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PRECESSION OF COLLIMATED OUTFLOWS FROM YOUNG STELLAR OBJECTS

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ABSTRACT

We consider several protostellar systems where either a precessing jet or at least two misaligned jets have been observed. We assume that the precession of jets is caused by tidal interactions in noncoplanar binary systems. For Cep E, V1331 Cyg and RNO 15–FIR the inferred orbital separations and disk radii are in the range 4–160 AU and 1–80 AU, respectively, consistent with those expected for pre–main sequence stars. Furthermore, we assume or use the fact that the source of misaligned outflows is a binary, and evaluate the lengthscale over which the jets should precess as a result of tidal interactions. For T Tau, HH1 VLA 1/2 and HH 24 SVS63, it may be possible to detect a bending of the jets rather than 'wiggling'. In HH 111 IRS and L1551 IRS5, 'wiggling' may be detected on the current observed scale. Our results are consistent with the existence of noncoplanar binary systems in which tidal interactions induce jets to precess.

Subject headings: accretion, accretion disks – binaries: general – stars: pre-main sequence – ISM: jets and outflows

1. INTRODUCTION

Most T Tauri stars are observed to be in multiple systems (Mathieu 1994). There is also indirect evidence that the sizes of circumstellar disks contained within binary systems are correlated with the binary separation (Osterloh & Beckwith 1995, Jensen, Mathieu & Fuller 1996). This suggests that binary companions are responsible for limiting the sizes of the discs through tidal truncation (Papaloizou & Pringle 1977, Paczyński 1977). There are indications that, in binaries, the plane of at least one of the circumstellar discs and that of the orbit may not necessarily be aligned. The most striking evidence for such noncoplanarity is given by HST and adaptive optics images of HK Tau (Stapelfeldt et al. 1998, Koresko 1998). Also, observations of molecular outflows in star forming regions commonly show several jets of different orientations emanating from an unresolved region the extent of which can be as small as $\sim$ 100 AU (Davis, Mundt & Eislöffel 1994). These jets are usually believed to originate from a binary in which circumstellar disks are misaligned, and in some of these systems a binary has indeed been resolved. In such cases, we expect tidal interaction to induce the precession of the disk (possibly both disks) which is not in the orbital plane, and thus of any jet it drives. Furthermore, a number of jets seem to be precessing (see below). The above discussion leads us to interpret this precessional motion as being driven by tidal interactions between the disk from which the jet originates and a companion on an inclined orbit.

In this *Letter* we consider several observed systems in the light of this model. In § 2 we review the theory of precessing warped disks. In § 3 we apply it to observed systems. We first consider cases where a precessing jet has been observed and calculate the parameters of the binaries in which tidal interactions would produce the observationally inferred precession frequencies. We next study cases where misaligned jets have been observed and, assuming or using the fact that the source of these outflows is a binary, we calculate the precession frequency that would be induced by tidal interactions in the binary and the lengthscale over which the jets should 'wiggle' or bend as a result of this precessional motion. In § 4 we give a summary and discussion of our results.

2. THEORY OF PRECESSING WARPED DISKS

We consider a binary system in which the primary and the secondary have a mass M_p and M_s, respectively. We suppose that the primary is surrounded by a disk of radius R with negligible mass so that precession of the orbital plane can be neglected. The binary orbit is assumed circular with radius D and is in a plane with inclination angle δ to the plane of this disk. In general, δ will be evolving with time. However, this evolution, *which is not necessarily toward coplanarity*, occurs on a long timescale (equal or larger than the disk viscous timescale) if the warp is not too severe (Papaloizou & Terquem 1995), so that we will consider here δ as a constant. This means that although the outer parts of the disk may be driven out of the initial disk plane on a relatively short timescale, the inner parts will retain their orientation with respect to the orbital plane for a timescale comparable to the disk viscous timescale. Since jets are expected to originate from the disk inner parts, their orientation relative to the orbital plane will be determined by that of the disk inner regions.

