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HIGH RESOLUTION H_2 OBSERVATIONS OF HERBIG-HARO FLOWS

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RESUMEN

Presentamos observaciones terrestres de H_2 de alta resolución para cuatro flujos Herbig-Haro: HH 7-11, HH 25-26, HH 33/40 y HH 212. Presentamos movimientos propios y mediciones cinemáticas de H_2 para los primeros tres de estos flujos. Presentamos evidencia que sugiere que las “balas” que emergen de la fuente de HH212 se encuentran en rotación, haciendo creer que los flujos son importantes en remover momentum angular de los discos de acreción circunestelares.

ABSTRACT

We present high-resolution, ground-based, H_2 observations of four Herbig-Haro flows: HH 7–11, HH 25/26, HH 33/40, and HH 212. H_2 proper motion and kinematic measurements are presented and discussed for the first three of these flows. Evidence is presented which suggests that the bullets emerging from the driving source of HH 212 are rotating, fueling the belief that outflows are integral in removing angular momentum from accreting circumstellar disks.

Key Words: **ISM: JETS AND OUTFLOWS — ISM: KINEMATICS AND DYNAMICS — STARS: FORMATION — STARS: MASS LOSS — STARS: PRE-MAIN SEQUENCE**

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1. INTRODUCTION

Herbig-Haro (HH) objects are by now well known and recognized phenomena, their role intimately and ubiquitously associated with the process of star formation. However, the detailed physics of their interaction with the surrounding ambient medium is still poorly understood. This is particularly true for those shock features that are only seen at near-infrared wavelengths.

In this paper we present results of recent observations of molecular hydrogen (H_2) emission towards a number of HH flows. Proper motion measurements are derived from images taken across a 4 year baseline and these are compared to high spectral resolution measurements providing us with velocity information for the H_2 emission. We demonstrate how the combination of these two techniques allows us to derive important information regarding the dynamics, kinematics and history of the HH flow. Finally, we present tentative evidence for rotation of the bullets in the HH 212 flow.

2. RESULTS

The observations were obtained at the United Kingdom Infrared Telescope (UKIRT) on the summit of Mauna Kea, Hawaii. The proper motion measurements are derived from H_2 images obtained using the IRCAM infrared camera in December 1994, compared with observations using the high resolution imager UFTI in October 1998. The high spectral resolution ($\sim$ 15 km s^{-1}) H_2 data were obtained in January 1999.

Standard reduction techniques were employed to obtain position-velocity diagrams for the H_2 emission in the HH objects and to derive their proper motions from the imaging data. These are described in more detail in Chrysostomou et al. (2000) and Davis et al. (2000).

2.1. *H_2 Proper Motions*

Figure 1 shows images obtained of HH 7–11 and HH 25/26 with the UFTI camera. No proper motions were reliably measured for HH 33/40. Overlaid on the images are the corresponding proper motion vectors for each of the HH objects measured. No significant morphological variations are seen for the HH objects between the two epochs, suggesting that the proper motions measured are reliable indicators of their true spatial motions across the sky.

For HH 7–11, the vectors point fairly uniformly away from the driving source (SVS13, located at $(0,0)$), as expected. The magnitude of the proper motions as a function of distance from the source is seen to increase, evidence that the flow is decelerating. For HH 11, the closest HH object to the source, the measured proper motion is $\sim$200 km s^{-1}. Further up the flow, HH 8 and HH 10 have a proper motion of $\sim$300 km s^{-1}, while the largest bow shock in the field (and the one furthest away from the source),

