The Flattened, Rotating Molecular Gas Core of Protostellar Jet HH 212

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ABSTRACT

The recently discovered protostellar jet known as HH212 is beautifully symmetric, with a series of paired shock knots and bow shocks on either side of the exciting source region, IRAS 05413-0104 (Zinnecker et al. 1998). We present VLA ammonia maps of the IRAS 05413-0104 molecular gas envelope in which the protostellar jet source is embedded. We find that the envelope, with mass of 0.2 M\(_\odot\) detected by the interferometer, is flattened perpendicular to the jet axis with a FWHM diameter of 12000 AU and an axis ratio of 2:1, as seen in NH\(_3\) (1,1) emission. There is a velocity gradient of about 4-5 km sec\(^{-1}\) pc\(^{-1}\) across the flattened disk-like core, suggestive of rotation around an axis aligned with the jet. Flux-weighted mean velocities increase smoothly with radius with a roughly constant velocity gradient. In young (Class 0) systems such as HH212, a significant amount of material is still distributed in a large surrounding envelope, and thus the observable kinematics of the system may reflect the less centrally condensed, youthful state of the source and obscuration of central dynamics. The angular momentum of this envelope material may be released from infalling gas through rotation in the HH212 jet, as recent observations suggest (Davis et al. 2000). A blue-shifted wisp or bowl of emitting gas appears to be swept up along the blue side of the outflow, possibly lining the cavity of a wider angle wind around the more collimated shock jet axis. Our ammonia (2,2)/(1,1) ratio map indicates that this very cold core is heated to 14 Kelvin degrees in a centrally condensed area surrounding the jet source. This edge-on core and jet system appears to be young and deeply embedded. This environment, however, is apparently not disrupting the pristine symmetry and collimation of the jet.

Subject headings: star: formation — stars: pre-main sequence — ISM: Herbig-Haro objects — ISM: jets and outflows — radio lines: ISM

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1. Introduction

The youngest protostars are often so deeply embedded in their parental cloud cores that shocks driven by their jets cannot be easily traced in visible shock line emission but are bright in near-infrared molecular hydrogen shock lines. Such is the case for the recently discovered highly collimated jet HH 212, near the Horsehead Nebula region of Orion (Zinnecker, McCaughrean, & Rayner 1998).

HH 212 is remarkable because of its high collimation and symmetric pairs of bow shocks and shock knots on either side of the driving source (Figure 1). Theories of protostellar jet structure often involve a heavy influence of the surrounding medium, with impacts creating shocked globules along the jet, sometimes even redirecting it. But the symmetry of HH 212 suggests that some pulsing mechanism from the source itself is responsible for the nearly periodic bow shock pairs. Somehow the symmetry is maintained even though the jet is moving through a dense gas core. In the innermost region, water masers have been found in motion along the outflow (Claussen et al. 1998).

The inferred position of the jet exciting source coincides with IRAS point source 05413-0104, which was detected at 25, 60, and 100 microns; it is still too cold and embedded to be detected strongly at 12 microns (see Beichman et al. 1986). It is surrounded by a cold (11.5 K), compact ammonia core out of which it presumably formed (Wouterloot, Walmsley, & Henkel 1988). The spectral energy distribution climbs to longer wavelengths. It is detected also at 1.3 mm, with a submillimeter to bolometric luminosity of about 2% (Chini et al. 1997). It has narrow NH$_3$ linewidths compared to emission found at the position of other maser sources. These characteristics suggest that the source is very young.

HH212 is classified as a Class 0 system, the youngest class of protostars with much material to be accreted still in the surrounding molecular gas envelope (Andr´e, Ward-Thompson, & Barsony 2000). Class 0 sources have a high rate of submillimeter to bolometric luminosity (over 0.5%) and high rates of infall and outflow (Andr´e, Ward-Thompson, & Barsony 1993, Adams, Lada, & Shu 1987). The morphology and kinematics of the surrounding gas at this early stage of the formation of a star are crucial to understand as an important link between prestellar gas cores and the resulting young T Tauri star/disk systems. Our VLA ammonia observations were conducted as a study of the gas density, temperature, and velocity distributions in this pristine, highly embedded young source.
2. Observations

Observations were carried out with the Very Large Array (VLA) of the National Radio Astronomy Observatory\(^2\). The ammonia (J,K) = (1,1) and (2,2) inversion transitions were observed simultaneously, at rest frequencies of 23.694495 GHz and 23.722733 GHz, respectively. The width of the antenna primary beam response was approximately 2' FWHP. The array was in its compact, “D” configuration. The synthesized beamsize was 8.4'' \times 8.8'' FWHM, with natural weighting and a 20 k\(\lambda\) taper applied to the UV data. The bandwidth was 3.125 MHz and the channel separation was 24.4 kHz, corresponding to 0.31 km sec\(^{-1}\).

