

REVIEW

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On the origin of jets from disc-accreting magnetized stars

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Abstract

A brief review of the origin of jets from disc-accreting rotating magnetized stars is given. In most models, the interior of the disc is characterized by a turbulent viscosity and magnetic diffusivity ('alpha' discs) whereas the coronal region outside the disc is treated using ideal magnetohydrodynamics (MHD). Extensive MHD simulations have established the occurrence of long-lasting outflows in the case of both slowly and rapidly rotating stars. (1) *Slowly rotating stars* exhibit a new type of outflow, *conical winds*. Conical winds are generated when stellar magnetic flux is bunched up by the inward motion of the accretion disc. Near their region of origin, the winds have a thin conical shell shape with half opening angle of $\sim 30^\circ$. At large distances, their toroidal magnetic field collimates the outflow forming current carrying, matter dominated jets. These winds are predominantly magnetically and not centrifugally driven. About 10-30% of the disc matter from the inner disc is launched in the conical wind. Conical winds may be responsible for episodic as well as long lasting outflows in different types of stars. (2) *Rapidly rotating stars* in the 'propeller regime' exhibit twocomponent outflows. One component is similar to the matter dominated conical wind, where a large fraction of the disc matter may be ejected in this regime. The second component is a high-velocity, low-density magnetically dominated *axial jet* where matter flows along the open polar field lines of the star. The axial jet has a mass flux of about 10% that of the conical wind, but its energy flux, due to the Poynting flux, can be as large as for the conical wind. The jet's magnetically dominated angular momentum flux causes the star to spin down rapidly. Propeller-driven outflows may be responsible for protostellar jets and their rapid spin-down.

When the artificial requirement of symmetry about the equatorial plane is dropped, the conical winds are found to come alternately from one side of the disc and then the other, even for the case where the stellar magnetic field is a centered axisymmetric dipole.

Recent MHD simulations of disc accretion to rotating stars in the propeller regime have been done with *no* turbulent viscosity and *no* diffusivity. The strong turbulence observed is due to the magneto-rotational instability. This turbulence drives accretion in the disc and leads to episodic conical winds and jets.

1 Review

Outflows in the form of jets and winds are observed from many disc accreting objects ranging from young stars to systems with white dwarfs, neutron stars and black holes. A large body of observations exists for outflows from young stars at different stages of their evolution, ranging from protostars, where powerful collimated outflows - jets - are observed, to classical T Tauri stars (CTTSs) where the outflows are weaker and often less collimated (see review by Ray et al. 2007). Correlation between the disc's

radiated power and the jet power has been found in many CTTSs (Cabrit et al. 1990; Hartigan et al. 1995). A significant number of CTTSs show signs of outflows in spectral lines, in particular in He I where two distinct components of outflows had been found (Edwards et al. 2003, 2006, 2009; Kwan et al. 2007). Outflows are also observed from accreting compact stars such as accreting white dwarfs in symbiotic binaries (Sokoloski and Kenyon 2003), or from the vicinity of neutron stars, such as from Circinus X-1 (Heinz et al. 2007).

Different theoretical models have been proposed to explain the outflows from protostars and CTTSs (see review by Ferreira et al. 2006). The commonly favored model for the origin of protostellar jets and outflows are the radi-