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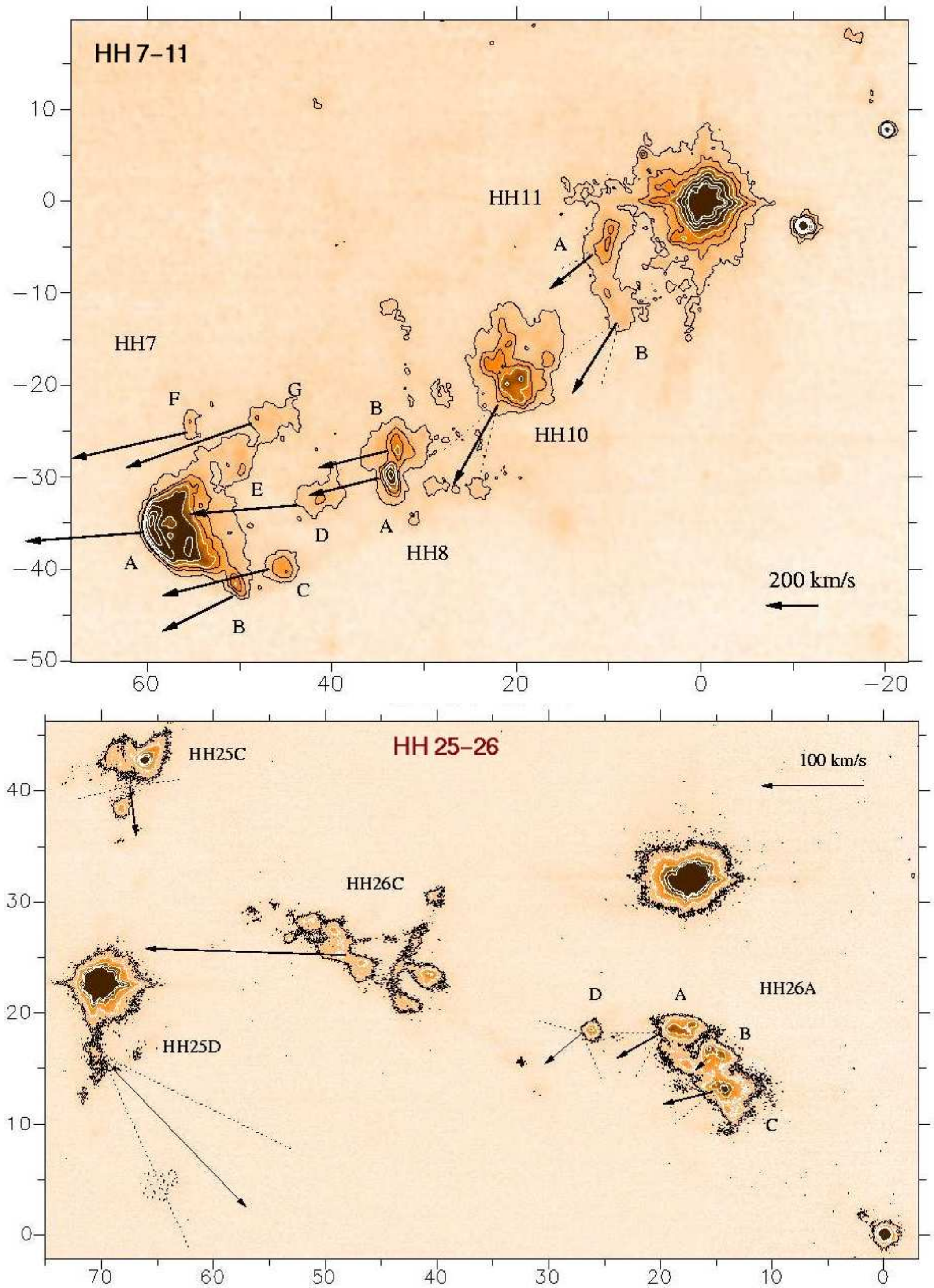

Fig. 1. Images and proper motion measurements for HH 7–11 (*top*) and HH 25/26 (*bottom*). In each case the source of the outflow is at a coordinate of $(0, 0)$. Dotted lines associated with proper motion vectors define the uncertainty of their measurement.

HH 7, has a proper motion of $\sim$400 km s^{-1}. We take this deceleration as evidence that the energy generated by the YSO to drive the flow is decreasing as the object evolves.

The HH 25/26 flows show slightly different characteristics. The source for the HH 25 flow is to the north and off the field. The source for the HH 26 flow (HH 26IR) is at the $(0, 0)$ coordinate. The group of H_2 knots associated with HH 26A have a relatively small proper motion ($\sim$20–70 km s^{-1}), consistent with the negligibly small proper motions measured in the optical by Jones et al. (1987). HH 26C, on the other hand, has a much larger proper motion $\sim$200 km s^{-1}(almost) due east. The simplest interpretation for these values is that the knots comprising HH 26A represent stationary and turbulent shock regions, while HH 26C is the leading edge, or working surface, of a bow shock. To explain the fact that the proper motion vector of HH 26C does not point directly away from the source, we postulate that the driving jet has been 'deflected' from its original trajectory by the surrounding molecular cloud. HH 26A represents the 'impact' site of that deflection.

The HH 25 flow shows similar behavior, HH 25C having a low proper motion ($<$70 km s^{-1}) while HH 25D has proper motion $\sim$200 km s^{-1}.

The high proper motions measured for these flows poses a potential problem for shock theories, as H_2 is easily dissociated for shock velocities greater than 40–50 km s^{-1}. Such high proper motions have been reported before in a number of other flows (e.g., Noriega-Crespo et al. 1997; Micono et al. 1998; Coppin, Davis, & Micono 1998). To reconcile the presence of high proper motions without high shock velocities, it is necessary to have the shocks form when a fast-moving jet catches up with previously ejected and more slowly-moving material. Thus, the shock produced is governed by the relative velocity of the two jets, while the 'pattern-speed' (i.e., proper motion) is governed by the absolute velocity of the working surface. A consequence of this argument is that we are not seeing the leading working surfaces of any HH object with a high proper motion; instead we are seeing internal working surfaces formed within the jet and perhaps fed by entrained material.

