Disk-Magnetosphere Interaction and Outflows: Conical Winds and Axial Jets

M.M. Romanova, G.V. Ustyugova, A.V. Koldoba, & R.V.E. Lovelace

Abstract We investigate outflows from the disk-magnetosphere boundary of rotating magnetized stars in cases where the magnetic field of a star is bunched into an X-type configuration using axisymmetric and full 3D MHD simulations. Such configuration appears if viscosity in the disk is larger than diffusivity, or if the accretion rate in the disk is enhanced. Conical outflows flow from the inner edge of the disk to a narrow shell with an opening angle 30-45 degrees. Outflows carry 0.1-0.3 of the disk mass and part of the disk’s angular momentum outward. Conical outflows appear around stars of different periods, however in case of stars in the “propeller” regime, an additional - much faster component appears: an axial jet, where matter is accelerated up to very high velocities at small distances from the star by magnetic pressure force above the surface of the star. Exploratory 3D simulations show that conical outflows are symmetric about rotational axis of the disk even if magnetic dipole is significantly misaligned. Conical outflows and axial jets may appear in different types of young stars including Class I young stars, classical T Tauri stars, and EXors.
1 Introduction

Jets and winds are observed in young stars at different stages of their evolution from very young stars up to classical T Tauri stars (CTTSs) where smaller-scale jets and winds are observed (see review by Ray et al. 2007). A significant number of CTTS show signs of outflows in spectral lines, in particular in He I (Edwards et al. 2006; Kwan, Edwards, & Fischer 2007). High-resolution observations show that outflows often have an “onion-skin” structure, with high-velocity outflows in the axial region, and lower-velocity outflow at larger distance from the axis (Bacciotti et al. 2000). High angular resolution spectra of [FeII]λ 1.644μm emission line taken along the jets from DG Tau, HL Tau and RW Auriga revealed two components: a high-velocity well-collimated extended component with $v \sim 200 - 400$ km/s and a low-velocity $\sim 100$ km/s uncollimated component which is close to a star (Pyo et al. 2003, 2006). High-resolution observations of molecular hydrogen in HL Tau have shown that at small distances from the star the flow shows a conical structure with outflow velocity $50 - 80$ km/s (Takami et al. 2007).

Different models have been proposed to explain outflows from CTTSs (see review by Ferreira, Dougados, & Cabrit 2006), including models where the outflow originates from the inner regions of the accretion disk (e.g., Lovelace, Berk & Contopoulos 1991; Königl & Pudritz 2000; Ferreira et al. 2006), and the X-wind type models (Shu et al. 1994; 2007; Najita & Shu 1994; Cai et al. 2008) where most of the matter flows from the disk-magnetosphere boundary. In this work we consider only the second type of models. We developed conditions favorable for X-type outflows and performed axisymmetric and exploratory 3D MHD simulations for both slowly and rapidly rotating stars including stars in the propeller regime.

Fig. 1 Snapshots from axisymmetric simulations of conical winds. The background shows the matter flux with light color corresponding to higher flux. The lines are magnetic field lines.
Fig. 2 Typical flow in conical winds (at $t = 380$ days). The background shows matter flux, lines are selected field lines, arrows are proportional to velocity. The numbers show poloidal $v_p$ and total $v_{tot}$ velocities and number density at sample places of the simulation region.

Fig. 3 Two components of winds from slowly rotating star are labeled.

Fig. 4 Left panel: matter flux to the star $\dot{M}_{\text{star}}$ and to conical wind $\dot{M}_{\text{wind}}$ (calculated at the radius $R = 0.1 \text{ AU}$) as function of time. Right panel: same but for a shorter time-interval.
Fig. 5 Conical winds obtained in 3D MHD simulations for $\Theta = 30^\circ$. Left panel: density distribution and sample field lines in the $\mu\Omega$ - plane. Right panel: same but in the perpendicular plane.

