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Infrared Jets from Protostars: The case of HH212

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Abstract. We describe the appearance and significance of HH212, the most symmetric two-sided molecular hydrogen jet/counterjet system yet discovered. This prototype embedded protostellar H_2 jet emanates from a low-luminosity isolated protostar in Orion. It exhibits matched pairs of knots and bow-shocks interpreted as arising from a time-variable source, which we take to indicate that protostellar accretion through the encircling disk is non-steady and pulsed.

1. What is HH212?

HH212, or Herbig-Haro object No. 212, is an optically invisible two-sided jet system traced in the shock-excited ro-vibrational v=1–0 S(1) emission line of molecular hydrogen at 2.12 μm (Figure 1a). Coincidentally, the 'HH' part of the name reflects the hydrogen molecule, while the symmetry of both 'HH' and '212' reflect the symmetry of the jet. It is no coincidence at all, however, that the number '212' also reflects the discovery wavelength!

HH212 is a textbook example of a jet: the extraordinary bilateral symmetry of matching inner knots and outer bow-shocks make it perhaps the prototype of a two-sided, young jet from a deeply embedded low-mass protostar, the latter in this case found to lie exactly between the two sides of the jet, as anticipated. An important point to emphasize at the outset is that the H_2 images do not trace the bulk jet fluid itself, but rather the radiative cooling from internal/external shocks where the jet fluid interacts with itself (inner knots) or with the ambient cloud core (outer bow shocks).

2. Observations

HH212 was originally discovered at the 3-m NASA Infrared Telescope Facility on Mauna Kea (Hawaii), using the infrared camera NSFCAM. The discovery image and a first account of the observations have been presented elsewhere (Zinnecker, McCaughrean, & Rayner 1996). Meanwhile new H_2 2.12 μm images (Figures 1a,b) in better seeing (0.7 arcsec) have been taken at the 3.5-m telescope on Calar Alto Observatory (Spain), using the MPIA infrared camera MAGIC.

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HH212 is extremely symmetric, with matching series of inner knots and outer bow shocks on both sides extending over a total length of 240 arcsec (0.6 pc in Orion). Radial velocities measured for the H_2 knots on either side of the center are almost identical, indicating that HH212 lies very close to the plane of the sky. Exactly between the two sides of the jet lies a cold, low-luminosity (15 $L_{\odot}$) IRAS and mm-continuum source (Zinnecker *et al.* 1992), coincident with a strong 1.3-cm water maser (Wouterloot & Walmsley 1986). Millimetre mapping and interferometry reveals a highly collimated ^{12}CO outflow extending the full length of the jet (Dent, personal communication), highly collimated shocked SiO along the inner jet, and an extended C^{18}O 'disk' perpendicular to the source (Sargent & McCaughrean 1997). Evidence for this disk and its extended envelope can also be seen in the near-infrared continuum, where the invisible central source is straddled by a matching pair of paraboloidal reflection nebulae, reminscent in structure (if not in scale) to those imaged around the HH30 driving source with the HST (Burrows *et al.* 1997).

3. Modelling

Prompted by the discovery of HH212, Suttner *et al.* (1997) developed new 3D jet simulations. For the first time, a standard explicit hydrodynamic code was combined with time-dependent calculations of the chemistry of molecular hydrogen and an appropriate cooling function appropriate for dense molecular gas, allowing them to follow the molecular shocks and generate emission maps of the H_2 1-0 S(1) line. No magnetic fields were incorporated.

Suttner *et al.* (1997) modelled a highly supersonic, overdense, cylindrical molecular jet (diameter 400 AU) entering a molecular cloud of constant density at a mean velocity of 100 km s^{-1}. Superimposed on the steady flow were sawtooth velocity variations with an amplitude of 10 km s^{-1} and a period of 100 yr (Figure 1c). Encouragingly enough, these simulations look rather similar to the observed jet, although the linear scales have not yet been matched precisely. The initial pulses steepen rapidly into double-teeth which then decay gradually (*cf.* Smith, Suttner, & Zinnecker 1997). The appearance of shock-heated molecules and their H_2 emission depends on both the amplitude and period of the oscillations: only in the intermediate-amplitude regime, between 10 and 20 km s^{-1}, will there be strong H_2 infrared emission. Hence the emission is confined to a few knots which decrease in brightness with increasing distance from the driving source. At the jet head, a knot of dense material piles up and breaks off after a few dynamical timescales, forming a clumpy structure in the wings of the bow shocks. Such a knot can appear as an arc-like feature upstream of the main bow shock, as shown in Figure 1c.