The absolute flux calibrator was 3C286, with a calculated flux density of 2.41 Jy at 1.3 cm. The bandpass calibrator was 3C84, and a phase closure solution was applied based on interleaved observations of the phase calibrator B0605-085 (1950). The “dirty” beam was deconvolved from the maps using the “Imager” algorithm in the NRAO AIPS image processing software.

3. A Flattened, Rotating, and Heated Gas Envelope

The integrated intensity of the NH\(_3\) (1,1) line is displayed in the contours of Figure 1, overlaid on the 2.12 \(\mu\)m image of HH 212 from Zinnecker, McCaughrean, & Rayner (1998). The gas core is flattened with an axis ratio of about 2:1. The major axis has a FWHM extent of 29'', corresponding to 12000 AU at an assumed distance of 400 pc, with full extent of over 15000 AU; it is centered on the jet source, and it lies perpendicular to the jet which has a position angle of about 25 degrees east of north and only 4deg from the plane of the sky (Claussen et al. 1998).

A velocity gradient is apparent across the flattened gas core. In Figure 2a the integrated intensity (moment 0) is again plotted in contours, while the underlying shades represent the (moment 1) velocity field. Radial velocities change smoothly from blue-shifted gas in the northwest side to redshifted gas in the southeast; the large velocity gradient of about 4-5 km sec\(^{-1}\)pc\(^{-1}\)is virtually constant. The direction of the gradient within the central FWHM intensity region of the core is perpendicular to the jet axis, with the nodes of constant velocity roughly parallel to the jet.

Along the eastern side of the core, a small amount of blueshifted material is seen to extend to the northeast alongside the northern, blueshifted side of the jet. To a lesser extent, the same effect is also seen to the south with a small protrusion of redshifted gas extending in the same direction as the redshifted side of the jet. Molecular gas is possibly being swept along by the outflow. There is even a hint, at least in the north, that molecular gas is found in a “bowl” surrounding the jet axis, possibly outlining a cavity of a wider-angle flow surrounding the collimated shock emission of the jet (see, e.g., Shu et al. 1995, Shang, Shu, & Glassgold 1998).

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Ammonia inversion lines are a convenient probe of both optical depth and temperature. Most ammonia inversion transitions are composed of multiple hyperfine components. The relative intensities of central and satellite component blends of the (1,1) transition can be used to calculate the optical depth. For the main component and total transition of the (1,1) line, we find \( \tau \) values of 0.8 and 1.6, respectively, at the core center. Using the procedures and assumptions described in Ho & Townes 1983 (see also Wiseman & Ho 1998), we also estimate an \( \text{NH}_3 \) column density of \( 1.6 \times 10^{14} \text{ cm}^{-2} \) and a total volume density \( n \) of \( 1 \times 10^5 \text{ cm}^{-3} \). The mass of the core gas detected with the interferometer is approximately \( 0.2 \, M_\odot \), assuming an \( \text{NH}_3/\text{H}_2 \) abundance ratio of \( 2 \times 10^{-8} \) (Harju, Walmsley, & Wouterloot 1993). Within the large uncertainties of this abundance ratio, the mass is the same as that needed to gravitationally bind the rotating system.

The ratio of intensity of the \( \text{NH}_3 \) (2,2) and (1,1) transitions reflects level populations and thus serves as a thermometer for rotational temperature within cold molecular gas cores. In Figure 2b, the contours again show the integrated intensity of (1,1) emission. The shades show the (2,2)/(1,1) ratio, indicating the relatively warmer regions. It is apparent that this is indeed a cold core of gas, with the (2,2) emission showing up only in the central region of the core. The (2,2)/(1,1) ratio peaks near the position of the embedded protostellar source, and extends slightly to the northwest. The peak rotational temperature here is 14 K, as calculated from the line ratio (Ho & Townes 1983). In colder regimes such as this, the kinetic temperature is approximately equal to the \( \text{NH}_3 \) rotational temperature (Danby et al. 1988, Kuiper 1994). The young protostar is evidently still in the center of the gas core, and we may be seeing here the warm gas heated by the protostar and the jet as they interact with the environment.