2 Conical Winds

Axisymmetric (2.5D) simulations. To investigate outflows from the disk-magnetosphere boundary it was important that the magnetic field lines be bunched into an X-type configuration. Such bunching will occur if magnetic field lines threading the disk move inward to the star faster than they diffuse outward. This happens for example when the viscosity in the disk is larger than the diffusivity. In axisymmetric simulations we have both viscosity and diffusivity incorporated in the code, both in $\alpha$ - prescription (Shakura & Sunyaev 1973). The coefficients $\alpha_v$ and $\alpha_d$ control these processes (Romanova, et al. 2005; Ustyugova et al. 2006). We investigate a wide range of parameters: $0 < \alpha_v < 1$ and $0 < \alpha_d < 1$ and choose $\alpha_v = 0.03$ and $\alpha_d = 0.1$ as a main case. We assume that after period of low accretion rate the disk matter comes to the region from the boundary. Matter efficiently bunches field lines and in our case $\alpha_v > \alpha_d$ this configuration exists for a long time. The disk matter comes close to the star, is stopped by the magnetosphere, and part of it moves into persistent conical outflows (see Fig. 1).

Our simulations are dimensionless. As an example we chose parameters of the typical CTTS with mass $M_\ast = 0.8 M_\odot$, $R_\ast = 2 R_\odot$, magnetic field $B_\ast = 1kG$, period $P_\ast = 5.4$ days. In the Figs. 1-3 the inner boundary corresponds to two radii of the star. We accepted this choice of units so as to compare results with the propeller case (see §4) where the inner boundary is a factor of two smaller. Analysis of conical winds done by Romanova et al. (2009) have shown that they are driven mainly by the magnetic pressure force (e.g., Lovelace et al. 1991) which is largest right above the disk and acts up to distances of about 12 stellar radii. Fig. 2 shows typical parameters in a conical wind. Fig. 2 shows that matter start to flow to a conical wind with very high azimuthal velocity, equal to Keplerian velocity at the base of the outflow ($v_\phi \approx 130$ km/s in our main case). The poloidal velocity increases along the flow from few km/s right above the disk up to $v_p = 40 - 60$ km/s at larger distances. Azimuthal velocity remains larger than poloidal velocity inside the simulation region. In the conical wind matter flows into a relatively narrow shell and the cone has an opening angle, $\theta = 30^\circ - 40^\circ$. This may be explained by the fact that the magnetic pressure force acts almost vertically. This may also explain frequent events of reconnection of the inflating magnetic field lines in the outflow. We note that in addition to the main conical wind there is matter acceleration along magnetic field lines closer to
the axis. The low-density matter is accelerated up to hundreds of km/s right near the
star and may be important in explanation of some highly blue-shifted spectral lines
which form near CTTSs. Matter which is accelerated in this region may come from
the star, or may be partially captured from the main accretion flow. Fig. 3 shows two
components of the flow around a slowly rotating star.

**The fluxes of matter and angular momentum** flowing to or out from the star and
fluxes flowing with conical winds through the surface with radius $R = 0.1$AU were
calculated. Fig. 4 shows that matter flux to the wind is only several times smaller
than that to the star, $\dot{M}_{\text{wind}} \approx 0.2 - 0.3 \dot{M}_{\text{star}}$. The matter flux going to the wind varies,
which is connected with frequent events of reconnection of the magnetic flux. It is
often the case that matter is outbursted to the conical winds in an oscillatory regime,
in particular if $\alpha_v$ and $\alpha_d$ are not very small, $\alpha_{vd} \sim 0.1 - 0.3$. If the diffusivity
is small, $\alpha_d = 0.01 - 0.03$, then outbursts to winds are sporadic and occur with a
longer time-scale. Analysis of the angular momentum shows that in the case of a
slowly rotating star the star spins-up by accreting matter (through magnetic torque
at the surface of the star, e.g. Romanova et al. 2002). Conical winds carry away part
of the angular momentum of the disk (0.5 in this example), however a star may spin-
up or spin-down depending on $P_\star$. It spins-up in our example of a slowly rotating
star. We also checked the case of very slow rotation, $P_\star = 11$ days, and observed
that persistent conical winds form in this case as well.