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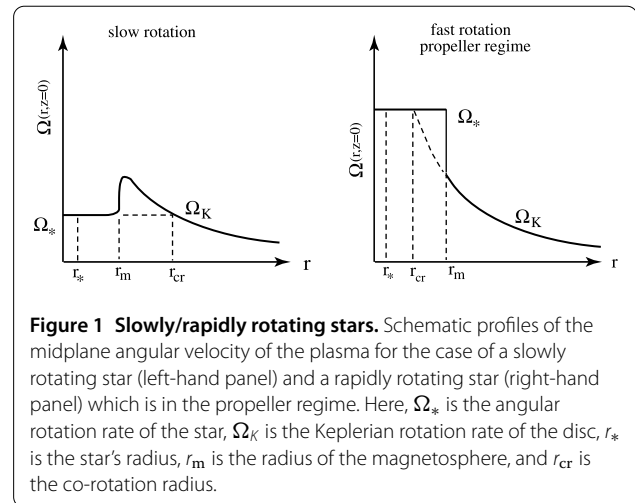
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ally distributed *magneto-centrifugal disc winds* which originate from discs threaded by a poloidal magnetic field (Blandford and Payne 1982; Königl and Pudritz 2000). MHD simulations disc winds were pioneered by Shibata and Uchida (1985) and Uchida and Shibata (1985) who used a Lax-Wendroff method to solve the axisymmetric MHD equations for a sub-Keplerian disc initially threaded by a vertical magnetic field. Subsequently, a large number of MHD simulation studies of the disc winds have been carried out with different codes and different assumptions (e.g., Ustyugova et al. 1995, 1999; Ouyed and Pudritz 1997; Romanova et al. 1997; Krasnopolsky et al. 1999; Casse and Keppens 2004; Ferreira et al. 2006; Matt and Pudritz 2008a, 2008b; Tzeferacos et al. 2009).

A less favored model for the origin of protostellar jets discussed in this review is one where the jets originate from the innermost region of the accretion disc (Lovelace et al. 1991) or the disc/magnetosphere boundary. This model is related to the *X-wind model* (Shu et al. 1994, 2007; Najita and Shu 1994; Cai et al. 2008) where the outflow originates from the vicinity of the disc-magnetosphere boundary. Progress in understanding the theoretical models has come from MHD simulations of accretion discs around rotating magnetized stars as discussed below. Laboratory experiments are also providing insights into jet formation processes (Hsu and Bellan 2002; Lebedev et al. 2005) but these are not discussed here.

Outflows or jets from the disc-magnetosphere boundary were found in early axisymmetric MHD simulations by Hayashi et al. (1996) and Miller and Stone (1997). A one-time episode of outflows from the inner disc and inflation of the innermost field lines connecting the star and the disc were observed for a few dynamical time-scales. Somewhat longer simulation runs were performed by Goodson et al. (1997, 1999), Hirose et al. (1997), Matt et al. (2002) and Küker et al. (2003) where several episodes of field inflation and outflows were observed. These simulations hinted at a possible long-term nature for the outflows. However, the simulations were not sufficiently long to establish the behavior of the outflows. MHD simulations showing long-lasting (thousands of orbits of the inner disc) outflows from the disc-magnetosphere have been obtained by our group (Romanova et al. 2009; Lii et al. 2012, 2014) and independently by Fendt (2009). We obtained these outflows/jets in two main cases: (1) where the star rotates slowly but the field lines are bunched up into an X-type configuration, and (2) where the star rotates rapidly, in the ‘propeller regime’ (Illarionov and Sunyaev 1975; Alpar and Shaham 1985; Lovelace et al. 1999). Field bunching occurs for conditions where the viscosity is larger than the magnetic diffusivity. Figure 1 shows sketches of the equatorial angular rotation rate $\Omega(r, z=0)$ of the plasma in the two cases. Here, r_* is the radius of the star; r_m is the magnetospheric radius where the kinetic energy density of



the disc matter is about equal to the energy density of the magnetic field; and $r_{cr} = (GM/\Omega_*^2)^{1/3}$ is the co-rotation radius where the angular rotation rate of the star Ω_* equals that of the Keplerian disc $\Omega_K = (GM/r^3)^{1/2}$. For a slowly rotating star $r_m < r_{cr}$ whereas for a rapidly rotating star in the propeller regime $r_m > r_{cr}$.

