CONFRONTING THREE-DIMENSIONAL TIME-DEPENDENT JET SIMULATIONS WITH HUBBLE SPACE TELESCOPE OBSERVATIONS

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ABSTRACT

We perform state-of-the-art, three-dimensional, time-dependent simulations of magnetized disk winds, carried out to simulation scales of 60 AU, in order to confront optical Hubble Space Telescope observations of protostellar jets. We “observe” the optical forbidden line emission produced by shocks within our simulated jets and compare these with actual observations. Our simulations reproduce the rich structure of time-varying jets, including jet rotation far from the source, an inner (up to 400 km s$^{-1}$) and outer (less than 100 km s$^{-1}$) component of the jet, and jet widths of up to 20 AU in agreement with observed jets. These simulations when compared with the data are able to constrain disk wind models. In particular, models featuring a disk magnetic field with a modest radial spatial variation across the disk are favored.

Key words: ISM: jets and outflows – magnetohydrodynamics (MHD) – methods: numerical – stars: formation – stars: pre-main sequence

Online-only material: color figures

1. INTRODUCTION

Jets and outflows are important dynamical components of star formation and are observed across the entire range of stellar masses, from brown dwarfs (Whelan 2005) to O stars (Shepherd 2005; Arce et al. 2007). They appear during the earliest stages of star formation and play a fundamental role in this process by removing angular momentum from the gaseous protostellar disks to which they are coupled. Jets are known to be associated with all astrophysical systems that have accretion disks—protostars, black holes of all masses, and compact objects—and may even be associated with the formation of giant planets (Fendt 2003). However, the physical conditions and origin of jets can be best studied in the context of protostellar systems because of their copious, collisionally excited, optical forbidden line emission (e.g., review by Ray et al. 2007), and their proximity.

Optical forbidden line emission is the result of collisionally excited oxygen, sulfur, and nitrogen atoms present in protostellar jets. While the mechanism(s) responsible for heating the jet and producing the line emission is still not completely understood, some possible models include radiative heating by X-rays from the central star (Shang et al. 2002), magnetic dissipation (Moll 2009), or heating by shocks occurring throughout the jet volume (Ouyed & Pudritz 1993; Shang et al. 2007). Recently, high-resolution observations of forbidden line emission from jets, obtained with the Hubble Space Telescope (HST), have been used to directly measure conditions within protostellar jets (Bacciotti & Eislöffel 1999; Bacciotti et al. 2002; Ray et al. 2007).

A particularly exciting result is the measurement of radial velocity gradients within jets that provide evidence for jet rotation far away from the jet’s origin (Bacciotti et al. 2002; Woitas et al. 2005; Ray et al. 2007; Coffey et al. 2008). These results suggest that jet rotation carries an appreciable amount of angular momentum—of the order of 60% of the underlying accretion disk. This result is crucial because angular momentum must be shed from the disk in order for material to spiral inward and build the star.

Theoretical models (Blandford & Payne 1982; Pelletier & Pudritz 1992; Ferreira 1997; Krasnopol’sky & Königl 2003) and computer simulations (Ouyed et al. 1997; Machida et al. 2008) have shown that an outflowing wind can be launched from magnetized disks. The magnetic fields that are frozen into the rotating outflow develop a helical structure resulting in a collimating force, which turns the outflow into a jet. Two different hydromagnetic models have been proposed in the literature to explain the origin of these outflows—disk winds that are launched from extended regions of magnetized, Keplerian, accretion disks (Blandford & Payne 1982; Pudritz et al. 2007), or X-winds originating from a narrow region on the inner edge of an accretion disk (Shu et al. 2000). An important dynamical distinction between these models is the amount of angular momentum transported, with disk winds carrying much more since they originate farther out in the disk.

The use of HST data to test disk wind models was first demonstrated by Anderson et al. (2003). Further progress in testing the theories has, until recently, been hindered by a lack of self-consistent, large-scale three-dimensional simulations (matching HST observations) including the launching and acceleration of the jet from the vicinity of a protostar and its accretion disk. The advent of high-performance computing resources has changed this situation. As an example, in addition to the work reported here Anderson et al. (2006) used a simulation box of the length of the 1/5th of the length we use and Moll (2009) used a simulation box with the same length as we do.

