deeply embedded or on the far side of the clouds might not be readily accessible to NIR observations. On the other hand, at far infrared (FIR) wavelengths, extinction is generally negligible ($A_{100\ \mu\text{m}} \lesssim 10^{-3} A_V$), except perhaps on the very smallest spatial (subarcsec) scales.

First FIR spectroscopic observations of HH flows have been presented by Cohen et al. (1988). These data were obtained from airplane altitude (KAO) and were restricted, therefore, to the few existing spectral windows of diminished telluric opacity. The space borne LWS, in contrast, is free of atmospheric limitations and has observed, for the first time, fully covering FIR-spectra of HH flows.

1.1. PRIMARY OBJECTIVES OF THE LWS-HH PROGRAMME

The LWS (Long-Wavelength Spectrometer: Clegg et al. 1996, Swinyard et al. 1996) aboard ISO (Infrared Space Observatory: Kessler et al. 1996) operates in the wavelength region $\sim 40\text{--}200\ \mu\text{m}$ and FIR-spectrophotometry of unextinguished HH flows offered thus the opportunity to address:

- the spatial distribution (extent) and morphology (degree of symmetry) of HH flows;
- the appearance of FIR-spectra and the importance of FIR line cooling (atomic and molecular) for the overall energy balance of HH flows;
- the nature of the HH-excitation in molecular clouds, i.e. to what degree the shocks are predominantly J- or C-type;
- the physics of mass loss from young stellar objects and the interrelation of molecular ('CO outflows') and HH flows.

In addition, since HH objects were expected to emit little, if any, continuous radiation at long wavelengths, LWS observations should also be suitable to obtain the FIR energy distributions of the associated clouds at high spectral resolution. This should permit the study of the dust opacity in dark, molecular clouds and the search for solid state spectral features in a previously unexplored wavelength regime.

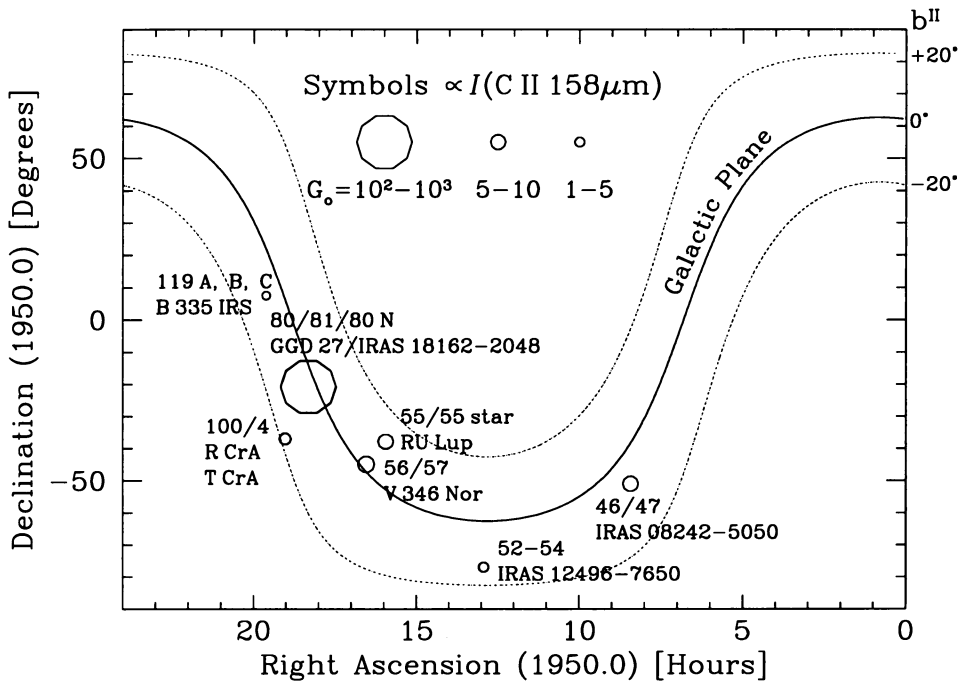


Figure 1. The sky distribution, in equatorial coordinates, of 17 HH flows in 7 star forming regions observed with the LWS is shown together with the driving stellar sources. Symbol sizes correspond roughly to the value of the interstellar radiation field, expressed in terms of G_0 (see text). For convenience, the run of the galactic plane and of the galactic latitudes $\pm 20^\circ$ are also shown

In this contribution, we concentrate mainly on the aspects of shock-type and mass loss during the early phases of stellar evolution.

