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Possible bending mechanisms of protostellar jets

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Abstract. Observations of several bipolar jet flows from young stellar objects reveal a slight difference in the apparent direction of propagation for jet and counter jet.

In this paper, possible mechanisms leading to such a jet deflection are investigated. We discuss various effects, such as the motion of the jet source within a binary system, gravitational pull due to an asymmetric external mass distribution, dynamical pressure of the external medium, inertial effects due to proper motion of the jet source, an inclined interstellar magnetic field, and the coupling between a magnetic jet and an external magnetic field.

We find that for typical protostellar jet parameters the most likely mechanisms leading to a bent jet structure are *Lorentz forces* on the magnetic jet and/or motion of the jet source in a *binary system*. *Dynamical pressure* of a dense external medium or a stellar wind from a companion star cannot be excluded as source of jet bending.

Key words: MHD – ISM: jets and outflows – galaxies: jets – stars: magnetic field – stars: mass loss – stars: pre-main sequence

1. Protostellar jets with counter jets

There is now quite a number of cases for protostellar jets/counter jets, where the observed direction of propagation for jet and counter jet is not exactly $180°$.

Zinnecker et al. (1996, 1997) find that in the otherwise perfectly collimated, symmetric jet/counter jet system HH 212 the direction of propagation for jet and counter jet deviates by an angle of about $2°$ from $180°$. In the case of HH 111, Gredel & Reipurth (1993) find a difference of $1°$between the two lobes; however, the other bipolar jet originating in the same source region, HH 121, shows a rather large angle difference between its lobes of $15°$- $20°$. Another case is HH 24, where the flow directions are misaligned by 6°for jet and counter jet (Mundt et al. 1991).

In addition, many of the observed jets do not propagate in a straight motion, but form a curved or bent jet structure. Eislöffel & Mundt (1997) observed Herbig-Haro flows on a parsec-scale, and report changes in the flow direction (up to $\sim 10°$). They point out possible mechanisms for such changes, in particular precession and Lorentz forces. Mundt et al. (1990) observed several cases, i.e. the HH 30 jet and the HL Tau jet/counter jet, where they derived curvature radii from 0.6 to $3\,10^{18}\,\mathrm{cm}$. They were first to point out that the jet transverse displacement from a straight motion of a protostellar jet may be due to Lorentz forces. There are several examples known, where the jet/counter and jet form an S-shape structure (Eislöffel & Mundt 1997).

For HH 30 López et al. (1995) derive a P.A. for the jet propagation of 30°and 217°for the outer jet and counter jet, respectively. They point out a 'mirror symmetry' of jet and counter jet, ruling out Lorentz forces as the driving force of the jet deflection, unless a complex structure of the ambient magnetic field is supposed (see below).

Bent jets are observed also for extragalactic jet sources. Eilek et al. (1984) investigated several bending models for 3C 465, which exhibits a drastic bending of about 30°-50°despite being a very well collimated jet/counter jet system initially. They conclude that either Lorentz forces or interaction with cool clouds may account for the bending.

In this paper we compare and discuss several physical mechanisms possibly responsible for a change of propagation direction for protostellar jets. Their effectiveness is estimated for typical protostellar jet parameters.

2. Formation and propagation of magnetic jets

We briefly outline the general aspects and conditions of protostellar jet formation. It is now almost accepted that protostellar jets are *magnetically* driven jets (Pudritz & Norman 1986; Camenzind 1990, 1997; Shu et al. 1994). Recently, these theoretical ideas received direct support by radio observations, which, for the first time, detected large-scale magnetic fields in the outflow from a young stellar object (Ray et al. 1997).

Following current jet models the jet originates in the innermost part of a magnetized star-disk system (Camenzind 1990; Shu et al. 1994; Fendt et al. 1995; Fendt & Camenzind 1996). Whether the jet field is basically anchored in the accretion disk or in the stellar surface, is, however, not yet clear.