In our simulations, the accretion disk is treated as a boundary condition whose initial conditions are based on the results of magnetized protostellar disk formation calculations (see below). This is a simplification of the problem. A more satisfying, but also more complicated approach would require the disk to be a part of the simulation. Axisymmetric simulations of such an
initial condition have recently been performed by Murphy et al. (2010) and Zanni et al. (2007) among others. This approach has been limited by the lack of strong large-scale magnetic fields. Even for this more general coupling of jet and disk dynamics, however, it is unclear what the appropriate initial state for the disk and jet should be. Moreover, most models assume stationary, two-dimensional, self-similar coupling of jet and disk solutions, for which there is no general physical justification.

A comprehensive approach to this problem is to start from initial conditions in which the disk and jet form and evolve together from an initial collapse of a magnetized, three-dimensional molecular core (Banerjee & Pudritz 2006; Machida et al. 2008; Duffin & Pudritz 2009). Magnetized collapse produces an early outflow that is launched from a small but growing disk. The strength and the geometry of the initial magnetic field still require further clarification (e.g., Hennebelle & Fromang 2008; Mellon & Li 2008). Banerjee & Pudritz (2006) found that \( B \) is the dominant component of the magnetic field across the disk and scales with disk radius as \( r^{-3/2} \). The toroidal field component—needed for winds and outflows—is automatically generated in the forming rotating disk. Simulations that also include ambipolar diffusion (Duffin & Pudritz 2009) find that the power-law fit to the \( B \) field varies with disk radius, with the region within 10 AU varying as \( r^{-1.67} \) in one case, and in all cases behaving as \( r^{-1.2} \) on larger disk scales. Jets tap accretion power and therefore simulations need to resolve the inner regions of disks. The presence of an internal “sink particle” in a disk (e.g., Bate et al. 1995; Federrath et al. 2010) prevents this inner region from being resolved, by construction. Unfortunately, this limits the usefulness of such simulations in tracking the long-term evolution (beyond \( 10^5 \) yr) of the inner few AU of protostellar disks.

This paper presents simulations with a jet that propagates out to the equivalent of 60 AU. We adopt a magnetic field structure on the disks in accord with the time-dependent simulations discussed above. Given the difficulties noted above, our approach is well justified. A 60 AU outflow scale can be directly probed by means of spectroastrometric observations in forbidden lines such as \([\text{O} \text{II}], [\text{N} \text{II}] \), and \([\text{S} \text{II}] \), using the \textit{HST}. As such, we view our simulated jets in the same lines as observers do in order to investigate the link between observed jet properties and their actual underlying dynamics. Stute et al. (2010) followed a similar approach constructing synthetic emission-line maps from axisymmetric simulations of protostellar jets.

Our results show that jets are highly dynamic and riddled with shocks throughout their volume. These heat the jet to produce forbidden line emission. Emission maps constructed from our simulations act as an excellent diagnostic for many aspects of jet collimation, density, and temperature structure, and transport rates of energy and angular momentum from the disk. Using these diagnostics, we are able to show that all jet dynamics and properties are shaped by the magnetic structure, the field strength, and the mass loading onto the field lines at the base of the flow. We confirm that jet rotation persists out to at least 60 AU from the source.

2. NUMERICAL SETUP

Our basic numerical setup consists of a Keplerian accretion disk as the fixed boundary condition for the jet (Ouyed et al. 2003). A major addition that we make to earlier three-dimensional work is to incorporate more general models for the configuration of the disk magnetic field. We present data from two such configurations, whose poloidal magnetic field strength at the disk surface falls off as power laws with the disk radius as

\[
B_p \propto r_\mu^{-\epsilon}, \quad \epsilon = -0.01, \quad -0.25.
\]

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The first model encapsulates initial field structures that can be derived from a potential (Ouyed & Pudritz 1997) designated as OP, while the second models the more steeply decreasing, self-similar configuration of Blandford & Payne (1982) designated as BP. These models for magnetic structure in the disks reflect those seen in the disk formation calculations as noted. Other than the power-law index of the field, the second major parameter in our model is the ratio of the thermal and magnetic energy at the inner edge of the disk, denoted as \( \beta_i \).

Another major extension of previous work is the increase in the spatial scale of the simulation to 60 AU, compared to the earlier (Ouyed et al. 2003) box size of less than 2 AU. This is sufficiently large to cover several pixels of observed jets. We note that the jets shown in our figures have a much higher angular resolution than can be reached by \textit{HST}—our images have resolutions down to 0.015 AU, whereas that of the \textit{HST} is 0.1 arcsec corresponding to a resolution of about 15 AU (Ray et al. 2007) at the observed distance of 140 pc.