Figure 2 shows examples of the outflows in the two cases. In both cases, two-component outflows are observed: One component originates at the inner edge of the disc near r_m and has a narrow-shell conical shape close to the disc and therefore is termed a ‘conical wind’. It is matter dominated but can become collimated at large distances due to its toroidal magnetic field. The other component is a magnetically dominated high-velocity ‘axial jet’ which flows along the open stellar magnetic field lines. The axial jet may be very strong in the propeller regime. A full discussion of the simulations and analysis can be found in Romanova et al. (2009) and Lii et al. (2012).

The simulation codes used by our US/Russia group have been extensively tested and refined in many respects over the past fifteen years. The tests include the different well-known shock problems described for example by Mignone et al. (2007) in regard to the testing of the PLUTO code as well as the magnetic rotor tests described by Romanova et al. (2009). More importantly, our group has pioneered the detailed comparison of MHD simulation results (Ustyugova et al. 1999) with the analytic theory of stationary axisymmetric MHD flows (Lovelace et al. 1986). Furthermore, detailed analysis of the simulations have been made to evaluate the different forces acting to drive outflows and jets (e.g., Lii et al. 2012). A major effort by our group has been to implement physically consistent boundary conditions at the outer boundaries of the simulation regions. We were the first to point out the necessity of having the fast-magnetosonic Mach cone of an outflow pointing outwards from the simulation region (Ustyugova et al. 1999). A number of published MHD simulations of

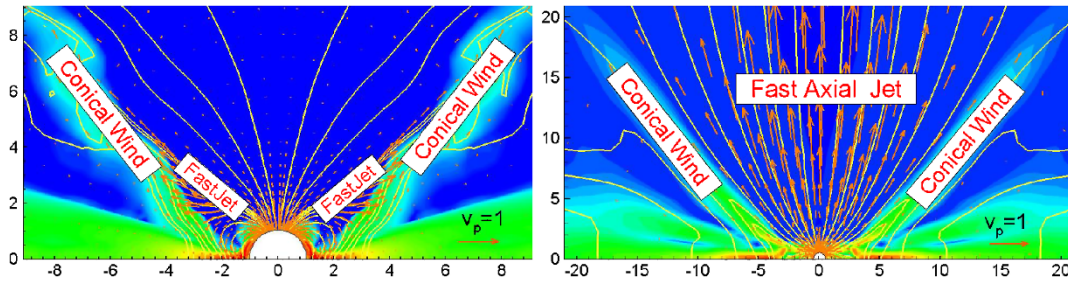


Figure 2 Two-component outflows observed in slowly (left) and rapidly (right) rotating magnetized stars. The background shows the poloidal matter flux $\mathbf{F}_m = \rho \mathbf{v}_p$, the arrows are the poloidal velocity vectors, and the lines are sample magnetic field lines. The labels point to the main outflow components. In the left-hand panel $\alpha_v = 0.3$ and $\alpha_\eta = 0.3$ while in the right-hand panel $\alpha_v = 0.1 = \alpha_\eta$.

jets in long axial cylindrical regions violate this requirement and are therefore unphysical.

Section 2 describes the simulations. Section 3 discusses the conical winds and axial jets, the driving and collimation forces, and the variability of the winds and jets. Section 4 discusses lopsided jets. Section 5 gives the conclusions.

2 MHD simulations

We simulate the outflows resulting from disc-magnetosphere interaction by solving the equations of axisymmetric MHD on grids using a Godunov type method. Outside of the disc the flow is described by the equations of ideal MHD. Inside the disc the flow is described by the equations of viscous, resistive MHD. In an inertial reference frame the equations are:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (1)$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot \mathcal{T} = \rho \mathbf{g}, \quad (2)$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) + \nabla \times (\eta_t \nabla \times \mathbf{B}) = 0, \quad (3)$$

$$\frac{\partial (\rho S)}{\partial t} + \nabla \cdot (\rho S \mathbf{v}) = Q. \quad (4)$$