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The principal mechanisms of jet formation can be summarized as follows. The underlying hypothesis is that jets can only be formed in a system with a *high degree of axi-symmetry*.

- *Magnetic field* is generated by the star-disk system.
- The star-disk system also drives an *electric current*.
- Accreting *matter* is ejected as a plasma wind (either from the stellar or disk surface) and couples to the magnetic field.
- The plasma becomes *accelerated magnetically*, i.e. by conversion of Poynting flux to kinetic energy.
- Plasma inertia leads to bending of the poloidal field (i.e. the field along the meridional plane including the jet axis). The pinching forces of the generated toroidal component (i.e. the field component winding around the jet axis) eventually collimate the wind flow, forming a collimated jet structure.
- The plasma velocity subsequently exceeds the speed of the magnetosonic waves. In the fast magnetosonic regime the flow is causally decoupled from outer boundary conditions.
- Where the jet front meets the interstellar medium (ISM), a *bow shock* develops, thermalizing the jet energy. Also, the electric current is closed via the bow shock, and the jet net current returns to the source of the current via the ISM.

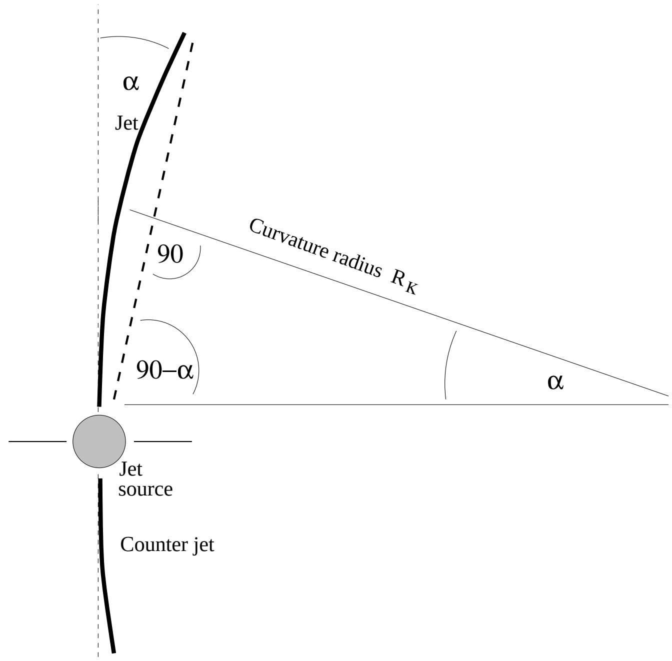

Fig. 1. Model geometry in a deflected jet/counter jet system (solid line) with an angle of deflection α. The corresponding curvature radius is R_κ. The direction of deflected jet propagation is approximated by the chord (thick dashed line). The jet source is represented as a star-disk-system.

3. Possible mechanisms leading to a jet deflection

A general point concerning the deflection of a jet from its original path of motion is that it can only be caused by some *acceleration/deceleration* mechanism. It cannot be caused by e.g. a steady, proper motion of the jet together with the jet source, since in this case the jet will have the same tangential velocity as its source. Thus, *forces* must be involved, either acting on the jet itself or on the jet source.

In the following we basically suppose the general model of jet formation outlined in Sect. 2. The jets are ejected as straight axisymmetric magnetosonic flows. The possible mechanisms leading to a change in the direction of jet propagation could be generally classified in three groups:

- *Internal effects* on small scales such as acceleration of the jet source (by e.g. a binary component), or precession of an accretion disk in a binary system.
- *Mixed effects* such as the interaction between intrinsic and external properties, such as a Lorentz force due to a jet net current and an external magnetic field.
- *External effects* on large scales such as a gravitational potential of a source outside the star-jet structure or a pressure /magnetic field of the ambient medium.