We compute the forbidden line emission using the densities and temperatures of the shocked gas within our simulated jet, allowing us to compare directly with observations. The shocks produced in the body of our jets are a direct consequence of the magnetohydrodynamics. It is well known that flows with a magnetic Mach number \( M_A > 0.3 \) spontaneously generate small, weak, “eddhy shocklets” (Kida & Orszag 1990). We model the optical emission from the jet by assuming that any material flowing with \( M_A > 0.3 \) leads to heating by shocks. This is supported by our previous simulations (Ouyed et al. 2003), which show that jets become unstable under these conditions leading to shocks and jet heating.

We note that our approach is complementary to those which include the detailed vertical structure of the underlying disk in order to model disk winds (Ferreira 1997; Krasnopolsky & Königl 2003). This is because disk winds and jets—in analogy with the origin of stellar winds—respond to physical conditions at their base. These can be described with a limited set of robust boundary conditions. Our simulations—when confronted with the \textit{HST} data—then provide highly physical constraints that can in principle constrain more detailed models that include disk substructure.

2.1. Parameters in the Model

Our simulations are technically controlled by the five parameters discussed in Ouyed & Pudritz (1997) and Ouyed et al. (2003). Those papers did not include the index of the power law modeling the disk field. We make many simplifications of this general scheme. Contrary to Ouyed et al. (2003), we do not introduce a toroidal magnetic field in the disk since it is automatically produced by the outflow. The magnetic field in the disk is simply an extension of the initial magnetic field in the corona. Similarly, the plasma \( \beta = P_g / P_B \) at the inner edge of the disk is also determined by physics—the magneto-rotational instability (MRI; Balbus & Hawley 1998). The MRI in the disk naturally amplifies weak fields and saturates at a value \( \beta_i \approx 1 \) which we use here. The Keplerian disk is set up in a similar way to that described in Ouyed et al. (2003), but there are a few differences. Because of the much larger simulation box, we have extended the outer edge of the disk to 80\( r_i \). As long as this parameter is large, the exact value does not seem to matter.
Contrary to Ouyed et al. (2003), we do not introduce a turbulent pressure in the initial disk corona in this work. The parameter $\delta_i$ used in Ouyed & Pudritz (1997) is therefore just $\delta_i = 3 \times 10^{-14} \rho_i/(0.5 \text{ AU})^2 (r_i/0.05 \text{ AU})/(0.5 M_\odot/M)^2 \text{ g cm}^{-3} \approx \rho_i$ at the inner edge of the disk. This density jump across the disk surface $\eta_i = 100$.

The code uses dimensionless equations, but real units are needed in order to calculate the forbidden emission lines in the post-processing of the simulation data. Hence, we need the radius of the inner edge of the disk $r_i = 0.03$ AU, the mass of the star $M = 1 M_\odot$, the magnetic field at the inner edge of the disk $B_i = 10$ G, the Keplerian velocity at the inner edge of the disk $v_{\text{ke}} = 104$ km s$^{-1}$, and the temperature at the inner edge of the disk $T_i = 56.5 \times 10^4$ K. These latter parameters are only used in the post-processing analysis and therefore do not affect the dynamics of the jet. They are, however, important for the details of the results. We have adopted standard values for these parameters (indicated above) taken from Ouyed & Pudritz (1997).

There are really only two free parameters determining the dynamics in our simulations, the initial magnetic field configuration (given by $\mu$) and the mass-loading parameter given by the injection velocity (defined as in Ouyed et al. 2003, $v_{\text{inj}} = 0.003$) from the disk into the corona. The effect of mass loading was extensively studied in previous two-dimensional simulations (Pudritz et al. 2007). In this work, we maintain the mass-loading parameter constant and use two different initial magnetic field configurations.

### 3.Forbidden Line Emission

In these simulations, a polytropic equation of state (EOS; $P \propto \rho^n$) has been used ($\gamma = 5/3$), and therefore we need not solve the energy equation. It was noted in Ouyed et al. (2003) that no significant difference was found in the dynamics of simulations containing the energy equation, and we take this as a justification for using this simpler approach. We calculated the radiation in the post-processing of the simulation data.

