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The Physics of Shocked Outflows In Star Forming Molecular Clouds

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Abstract. Recent near-IR imaging of the Orion molecular cloud has revealed a complex of dense bullets, visible as [FeII] emitting HH-objects at the tips of H_2 wakes, ejected explosively from the cloud core. Having resolved individual bow-shock structures for the first time in this bright source, we have observed [FeII] 1.644μm velocity profiles of selected bullets and H_2 1-0 S(1), 2.122μm velocity profiles for a series of positions along and across the corresponding bow-shock wakes. We present observed profiles for the bullet M42 HH1 and its associated wake and compare with theoretical bow-shock models.

1. Introduction

The nature of molecular shocks, which play an important role in the processes of momentum and energy transfer within starforming molecular clouds (McKee 1989), is still uncertain (Draine & McKee 1993). The H_2 bullet wakes in the Orion outflow emphasise the importance of bow shock morphology. It is now established that (a) planar C(magnetised)-shock models cannot explain the H_2 line intensities in outflows, while planar J-shock models can (Brand et al. 1988); (b) neither planar nor bow J-shock models can reproduce the line profiles while highly magnetised C-shock models can (Brand et al. 1989); (c) the H_2 excitation conditions throughout the bright part of the Orion outflow appear remarkably constant, not easily explained by bow shock models (Brand et al. 1989, McKee 1989).

Recent near-IR imaging of Orion with 0.5″ spatial resolution in the emission lines of H_2 (2.122 μm) and [FeII] (1.644 μm) has clarified our view of the shocked molecular outflow (Allen & Burton 1993). Many new Herbig-Haro objects were

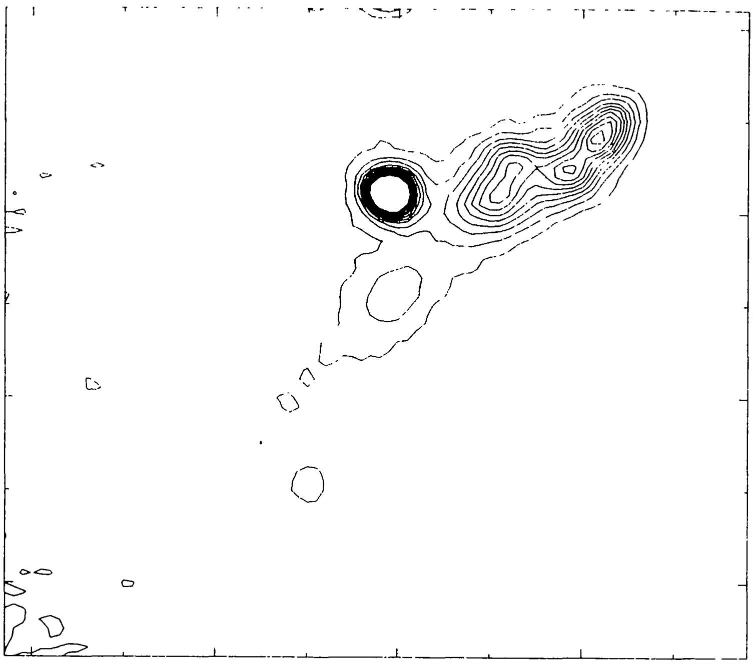

Figure 1. [FeII], 1.644 μm contour plot of M42 HH1.