2. HH observations with the LWS

The data presented in this contribution have been obtained during Guaranteed Time observations of the LWS-team. In 7 different regions of star formation, the number of individual HH objects observed was 17 and their distribution in the sky is shown in Fig. 1. The lack of objects in the constellations of, e.g., Perseus, Taurus-Auriga and Orion reflects the visibility restrictions of ISO. HH flows in these regions are expected to be observed during the extended ISO-mission in 1997/98.

Full LWS-grating scans ($43-193 \mu\text{m}$) have been obtained for all objects, at the spectral resolution $R_\lambda \sim 150-300$. The observations with the $80''$ circular beam were made both in pointed and in mapping mode, i.e. point-

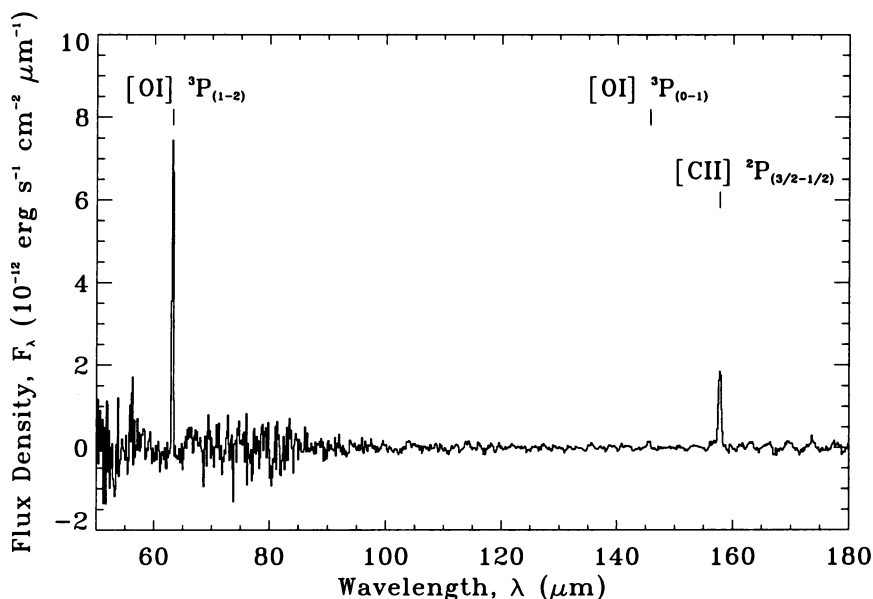


Figure 2. Typical FIR line spectrum of HH objects

ing the telescope towards optically identified HH positions as well as obtaining unbiased raster scan maps of the flows. The absolute flux calibration is believed to be better than about 30%. Within integration times of about 700 to 4500 s per position a continuum sensitivity (1σ) of ~ 1 Jy at 60 and 100 μm was achieved, comparable to that of IRAS at much lower spectral resolution. The sensitivity (1σ) to spectral line flux was about $2 \cdot 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ at 60 μm and $3 \cdot 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ at 160 μm respectively.

3. Results and discussion

3.1. EXTENDED [C II] 158 μm EMISSION AND MOLECULAR CLOUD PDR

First results have been published by Liseau et al. (1996) and by Nisini et al. (1996). These regarded our observations of HH 52–54 and revealed the remarkably rich line spectrum of HH 54, displaying, in addition to atomic fine structure lines, rotational molecular lines of CO, OH and H₂O. These latter lines were not seen towards either HH 52, HH 53 nor in the mapped part of the molecular outflow and it was reasonable to assume that the non-detections were due to insufficient signal-to-noise in these somewhat weaker

spectra. The LWS observations of the significantly increased sample of HH flows presented here show, however, that molecular line emission is rarely present in the far infrared spectra of these objects. The median spectrum of the flows (Fig. 2) emphasizes this point: the only lines present at any appreciable strength are due to the fine structure transitions [O I] 63 μm and [C II] 158 μm .