We find the temperature from the polytropic EOS as

$$T = \rho^{\gamma - 1}. \quad (2)$$

If the Alfvén Mach number ($M_A$) is greater than 0.3, we assume the gas to be shocked and the temperature is then (Ouyed & Pudritz 1993)

$$T = \rho^{\gamma - 1} M_A^2 \beta \frac{\gamma - 1}{2}, \quad (3)$$

where $M_A$ is the Alfvén Mach number and $\beta = P_e/P_B$ is the plasma beta.

Given the temperature and assuming standard relative abundances for the elements in question, the emission from each cell in the simulation can be found from a well-known relation given by Haffner et al. (1999) for [O I]:

$$\epsilon_{\text{O I}} = f_i d\exp(-n/n_{\text{crit,O I}}) \exp(-E_{\text{ij,O I}}/kT)x_i n_{\text{O I}} n_{\text{O}} \times (T/10^4)^{\gamma_0} T^{-0.5} \Omega(i,j)/\omega_i. \quad (4)$$

where $f_i$ is the fraction of downward transitions that produce the emission line, $dl$ is the size of the zone along the line of sight, $n$ is the number density, $n_{\text{crit,O I}} = 1.3 \times 10^7$ cm$^{-3}$, $E_{\text{ij,O I}} = h\nu/\lambda_{\text{O I}}$, $\lambda_{\text{O I}} = 6300$ Å, $\gamma_0 = 0.95$ (Mendoza 1983), $k$ is Boltzmann’s constant, $x_e = 0.1$ is the electron fraction (Ray et al. 2007), $\Omega(i,j)$ is the collision strength of the transition, and $\omega_i$ is the statistical weight of the ground level.

It may be instructive to pause for a moment and consider the individual terms in Equation (4). In our simulations, the density $n$ rarely approaches the critical density for O I, $n_{\text{crit,O I}}$ so the term $\exp(-n/n_{\text{crit,O I}})$ remains close to unity and does not play a significant role. The temperature $T$ also rarely approaches $E_{\text{ij,O I}}/k$ meaning that the term $\exp(-E_{\text{ij,O I}}/kT)$ does vary a lot and showing a single peak along the line of sight. Around the peak this term does not change much, and instead the density squared term $(n_{\text{O I}}^2)$ determines the behavior. We note that the $(T/10^4)^{\gamma_0} T^{-0.5}$ terms behave similarly to the $\exp(-E_{\text{ij,O I}}/kT)$ term and enhance the temperature dependence. Since we integrate $E_{\text{ij,O I}}$ along the line of sight, a few bright shining cells will completely dominate the emission. These dominant cells have high temperature and high density, and as it turns out they also have a high Mach number ($M_A > 1$). We chose to include shock heating for $M_A > 0.3$ (see Section 2), but as it turns out the result is quite insensitive to this choice and had we chosen to include shock heating for $M_A > 1$ instead our results would be similar.

The important point to remember is that we integrate along the line of sight. Even though all the cells with $0.3 > M_A > 1$ will have different emission depending on whether shock heating is used for $M_A > 0.3$ or $M_A > 1$, this is irrelevant for the final result as long as the line of sight contains dominant cells with $M_A > 1$.

We construct forbidden emission lines from our simulations in order to compare directly with observations. In order to do the comparison properly, we should also use the same resolution and integration time as the observations. Our simulation box covers 8 pixels of HST observations of some of the nearby jets. If we were to reduce our simulations to only 8 pixels, most details in our simulations would be lost. We have therefore decided to maintain this high resolution in our emission-line maps to capture more details and keep in mind that this resolution is much higher than what can currently be achieved by observations. The observations have a limiting magnitude that may be improved in the future, which can reveal some of the fainter parts of the jet that may otherwise not show up. In this work, we will assume an integration time of 10,000 s and a limiting magnitude of 30 for the resolution that we have.

### 4. Results: Diagnostics for Jet Dynamics

We compare the results from the end states of the OP and BP simulations throughout the rest of the paper. The simulations ran until the front of the jet reached the end of the grid, which happened after 2300 orbits of the inner disk (650 days) for the OP simulation and 2550 orbits of the inner disk (721 days) for the BP simulation. The conversion between code time units and real time units is given by $t_{\text{orb, id}} = 0.86 G_\odot/(0.05 \text{ AU})^{3/2} \sqrt{M/(0.5 M_\odot)}$ (Ouyed & Pudritz 1997). Figure 1 presents three-dimensional snapshots of the numerical jet data for these two models. These two panels show the presence of a strong helical field that wraps the jet, thereby providing the pinch force that collimates the jet toward its axis. The bow shock, wherein the external medium is shocked by the jet, is clearly seen in both cases.