Here, ρ is the density, S is the specific entropy, \mathbf{v} is the flow velocity, \mathbf{B} is the magnetic field, η_t is the magnetic diffusivity, \mathcal{T} is the momentum flux-density tensor, Q is the rate of change of entropy per unit volume, and $\mathbf{g} = -(GM/r^2)\hat{\mathbf{r}}$ is the gravitational acceleration due to the star which has mass M . In the simulations reviewed here it is assumed that the viscous plus Ohmic heating is balanced by radiative cooling so that $Q = 0$. Most of the volume of the simulated flows does not have shocks and there is no shock heating; however, at the surface of the star where the funnel flows impact the star's surface there are strong shocks and the shock heating is included (Koldoba et al. 2008). The total mass of the disc is assumed to be negligible com-

pared to M . Here, \mathcal{T} is the sum of the ideal plasma terms and the α -viscosity terms discussed in the next paragraph. The plasma is considered to be an ideal gas with adiabatic index $\gamma = 5/3$, and $S = \ln(p/\rho^\gamma)$. We use spherical coordinates (r, θ, ϕ) with θ measured from the symmetry axis. The equations in spherical coordinates are given in Ustyugova et al. (2006).

Both the viscosity and the magnetic diffusivity of the disc plasma are considered to be due to turbulent fluctuations of the velocity and the magnetic field. Both effects are non-zero only inside the disc as determined by a density threshold. The microscopic transport coefficients are replaced by turbulent coefficients. The values of these coefficients are assumed to be given by the α -model of Shakura and Sunyaev (1973), where the coefficient of the turbulent kinematic viscosity is $\nu_t = \alpha_v c_s^2 / \Omega_K$, where c_s is the isothermal sound speed and $\Omega_K(r)$ is the Keplerian angular velocity. We take into account the viscous stress terms $\mathcal{T}_{r\phi}^{\text{vis}}$ and $\mathcal{T}_{\theta\phi}^{\text{vis}}$ (Lii et al. 2012). Similarly, the coefficient of the turbulent magnetic diffusivity $\eta_t = \alpha_\eta c_s^2 / \Omega_K$. Here, α_v and α_η are dimensionless coefficients which are treated as parameters of the model. The inward advection of matter and large-scale magnetic field in accretion discs with different (α_v, α_η) values has been studied by Dyda et al. (2013). Note that shearing box simulations by Guan and Gammie (2009) suggest that $\alpha_v \sim \alpha_\eta$. In the simulation studies of our group we have studied cases with (α_v, α_η) in the ranges 0.03-0.3. For these values the viscosity and diffusivity are much larger than the numerical values due to the finite grids.

The MHD equations are solved in dimensionless form so that the results can be readily applied to different accreting stars (see Table 1). Equations (1)-(4) have been integrated numerically in spherical (r, θ, ϕ) coordinates using a Godunov-type numerical scheme. The flux densities of the different quantities are calculated using an eight-wave Roe-type approximate Riemann solver analogous to one described by Powell et al. (1999). The calculations were