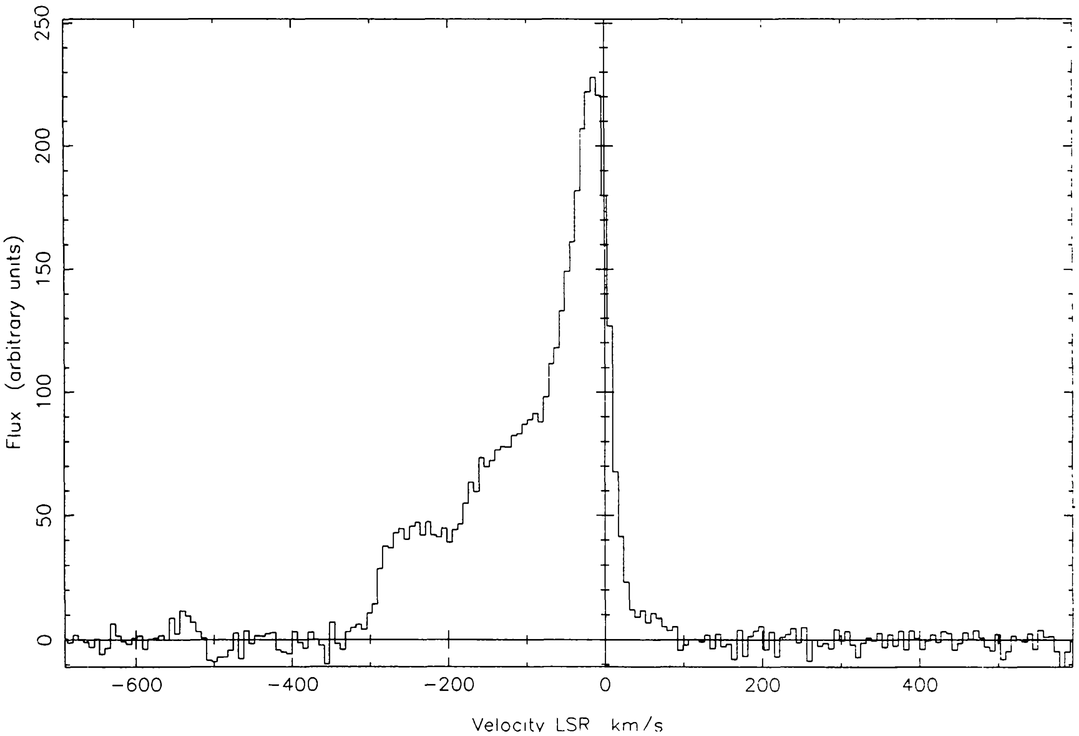

Figure 2. [FeII], 1.644 μm integrated velocity profile for M42 HH1.

Figure 3. H_2 1-0 S(1), 2.122 μm contour plot of same region as Fig.1. The shaded area indicates the position of the [FeII] bullet M42HH1 while dashed lines indicate an idealised bow-shock wake. Numbered boxes indicate the location of 3 line profile positions.

revealed, visible as [FeII] 'bullets', at the heads of wakes of H_2 emitting gas. The bullets (originating within 5″ of IRc2) have been ejected over a wide opening angle and we have measured [FeII] line profile widths of up to 400 km s^{-1} (Tedds et al., in preparation), in agreement with [OI] (6300 Angstrom) linewidths (Axon & Taylor 1984) indicating an explosive origin in the core of Orion within the last 1000 years. We cannot yet identify the cause of this event although an FU-Orionis event (Hartmann & Kenyon 1985) was suggested by Allen & Burton (1993).

2. Observations and Results

We have used the UKIRT near-IR spectrometer CGS4 in its echelle mode to obtain [FeII] line profiles of some of the bullets together with H_2 line profiles in two of the most clearly defined bow shock wakes (Tedds et al., in preparation). Figure 1 shows the bullet M42 HH1 imaged in [FeII] together with an integrated velocity profile of the contributing [FeII] 1.644 μm emission line (Figure 2). Figure 3 shows the same region imaged in H_2 together with the location of 3 pixels from 3 slit positions observed at 1.7″ steps across the associated bow shock wake. The resultant H_2 1-0 S(1) 2.122 μm line profiles at each pixel are shown in Figure 4.

A clear change from a double-peaked to single-peaked H_2 line profile is observed with each step across the bow. This is as expected since at central wake positions two distinct shocked regions on either side of the bow-shock wake