This picture remains consistent with our observations of HH 33 and HH 40 for which no appreciable proper motions were detected. Our best estimate of the proper motion of HH 33 is $\sim$70 km s^{-1}, but this is associated with a large error so we must presume that it represents an upper limit. This proper motion is consistent with the optical proper motion measured by Devine et al. (1997), who present convincing evidence that HH 33 represents the terminus of the 'parsec-scale' HH 34 outflow.

2.2. *H_2 Echelle Spectroscopy*

2.2.1. *HH 7 and HH 26*

The results we find from our velocity-resolved H_2 spectroscopy support our conclusions concerning the kinematics of each of the components in the flows studied. If all the H_2 emission were produced in bowshocks then theory predicts that the H_2 line profiles should be double-peaked in the wings of the bow (e.g., Smith et al. 1991). In instances where the excitation of H_2 occurs in more turbulent conditions, the profile should be single-peaked and symmetric.

In Figure 2, position-velocity diagrams are shown for three sources that depict these characteristics. HH 7 is a classical bow shock, both in its shape and velocity structure. At the head of the bow, the velocity profile is singly peaked but as one moves behind the apex and down the bow wings, the characteristic double-peaked profile is clear to see; in this instance, the peaks are separated by $\sim$80 km s^{-1}.

HH 26C also shows the same double-peaked structure to its H_2 line profile. It is not obvious from the intensity image alone that this object is a bow shock, however, its proper motion and line profile mean that it is very difficult to ascribe it to anything else. No significant proper motions were found associated with HH 26A, evidence which we take to mean that this group of H_2 knots are more likely turbulent regions excited when the flow impacted onto the molecular cloud. The broad and symmetric line profiles support this interpretation.[4]

2.2.2. *HH 212*

This particular flow (discovered by Zinnecker, McCaughrean, & Rayner 1998) is remarkable in being highly symmetric about the embedded driving source, IRAS 05413–0104. The total flow length is $\sim$0.5 pc and it lies very close to the plane of the sky, making it an ideal laboratory for shock physics and star-formation phenomena in general. Only echelle spectroscopy was obtained for this source but the position-velocity diagrams (see Davis et al. 2000) reveal two interesting phenomena in the flow.

The spatial symmetry of the emission knots about the outflow source is also reflected in their velocities. An apparent acceleration of the knots is

[4]Note the small knot of H_2 emission seen to the east of HH 26A whose wing is just sampled by the second slit. Clearly associated with a double-peaked profile, this knot probably represents an unresolved bow shock, possibly material caught up in the main flow.