4. Discussion

4.1. Rotation in Protostellar Systems

Envelopes of Class 0 protostars carry much (often most) of the mass of the system and can extend to diameters of several thousands of AU. Interferometric maps of such systems tend to show flattened disks perpendicular to the axis of the associated jet (Myers, Evans, & Ohashi 2000). The flattened molecular gas envelope of the HH 212 jet source has a smooth and roughly constant velocity gradient perpendicular to the jet axis (Figure 2a, 2c).

Turbulence in cloud cores can produce velocity gradients that mimic rotation (Burkert & Bodenheimer 2000 (BB)). However, the gradient we find in HH 212 is faster than the most likely effect produced in the BB turbulence models. It should be noted that the BB models were based on more massive cores, so proper scaling of the models would be required to better assess the possibility of a turbulent component to the observed velocity gradient in HH 212. But it is also true that the HH 212 gradient extends systematically across the long axis of the core, and perpendicular to the jet, for over 5 synthesized beamwidths. Thus the combined evidence suggests that the gradient is more likely dominated by rotation.
The more evolved T Tauri systems often show Keplerian rotation signatures in the less plentiful envelope gas, with the radial velocities increasing and diverging toward the central source (\(V \propto R^{-1/2}\)). An early report of Keplerian rotation in a young stellar disk was made for \(^{13}\)CO observations of HL Tau (Sargent & Beckwith 1987, 1991), though in this source the kinematics proved to be much more complicated, with evidence for infall (Hayashi et al. 1993) and outflow (Cabrit et al. 1996). The strongest Keplerian velocity curves are seen in circumstellar disks of a few hundred AU in Class II T Tauri systems without much envelope material left, thus having little confusion from large scale infall or outflow motions (Mundy, Looney, & Welch 2000, Dutrey et al. 1998). Keplerian rotation has been detected in the gas disks of GM Aur (Dutrey et al. 1998) and DM Tau (Guilloteau & Dutrey 1998), for example, as well as in multiple systems such as UY Aur and the beautiful ring of GG Tau (Duvert et al. 1998, Guilloteau, Dutrey, & Simon 1999).

Several Class 0 systems such as HH 212 are in dense gas cores that appear to have a more rigid rotation signature (Myers, Evans, & Ohashi 2000); this is consistent with their character of having much of the system mass still distributed in the gas envelope around the embedded accreting protostar(s). Indeed, the 0.2 M\(_\odot\) we detect with the VLA in the HH 212 core is 10 times the circumstellar gas mass found in some T Tauri systems (e.g. \(\leq 0.01\)M\(_\odot\) for UY Aur (Duvert et al. 1998)). In such early systems, a gradient in the intensity-weighted mean velocity that is constant rather than diverging toward the center can indicate that either a) the non-Keplerian rotation curve is reflecting a mass distribution that is not yet dominated by a central condensation, or b) the system is in Keplerian rotation, but high optical depths result in velocity maps that are dominated by motion in the outer layers along the line of sight toward the center of the core. Models of expected channel map emission can be used to test for Keplerian rotation (e.g. Koerner, Sargent, & Beckwith 1993, Dutrey, Guilloteau, & Simon 1994). Higher spatial and spectral resolution maps would be needed to fully model the HH 212 envelope, although the slightly broader line widths we observe toward the center of the core are possible evidence for some Keplerian component to the motion. In any case, it now appears that the observed kinematics of the protostellar envelope can signify the developmental stage of the embedded YSO. More high resolution kinematical studies are needed to confirm this pattern. The large envelopes such as we observe in HH 212 may feed mass directly to the embedded protostar (if at the earliest stage) or to the inner circumstellar accretion disk just beginning to form. It is important to note that this inner disk (< 100 AU and thus unobservable in our NH\(_3\) maps) probably rotates with near-Keplerian velocities (Stahler 2000).

Many rotating cores of these large sizes (≥12000 AU) do not appear to conserve specific angular momentum, defined as \(V_{\text{rot}} \times R_{\text{rot}}\), where \(V_{\text{rot}}\) is the velocity of rotation at radius \(R_{\text{rot}}\) (Myers, Evans, & Ohashi 2000). Our results show that, with a specific angular momentum of 0.012 km s\(^{-1}\) pc at a radius of 6000 AU, the HH 212 gas envelope would fit well with other cores of similar size in a plot of Ohashi et al. (1997) showing specific angular momentum falling with decreasing source radius. However, Ohashi et al. showed that there is a transition at about this same size scale; smaller dense core regions do show conserved specific angular momentum in regions of both massive infall and rotationally supported disks. Thus this would serve as the size scale for
dynamical collapse, where angular momentum is conserved. The HH 212 core seems to be in fast, bound rotation at the size scale of this transition.