The secular perturbation caused by the companion leads to the precession of the disk about the orbital axis, as in

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a gyroscope. *The disk is expected to precess as a rigid body* if it can communicate with itself through some physical process on a timescale less than the precession period. In non–self gravitating protostellar disks, communication is governed by bending waves (Papaloizou & Lin 1995, Larwood et al. 1996, Terquem 1998). The condition for rigid body precession is then satisfied if $H/r > |\omega_p| / \Omega_0$, where ω_p is the (uniform) precession frequency in the disk and Ω_0 is the angular velocity at the disk outer edge (Papaloizou & Terquem 1995). An expression for ω_p has been derived by Papaloizou & Terquem (1995). Here we just give an approximate expression, that we derive by assuming that the disk surface density is uniform and that the rotation is Keplerian:

$$\omega_p = -\frac{15}{32} \frac{M_s}{M_p} \left(\frac{R}{D} \right)^3 \cos\delta \sqrt{\frac{GM_p}{R^3}}, \quad (1)$$

where G is the gravitational constant. The assumptions under which this expression is valid (see Terquem 1998 for a summary) are usually satisfied in the case of the relatively wide binaries we will be discussing here and for the values of D/R we will be considering. Although we have assumed a circular orbit, an eccentric binary orbit can be considered by replacing D by the semi-major axis and multiplying the precession frequency by $(1-e^2)^{-3/2}$, where e is the eccentricity. On this basis we consider that the discussion presented below should remain valid for $0 < e < 1/2$.

3. APPLICATION TO PARTICULAR SYSTEMS

3.1. *Expected parameters of binary systems with precessing jets*

Observations of molecular outflows in star forming regions show in some cases "wiggling" knots (or a helical pattern in projection onto the plane of the sky), which can be interpreted as being the result of the precession of the outflowing jet. In this section we will assume that such precession is caused by tidal interaction between the disk from which the outflow originates and a companion star in a noncoplanar orbit. In cases where the outflow has lasted many precession periods the implication is that the "wiggling" should be periodic. If we indeed assume that this is the case, the observations give the projected wavelength λ_{proj}. When the angle i between the outflow and the line of sight can be estimated, the actual wavelength $\lambda = \lambda_{proj}/\sin i$ can be derived. The precession period is then given by $T = \lambda/v$, where v is the outflow velocity, and $|\omega_p| = 2\pi/T$. Furthermore, if the outflow is precessing because the disk plane and that of the orbit are misaligned, the angle δ between these two planes is equal to the angle between the central flow axis and the line of maximum deviation of the flow from this axis. This angle can also be observed. In all the cases studied in this section, δ is small enough ($\sim 10 - 20^\circ$) so that we will consider $\cos\delta = 1$.

In this section we will adopt $M_p = 0.5\ M_\odot$. Since we do not know whether the jet which is observed to precess originates from the primary or the secondary, we will consider mass ratios M_s/M_p between 0.5 and 2. The lowest (largest) values would correspond to the case where the jet originates from the primary (secondary). These values are typical for pre–main sequence binaries. Finally, the disk from which the outflow originates is expected to have its size truncated by tidal interaction with the companion star in such a way that D/R lies between 2 and 4. Since Larwood et al. (1996) have shown that tidal truncation is only marginally affected by lack of coplanarity, in this section we will consider $2 \leq D/R \leq 4$. Assuming a fixed ratio R/D, equation (1) can then be used to calculate the disk radius:

$$R = \left(\frac{15}{32} \frac{M_s}{M_p} \cos\delta \frac{\sqrt{GM_p}}{|\omega_p|} \right)^{2/3} \left(\frac{R}{D} \right)^2. \quad (2)$$

Since M_p appears with the power 1/3, an uncertainty of a factor 2 over M_p is equivalent to an uncertainty of only a factor 1.26 over R. The main uncertainty over R comes through the ratio R/D. We now consider some particular protostellar systems in the light of the above discussion.

Cep E, at a distance of 730 pc, drives two outflows almost perpendicular to each other Eislöffel et al. (1996), which suggests that this source is a binary. In addition, they have interpreted the morphology of one of these jets as due to precession, and they have inferred $T = 400$ years. Figure 1.a shows a plot of D against R, as calculated from equation (2). We see that R lies in the range $1 - 10$ AU while D lies in the range $4 - 20$ AU. Binary separation would be 0."005 to 0."03, which is not currently resolvable.

V1331 Cyg is located at a distance of 550 pc. Visible line emission shows a very faint and diffuse feature in the vicinity of this object, which appears to be a strongly 'wiggling' jet (Mundt & Eislöffel 1998). The observations give $\lambda_{proj} \simeq 0.5$ pc (a full period is observed). Using $i \sim 42^\circ$ (Mundt & Eislöffel 1998), we derive $\lambda = 0.71$ pc. Since $v \sim 300$ km s^{-1} (Mundt & Eislöffel 1998), we get $T = 2,300$ years. Figure 1.b shows a plot of D against R, as calculated from equation (2). We see that R lies in the range $3 - 33$ AU while D lies in the range $13 - 66$ AU. Binary separation would be 0."02 to 0."1. This upper value may be possible to resolve with the VLA or adaptive optics in the near–infrared.