In general, we assume that the jet/counter jet with a length scale $L_{\rm jet}$ follows a *curved* trajectory with the corresponding curvature radius R_κ. This assumption is consistent with the observations, although a straight jet trajectory in the case of a small angle of deflection can not be excluded. Usually, the deflection angle α is small and of the order of some degrees, $\alpha \simeq \tan(\alpha) = 0.5\, L_{\rm jet}/R_\kappa$, (see Fig. 1).

3.1. Binary (multiple) system

Could an orbital motion of the jet source in a binary system account for the jet deflection? Binary systems are very common among main-sequence stars, and there is evidence that the binary frequency among protostars and PMS stars is at least as high as among main-sequence stars (see Mathieu 1994; Zinnecker & Brandner 1997).

To date, there are only few examples known of a jet source being member of a multiple systems. Among them is T Tau (Herbst et al. 1996) and RW Aur (Hirth et al. 1997). However, the separation of the components in T Tau and RW Aur is rather large. In turn, this may be the reason why jet motion occurs at all, since the formation of a jet requires a system with a high degree of axisymmetry, which would be disturbed by a close companion.

Here we assume a scenario of a young stellar binary system with one component emitting jets (see Fig. 2). The jet source moves a distance Δx while ejecting a series of different portions of the jet. The observed jet appears deflected, as the velocity components of the jet are different for different times t_1 and t_2.

We estimate a kinematic time scale $\tau_{\rm kin} \simeq 100\,{\rm yrs}$ for an observed jet length $L_{\rm jet} \simeq 10^{17}{\rm cm}$ and for a typical jet speed of $300\,{\rm km\,s^{-1}}$. This time scale might be larger, if the jet axis is inclined against the orbital axis.

In the case of a small ratio $\Delta x/L_{\rm jet}$, we define α as the angle between a straight jet propagation and the observed orientation, which for analytical reasons is approximated as straight line, $\sin\alpha = \Delta x/L_{\rm jet}$. With the assumption that this motion is due to