From the mapping observations it became evident that the [C II] 158 μm emission is spatially extended and relatively uniform in intensity, contrary to what is observed for [O I] 63 μm being localized and of variable strength.

The relative constancy of the extended [C II] 158 μm emission leads us to suspect that this line is not dominated by the HH shocks, but rather originates in the PDR (Photon Dominated Region) of the molecular host clouds. This suspicion is supported by the theoretical predictions for [O I] 63 μm and [C II] 158 μm of PDR models (Wolfire et al 1990; Hollenbach et al. 1991) and those of J-shock models (Hollenbach & McKee 1989). As long as the interstellar UV-field, expressed in terms of the local value of the solar neighbourhood, G_0 , does not greatly exceed 10^3 , the intensity ratio [C II] 158 μm /[O I] 63 μm $\gg 1$ in a low density PDR, whereas this ratio is inverted behind fast dissociative J-shocks. From the measured [C II] 158 μm intensities towards the HH flows and the PDR models, we have estimated the values of G_0 for the different environs. With the exception of HH 80–81, these values are generally in the range 1–10 (cf. Fig. 1).

3.2. [O I] 63 μm LINE LUMINOSITY AND STELLAR MASS LOSS RATE

The localized character of the [O I] 63 μm emission certainly associates it with the HH objects. As evidenced in Fig. 2, the level of molecular line emission (in particularly CO and H₂O) is very low *compared to that in* [O I] 63 μm . From comparison with the theoretical models of C-shocks by Draine et al. (1983) we infer that HH shocks appear generally not to be dominated by the magnetically supported, non-dissociative C-type. Rather, our LWS observations demonstrate that the FIR cooling of these flows is completely dominated by [O I] 63 μm emission. For the HH excitation, our data are in favour, therefore, of dissociative J-shock models (Hollenbach & McKee 1989).

It was realized by Hollenbach (1985; see also: Hollenbach & McKee 1989) that, in certain conditions, the [O I] 63 μm line luminosity is a direct measure of the rate at which the central stellar source loses mass. Specifically, for a dissociative ‘wind shock’ with particle flux, Φ_{H} , expressed in terms of the pre-shock particle density n_0 and the shock velocity v_s , such that

$$\left[\frac{\Phi_{\text{H}}}{\text{cm}^{-2} \text{s}^{-1}} \right] \lesssim 1.0 \left[\frac{n_0}{10^5 \text{ cm}^{-3}} \right] \left[\frac{v_s}{100 \text{ km s}^{-1}} \right],$$