An important difference between these simulations can be discerned. Whereas the BP models appear to have a density structure that is strongly peaked toward the jet axis, the OP
model is more bimodal. In the OP model there is material at the core of the jet, as well as gas that is separated from it. The jet creates a cavity outside the narrow inner jet. In the OP case, the material pushed away in this process is collimated by the magnetic field, becoming the outer jet component. In the BP case, this cavity is wider and opens up faster than in the OP case. The BP magnetic field (which drops off faster than the OP field) does not collimate this material very well, explaining why there is no outer jet component in the BP case. It turns out that this more extended off-axis component moves at much lower velocities than the jet core.

Both the inner OP jet and the thin BP jet are found to wobble from side to side. This is a consequence of a finite amplitude instability found for a much more restricted magnetic geometry by Ouyed et al. (2003). Our present simulations show that this behavior is quite general—that jets survive nonlinear saturated modes that give rise to kinks and wobbles and that nevertheless propagate to great distances from their source. Movies showing the full time evolution of these jets can be found at http://www.phys.lsu.edu/~astroshare/jstaff/jetmovies/.

Our simulations show that the jet remains stable out to large distances from the disk. The movies on our Web site show that the stable part of the jet grows outward with time. Closer to the front of the jet the Keplerian velocity profile is lost, which we attribute to the kink instability. This effect seems to follow behind the bow shock. The simulations presented in Ouyed et al. (2003) were on a much smaller spatial scale (and with a very different initial magnetic field configuration), so this effect could not be well studied in that work. We will focus more on jet stability in an upcoming paper.

The integrated \([\text{O} \text{i}]\) line map for the OP and BP jets is shown in Figure 2. This map is the sum of all the emission through the whole body of the jet, and projected onto the sky. We recall that these maps have a resolution of 0.015 AU in the inner region as compared to 15 AU for \(HST\) images. The core and wider angle structure that we noted previously can be clearly seen in the OP jet. The jet widths can be measured from Figure 2. At about 10 AU from the disk both jets have a full width of 4–8 AU. Further away from the disk the bright inner jet component remains collimated and does not widen much. In the OP jet, the dimmer outer component reaches its full width of about 18 AU around 20 AU from the disk. This is in agreement with the observed jet widths (Ray et al. 2007) which are resolved and
found to be about 15–20 AU close to the source. The BP jet is less collimated; within our simulation box we find no outer jet in the BP simulation. The width of the BP jet is therefore just the width of the thin (inner) jet. We will discuss jet collimation in more detail in the upcoming paper. The side boundaries in our simulation box allow for gas to flow out, and a little bit of gas is indeed leaving through the side boundaries. A larger simulation box that minimizes this effect may be preferable as it may reveal an outer jet in the BP case at a larger radius.

The density and thermal structure in the OP and BP jets, inferred from maps of [O\textsc{i}] emission, are shown in Figure 3. The figure may be compared with that of Figure 6 in Ray et al. (2007). The left and right panels show the results for the OP and BP simulations, respectively. The second row in this figure shows the temperature structure of the jets along two cuts taken parallel to the jet axis—one being along the axis itself and a second parallel cut displaced from it by 2.5 AU. The OP and BP models have a similar temperature structure. We find that in the core region of the jet, the temperature is higher than what was reported by Ray et al. (2007) but decreasing away from the axis. The third row shows the jet density inferred by the [O\textsc{i}] diagnostic for these two simulations. Again their density structure is similar and is of the right magnitude, although in the core of the jet it is higher than what observed jet densities indicate. At the very high spatial resolution shown here, there are large fluctuations in the jet density—reflecting the underlying noisiness of the jet that is a consequence of its rich shock structure. This matches the observed forbidden line emission which also appears to be highly variable on similarly small spatial scales (Ray et al. 2007).

The fourth row of Figure 3 shows an estimate for the mass-loss rates that are inferred directly from the simulation data. The rate is of the order $10^{-8} M_\odot \text{yr}^{-1}$ (adopting $x_e = 0.1$) which is in good agreement with the observed values (Ray et al. 2007).