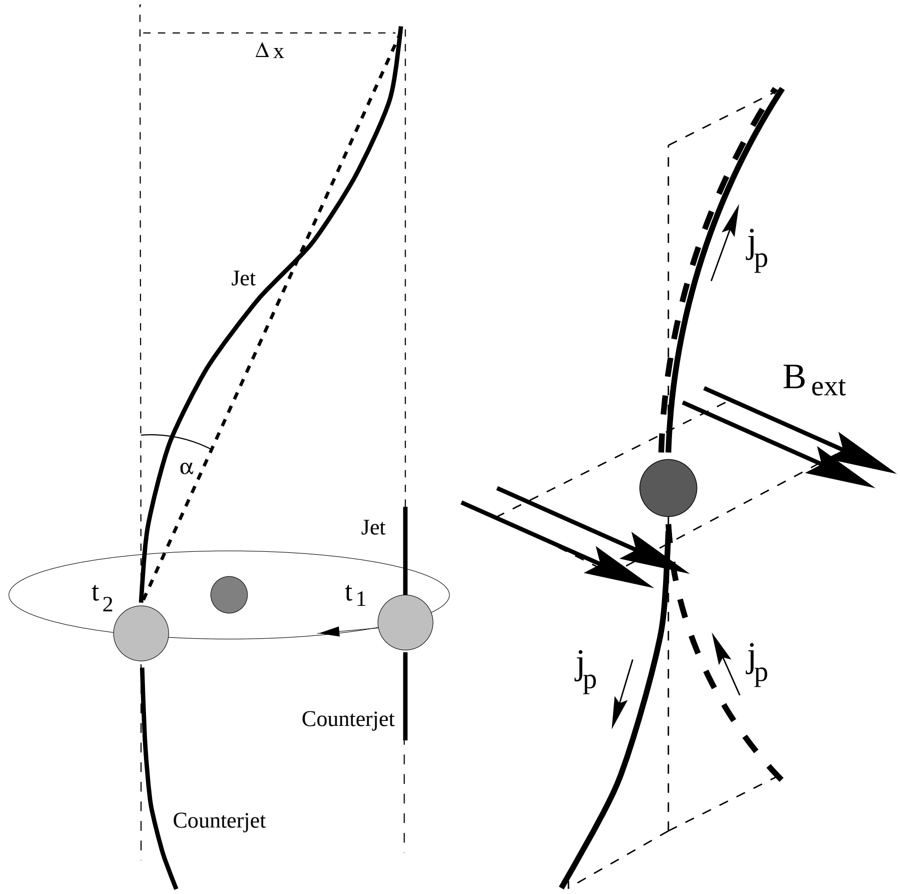

Fig. 2. Model geometries in deflected jet/counter jet systems. *Left:* Binary star - jet system. Shown is the jet source at different times t_1 and t_2. The observed jet is ejected between t_1 and t_2. The dynamical time of the jet motion is $\tau_{\rm dyn} = t_2 - t_1$. The angle of deflection α is approximated by a straight line (thick dashed line). *Right:* A poloidal current density $j_{\rm p}$ in the jet and an external magnetic field $B_{\rm ext}$ perpendicular to the jet axis give rise to Lorentz forces. The S-shape (solid line) and C-shape (dashed line) of the jet system depend on the direction of the current flow, as indicated.

acceleration by a companion star, the derived *minimum* binary separation is Δx. It might be larger because of two reasons. First, the binary system may not have completed half of its orbit. Second, the jet axis might be inclined against the orbital axis (different from Fig. 2).

In the case of HH 212 the angle of $\alpha = 2°$ corresponds to $\Delta x = 120\,{\rm AU}$, if we assume a length scale $L_{\rm jet} \simeq 10^{17}{\rm cm}$ for the inner jet as observed (i.e. the series of the inner jet knots). Δx is a lower limit for the binary separation with regard to a detection of a jet bending within the kinematic time scale. In turn, the binary separation gives the maximum value for Δx.

Thus, there are two constraints on the binary period with regard to a detection of a jet bending: (i) If the period is too large, the low orbital speed of the jet source, $v_\star$, leads to an angle of deflection $\alpha \simeq \tan\alpha \simeq (v_\star/v_{\rm jet})$ too small for a detection, within the kinematic timescale. (ii) Similarly, a small period, equivalent to a small binary separation D, the jet deflection is too small, since $\Delta x \lesssim D$.

For the example of HH 212 from Kepler's Third Law follows an orbital period of the binary system of $P \gtrsim 500\,{\rm yrs}$, assuming a total mass of the system $M_{\rm tot} = 1\,{\rm M}_\odot$ and a minimum binary separation of $D = 0.5 \cdot 120$ AU.

This period is several times larger than the jet propagation time scale for $10^{17}{\rm cm}$, in other words, the jet bending time scale is shorter than the period of the orbit of the jet source. Therefore, jet bending would be observable within the kinematic time scale. (Note that, on the other hand, this implies that the formation the jets is just a short event along the path of the binary).

From the constraints (i) and (ii) it can be derived that the condition for an observation of the bending is $P \gtrsim \pi\tau_{\rm kin}$. The upper limit for P is given by the observational resolution for Δx. The ratio

$$\frac{P}{\tau_{\rm kin}} \gtrsim 25 \left(\frac{L_{\rm jet}}{10^{17}{\rm cm}}\right)^{\frac{1}{2}} \left(\frac{\sin\alpha}{\sin 2°}\right)^{\frac{3}{2}} \left(\frac{v_{\rm jet}}{300{\rm km\,s^{-1}}}\right) \left(\frac{M_{\rm tot}}{{\rm M}_\odot}\right)^{-\frac{1}{2}} \quad (1)$$

does not strongly depend on the jet length and the total mass of the system.