Table 1 Reference values for different types of stars

	Protostar	CTTS	Brown dwarf	White dwarf	Neutron star
$M (M_\odot)$	0.8	0.8	0.056	1	1.4
R_*	$2R_\odot$	$2R_\odot$	$0.1R_\odot$	5,000 km	10 km
R_0 (cm)	$2.8 \cdot 10^{11}$	$2.8 \cdot 10^{11}$	$1.4 \cdot 10^{10}$	10^9	$2 \cdot 10^6$
v_0 (cm s ⁻¹)	$1.95 \cdot 10^7$	$1.95 \cdot 10^7$	$1.6 \cdot 10^7$	$3.6 \cdot 10^8$	$9.7 \cdot 10^9$
P_*	1.04 days	5.6 days	0.13 days	89 s	6.7 ms
P_0	1.04 days	1.04 days	0.05 days	17.2 s	1.3 ms
B_* (G)	$3.0 \cdot 10^3$	10^3	$2 \cdot 10^3$	10^6	10^9
B_0 (G)	37.5	12.5	25.0	$1.2 \cdot 10^4$	$1.2 \cdot 10^7$
ρ_0 (g cm ⁻³)	$3.7 \cdot 10^{-12}$	$4.1 \cdot 10^{-13}$	$1.4 \cdot 10^{-12}$	$1.2 \cdot 10^{-9}$	$1.7 \cdot 10^{-6}$
n_0 (cm ⁻³)	$2.2 \cdot 10^{12}$	$2.4 \cdot 10^{11}$	$8.5 \cdot 10^{11}$	$7 \cdot 10^{14}$	10^{18}
\dot{M}_0 (M_\odot yr ⁻¹)	$1.8 \cdot 10^{-7}$	$2 \cdot 10^{-8}$	$1.8 \cdot 10^{-10}$	$1.3 \cdot 10^{-8}$	$2 \cdot 10^{-9}$
\dot{E}_0 (erg s ⁻¹)	$2.1 \cdot 10^{33}$	$2.4 \cdot 10^{32}$	$2.5 \cdot 10^{30}$	$5.7 \cdot 10^{34}$	$6 \cdot 10^{36}$
\dot{L}_0 (erg s ⁻¹)	$3.1 \cdot 10^{37}$	$3.4 \cdot 10^{36}$	$1.7 \cdot 10^{33}$	$1.6 \cdot 10^{35}$	$1.2 \cdot 10^{33}$
T_d (K)	2,290	4,590	5,270	$1.6 \cdot 10^6$	$1.1 \cdot 10^9$
T_c (K)	$2.3 \cdot 10^6$	$4.6 \cdot 10^6$	$5.3 \cdot 10^6$	$8 \cdot 10^8$	$5.6 \cdot 10^{11}$

We choose the mass M , radius R_* , equatorial magnetic field B_* and the period P_* of the star and derive the other reference values. The reference mass M_0 is taken to be the mass M of the star. The reference radius is taken to be twice the radius of the star, $R_0 = 2R_*$. The surface magnetic field B_* is different for different types of stars. The reference velocity is $v_0 = (GM/R_0)^{1/2}$. The reference time-scale $t_0 = R_0/v_0$, and the reference angular velocity $\Omega_0 = 1/t_0$. We measure time in units of $P_0 = 2\pi t_0$ (which is the Keplerian rotation period at $r = R_0$). In the plots we use the dimensionless time $T = t/P_0$. The reference magnetic field is $B_0 = B_*(R_*/R_0)^3/\bar{\mu}$, where $\bar{\mu}$ is the dimensionless magnetic moment which has a numerical value of 10 in the simulations discussed here. The reference density is taken to be $\rho_0 = B_0^2/v_0^2$. The reference pressure is $p_0 = B_0^2$. The reference temperature is $T_0 = \rho_0/\mathcal{R}\rho_0 = v_0^2/\mathcal{R}$, where \mathcal{R} is the gas constant. The reference accretion rate is $\dot{M}_0 = \rho_0 v_0 R_0^2$. The reference energy flux is $\dot{E}_0 = \dot{M}_0 v_0^2$. The reference angular momentum flux is $\dot{L}_0 = \dot{M}_0 v_0 R_0$. The poloidal magnetic field of the star (in the absence of external plasma) is an aligned dipole field.

done in the region $R_{\text{in}} \leq r \leq R_{\text{out}}$, $0 \leq \theta \leq \pi/2$. Matter flowing into the star is absorbed. The grid is uniform in the θ -direction with N_θ cells. The N_r cells in the radial direction have $dr_{j+1} = (1 + 0.0523)dr_j$ ($j = 1, \dots, N_r$) so that the poloidal-plane cells are curvilinear rectangles with approximately equal sides. This choice results in high spatial resolution near the star where the disc-magnetosphere interaction takes place while also permitting a large simulation region. We have used a range of resolutions going from $N_r \times N_\theta = 51 \times 31$ to 121×51 in order to establish the numerical convergence of our results.

