Hydrodynamic Simulations of Rotating Molecular Jets

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ABSTRACT

Molecular outflows and the jets which may drive them can be expected to display signatures associated with rotation if they are the channels through which angular momentum is extracted from material accreting onto protostars. Here, we determine some basic signatures of rapidly rotating flows through three dimensional numerical simulations of hydrodynamic jets with molecular cooling and chemistry. We find that these rotating jets generate a broad advancing interface which is unstable and develops into a large swarm of small bow features. In comparison to precessing jets, there is no stagnation point along the axis. The greater the rotation rate, the greater the instability. On the other hand, velocity signatures are only significant close to the jet inlet since jet expansion rapidly reduces the rotation speed. We present predictions for atomic, H$_2$ and CO submillimetre images and spectroscopy including velocity channel maps and position-velocity diagrams. We also include simulated images corresponding to Spitzer IRAC band images and CO emission, relevant for APEX and eventual ALMA observations. We conclude that protostellar jets often show signs of slow precession but only a few sources display properties which could indicate jet rotation.

Key words: hydrodynamics – shock waves – ISM: clouds – ISM: jets and outflows – ISM: molecules

1 INTRODUCTION

The prevalent models for the launching of jets associated with forming stars allow for or even require jet rotation (e.g. disk wind, Blandford & Payne 1982; X-wind, Shu et al. 1994; and circulation models, Lery et al. 2002). In theory, the rotation is connected to the necessary extraction of angular momentum from an envelope, accretion disk and magnetosphere associated with the development of a protostar. Processes related to the winding up of a magnetic field are often invoked to transfer angular momentum into the jet although other models exist in which jet rotation is not essential (e.g. Soker 2005).

There is also some observational evidence that is consistent with jet rotation. We can now resolve jets at very small distances from some young stars where the transverse velocity gradients are expected to be largest (Bacciotti et al. 2002; Coffey et al. 2004; Woitas et al. 2005). Further out along the jet, indications of transverse velocity gradients within the knots of HH 212 have been found Davis et al. (2000).

The purpose of this work is to predict the observable signatures which may be exclusively related to hydrodynamic jet rotation. We execute three dimensional simulations of molecular jets with solid body rotation. The jets are injected into a lower density uniform molecular medium. We wish to examine both spatial and velocity structure (e.g. helical or toroidal features, rotation curves etc). We also run a sequence of simulations with increasing rotation speed to test how the outflow structure depends on this parameter. High rotation speeds are assumed here to emphasize the influence of rotation. Such rotation speeds are achievable in disc wind and X-wind models albeit at considerably smaller scales (under 10 AU) (see e.g. Ferreira et al. 2006). The jet radius in the present numerical experiments is taken as 113 AU.

This series of 3D molecular simulations began by investigating the consequences of pulsating, sheared and sprayed jets (Suttner et al. 1997; Völker et al. 1999). With a revised code, we studied the global evolution of the jet power (Rosen & Smith 2003), the influence of the density ratio (Rosen & Smith 2004b) and the precession angle and period (Rosen & Smith 2004a; Smith & Rosen 2005a). Detailed observational consequences for Spitzer infrared bands have been subsequently explored in Smith & Rosen (2005b).

Simulations of rotating atomic jets have already been presented by Cerqueira & de Gouveia Dal Pino (2004). They found that the physical structure of the outflow possessed...
Figure 1. Slices through the jet midplane displaying the mass density for runs Rot5 (upper), Rot10 (middle) and Rot20 (lower panels). All three simulations are shown at a time close to when the bow shock has traversed the grid.

essentially the same features as the equivalent non-rotating precessing jet except for an increased width caused by the centrifugal forces. Near the jet nozzle, shifts in the density-averaged radial velocity across the jet were demonstrated, as expected since the injected material is rotating. Cerqueira et al. (2006) demonstrated that the atomic emission line properties of rotating and non-rotating precessing jets were strikingly similar and, therefore, the interpretation of observations requires caution. In contrast, we here find significant signatures that are specifically due to rotation; we will demonstrate in Section 4 that our results are consistent with those of Cerqueira et al. (2006).