The most likely main-sequence binary separation in the solar neighborhood is about $a \simeq 30\,{\rm AU}$ (Duquennoy & Mayor 1991). For pre-main-sequence binaries the semi-major axis follows roughly a $1/a$ distribution between 120 AU and 1800 AU (Reipurth & Zinnecker 1993; Köhler & Leinert 1997). These values are in agreement with the Δx estimated above for HH 212 as a requirement for a minimum binary separation in order to influence the shape of the jet.

Note that, although the binarity of the young stellar system breaks the axisymmetry on the large scale, the jet source itself must provide an axisymmetric geometry in order to produce a jet in the first place. The scenario of a 'stellar' jet formation might be preferred in close binary systems compared to a 'disk' jet formation. This is because tidal interaction between disk and companion star may disturb the axisymmetry needed for jet formation and thus prohibit the jet formation.

Jet wiggling is observed for a number of protostellar jets. Examples are HH 30 (Burrows et al. 1996) and HH 83 (Reipurth 1989). It is, however, not yet clear whether this type of motion is due to precession or other effects. One should keep in mind that HH 30 is a very elongated, and thus presumably very stable jet structure, with a full length of about $2'$(Mundt et al. 1990) or even $5'$(López et al. 1995). For HH 83, Reipurth (1989) give a physical amplitude of the wiggling helical motion of 400 AU. This length scale would be identical to the binary separation, if we suppose that the wiggling arises not from tidal interaction, but from kinematic motion of the jet source in a binary system.

Evidence for tidal interaction and a precessing jet is found in the case of the famous SS 433 system (Margon & Anderson 1989). The precession amplitude is 5° with a period of 160 days. This jet is, however, relativistic and presumably highly magnetized, which is in difference to protostellar jets.

3.2. Gravitational/inertial effects

Could an external gravitational potential due to a mass asymmetry in the ISM account for a deflection of the jet? From comparison of gravitational to centrifugal forces on the jet,

$$G\frac{\rho_{\rm jet}\Delta M_{\rm ext}}{R_\kappa^2} = \frac{\rho_{\rm jet} v_{\rm jet}^2}{R_\kappa} \tag{2}$$

where $\Delta M_{\rm ext}$ is the external mass asymmetry (corresponding to an external attractor with mass $\Delta M_{\rm ext}$ at a distance R_κ), one calculates a deflection angle for typical jet parameters,

$$\begin{aligned}\alpha \;\simeq\; \tan(\alpha) &= \frac{L_{\rm jet}\, v_{\rm jet}^2}{2\,G\,\Delta M_{\rm ext}} = \\ &= 0.03\left(\frac{L_{\rm jet}}{10^{17}\,{\rm cm}}\right)\left(\frac{v_{\rm jet}}{300\,{\rm km\,s^{-1}}}\right)^2\left(\frac{\Delta M_{\rm ext}}{10^7\,{\rm M_\odot}}\right)^{-1}\end{aligned} \tag{3}$$

Thus, the deflection of the jet by a gravitational potential requires an unreasonably high mass asymmetry in the ISM. Therefore, these large scale gravitational/inertial effects can hardly account for the observed jet deflection.

Another possibility is that the star, or rather the jet source, becomes accelerated itself, while the jet remains in a steady motion. Since a large scale external gravitational potential attracts both star and jet, only internal, i.e. small scale, potential differences may account for a specific acceleration of the star. The most reasonable source for such a potential would be a binary companion (see Sect. 3.1)

3.3. Dynamical pressure of external medium

Suppose that the star-disk-jet system as a whole performs a steady motion. If it then penetrates a large cloud in the ISM, the ‘light’ jet flow will be deflected due to the dynamical pressure of the cloud, while the ‘heavy’ star will continue on its path. (Note that this scenario is different from that of a jet source at rest, where the jet bores a funnel through the ISM.)