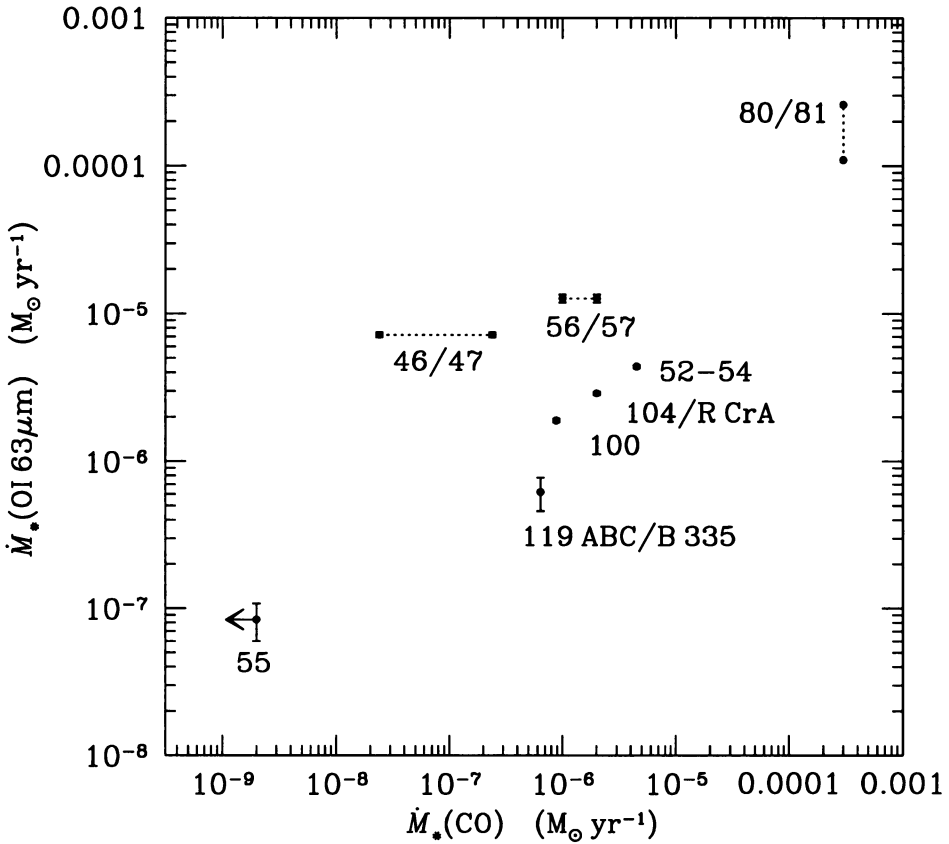


Figure 3. Stellar mass loss rates, based on observations of [O I] 63 μm and on CO observations taken from the literature, for the HH flows observed with the LWS

the [O I] 63 μm luminosity is directly proportional to the stellar mass loss rate, viz.

$$\dot{M}_* = 10^{-6} \left[\frac{L(\text{OI } 63 \mu\text{m})}{10^{-2} L_\odot} \right] \text{ (M}_\odot \text{ yr}^{-1}) .$$

Similarly, from spatial maps of the wing intensity of mm-wave CO lines, estimates of \dot{M}_* can be deduced, commonly by assuming (for low luminosity sources) momentum to be conserved, viz. $\dot{P} = \text{constant}$, so that

$$\dot{M}_* = 10^{-6} \left[\frac{M}{0.1 M_\odot} \right] \left[\frac{\Delta v}{10 \text{ km s}^{-1}} \right] \left[\frac{\Delta t}{10^4 \text{ yr}} \right]^{-1} \left[\frac{v_\infty}{100 \text{ km s}^{-1}} \right]^{-1} \text{ (M}_\odot \text{ yr}^{-1}) ,$$