**3D simulations.** We performed exploratory 3D MHD simulations of conical winds
in the case where the dipole magnetic field is misaligned relative to rotational axis
by an angle $\Theta = 30^\circ$. Compared with the axisymmetric simulations, the accretion
disk is situated at $r > 10 R_\star$ and the simulation region is much larger. Viscosity is
incorporated in the code and we chose $\alpha_{vis} = 0.3$ while the diffusivity is not incor-
porated and is only numerical (small, at the level $\alpha_d = 0.01 - 0.02$ at the disk-
magnetosphere boundary). We observed that the disk moved inward, bunched field
lines and formed conical winds. Fig. 5 shows that conical winds are approximately
symmetric about rotation axis. There is however enhancement in the density dis-
tribution inside conical winds which is associated with a spiral wave generated by
the misaligned dipole. Recent 3D modeling have shown that at a wide range of pa-
rameters matter penetrates through the magnetosphere due to interchange instability
(Romanova, Kulkarni & Lovelace 2008; Kulkarni & Romanova 2008). 3D simula-
tions of conical wind show that formation of conical winds occurs at larger distances
from the star and are not influenced by instabilities.

### 3 Enhanced Accretion and Outflows

CTTSs are strongly variable on different time-scales including a multi-year scale
(Herbst et al. 2004; Grankin et al. 2007). This is connected with variation of the ac-
cretion rate through the disk which may lead to the enhancement of outflows (e.g.,
Cabrit et al. 1990). Simulations have shown that the bunching of field lines by the
new matter after period of the low-density accretion may lead to quite long outburst
During the outburst, the accretion rate is enhanced so that the magnetospheric radius $R_m$ decreases and the magnetic field lines become bunched (A). This results in a fast, hot outflow. As the accretion rate decreases, the disk moves outward and this results in a slower, cooler CO outflow (B). Further decrease in the accretion rate leads to a quiescence state where the production of warm outflows stops (C). From Brittain et al. (2007).

Outflows in the propeller regime. The background shows matter flux, lines are selected field lines, arrows are proportional to velocity. Labels show total velocity and density at sample points. Of matter to the conical winds and may be the reason for formation of micro-jets in the CTTSs. If CTTS is in a binary system, then an accretion rate may be episodically enhanced due to interaction with the secondary star. Events of fast, implosive accretion are possible due to thermal instability or global magnetic instability, where the accretion rate is enhanced due to the formation of disk winds (Lovelace, Romanova, & Newman 1994). Enhanced accretion may lead to outbursts in EXors, where the accretion rate increases up to $10^{-5} M_\odot/yr$ and strong outflows are observed. Brittain et al. (2007) reported on the outflow of warm gas from the inner disk around EXor V1647 observed in the blue absorption of the CO line during the decline of the EXor activity. He concluded that this outflow is a continuation of activity associated with early enhanced accretion and bunching of the field lines (see Fig. 6). In our main example of a CTTS the disk stops at $R_m = 2.4 R_\ast$. In EXors, we take the radius of a star at the Figs. 1-3 equal to the inner boundary, so that the disk stops much closer.
to the star, \( R_m = 1.2R_* \). Then all velocities are a factor 1.4 higher and densities a factor of 32 higher (compared to Figs. 2, 7), and matter fluxes in Figs. 4 and 9 are a factor of 11 higher than in the main example relevant to CTTSs.