RNO 15–FIR, located at a distance of 350 pc, drives a molecular outflow which appears to be 'wiggling' (Davis et al. 1997). It is possible to interpret this morphology as due to precession within the uncertainty of the measurement (see Fig. 7 of Davis et al. 1997). From the observations, we derive $\lambda_{proj} = 0.065$ pc. Assuming $i = 45^\circ$ (Cabrit 1989) and $v = 10$ km s^{-1} (Davis et al. 1997), we get $\lambda = 0.092$ pc and $T = 9,000$ years. Figure 1.c shows a plot of D against R, as calculated from equation (2). We see that R lies in the range $8 - 82$ AU while D lies in the range $33 - 165$ AU. Binary separation would be 0."09 to 0."47. Such a separation may be possible to resolve with the VLA or adaptive optics in the near-infrared.

3.2. *Expected precession in binary systems with nonaligned jets*

In the systems presented in this section, misaligned "binary" jets have been observed. Since it is very unlikely that one single source can drive two jets with very different orientations, it is assumed that each of the outflows originates from its own component of a binary system. In some cases a binary has actually been resolved, in other cases observations only allow us to put an upper limit on the separation of the hypothetical binary. Since the outflows are not parallel, it is probable that the disks which surround these sources are themselves misaligned. Therefore, at least one of these disks is not in the orbital plane and should precess. We evaluate here the precession period T and give an estimate of the lengthscale $\lambda = v/T$ over which the outflows should 'wiggle' as a result of this precessional motion. Since in general we do not know from which member of the binary each jet originates, we will here again consider mass ratios $0.5 \leq M_s/M_p \leq 2$, unless otherwise specified. We will also take $M_p = 0.5$ $M_\odot$ unless otherwise specified, and $\cos\delta = 1$ (the results can be scaled for different values of δ since $\omega_p \propto \cos\delta$).

T Tau is a binary located in Taurus, at a distance of 140 pc. Observations show that two almost perpendicular jets originate from this system (Böhm & Solf 1994). A disk of estimated radius $R \sim$ 27–67 AU has been resolved around the visible component, T Tau N (Akeson, Koerner & Jensen 1998). Here we assume that the disk around T Tau N is not in the orbital plane. We take $D = 102$ AU (Ghez et al. 1991) and for R the observational values reported above. We fix $M_p = 0.7$ $M_\odot$. Since we are interested in the precession of the jet emanating from the primary, we consider $0.5 \leq M_s/M_p \leq 1$. We then get $T \sim 5,000$–4×10^4 years. Since $v = 70$ km s^{-1} for the jet emanating from T Tau N (Eislöffel & Mundt 1998), $\lambda \sim$ 0.4–3 pc for this jet. These values of λ are larger than the scale over which the jet has been observed so far (which about 0.1 pc), so that a bending rather than 'wiggling' may be detectable in that case.

HH1 VLA 1/2 is located at a distance of 480 pc. The two sources VLA 1 and 2, separated by 1,400 AU, drive the two misaligned jets HH 1–2 and HH 144, respectively (Reipurth et al. 1993). We assume that this system is bound and noncoplanar, and that tidal truncation has operated such that $2 \leq D/R \leq 4$ (note however that, in such a young and wide system, D/R may actually be significantly larger). We also assume that the angle between the line of sight and the orbital plane is 45°, so that $D \simeq 1,980$ AU. Then $T \sim 4 \times 10^5$–4×10^6 years. Since $v \sim 200$ km s^{-1} for both flows (Eislöffel, Mundt & Böhm 1994), we get $\lambda \sim$ 77–870 pc. Since T is probably comparable to the age of the system, a bending rather than wiggling of the jet may be expected on a scale of a few pc. We note that 'wiggling' or bending of the jets has been suggested on the current observed scale, which is about 0.5 pc for both jets (Reipurth et al. 1993). This clearly cannot be due to interaction between VLA 1 and 2, but it may be the sign that this system contains more sources. This is supported by the existence of at least two more outflows with different orientations (Eislöffel et al. 1994).

HH 111 IRS: Perpendicular to the HH 111 jet, located at a distance of 480 pc in Orion, is another outflow called HH 121 (Gredel & Reipurth 1993; Davis et al. 1994). We assume that the source of these two outflows is a binary. From the unresolved central source in VLA observations (Rodríguez 1997) we infer an upper limit on the separation D of about 0."1, or 48 AU. By adopting $D = 48$ AU and $2 \leq D/R \leq 4$, we find that $T \sim 1,000$–$8,000$ years. Since $v \sim 350$ km s^{-1} for HH 111 (Reipurth, Raga & Heathcote 1992), $\lambda \sim$ 0.5– 6 pc for this jet. The lowest of these values is close to the extent over which the jet has been observed so far, which is 0.45 pc in projection (Reipurth 1989). We note that tidal effects in a putative binary system have been invoked by Gredel & Reipurth (1993) as a possible cause of the asymmetry of HH 121.