2 DESCRIPTION OF NUMERICAL CODES AND SIMULATIONS

Previous studies by the authors have used a version of ZEUS-3D with modifications as described in Smith & Rosen (2003). The three new simulations add significant solid body rotation to the same initial conditions as the standard dense molecular jet described by Rosen & Smith (2004b) i.e. the nominal axial jet speed is 100 km s⁻¹, the initial jet radius, $R_j$, is $1.7 \times 10^{15}$ cm, a hydrogen density of $10^5$ cm⁻³ in the jet and an ambient hydrogen density of $10^4$ cm⁻³.

The rotation rate is $\nu_{\text{rot}}(R_j) \sim 5, 10, \text{and } 20 \text{ km s}^{-1}$ for the three new runs which we designate as Rot5, Rot10, and Rot20, respectively. The simulations have a slight (half angle = 1°) but fast ($T_{\text{precc}} = 50$ years) precession and a significant pulse, set to ±30 km s⁻¹ with a period of 60 years. In addition, the jet velocity is also modified by a 20% shear such that the axial velocity is reduced to 80% of the central value at the jet edge ($r = R_j$).

The computations for Rot5 and Rot10 were performed on a uniform Cartesian grid of $625 \times 150 \times 150$ zones while Rot20 was run on one of $480 \times 230 \times 230$ zones. The zone size is $2 \times 10^{14}$ cm in each dimension in all cases presented here. For the jet density we have chosen, this implies that the post-shock cooling region is not fully resolved with approximate tracking of the temperatures in this region. Thus, one should take some care in interpreting the emission from the higher temperature molecular hydrogen emission (e.g. the $\text{H}_2$ 1-0 S(1) line, with an excitation temperature of nearly 7000 K) as well as the simulated images of atomic emission.

Figure 2. Evolution of the Rot10 outflow (upper panels) and the Rot20 outflow (lower panels) as seen in molecular hydrogen emission from the $\text{H}_2$ 1-0 S(1) line. Intensity scaling is grayscale but not linear. The jet axis lies in the plane of the sky. In all simulated images, the flux has been calculated by integration along the line of sight assuming the region is optically thin.
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3 RESULTS

3.1 Physical structure

The midplane density cross sections displayed in Fig. 1 demonstrate that the jet expands on entering the grid. The pulsations develop into internal shocks within the jet. These curved shocks also expand, generating a series of broad oblate arcs in the rapidly rotating cases. The internal shocks advance upon the ambient medium where their direct impact leads to the disruption of the interface/bow shock.

A cocoon, which is expected to exist between the jet and the shocked ambient medium, is absent, the interface being reduced to a very thin shell. Thus, most of the jet and ambient material is pushed along in the turbulent head rather than being deflected to the side by a large-scale advancing bow shock.

The rotation leads to a spreading jet with an effective spray of momentum flux that is applied over a wide area. The initial angle of expansion is roughly proportional to the rotation speed. Given the low ambient pressure, the rapidly spinning jet material meets little resistance until the lateral expansion reduces the jet pressure.

This leads to long propagation times as compared to flows in which the jet remains highly collimated. The average advance speeds for Rot5, Rot10, and Rot20 calculated from Fig. 1 are 85, 69, and 57 km s$^{-1}$, respectively. These speeds are much lower than implied by ram pressure balance of the 70–130 km s$^{-1}$ range of the axial speed at the origin.

Figure 3. Images of molecular and atomic emission from simulation Rot10 derived by integration along the line of sight assuming the flow lies in the plane of the sky.

(derived directly from the atomic cooling function for temperatures exceeding 8000 K).

Here, rather than a single bow being accelerated away, different parts of the interface separate ballistically, each part following its own path.

On assuming equal jet and ambient ram pressures, the above average velocities suggest that the jet in Rot10 should be (averaged over the length of the jet) 1.2 times wider and Rot20 1.3 times wider than the jet at the inlet. However, the displayed density distributions indicate that the momentum flux is being spread considerably wider than that. Hence, the forward propagation is maintained at surprisingly high speeds despite the large jet spread. The reason is that the jet mass is retained at the interface rather than being deflected and dispersed laterally. Therefore, the larger inertia reduces the deceleration.