We have taken the jet radius to be 9 AU (OP) or 4.5 AU (BP). The gas outside of 4.5 AU in the BP jet does not appear to be collimated.

Observations of the velocity structure of jets show that jet velocities (Bacciotti et al. 2000) can range up to 300–400 \text{km s}^{-1}. We find that OP jets attain slightly higher absolute jet velocities ($\sim 440$ \text{km s}^{-1}) than BP models ($\sim 400$ \text{km s}^{-1}). The lower velocities have a broad spatial scale, whereas the higher velocity material is much more collimated toward the axis. Figure 4 very clearly reproduces this observed velocity structure. We show a series of images of [O\textsc{i}] emission from material that moves in the following velocity channels; 0–110, 110–220, 220–330, and 330–440 \text{km s}^{-1}. The higher velocity material is progressively more collimated and closer to the axis. The fastest material clearly shows the greatest signs of a “wobble” that is induced by the underlying, kink instability (Ouyed et al. 2003). The right panel shows a composite color image of the four velocity channels.

One of the most important tests of hydromagnetic-driven wind models for jets is that they should be observed to rotate (Blandford & Payne 1982; Ouyed et al. 1997; Anderson et al. 2003). The measured jet rotation and density can be used to measure the angular momentum of the jet and its likely source. Using slits placed perpendicular to the jet axis, measured velocity gradients of 20–30 \text{km s}^{-1} can be interpreted as due to jet rotation (Bacciotti et al. 2002).

In Figure 5, we show the magnitude of the expected jet rotation measured by [O\textsc{i}] lines for both the OP and BP configurations. We show that material everywhere in the jet (except in the very front of the jet) has inherited the sense of rotation that is imposed by the underlying disk. The shock structure induces some local shear gradients on top of this basic pattern. In
Figure 4. Velocity channel maps. Shown in the top figure are \( [\text{O} \text{I}] \) maps in decreasing (from top to bottom) velocity channels for the OP configuration, and similar for the BP configuration in the bottom figure. The fastest velocities capture the inner jet and its spiral structure, while the slowest velocities capture the broad outer flow. In the right panel of each figure is a composite color image of the four velocity channels (purple (0–110 km s\(^{-1}\)), green (110–220 km s\(^{-1}\)), red (220–330 km s\(^{-1}\)), and blue (330–440 km s\(^{-1}\))). (A color version of this figure is available in the online journal.)

Figure 6, we take a “cut” across this forbidden line map (shown in Figure 5) to show the measured rotation velocities. For both OP and BP models, the signature of Keplerian rotation is unmistakable and is of the correct magnitude. This makes sense since it is ultimately the mass of the central star that sets the rotation speed of the Keplerian disk, and hence of the jet that arises from it. The rotational signature is more variable in the OP model because of the wide component. This wide component can also be seen in the contour plot in Figure 5. The BP simulation shows a hint of an outer rotating component around 10 AU, but due to the limited size of our simulation box we cannot tell if this will evolve into an outer component such as that seen in the OP simulation. In general, our simulations confirm that the signature of rotation is robust even in highly varying jets and matches the predictions of disk wind theory.

The main difference between the OP and BP simulations is that the OP simulation collimates most of the wind from the disk into a jet, whereas the BP simulation only collimates part of it. However, changes in disk parameters can lead to a range of detailed physical values for jet quantities. The choice of outer radius of the disk has little effect, as not much more mass is lost from a bigger disk. The width of the OP jet (∼18 AU) is a better fit to the observed jet widths. However, by using \( r_i = 0.05 \) AU (instead of 0.03 AU) the BP jet becomes ∼15 AU wide, similar to observed jet widths. Changing \( r_i \) also leads to velocities that are ∼30% lower than reported here, densities that are ∼60% higher, and mass fluxes that are ∼30% higher. In addition, it will also affect the emission-line maps. There are many parameters that can be changed like this resulting in a range of possible results. These parameters are unlikely to be strongly...
Figure 5. Line-of-sight velocity. The line-of-sight velocity captures the toroidal velocity from \([\text{O} \text{i}]\) emission for the OP configuration (left panel) and BP configuration (right panel). The maximum line-of-sight velocity is very high (~100 km s\(^{-1}\)) but this high velocity is only reached a few places in connection with the kink instability. The line-of-sight velocity from the bulk of the jet is up to about 40 km s\(^{-1}\) in both cases.