4 Outflows in the “Propeller” Regime

In the propeller regime the magnetosphere rotates faster than inner region of the disk. This occurs if the co-rotation radius \( R_{cr} = (GM/\Omega^2_*)^{1/3} \) is smaller than magnetospheric radius \( R_m \) (e.g., Lovelace et al. 1999). Young stars are expected to be in the propeller regime in two situations: (1) At the early stages of evolution (say, at \( T < 10^6 \) years), when the star formed but did not have time to spin-down, and (2) at later stages of evolution, such as at CTTS stage, when the star is expected to be on average in the rotational equilibrium state (e.g., Long et al. 2005) but variation of the accretion rate leads to variation of \( R_m \) around \( R_{cr} \), where \( R_{cr} < R_m \) is possible. We performed axisymmetric simulations of accretion to a star in the propeller regime, taking a star with the same parameters as in case of conical winds, but with period \( P_* = 1 \) day (Romanova et al. 2005; Ustyugova et al. 2006). We chose \( \alpha_v = 0.3 \) and \( \alpha_d = 0.1 \) and thus bunched the field lines to the X-type configuration. We observed that in addition to conical wind there is a fast axial jet (see Fig. 7) so that the outflow

![Fig. 8](image)

**Fig. 8** Two components of outflows in the propeller regime.

![Fig. 9](image)

**Fig. 9** Left panel: matter fluxes to the star \( \dot{M}_{\text{star}} \) and to the conical wind \( \dot{M}_{\text{wind}} \) (calculated at \( R = 0.1 \) AU) as function of time. Right panel: same but for a shorter time-interval.
has two components (Fig. 8). The conical wind in this case is much more powerful - it carries most of the disk matter away. The axial jet carries less mass, but it is accelerated to high velocities. Acceleration occurs due to the magnetic pressure of the "magnetic tower" which forms above the star as a result of winding of magnetic field lines of the star. Outbursts to conical winds occur sporadically with a long time-scale interval (see Fig. 9) which is connected with the long time-scale interval of accumulation and diffusion of the disk matter through the magnetosphere of the star (see also Goodson et al. 1997; Fendt 2008). These propeller outflows were obtained in conditions favorable for such a process: when the star rotated fast and an X-type configuration developed. Future simulations should be done for the case of propeller-driven outflows from slower rotating CTTS. Collimation of conical winds may occur at larger distances from the star for example, by disk winds (e.g., Königl & Pudritz 2000; Ferreira et al. 2006; Matsakos et al. 2008).

5 Conclusions

We discovered a new type of outflows - conical winds - in numerical simulations where magnetic field lines are bunched into an X-type configuration. In many respects these winds are similar to X-winds proposed by Shu and collaborators (e.g., Shu et al. 1994): (1) They both require bunching of the field lines; (2) They both have high rotation of the order of Keplerian rotation at the base of outflow, and gradual poloidal acceleration; (3) They both are driven by magnetic force. However, there are a number of important differences: (1) Conical winds flow in a thin shell, while X-winds flow at different angles below the "dead zone"; (2) Conical winds form around stars of any rotation rate including slow rotation, and do not require the fine tuning of angular velocity of the inner disk to that of magnetosphere; (3) Conical winds are non-stationary: the magnetic field constantly inflates and reconnects; (4) Conical winds carry away part of the angular momentum of the inner disk and are not responsible for spinning-down the star, while X-winds are predicted to take away angular momentum from the star and thus to solve the angular momentum problem; (5) In conical winds there is a fast component of the flow along field lines threading the star. Some of these differences, such as non-stationarity of conical winds is connected with natural restrictions of the stationary model of X-winds. Conical winds can explain conical shape of outflows near young stars of different type (CTTSs, EXors, Type I objects) which have been recently resolved. In another example, Alencar et al. (2005) analyzed blue-shifted absorption of Hβ line in RW Aurigae and concluded that conical shape wind with opening angle 30°–40° and narrow annulus gives best match to the observations of this line (see Fig. 10).

In the propeller regime the flow has two components: (1) a rapidly rotating, relatively slow, dense conical wind, and (2) a fast, lower density axial jet where matter is accelerated by magnetic pressure up to hundreds of km/s very close to the star. Young stars of classes 0 and I may be in the propeller regime and can lose most of their angular momentum by this mechanism (Romanova et al. 2005). Or any
slower rotating magnetized stars may enter the propeller regime if the accretion rate becomes sufficiently low and the magnetospheric radius becomes larger than the corotation radius. The last possibility requires additional numerical simulations and analysis.

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