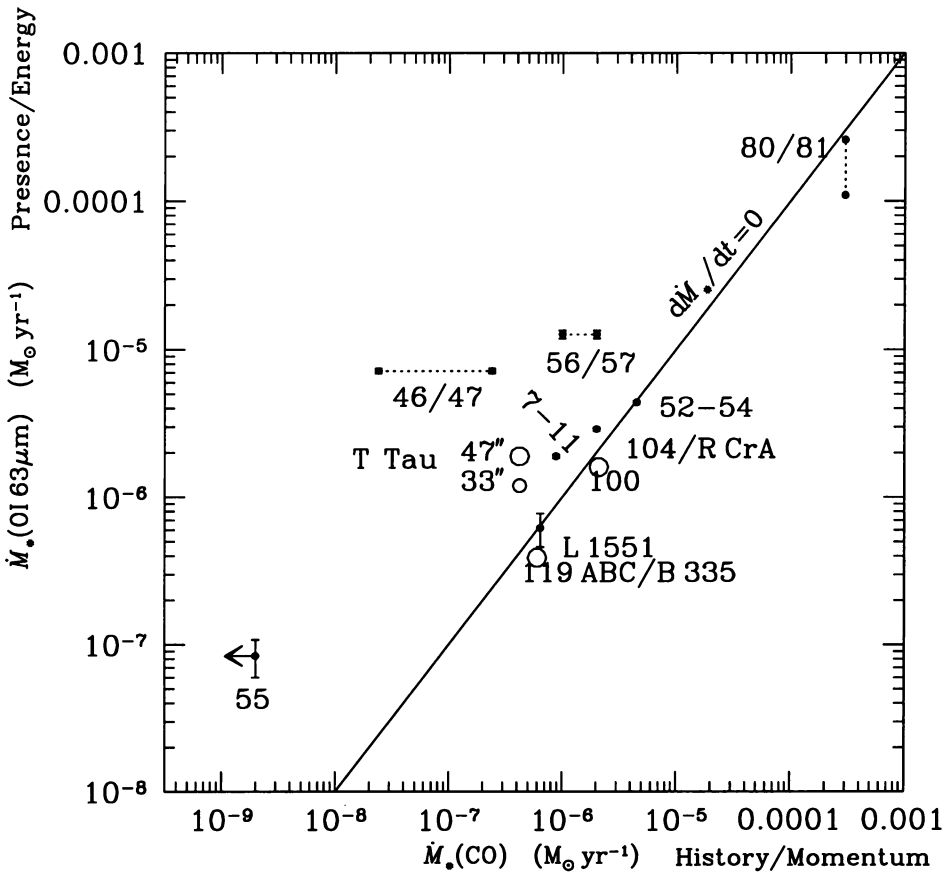


Figure 4. Same as Fig. 3 but data for HH7-11, L1551 IRS5 and T Tau (Cohen et al. 1988) are also shown (open symbols). In addition, a line of unit slope is shown for reference

where M and Δv are the mass and the velocity of the molecular gas, respectively, Δt is an estimate of the CO flow time scale and v_∞ is the terminal velocity of the stellar wind which has accelerated the molecular gas. Neglecting contributions from the CO line core, not accounting for opacity and/or projection effects will imply uncertainties of the mass loss rates as large as more than *one order of magnitude* (e.g. Cabrit & Bertout 1992). Further, what regards distance uncertainties, the dependencies for these two methods are different, viz. $\dot{M}_*([OI] 63 \mu\text{m}) \propto D^2$, whereas $\dot{M}_*(CO) \propto D$.

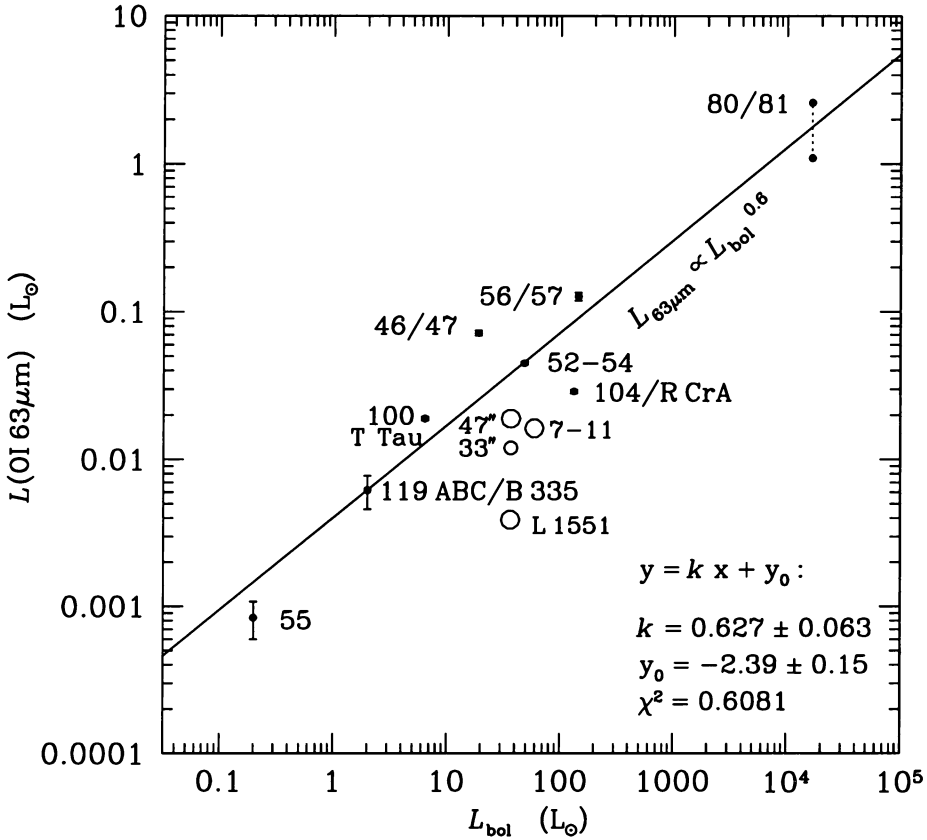


Figure 5. Luminosity in [O I] 63 μm versus stellar L_{bol} . The former is directly proportional to the stellar mass loss rate, \dot{M} . Filled points are LWS data, whereas open symbols refer to data by Cohen et al., shown for comparison. The least squares fit, shown by the straight line, refers to LWS data only