(A color version of this figure is available in the online journal.)

Figure 6. Toroidal velocity. A slice across the jet taken 30 AU from the disk (illustrated with a vertical line in Figure 5). The outer jet component in the OP case (black solid line) starting at about 5 AU is clearly absent in the BP case (dashed line). Shown in red is a Keplerian velocity profile that fit OP and BP line-of-sight toroidal velocity. The OP rotational profile follows the Keplerian one only until about 5 AU, whereafter it deviates because of the outer jet.

(A color version of this figure is available in the online journal.)

pinned down by observations in the near future. However, the dynamics remain unchanged by these choices. With only two unconstrained parameters, the mass loading and the magnetic field configuration, we found that within our simulation box the OP simulation collimates the flow much better than the BP simulation.

5. DISCUSSION AND CONCLUSIONS

There appear to be two important physical parameters for jets in these models—the power-law index \(\mu\) that controls how steeply the magnetic field falls with radius on the disk at the base of the jet (Pudritz et al. 2006) and the mass loading. This paper explores the role of the former—the latter having been explored in two dimension in earlier simulations (Ouyed & Pudritz 1999). Numerical data with the OP model \((\mu = -0.01; \quad B \propto r^{-1};\) which features a more slowly varying poloidal field in contrast with the BP field \(B \propto r^{-5/4}\) match observations better. Since the magnetic field featured in the X-wind theory falls off even more quickly with disk radius than the BP configuration, these results suggest that much more steeply raked magnetic configurations—such as the X-wind configuration—may have difficulties in predicting the complete structure of optical emission in jets.

Most of the other parameters that control jet structure and emission in our simulations have values that are established without any fine tuning. Emission arises from shocked gas that pervades the body of the jet. Thus, taking all gas with \(M_A > 0.3\) as the source of emission is based on physics. Second, the disk is a region that is susceptible to MRI (Balbus & Hawley 1998) whose natural saturation results in disk field strengths that are comparable with thermal pressure—hence \(\beta_i \approx 1\) is also the natural setting for this parameter. We found that simulations with very high values of \(\beta_i\) produced only very low velocity jets that do not match the observational data.

Previous efforts have been made to match the \(HST\) observations using stationary, two-dimensional MHD, self-similar disk wind models as a theoretical framework (Dougados et al. 2004; Garcia et al. 2001). This approach does not self-consistently compute wind heating as a consequence of shock dynamics, but assumes it occurs by ambipolar diffusion in stationary flows. Such models have been shown to reproduce the collimation scales of jets if an underlying “warm” solution is adopted (Dougados et al. 2004). There is no direct correspondence between our simulations and parameters with those of the self-similar models. We note, however, that the preference for warm solutions—i.e., ones which require a disk corona as opposed to a completely cold start for the MHD disk wind—connects well with our own simulations which have always proposed that disk coronae exist at the base of disk winds (Ouyed et al. 1997; Ouyed & Pudritz 1999; Ouyed et al. 2003). A second point of contact is the stated importance of the mass ejection index in the Dougados et al. (2004) work—which is somewhat related to our mass-loading parameter. Self-similar models, though important guides, are by construction highly restricted and cannot explore the range of three-dimensional, time-dependent solutions that are required to understand jet dynamics.

We conclude that our simulations reproduce many of the observed properties of jets as deduced from their optical emission lines. An important result is that the strong signature of jet rotation observed in our models persists despite rapid
time variability and the operation of a saturated instability—the jet wobble. These features do not wash out the overall sense of rotation that a jet inherits from its source—the Keplerian accretion disk. Internal structure in the OP model does produce variations in the radial velocity gradients, but overall the interpretation that jets are rotating is well supported by the observations we make of our simulated jets. Indeed, it is these various instabilities and shocks that make jet emission possible in the first place.

Two exciting consequences of our work are that jet rotation is not washed out by time-dependent jet evolution, and that our prediction of magnetic field structure on disks could be tested by future Atacama Large Millimeter Array observations. Our results open up many fascinating new and testable questions about the nature of jets from disks. Why are such slowly varying disk fields preferred? Do all jets in protostellar systems have similar magnetic rotors—or does magnetic field structure in disks evolve with them? Answers to these questions will provide deep insights into the nature of disks and the outflows that they drive.

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