HH 24 SVS63: The region of HH 24, located in Orion at a distance of 480 pc, contains several highly collimated outflows (Eislöffel & Mundt 1997) and a hierarchical system of four or even five young stars. The sources SSV 63E and SSV 63W are separated by about 4,500 AU in projection onto the sky (Davis et al. 1997). SSV 63W is itself a binary. On the images taken by Davis et al. (1997) and given to us, we have measured that its projected separation is 920 AU. We find that SSV 63E is probably a triple system: the projected separation is 350 AU between SSV 63E A and B and 975 AU between SSV 63E A and C. We will take these projected separations as indicative values of the actual separations. At least two outflows with very different orientations originate from SSV 63E. These are HH 24 G (Mundt, Ray & Raga 1991) and HH 24 C/E (Solf 1987; Eislöffel & Mundt 1997) , which extend over 0.2 and about 1 pc, respectively. SSV 63W is the source of another parsec–scale outflow, HH 24 J (Eislöffel & Mundt 1997). Here again we fix $2 \leq D/R \leq 4$. The velocities of the jets, in km s^{-1}, are about 140, 180 (if we assume the radial and tangential velocities to be similar), 370 and 50 for HH 24 J, HH 24 G, HH 24 C/E and for the redshifted lobe HH 24 E, respectively (Jones et al. 1987). The different interactions within the two systems then lead to λ between 5 and 556 pc, which is at least one order of magnitude larger than the extent over which the jets have been observed so far. This indicates that a bending rather than a 'wiggling' would be more likely to be observed.

L1551 IRS5 is located in Taurus, at a distance of 150 pc. It has been suggested that two jets could be emanating from this source (Moriarty–Schieven & Wannier 1991, Pound & Bally 1991). Furthermore, Rodríguez et al. (1998) have shown that this system is a binary with separation 45 AU and they have resolved two circumstellar discs for which they infer $R \sim 10$ AU. Their results are also consistent with the presence of two outflows which appear to be misaligned (see their Fig. 2). We take D between 45 and 63 AU, corresponding to an angle between the orbital plane and the line of sight in the range 0–45°, and we fix $R = 10$ AU. Then $T \sim 4,000$–5×10^4 years. Since for the jet which has been unambiguously observed $v \sim 200$ km s^{-1} (Sarcander, Neckel & Elsässer 1985), we derive $\lambda \sim$ 1–10 pc. The projected extent over which the jet has been observed so far is about 1 pc (Moriarty–Schieven & Snell 1988). Therefore, even though a full period may not yet be seen, 'wiggling' could already appear in the observations. We note that the outflow as observed appears to be very complex, and it may well be seen to precess.

4. DISCUSSION AND SUMMARY

In this *Letter* we have considered several protostellar systems where either a precessing jet or at least two misaligned jets have been observed. In the case where a jet is seen to precess (or rather interpreted as precessing), we have assumed it originates from a disk which is tidally perturbed by a companion on an inclined orbit, and we have evaluated the parameters of the binary system. For Cep E, V1331 Cyg and RNO 15–FIR, we found the separation to range from a few AU up to 160 AU and the disk size to be between 1 and 80 AU. These numbers correspond to what is expected in pre–main sequence binaries (see Mathieu 1994 and references therein). We note that larger separations for this range of disk sizes would be associated with longer precession timescales, and thus it would be more difficult to detect the precessional motion over the observed lengthscale of the jet. A bending rather than 'wiggling' would be expected in that case.

In the case where misaligned jets have been observed, we have assumed or used the fact that the source of these outflows is a binary, and we have calculated the precession frequency that would be induced by tidal interactions in the binary and the lengthscale over which the jets should 'wiggle' as a result of this precessional motion. For T Tau, HH1 VLA 1/2 (which may actually be a hierarchical system) and HH 24 SVS63, it may be possible to detect a bending of the jets rather than 'wiggling' on the current observed scale of the jets. In HH 111 IRS and L1551 IRS5 (assuming there are indeed two misaligned outflows in this system), 'wiggling' may be detected on the projected scale (0.5–1 pc) over which the jets have been observed.

Our results are consistent with the existence of non-coplanar binary systems in which tidal interactions induce jets to precess. Some of the predictions of this *Letter* could be tested observationally in a near future.

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