3.2 Synthetic images

Fig. 2 shows that the gradual spreading of the flows reduces the surface brightness of the $^{12}$CO 1-0 S(1) emission. The interface broadens since rotation has caused the jet to widen. The

Figure 4. Images of molecular and atomic emission from simulation Rot20 derived by integration along the line of sight assuming the flow lies in the plane of the sky.
subsequent propagation of jet pulses through the broadened layer leads to substantial brightening.

Images of molecular and atomic emission lines display familiar features (Figs. 3 and 4), from the discrete regions of shocked gas in molecular hydrogen emission lines to the shape of the accumulated mass behind the bow in CO R(1), and the combination of both in CO R(5). That is, there are no signatures specific to the jet rotation. The appearance of numerous mini-bow shocks in H$_2$ lines occurs in other cases where the flow sprays over wide angles due to a wide opening angle (Völker et al. 1999) or due to wide-angle precession (Rosen & Smith 2004a). One contrasting feature to wide-angle precession is that the flow extends furthest along the axis whereas a stagnation point develops in the case of precession.

A common result in our simulations is that only the first internal bow shocks appear in the H$_2$ 1-0 S(1) emission line synthetic image. In the images shown, the first internal bow shock is quite weak but an animation of the evolution of this emission shows that this first shock brightens and fades as it moves through a region some distance from the inlet.

The instability of the leading bow leads to greater atomic emission. These Herbig-Haro objects are associated with the tips of some molecular bows but also appear as independent arcs, many located in the jet facing the jet source.

In contrast, the emission from low-J CO is contained within entire giant lobes.

Integrations of molecular hydrogen lines in the Spitzer bands are displayed for the Rot20 case in Fig. 5. The Band 4 image (lower panel) displays much of the same characteristics as the CO R(5) image whereas the Band 1 image is very similar to the H$_2$ 1-0 S(1) image, consistent with the excitation temperatures of the associated upper energy levels of the individual contributing lines (Smith & Rosen 2005b). This is also illustrated in the rotational CO emission images from J = 2–1 to J = 20–19 displayed in Fig. 6.

### 3.3 Radial velocity structure

By comparing the mass-velocity and CO intensity-velocity profiles of Rot5 and Rot20 in Fig. 7, we see that the faster rotation leads to a flatter distribution (smaller value of $\gamma$ where log(mass) $\propto -\gamma$ log(velocity)). In addition, the largest rotational velocity studied here has a distribution that is not well fit by a power-law. This may be general property of wider, more easily decelerated, flows as also found by Rosen & Smith (2004a). The mass and CO intensity profiles possess a high velocity bump in Rot5 which is absent in the Rot20 case, which indicates that the larger rotation rate is associated with an easier deceleration of fast moving material.

Global position-velocity diagrams, integrated in the di-
Figure 7. Distributions of mass and intensity as a function of radial velocity for Rot5 (left panels) and Rot20 (right panels). The five curves correspond to jet viewing angles of 15° (dot-dot-dashed lines) to 75° (full lines) to the line of sight. These distributions are computed for t = 450 years and t = 500 years, respectively.

Figure 8. Position-velocity diagrams of molecular emission lines in Rot20 for viewing angles of 15° (left) and 60° (right).
directions transverse to the jet axis, show a familiar sequence of Hubble Law like distributions (Fig. 8). For a viewing angle close to the line of sight, e.g. $15^\circ$ as in the left panel of Fig. 8, the locus of high velocity emission takes a more rounded form than in the standard non-rotating jet. The roundedness seen with viewing angle of $15^\circ$ is not as pronounced when the angle is increased to $60^\circ$. However, no clear signature of rotation is found here also.

We finally investigate position-velocity diagrams for several slits parallel to the jet axis. The slit width was taken as $6 \times 10^{14}$ cm (three zones in $y$). We note that this is similar to the analysis on display in Cerqueira & de Gouveia Dal Pino (2004).