For a system tangential velocity $v_\star$ and an external medium of constant density $n_{\rm ism}$, the stationary dynamic pressure exerted by the ISM is $P_D = n_{\rm ism} v_\star^2$. The force density is ∇P_D. If we assume that P_D drops on length scales of some jet radii $R_{\rm jet}$, comparison of centrifugal force with dynamical pressure force gives

$$\frac{n_{\rm jet} v_{\rm jet}^2}{R_\kappa} = \frac{n_{\rm ism} v_\star^2}{R_{\rm jet}}. \tag{4}$$

If we again define $\alpha \simeq \tan(\alpha) = 0.5\, L_{\rm jet}/R_\kappa$ as the angle of deflection, we find

$$\begin{aligned}\alpha \;\simeq\; \tan(\alpha) &= \frac{1}{2}\frac{L_{\rm jet}}{R_{\rm jet}}\frac{n_{\rm ism}}{n_{\rm jet}}\left(\frac{v_\star}{v_{\rm jet}}\right)^2 = \\ &= 10^{-3}\left(\frac{L_{\rm jet}/R_{\rm jet}}{20}\right)\left(\frac{n_{\rm ism}/n_{\rm jet}}{1}\right)\left(\frac{v_\star/v_{\rm jet}}{0.01}\right)^2.\end{aligned} \tag{5}$$

This value for α is below the observed angles. The maximum deflection angle is observed if we look perpendicular to the motion of the star (but depends on the inclination of the jet axis). The observed deflection angle becomes larger if the jet axis is inclined.

The energy density involved in this stationary process is $m_p n_{\rm ism} v_\star^2$, being released in heating the jet and the ambient medium. The resulting jet luminosity due to this ‘braking’ process is of the order of

$$\begin{aligned}L_{\rm rad} &\simeq 2 m_p n_{\rm ism} v_\star^3 L_{\rm jet} R_{\rm jet} = \\ &= 8\,10^{-8} L_\odot \left(\frac{n_{\rm ism}}{10^3{\rm cm^{-3}}}\right)\left(\frac{R_{\rm jet}}{10^{15}{\rm cm}}\right)\left(\frac{L_{\rm jet}}{10^{17}{\rm cm}}\right)\left(\frac{v_\star}{\rm km\,s^{-1}}\right)^3.\end{aligned} \tag{6}$$

In terms of the jet kinematic luminosity we calculate

$$\frac{L_{\rm rad}}{L_{\rm kin}} \simeq \frac{n_{\rm ism}}{n_{\rm jet}}\frac{L_{\rm jet}}{R_{\rm jet}}\left(\frac{v_\star}{v_{\rm jet}}\right)^3 \simeq \frac{1}{2}\,\alpha\left(\frac{v_\star}{v_{\rm jet}}\right), \tag{7}$$

which is very small for typical protostellar jet parameters, and therefore hardly observable.

Dynamical pressure of an external medium might however be important if the jet is propagating under the influence of a *stellar wind* from young stars in its vicinity (Mundt, 1997, private communication). This scenario of the protostellar jet environment is likely, since star formation produces groups of young stars.

In order to estimate this effect we have to rewrite Eq. (5), with the wind density $n_{\rm ism} \rightarrow n_{\rm wind}$ and velocity of the wind $v_\star \rightarrow v_{\rm wind}$. With the estimates $v_{\rm wind} \simeq 0.1 v_{\rm jet}$ and the density contrast $n_{\rm wind}/n_{\rm jet} \simeq 0.1$ we find $\alpha \simeq 0.01$, which is of the order of the observed angles.

3.4. Inclined strong external magnetic field

Without a detailed consideration, we mention another possibility of deflection of jets from their propagation direction. That is by strong external (poloidal) magnetic fields inclined against the jet axis. In a simple picture, this field acts like a wall for the conducting jet plasma (ideal magnetohydrodynamics, frozen in magnetic field), and, depending on the field strength and on the inclination angle, the jet will tend to flow along this wall. Jet and counter jet are deflected in opposite direction, forming a S-shaped structure (see Fig. 2).