Since the velocity gradient and the long axis of the envelope are both perpendicular to the jet axis, it is suggestive that rotation may contribute to the observed flattening. We calculate rotational energy of the system to reach up to about 3-10% of each of the thermal, turbulent, and gravitational energy (Harju et al. 1993, Myers 1983). Preferential contraction along an axis perpendicular to the disk plane, along possible magnetic field lines, could also produce flattened morphology. Another intriguing possibility is that the outflow itself contributes to the morphology by clearing out dense gas along the flow. Indeed, the blue-shifted wisps of gas extending to the northeast alongside the (northward) blue-shifted side of the jet (Figure 2a) seems to form part of a “bowl” around the jet and the associated CO outflow recently studied by Lee et al. (2000); part of the blue lobe of the CO flow shifts to the east corresponding to the NH$_3$ wisp. It has been suggested that molecular outflows associated with jets may broaden over time, as has been seen in B5-IRS1; the broadening flow could contribute to the eventual decline of accretion (Velusamy & Langer 1998). Thus we may be seeing the HH 212 flow in an early stage of broadening and sweeping out envelope material.

4.2. Angular Momentum Release Through the Jet

Bipolar outflows appear to be a ubiquitous product of the formation of stars. Strong winds from young stellar sources are collimated into jets which are observed in visible and infrared shock emission. Magnetic fields may be responsible for channeling and collimating the jets (see, e.g., Shu et al. 1995).

Outflows are thought to be a 'release valve' for the angular momentum carried into the protostellar accretion region by infalling material. Otherwise, matter infalling from even a very slowly rotating circumstellar envelope will have too much conserved angular momentum to fall into the inner accretion region, unless sufficient angular momentum is lost through disk viscosity.

Observational evidence for jets as significant angular momentum carriers has been virtually nonexistent. Recently, however, results of slit spectroscopy on the shock knots in the HH 212 jet have given some evidence of jet rotation (Davis et al. 2000). Five of six knots studied show similar evidence of rotation; in the inner part of the southern flow, for example, a clear velocity gradient is seen. If this gradient represents rotation, the jet rotation is in the same directional sense as that of the rotating molecular gas envelope we observe in ammonia. A rough extrapolation of the large scale angular momentum in the envelope gas fits the observed gradient in the jet, assuming a fraction of infalling mass is channeled into the flow. Thus this may be the first observational evidence for a rotating jet carrying away the angular momentum of material falling in from a rotating envelope. Clearly more detailed observations and evidence of jet rotation and inner disk kinematics are needed.
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Fig. 1.— The HH 212 jet, as imaged in H$_2$ 2.12 micron shock emission (Zinnecker, McCaughrean, & Rayner 1998). The observations were carried out in Spain in 1997 with the Calar Alto 3.5-m telescope using its Omega Prime wide field infrared camera and kindly given courtesy of T. Stanke. The contours represent the integrated NH$_3$ (1,1) emission of the dense protostellar envelope gas, as mapped with the VLA. Contour levels begin at 16 mJy beam$^{-1}$ km s$^{-1}$ and increase by steps of 16 mJy beam$^{-1}$ km s$^{-1}$.

Fig. 2.— (a): The velocity field of the dense gas around the HH 212 jet, as imaged with the VLA in the ammonia (1,1) line. The shades represent the moment 1 velocity field, showing a velocity gradient across the flattened gas envelope as evidence of rotation. Contours are the integrated intensity as in Figure 1. The arrows indicate the orientation of the HH 212 jet. (b): Heating in the HH 212 NH$_3$ core. Contours are the integrated intensity of the (1,1) line, as in Figure 1. The shades represent the (2,2)/(1,1) intensity ratio, which increases with temperature and optical depth. The inner region is slightly heated to 15 K, possibly where the embedded YSO and jet are heating the surrounding gas. (c): Velocity-position cut across the FWHM long axis of the HH 212 flattened envelope, showing the gradient in first moment velocity. Positions are taken across the midline of the flattened envelope of panel (a), with offsets taken from the core center along an axis perpendicular to the jet.