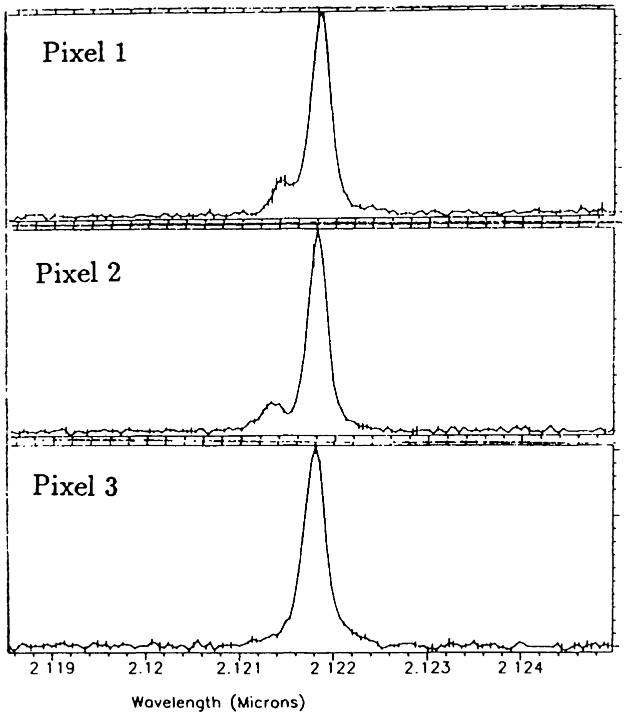

Figure 4. H_2 1-0 S(1), 2.122 μm line profiles at 3 pixel positions (Fig.3) in the wake of M42 HH1.

will contribute to the emission. If the orientation of the bow to the line-of-sight, $\phi < 90°$, the two components sampled will be at different positions in the wake and hence have different normal velocities - giving rise to a doubly-peaked line profile. However, in moving across a bow the two components will approach the same normal velocity, hence the change to a singly-peaked profile at the edge of the bow. Similar changes occur in sampling adjacent pixels further along the bow axis, away from the bullet and are being analysed and modelled (Tedds et al., in preparation).

The two most important parameters in modelling bow-shock line profiles are the incident shock velocity, v_s and the orientation, ϕ. Observationally, we can directly measure v_s since it is equal to the full width near zero intensity of the integrated emission over an entire bow shock front independent of the shape of the bow-shock, orientation angle, preshock density, elemental abundances and reddening (Hartigan et al. 1989) Furthermore, by measuring the maximum and minimum radial velocities for the integrated line profile we obtain both the shock velocity and orientation angle. In the case of the bullet M42 HH1, the integrated [FeII] profile yields a shock velocity of $v_s = 380 \pm 10$ km s^{-1} and an orientation angle of $\phi = 55 \pm 5°$.

Comparison of the observed [FeII] profile shape (Fig. 2) with radiative bow-shock model predictions (Hartigan et al. 1989) shows closest agreement for a $v_s = 400$ km s^{-1}, $\phi = 60°$ bow-shock. We note that the stronger of the two peaks lies near zero radial velocity as predicted in bullet models and also that both the [FeII] and H_2 profiles indicate enhancement of this peak.

The H_2 profiles sample only a 'slice' through the bow and hence can only provide a radial velocity range in that region of the wake. At the 3 pixel positions shown in Figure 3 the radial velocity width is of order 180 km s^{-1}, consistent with the calculated value of v_s.

3. Discussion

We have demonstrated that [FeII] and H_2 emission line profiles in Orion are consistent with theoretical bow-shock predictions. By mapping line profiles in this way for a number of different Orion bullet wakes we can test bow-shock models over a range of values of v_s and ϕ and also determine if all of the observed shocked molecular hydrogen emission in this region is dominated by this single event rather than by a steady bubble-type outflow as was previously indicated and commonly observed in starforming regions.

It is important to determine the nature of the shock-fronts within such bow structures. Fernandes (1993) has demonstrated that shocked H_2 emission line intensities in the bow shock-shaped HH7, the consequence of a jet of highly collimated neutral material from the young stellar object SVS3 ploughing into the surrounding molecular cloud (Solf & Bohm 1987), are well explained by a C-shock in a bow configuration in which the 'cap' is completely dissociated, and H_2 fluorescence produced by Lyman alpha resonance pumping in the hot post-shocked layers (Black & van Dishoeck 1987) in the cap irradiate the downstream flow. The same type of shock + fluorescent spectrum as seen in HH7 has been seen in DR21 (Fernandes 1993) and we would expect this model to give a description of the Fe[II] bullets and their H_2 wakes in Orion. Future observations at increased spatial resolution may soon constrain the cooling distance behind shock-fronts. This will provide an important new diagnostic of shock excitation mechanisms.

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