For a viewing angle in the plane of the sky, position velocity diagrams in CO R(1) from slits parallel to the jet axis but offset to either side clearly reveal the rotation only in the region before the first shock (i.e. for $x < x_{\text{shock}}$) (Fig. 9). Since the molecular hydrogen lines show only the region near the first internal shock and the bow shock, position velocity maps in H$_2$ 1-0S(1) possess more subtle evidence for the rotation, and this is characterised by a shift in radial velocity across the internal shock (right panels of Fig. 9). The internal shocks themselves, with their associated higher densities, dominate the appearance of the CO R(1) position-velocity diagrams.

For a viewing angle of $45^\circ$, position velocity diagrams in CO R(1) show a separation of the jet and ambient components (Fig. 10). There is a shift in radial velocity at the jet origin but this is rapidly lost downstream.

The velocity channel maps in CO at a viewing angle of $15^\circ$ shows similar morphological traits that exist both in our previous simulations and in observations of molecular outflows (e.g. HH 288, an outflow associated with an intermediate mass protostar Gueth et al. 2001). This morphological sequence shown in Fig. 11 includes emission from the shocked ambient medium region behind the bow at low...
velocities and the internal structure closer to the jet axis at high velocities. In Rot20, the high velocity maps show the internal shocks that have a circular appearance. These bows are hollow at intermediate velocities but partially filled at low velocities (Fig. 11).

To elucidate the nature of the radial velocity profile, we present the velocity distributions transverse to the jet axis in the left panels of Fig. 12. Both mass and H$_2$ emission are represented. Note how the radial speeds rapidly drop and the jet widens along the jet axis. The right panels show the differences in the mean radial velocities as a function of distance from the axis. In contrast, the profiles for fast precession do not display such clear asymmetries, providing a straightforward diagnostic to differentiate rotation from precession.

3.4 Rotational analysis

We here perform three dimensional spectroscopy by placing several parallel slits transverse to the jet axis (Figs. 13 & 14). A viewing angle of 43° is chosen for these experiments to permit a comparison with the study of Cerqueira et al. (2006), motivated by the atomic jet associated with the young star DG Tau (Bacciotti et al. 2002).

The rows of slits are placed near the jet inlet. The size of each so-called ‘slit’ is 3 × 3 pixels with no separation between the slits in $y$ and a separation of 1 pixel in $x'$. Each pixel is equivalent in size to a zone used in the simulations, i.e. $2 \times 10^{14}$ cm.

We remove the contribution to the CO R(1) emission from the ambient molecular cloud, as has been done in the analysis of Yu et al. (2000) (and suggested to be necessary for correct estimation of the mass-velocity slope by Arce & Goodman 2001). The image only includes emission from zones with total velocity exceeding 1 km/s.

The radial velocities we show in the upper right of the analysis figures represent the emission peak location for

![Figure 11](image)

**Figure 11.** Velocity channel map of CO emission for the Rot20 simulation at a viewing angle of 15°.

![Figure 12](image)

**Figure 12.** Velocity profiles and differences across jet for the Rot20 simulation (top) and the fast precession simulation P20 (bottom) from Rosen & Smith (2004a). In the left hand panels, for zones near a certain value of $x'$, we plot the minimum, maximum velocities, which are designated by the line at each y-position, and three differently weighted mean radial velocities. The three mean velocities are the usual mean (star), mass-weighted mean (triangle), and the 1-0 S(1) emission line weighted mean (diamond). In the right panels, we show the means that are of equal distance from the jet center subtracted from one another (vel(r-) - vel(r+)). The jet axis is in the plane of the sky, a 0° viewing angle. Note that the horizontal and vertical scales are not necessarily the same in all of the plots above.
\( v_{\text{rad}} < -20 \text{ km/s}, \) since the radial velocity profiles also may have a maximum intensity with \( v_{\text{rad}} \) near 0 km/s. These profiles do not include thermal broadening; with 1 km/s bins for CO R(1) emission we consider this unnecessary. Additionally, the integration of the emission again makes the optically thin assumption.

The sense of rotation and of precession are the same. Specifically, the angular momentum of both motions, \( J \), is in the \(-x\) direction (+z \( \times \) +y). Naturally, for Rot5, the precession (1° half-angle) is small enough that its effect is not significant.