3 Conical winds and axial jets

A large number of simulations were done in order to understand the origin and nature of conical winds. All of the key parameters were varied in order to ensure that there is no special dependence on any parameter. We observed that the formation of conical winds is a common phenomenon for a wide range of parameters. They are most persistent and strong in cases where the viscosity and diffusivity coefficients are not very small, $\alpha_v \gtrsim 0.03$, $\alpha_\eta \gtrsim 0.03$. Another important condition is that $\alpha_v \gtrsim \alpha_\eta$; that is, the magnetic Prandtl number of the turbulence, $\mathcal{P}_m = \alpha_v/\alpha_\eta \gtrsim 1$. This condition favors the bunching of the stellar magnetic field by the accretion flow.

The velocities in the conical wind component are similar to those in conical winds around slowly rotating stars. Matter launched from the disc-magnetosphere region initially has an approximately Keplerian azimuthal velocity, $v_K = \sqrt{GM_*/r}$. It is gradually accelerated to poloidal ve-

locities $v_p \sim (0.3-0.5)v_K$ and the azimuthal velocity decreases. The flow has a high density and carries most of the disc mass into the outflows. The situation is the opposite in the axial jet component where the density is 10^2 - 10^3 times lower, while the poloidal and total velocities are significantly higher. Thus we find a *two-component outflow*: a matter dominated conical wind and a magnetically dominated axial jet.

We observe conical winds in both slowly and rapidly rotating stars. In both cases, matter in the conical winds passes through the Alfvén surface (and shortly thereafter through the fast magnetosonic point), beyond which the flow is matter-dominated in the sense that the energy flow is carried mainly by the matter. The situation is different for the axial jet component where the flow is sub-Alfvénic within the simulation region. For this component the energy flow is carried by the Poynting flux and the angular momentum flow is carried by the magnetic field. X-ray observations of the jet from the protostellar object L1551 IRS 5 suggest a high-velocity, highly collimated inner jet and a lower-velocity, less-collimated outer outflow component (Schneider et al. 2011).

Collimation and driving of the outflows Figure 3 shows the long-distance development of a conical wind from a slowly rotating star. At large distances the conical wind becomes collimated. To understand the collimation we analyzed total force (per unit mass) perpendicular to a poloidal magnetic field line (Lii et al. 2012). For distances beyond the Alfvén surface of the flow this force is approx-