Given these sources of large uncertainty we would expect considerable scatter in a $\dot{M}_*([\text{O I}] 63 \mu\text{m}) - \dot{M}_*(\text{CO})$ plot. However, the contrary is revealed by Fig. 3 showing these quantities to correlate. This trend is clearly supported by data from Cohen et al. (1988), which are shown superposed in Fig. 4.

Also shown in Fig. 4, for reference, is a straight line of unit slope, designating the locus of complete congruence between $\dot{M}_*([\text{O I}] 63 \mu\text{m})$ and $\dot{M}_*(\text{CO})$ (note that this is *not* a fit to the data points).

These two determinations of \dot{M}_* refer to two different aspects of the

mass loss, though. In the [O I] 63 μm emission, the instantaneous energy dissipation is observed, whereas the CO flows measure the momentum transfer over time scales, Δt , much longer than the cooling time of [O I] 63 μm . One interpretation of the straight line would be, then, that of temporal constancy of the mass loss from the central stellar source. According to the figure, for most sources \dot{M}_* seems not to vary much. Interestingly, however, the position of HH 46/47 appears most disparate: for this system independent evidence for time variable flows does exist (e.g. Hartigan et al. 1993).

3.3. [O I] 63 μm LINE AND STELLAR BOLOMETRIC LUMINOSITY

One ‘prediction’ of the correlation of Figs. 3 and 4 is that there should exist a Lada-relation for outflows (Lada 1985), i.e. for the mechanical luminosity (the [O I] 63 μm luminosity) and the bolometric luminosity of the mass losing stellar source. Such dependence is indeed implied by the data displayed in Fig. 5. Formally, our LWS data yield (with luminosities in L_\odot)

$$L_{63\mu\text{m}} \sim 0.004 L_{\text{bol}}^{0.6} .$$

This power law exponent, 0.6, is identical to that found by Edwards et al. (1993) for stellar jets, and similar to that (0.8) determined by Cabrit & Bertout (1992) for CO outflows, but contrasting to earlier findings, according to which exponents $\gtrsim 1$ have commonly been inferred (see, e.g., review by Bally & Lane 1991). These works were generally biased towards high luminosity objects. Consequently, the more recent findings suggest that low luminosity (low mass) young stellar objects are relatively more efficiently ‘generating’ mass loss than their high mass counterparts. However, whether this could mean that the mass loss processes (the ‘drivings’) are different in this stellar mass dichotomy, is not possible to tell on the basis of the presented observational evidence.

4. Conclusions

ISO-LWS observations of 17 HH Objects in 7 regions of stellar formation lead us to conclude:

- The FIR spectra of HH flows show a general lack of prominent molecular line emission, indicating that magnetically supported shocks do not play a dominant rôle in HH excitation.
- The uniformly extended [C II] 158 μm line emission from (low luminosity) HH regions can generally be attributed to weak PDRs at the cloud surface ($G_0 \sim 1 - 10$).
- In mapped flows, the [O I] 63 μm line displays strong spatial variations, apparently related with optically identified HH emission.

- Comparison of stellar mass loss rates estimated using the [O I] luminosity with those determined from mm-wave CO observations results in remarkable agreement, providing empirical proof that HH flows and molecular flows ('CO outflows') are physically associated.
- These data provide also a demonstration of the potential of the [O I] 63 μm line as a mass loss diagnostic.
- The [O I] luminosity, $L([\text{O I}] 63 \mu\text{m})$, being a measure of the stellar mass loss rate, correlates with the bolometric luminosity, L_{bol} , of the central driving source.
- From this relation it is inferred that low mass young stellar objects are more efficient 'mass losers' than are young stars of high mass.

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