4. The significance of highly symmetric embedded H_2 jets

The association of a cold, deeply embedded protostellar source with HH212 suggests that wide-field infrared emission line surveys of molecular clouds for symmetric H_2 jets might prove an important new tool for revealing such protostars, since the symmetry of such a jet allows us to guess the location of its source. While the very young protostellar source is likely heavily enough ob-

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scured to be undetectable even at near- or mid-infrared wavelengths, the jet will be less heavily obscured, due to a drop in the gas and dust density away from the central source and its envelope. This concept was amply validated by HH211 (McCaughrean, Rayner, & Zinnecker 1994), the first jet to be discovered through imaging in the $2.12\,\mu$m H_2 line, and subsequently found to have a deeply embedded driving source at its centre of symmetry.

Another advantage of such jets is that their structural symmetry with respect to the central engine uniquely allows us to measure the proper motion of the structure (*e.g.,* discrete knots as in HH212 or more diffuse structural details as in HH211) *without* any reference star, which are rare in dark cloud regions where new stars are born. The motions of the two sides of the jet are in opposite directions, so the proper motion of knots with respect to the central source can be obtained by just dividing the full expansion motion of the two sides in half. In addition, by measuring matching pairs of knots on either side of the system, differential motions of knots can be studied. This method is more accurate by a factor of two than the conventional method of measuring proper motions, and thus allows proper motions to be measured at larger distances in a given time, or or more quickly at a given distance.

5. The particular significance of HH212

The particular significance of HH212 lies in its high degree of spatial symmetry, which implies that the quasi-periodic structure of the jet must be due to source variations rather than flow instabilities, indicating, in turn, variations of the accretion flow onto the underlying central engine. There seem to be two periodicities, one related to the spacing of the inner knots and another related to the spacing of the outer bow shocks. For a jet fluid speed of around $100\,\mathrm{km\,s^{-1}}$, the corresponding timescales are of the order of 100 and 1000 yr. The former could be related to small velocity variations of the jet flow (possibly due to oscillations of the nozzle diameter at a constant mass outflow rate), while the latter could result from FU Orionis type instabilities in the protostellar accretion disk.

6. Future work

We expect that a great deal of new information will be revealed by high spatial resolution imaging of HH212 using the new NICMOS near-infrared camera on the HST over the next few years, noting that since there are no reference stars within 1 arcmin of HH212, it will not be possible to obtain equivalent data using ground-based adaptive optics. The inner knots in HH212 are only marginally resolved in the present 0.7 arcsec FWHM ground-based data, and in order to understand their structure (*e.g.,* are they bow- or crossing-shocks?), higher resolution images are required. For reference, typical H_2 cooling lengths for gas at 2000 K and $10^5\,\mathrm{cm^{-3}}$ are 10^{15} cm (Smith & Brand 1990), *i.e.,* 0.15 arcsec at 450 pc, just below the diffraction limit of the HST at $2.12\,\mu$m. As discussed above, proper motions should be relatively easily measured in HH212. At the distance of 450 pc, a velocity of $200\,\mathrm{km\,s^{-1}}$ corresponds to proper motion of ~ 0.1 arcsec/yr, easily measurable in a few years using NICMOS. It will be important to measure these motions over the shortest possible time interval, in order to

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separate them from other expected temporal changes, including knot fading and merging. Finally, deep continuum images of the reflection nebulae at the base of the jet can be used to trace the nebular shapes as accurately as possible, to allow modelling in terms of the upper and lower surfaces of the circumstellar disk around the driving source, similar to those seen in the optical HST images of HH30 (Burrows *et al.* 1997).