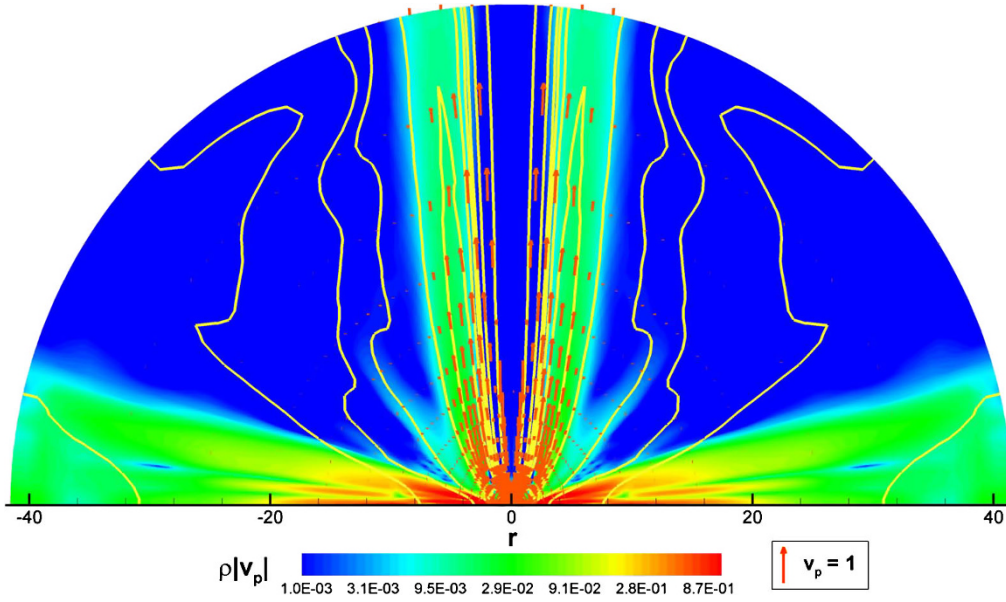


Figure 3 The conical wind/jet from a slowly rotating star at time $t = 860$. The background shows the poloidal matter flux density ρv_p and the lines show the poloidal projections of the magnetic field. The red vectors show the poloidal matter velocity \mathbf{v}_p . Dimensional values can be obtained from Table 1. For example for a CTTS, $t_0 = 0.366$ days, $R_0 = 2R_\odot$, $t = 860$ corresponds to 315 days, and the simulation region is 0.39 AU in radius. The horizontal axis shows the distance from the star in units of the reference radius R_0 . For this case $\alpha_v = 0.3$ and $\alpha_\eta = 0.1$.

imately

$$f_{\text{tot},\perp} = -v_p^2 \frac{\partial \Theta}{\partial s} - \frac{1}{8\pi\rho} \frac{\partial \mathbf{B}_p^2}{\partial n} - \frac{1}{8\pi\rho(r\sin\theta)^2} \frac{\partial (r\sin\theta B_\phi)^2}{\partial n} + \frac{v_\phi^2 \cos\Theta}{r \sin\theta} \quad (5)$$

(Ustyugova et al. 1999). Here, Θ is the angle between the poloidal magnetic field and the symmetry axis, s is the arc length along the poloidal field line, n is a coordinate normal to the poloidal field, and the p -subscripts indicate the poloidal component of a vector. Once the jet begins to collimate, the curvature term $-v_p^2 \partial \Theta / \partial s$ also becomes negligible. The magnetic force may act to either collimate or decollimate the jet, depending on the relative magnitudes of the toroidal $(r\sin\theta B_\phi)^2$ gradient (which collimates the outflow) and poloidal \mathbf{B}_p^2 gradient (which ‘decollimates’). In our simulations, the collimation of the matter implies that the magnetic hoop stress is larger than the poloidal field gradient. Thus the main perpendicular forces acting in the jet are the collimating effect of the toroidal magnetic field and the decollimating effect of the centrifugal force and the gradient of \mathbf{B}_p^2 . The collimated effect of B_ϕ dominates. Note that in MKS units $2\pi r \sin\theta B_\phi / \mu_0$ is the poloidal current flowing through a surface of radius r from colatitude zero to θ . For the jets from young stars this current is of the order of 2×10^{13} A.

The driving force for the outflow is simply the force parallel to the poloidal magnetic field of the flow $f_{\text{tot},\parallel}$. This is obtained by taking the dot product of the Euler equation with the $\hat{\mathbf{b}}$ unit vector which is parallel to the poloidal magnetic field line \mathbf{B}_p . The derivation by Ustyugova et al. (1999) gives

$$f_{\text{tot},\parallel} = -\frac{1}{\rho} \frac{\partial P}{\partial s} - \frac{\partial \Phi}{\partial s} + \frac{v_\phi^2}{r \sin\theta} \sin\Theta + \frac{1}{4\pi\rho} \hat{\mathbf{b}} \cdot [(\nabla \times \mathbf{B}) \times \mathbf{B}]. \quad (6)$$

Here, the terms on the right-hand side correspond to the pressure, gravitational, centrifugal and magnetic forces, respectively denoted $\mathbf{f}_{p,G,C,M}$. The pressure gradient force, \mathbf{f}_p , dominates within the disk. The matter in the disk is approximately in Keplerian rotation such that the sum of the gravitational and centrifugal forces roughly cancel ($\mathbf{f}_{G+C} \approx 0$). Near the slowly rotating star, however, the matter is strongly coupled to the stellar magnetic field and the disk orbits at sub-Keplerian speeds, giving $\mathbf{f}_{G+C} \lesssim 0$. The magnetic driving force (the last term of Eq. (6)) can be expanded as

$$f_{M,\parallel} = -\frac{1}{8\pi\rho(r\sin\theta)^2} \frac{\partial}{\partial s} (r\sin\theta B_\phi)^2 \quad (7)$$