Currents are not considered here (but see Sect. 3.5). Estimation of the involved field and jet kinetic energy shows that a typical protostellar jet will clearly dominate the external field,

$$\frac{\rho_{\rm jet} v_{\rm jet}^2}{B_{\rm ext}^2/4\pi} = 4\,10^3 \left(\frac{n_{\rm jet}}{100{\rm cm}^{-3}}\right)\left(\frac{v_{\rm jet}}{100{\rm km\,s}^{-1}}\right)^2 \left(\frac{B_{\rm ext}}{10\,\mu{\rm G}}\right)^{-2}. \quad (8)$$

This process is therefore unlikely for protostellar jet deflection. The 'magnetic wall' consisting of the interstellar magnetic field of typical field strength is too soft in order to deflect the jet motion.

3.5. Lorentz forces

Here we estimate the Lorentz forces between the current carrying jets and an external (interstellar) magnetic field. A net poloidal current along the jet is necessary in order to achieve a high degree of collimation (Heyvaerts & Norman 1989).

Comparison of the centrifugal force due to the curved jet motion and the Lorentz force due to jet current and external magnetic field gives

$$\frac{1}{c}\boldsymbol{j}_{\rm P} \times \boldsymbol{B}_{\rm ext} = \frac{\rho_{\rm jet} v_{\rm jet}^2}{R_\kappa}, \quad (9)$$

where $\boldsymbol{j}_{\rm P}$ is the poloidal current density and $\boldsymbol{B}_{\rm ext}$ the poloidal component of the external magnetic field (see Fig. 2). Integrating over the jet diameter, only the *poloidal* external magnetic field component which is *perpendicular* to the jet axis, $B_{\rm ext}\sin\delta$, gives a net Lorentz force perpendicular to the jet axis (with the angle δ between the jet and the poloidal field). The toroidal part of the external field does not contribute to the bending of the jet as a whole, it rather pinches and collimates the jet structure itself. The jet magnetic field $\boldsymbol{B}_{\rm jet}$ is responsible for the internal jet structure, i.e. the collimation and acceleration of the jet, and cannot bend the jet.

In Eq. (9), it was assumed that the external field is *homogeneous* on a large scale, at least on the scale of the jet length. Otherwise the bending effect will vary along the jet axis.

In particular, it was assumed that the external field is present also *within* the jet, after all in Eq. (9) $\boldsymbol{j}_{\rm P}$ and $\boldsymbol{B}_{\rm ext}$ have to be measured at the same physical position. This is a critical point if we consider highly conductive jets, where the jet plasma, as it flows along the jet, may potentially sweep any external field out of the jet funnel. In this case the Lorentz force in Eq. (9) would vanish and the problem is similar to that of Sect. 3.4.

From Eq. (9), it is straightforward to find an expression for small deflection angles,

$$\alpha \simeq \tan(\alpha) = \frac{I_{\rm jet} B_{\rm ext}\sin\delta}{c} \frac{L_{\rm jet}}{2\pi m n_{\rm jet} R_{\rm jet}^2 v_{\rm jet}^2} \quad (10)$$

with the jet particle density $n_{\rm jet}$, the jet radius $R_{\rm jet}$, the jet velocity $v_{\rm jet}$, and the particle mass m (in the following $m \sim 10^{-24}$ g). With typical jet parameters (see Camenzind 1990; Fendt et al. 1995) we find

$$\alpha \simeq 0.018\sin\delta \left(\frac{I_{\rm jet}}{10^{11}\,{\rm A}}\right)\left(\frac{B_{\rm ext}}{10\,\mu{\rm G}}\right)\left(\frac{L_{\rm jet}}{10^{17}\,{\rm cm}}\right) \quad (11)$$
$$\left(\frac{R_{\rm jet}}{10^{15}\,{\rm cm}}\right)^{-2}\left(\frac{n_{\rm jet}}{100\,{\rm cm}^{-3}}\right)^{-1}\left(\frac{v_{\rm jet}}{300\,{\rm km\,s}^{-1}}\right)^{-2},$$