The general result (as shown here specifically for Rot20 in Fig. 13) is that near the inlet, the differences of the peak emission \( v_{\text{rad}} \) from each side of the jet become larger with distance from the jet axis (S1 - S7 is more positive than S2 - S6, which is larger than S3 - S5). This is a clear signature of rotation, although the plot of \( v_{\text{rad}} \) for each slit shows a flattening as the slits progress across the jet. Note also that the high velocity emission in the profiles (at the bottom of the figure) appear to move toward more negative \( v_{\text{rad}} \) for each successive row of slits.

In Fig. 14, we show the results from a ‘fast’ precessing jet with a 5° precession half-angle, designated simulation P5 by Rosen & Smith (2004a). Even with this small precession, the short period leads to a bent jet. Hence, we have centred each row of slits on the centre of the CO R(1) bright region associated with the jet. The profiles in each of the number 4 slits for rows I through IV appear similar to each other. While there do appear to be some non-zero \( \Delta v_{\text{rad}} \) in rows III and IV for this case, there is still no compelling evidence that precession mocks rotation, contrary to the stated results from atomic line profiles analysed by Cerqueira et al. (2006). This will be explained below to be a result of the chosen conditions.

4 CONCLUSIONS

We have investigated the properties of fast rotating jets. In particular, we have searched for specific features which could be used to identify rotation. Firstly, rotation influences the mass-velocity profiles, flattening the relationship. High rotation speeds also lead to profiles less well fitted by power laws over large ranges of radial velocity.

The only reliable means of detecting rotation involves taking a series of position-velocity diagrams from slits parallel to the jet axis but offset to either side i.e. three-dimensional spectroscopy. Then, the diagrams reveal the rotation only in the initial region between the jet entry and before the first shock. In many molecular outflows this region is obscured in the near-infrared, leaving submillimetre and far-infrared molecular observations as the most likely
Figure 14. Standard rotation analysis of simulation P5: fast precession with a 5 degree half-opening angle. The same layout as Fig. 13 applies.

means of testing for rotation. The necessary resolution will be achievable with Herschel and ALMA.

Results from the rotational analysis of a number of our 3D molecular simulations show that CO R(1) emission from fast moving gas can reveal jet rotation. Additionally, in our simulations that precess significantly but do not have any initial rotation, we see no evidence for rotation. This is in contrast to the results of Cerqueira et al. (2006), who find the signature for rotation in both rotating and precessing jets.

The basic signature of rotation is the rotation curve, as displayed by the radial velocity profiles shown in the top panels of Fig. 12. The figure demonstrates that this signature is also present in the H$_2$ line emission. In contrast, fast precession was shown to result in blue-shifted and red-shifted gas observed in projection on both sides of the jet (lower panels of Fig. 12). Interestingly, this effect was not apparent in the jet simulations presented by Cerqueira et al. (2006). However, it should be noted that, whereas we inject a jet with high solid-body rotation and axial shear, their injected jet rotation speed varied inversely with radial distance, peaking at just 0.15 of the jet radius. In addition, the jet was highly over-pressured and thus expands ballistically. This means that the fluid elements continue on tangential paths (not circular paths), maintaining a high radial velocity gradient only close to the jet axis. Therefore, rotation signatures should be limited to their inner slits (between slits 3 and 5). This was indeed found, with the precession simulation (run M2) generally displaying only small velocity gradients and rotating jets (run M4) displaying high gradients across the inner slits.

Concerning the images, no prominent features were uncovered in all the simulations. Although rotation does lead to a broad and fragmented interface with the ambient medium, this was also found previously in simulations of fast precession and wide-angle spraying jets. Collections of co-moving multiple bows are found in several bipolar outflows, especially those from high-mass protostars e.g. Cepheus A (Hartigan et al. 2000) and OMC-1 (Allen & Burton 1993). In fact, the centrifugal expansion of a rotating collimated molecular flow produces a multiple-bow structure similar to the model presented by Allen & Burton (1993) involving a variable velocity spherical expansion (Stone et al. 1995).

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