Secondly, the spatial structure of the H_2O maser associated with the driving source of the HH212 jet (IRAS 05413–0104) should be studied at the highest possible spatial resolution using the VLBA. While observations at 1.3-cm have found two velocity components of the maser (at 2 and 4.5 $km\,s^{-1}$; Wouterloot, Henkel, & Walmsley 1989), the maser was found to be compact at a VLA spatial resolution of 0.3 arcsec or 150 AU (Claussen, Wilking, & Wootten, personal communication). It is hoped that VLBA observations would be able to spatially resolve these velocity components and determine whether they lie along the edge-on disk axis or along the jet axis. If the masers are formed in the circumstellar disk, their rotation curve could be used to infer the enclosed mass of the protostar: in this case, HH212 could be considered a galactic analogue to the NGC4258 galaxy, where maser emission in the circumnuclear disk was used to measure the rotation curve and thus the mass of the central black hole.

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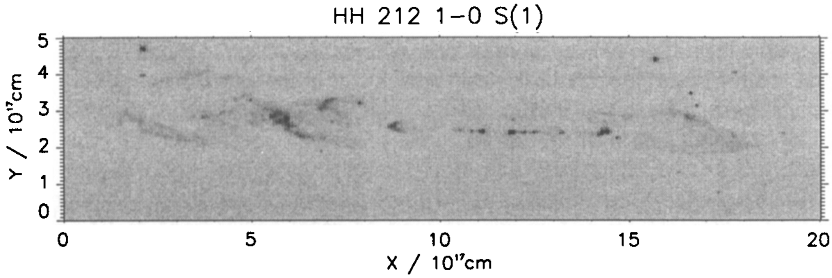

Figure 1a: S(1) H_2 image of the HH212 jet taken at the Calar Alto 3.5m telescope in 0.7 arcsec seeing. The jet system consists of matching pairs of inner knots and outer bow shocks, exhibiting an extraordinary high degree of spatial symmetry.

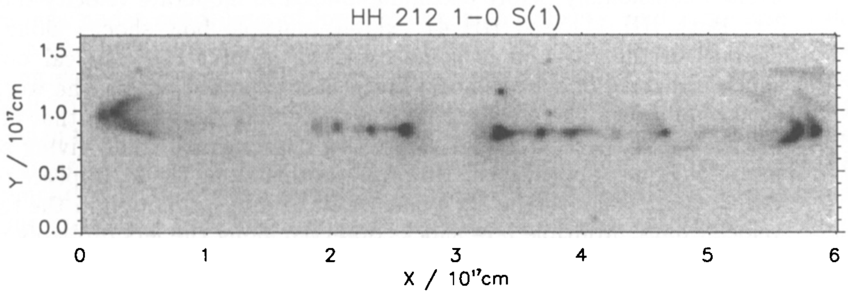

Figure 1b: Zooming in on the inner part of the HH212 jet: note the periodically spaced emission knots whose symmetry points to the position of the driving source in the center. This deeply embedded protostellar IRAS source is not detected at near-infrared wavelengths, but is detected as a compact mm continuum source and H_2O maser.

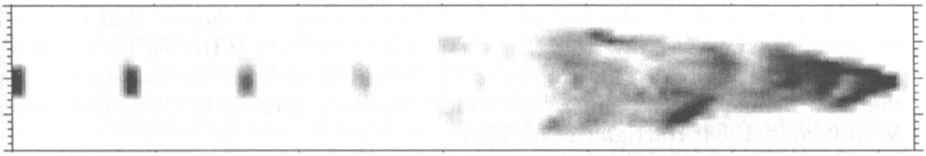

Figure 1c: H_2 emission line image from a 3D numerical simulation of a pulsed jet (from Suttner et al. 1997). Only one side of the jet is shown, at a magnified (times 2.5) scale relative to the image in Figure 1b. It is seen that the emission knots and the complex structure in the bow-shock near the jet head in HH212 can both be well-reproduced by the numerical simulation.

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