which is of the order of the observed values $(1-2^\circ)$,

We see from Eq. (10) that the deflection angle is rather sensitive to the jet parameters. The question arises, why only small deviations from the intrinsic direction of propagation have been observed? We suspect that a hypothetical larger deflection will just destroy the jet as such. Furthermore, it is not that plausible to change all the protostellar jet parameters in the brackets with a positive exponent in Eq. (11) by, say, an order of magnitude. Thus, Lorentz bending may change the direction of jet propagation only slightly.

However, considering the possibility of sweeping the external magnetic field out of the jet funnel (see above), the magnetic field in Eq. (11) may be strongly over-estimated concerning its strength *inside* the jet. In this case the deflection due to Lorentz forces would be much weaker. In turn, one may conclude that only jets with finite conductivity could be deflected.

The direction of the jet deflection is determined by the direction of the poloidal current, if we assume that the external field remains constant along the whole jet/counter jet structure (see Fig. 2). We expect an S-shape structure of the jets, if the poloidal current flows in opposite direction in the jet and counter jet. Similar shapes were observed (see discussion in Eislöffel & Mundt 1997). Alternatively, in a C-shaped jet/counter jet topology the poloidal current would flow in the same direction in both the jet and counter jet (see below). This scenario would be appropriate for e.g. the HH 212 jets, where jet and counter jet are deflected in the same (western) direction (Zinnecker et al. 1996).

In order to explain both types of jet bending, one may hypothesize that the physical parameters of the accretion disk play a role for the closure of the current system. In the case of the S-shaped topology the jet current system closes via the bow shock and the ISM to a *highly conductive* accretion disk (and possibly continues to the star), and the same holds for the counter-jet current. In the case of a C-shaped topology the jet current closes from the bow shock via the ISM to the counter jet, and does not penetrate the *weakly conductive* accretion disk. The difference in the disk conductivity could be caused by a different temperature, accretion rate, different composition of the disk material. These differences may develop at various stages during the lifetime of the accretion disk.

4. Conclusions

In this paper we have discussed several possible mechanisms providing a deflection of protostellar jets from their original direction of propagation.

Among these physical mechanisms, *gravitational* attraction of a mass external to the star-jet system, *inertial* effects of the jet source and jet in an ambient medium, and an *inclined magnetic field* are probably irrelevant for the observed jet deflection of several degrees.

Dynamical pressure of the ambient medium on the jet cannot be ruled out, but requires lower jet velocities and a higher density contrast between jet and ambient medium than observed.

We find two physical processes, which are possible reasons for jet deflection. These are (1) the action of Lorentz forces between the jet and interstellar magnetic field, and (2) orbital motion of the jet source in a binary (or multiple) system. Mechanism (1) requires a net electric current flow in the jet, a realistic possibility in the case of a highly collimated jet. The conductivity of the accretion disk might play a role concerning the closure of the current system and the shape of jet / counter jet systems (S-shape vs. C-shaped). However, depending on how the interstellar magnetic field is distributed *within* the jet, the magnitude of jet bending due to Lorentz forces remains uncertain. Mechanism (2) requires a certain interrelation between the kinematic parameters of the jet and binary components. Otherwise the bending is too small (for high jet speeds or large binary separation). For typical jet speeds of $300\,\mathrm{km\,s^{-1}}$ the binary separation must be of the order of $\simeq 100$AU in order to obtain a jet deflection angle of several degrees. This is, indeed, what is observed as a typical separation in pre-main sequence binaries.

Although all processes discussed above imply non-axisymmetry of the jet source - jet system on large scale, we emphasize that the jet formation itself always requires an intrinsically axisymmetric topology. A high degree of non-axisymmetry would disrupt the jet. This might be the reason why protostellar jets show only small deflection angles.

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