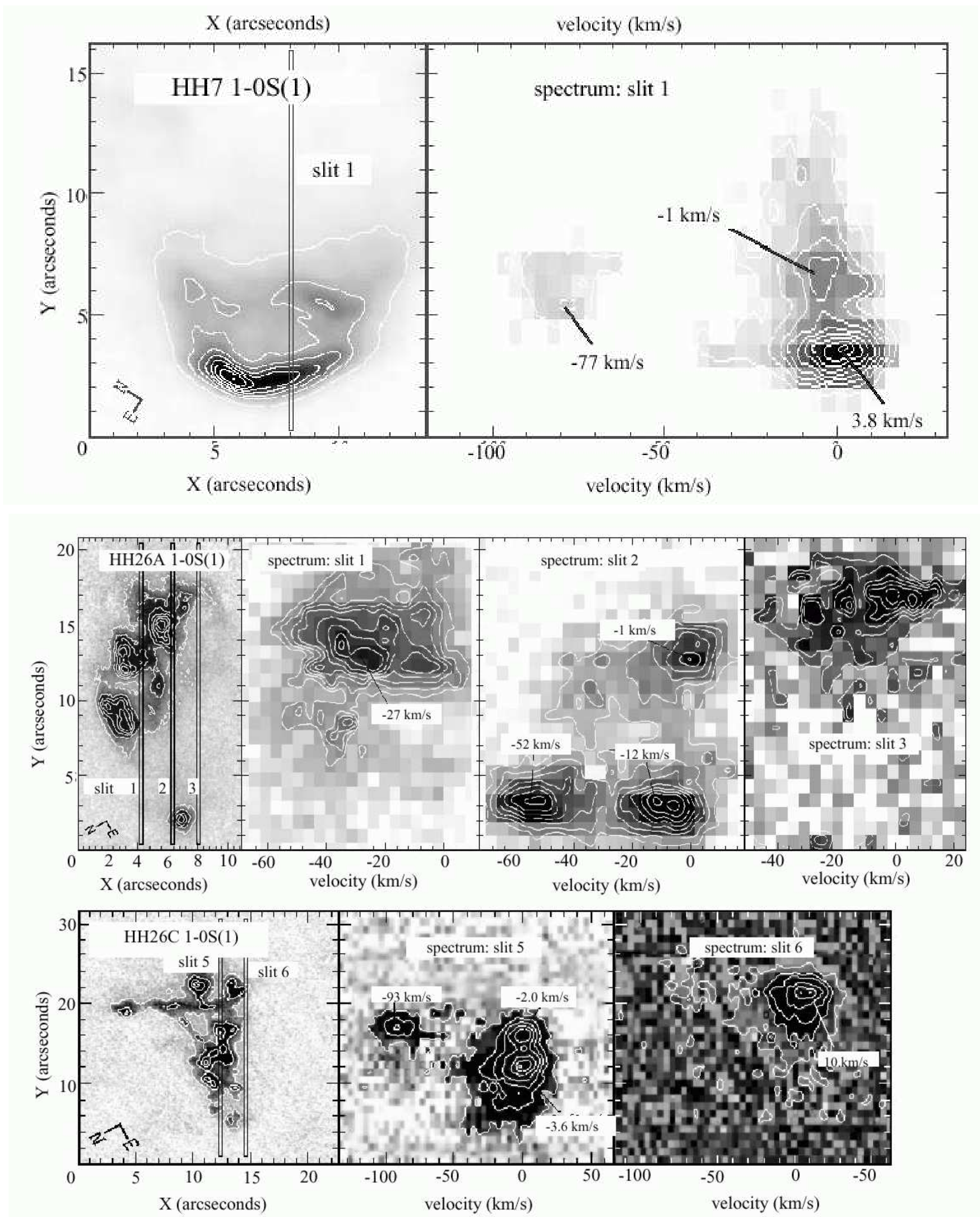

Fig. 2. Position-Velocity diagrams for HH 7 (*top*), HH 26A (*middle*) and HH 26C (*bottom*). Note the classical double-peaked profiles associated with HH 7 and HH 26C, while HH 26A exhibits more symmetric profiles, typical of turbulent excitation.

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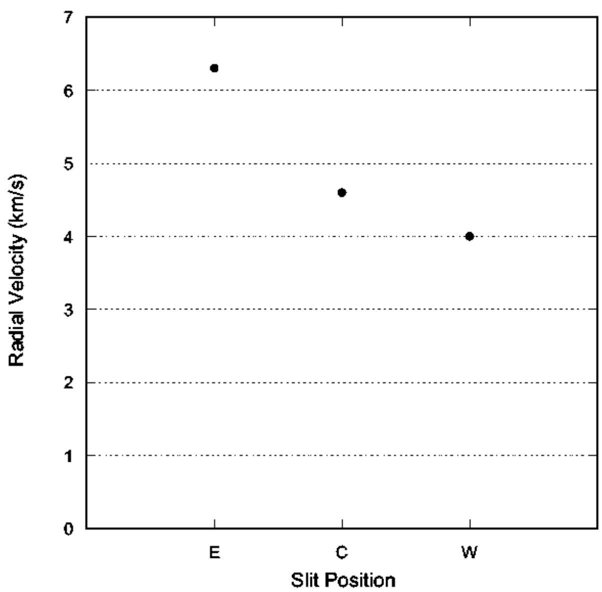

Fig. 3. Radial velocity measurements for the first southern bullet emerging from the source of HH 212. The velocity gradient from east to west is consistent with the velocity gradient seen in NH_3 emission from the circumstellar disk.

seen, most clearly in those closest to the source. It would be interesting to see if the knots' proper motions exhibited similar acceleration.

Finally, we report tentative evidence that the innermost bullets are rotating (see Ray 2002, these proceedings). Figure 3 shows the radial velocity for the H_2 emission plotted at the 3 slit positions used, for bullet SK1 (see Davis et al. 2000). The gradient in the radial velocity is indicative of a rotational component to the bullets' radial velocity. Making simple assumptions regarding the amount of material ejected by each bullet 'event'[5]—Keplerian rotation of the disk and conservation of angular momentum—we find that this gradient is consistent with that found by Wisemann et al. (2001) from NH_3 observations of the circumstellar disk of this object. Furthermore, the sense of rotation of the bullets, the disk and H_2O masers (Claussen et al. 1998) is the same. Our observations of this phenomenon need to be improved, especially in terms of image quality and stability. This could be a crucial result for star formation theory as accretion onto the central protostar cannot proceed unless angular momentum is somehow seen to be removed by the outflow.

3. CONCLUSIONS

We have shown how the combination of kinematical and dynamical information from outflow sources, based in this instance on proper motion and velocity resolved H_2 spectroscopy, can be combined to improve and refine our understanding of physical models for outflows. We also present tentative evidence for rotation of the HH 212 outflow, which if proven, would have great import for the theory of star formation.

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[5]We have assumed that 10% of the disk mass is ejected with each bullet.

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