Characteristics of shocks in bipolar outflows observed in pure rotational lines of \( \text{H}_2 \) with ISOCAM

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Abstract. We present spectro-imaging observations with ISOCAM\(^1\) in pure rotational lines of \( \text{H}_2 \) (0–0 S(2)-S(7)) of a sample of 6 bipolar outflows: HH 54, IRAS 3282, L 483, L 1551, IRAS 4A, and HH 7-11. These observations allow us to map the excitation conditions and the orthopara ratio (o/p) in the shocked gas. We find that for 2 outflows the (o/p) has not reached its high temperature equilibrium value of 3.

Interpretation is made with the help of a new grid of C- and J-type stationary molecular planar shocks (Wilgenbus et al. 2000), taking advantage of the most recent collisional excitation rates for \( \text{H-H}_2 \) and \( \text{H}_2-\text{H}_2 \) (Le Bourlot et al. 1999). We also compare ISOCAM data with observations of the same outflows in the \( \text{H}_2 \) 2.12 \( \mu \text{m} \) line and in CO lines in terms of morphology and shock energetics.

We used the CVF mode of ISOCAM to observe 6 bipolar outflows (HH 54, IRAS 3282, L 483, L 1551, IRAS 4A, and HH 7-11) in the pure rotational lines of \( \text{H}_2 \): 0–0 S(2)-S(7). Maps with a field of \( 3.2' \times 3.2' \) and a resolution of \( 6''/\text{pixel} \) were obtained. Particular attention has been paid to the excitation temperature and the orthopara ratio (o/p), empirically calculated using the method described by Wilgenbus et al. (2000).

\(^1\)Based on observations with ISO, an ESA project with instruments funded by ESA Members States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) with the participation of ISAS and NASA.
Figure 1. Comparison of observed values of $(\alpha/p)$ and $T_{\text{ex}}(J = 7)$ in HH 54 (crosses) with expected values from C- (solid lines) and J- (dashed lines) type planar shocks with initial $(\alpha/p) = 0.01$ (upper) and 1 (lower). Each curve refers to one preshock density $n_H$ (see symbols, upper) with different shock speeds $v_s$ (models taken from Wilgenbus et al. 2000). Shock speeds are: $v_s=10, 20, 30, 40$ km s$^{-1}$ for C-shocks (except for $n_H = 10^6$ cm$^{-3}$ where $v_s=10, 15, 20, 25, 30$ km s$^{-1}$) and $v_s=5, 10, 15, 20, 25, 30$ km s$^{-1}$ for J-shocks.
The ortho:para ratio is $\simeq 3.0$ (LTE value) in IRAS 3282 and HH 7-11. In HH 54 and L 483, however, we find non-LTE values of the $(o/p) \simeq 1.5$. In HH 54, the $(o/p)$ varies spatially and is correlated to the radial $H\alpha$ velocity of the optical knots (Graham et al. 1988, Sandell et al. 1987) and to the $H_2$ excitation temperature between levels $J = 6$ and $J = 8$ ($T_{ex}(J = 7)$), see Fig. 1.

By comparison with a new grid of C- and J-type molecular shocks (Wilgenbus et al. 2000) we infer in HH 54 a low initial $(o/p)$ in the preshock gas $\simeq 0$ if the shocks are C-type, $\simeq 1$ if they are of J-type (cf Fig. 1). Note that the estimated $(o/p)$ for shock models is an average over the width of the shock (see Wilgenbus et al. 2000). Same results were found in L 483, the initial $(o/p)$ is not well constrained in the other flows.

![Figure 2](image.png)

**Figure 2.** Comparison of the morphologies of the IRAS 4A and HH 7-11 outflows as seen in the $H_2$ $v=1-0$ S(1) 2.12 $\mu$m line (mosaic central image, Hodapp et al. 1995) and in the $v=0-0$ S(5) 6.9 $\mu$m line observed with ISOCAM (upper and right images).
For the outflows in our sample, the morphology in ISOCAM pure rotational lines is very similar to that obtained in H$_2$-2.12 μm (see Fig. 2), except in HH 54 where the v=0-0 lines probe a larger region resembling a wide bowshock. In this object, the excitation temperature in rotational lines is lower than inferred from 2 μm (Gredel, 1994). We also find a rotational (o/p) lower than in 2 μm lines. This situation implies that the rotational and ro-vibrational lines do not probe a unique planar stationary shock (see Wilgenbus et al. 2000). A possible explanation could be a curved shock front (bow shock) or a shock which has not reached steady state and possesses both C and J characteristics (Chièze et al. 1998).

Comparison with shock models also allows us to estimate the mechanical luminosities and momentum fluxes of the shocks involved in our objects. These values are in good agreement with the global time-averaged energetics obtained from CO observations of the associated molecular outflows, suggesting that the CO parameters are not widely in error. Extensive report of this work will be presented in a forthcoming paper (Wilgenbus et al., in preparation).

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References