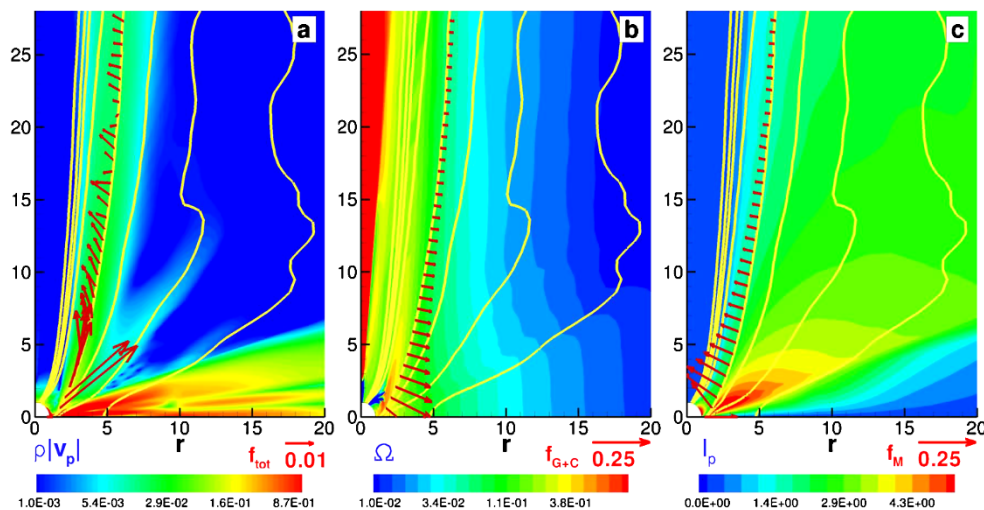


Figure 4 Forces along a field line in the jet. Panel (a) shows the poloidal matter flux density $\rho|v_p|$ as a background overplotted with poloidal magnetic field lines. The vectors show the *total* force \mathbf{f}_{tot} along a representative field line originating from the disk at $r = 1.24$. Panel (b) plots the angular velocity Ω as the background. The vectors show the sum of the *gravitational + centrifugal* forces \mathbf{f}_{G+C} along the representative field line. Panel (c) shows the poloidal current I_p as the background. The vectors show the *total magnetic* force \mathbf{f}_M along the representative field line.

(Lovelace et al. 1991). Figure 4 shows the variation of the total force \mathbf{f}_{tot} , the gravitational plus centrifugal force, and the magnetic force along a representative field line. This analysis establishes that the predominant driving force for the outflow is the magnetic force (Eq. (7)) and not the centrifugal force. This is in agreement with the analysis of Lovelace et al. (1991).

Variability For both rapidly and slowly rotating stars the magnetic field lines connecting the disc and the star have the tendency to inflate and open (Lovelace et al. 1995). Quasi-periodic reconstruction of the magnetosphere due to inflation and reconnection has been discussed theoretically (Aly and Kuipers 1990) and has been observed in a number of axisymmetric simulations (Hirose et al. 1997; Goodson et al. 1997, 1999; Matt et al. 2002; Romanova et al. 2002). Goodson and Winglee (1999) discuss the physics of inflation cycles. They have shown that each cycle of inflation consists of a period of matter accumulation near the magnetosphere, diffusion of this matter through the magnetospheric field, inflation of the corresponding field lines, accretion of some matter onto the star, and outflow of some matter as winds, with subsequent expansion of the magnetosphere. There simulations show 5-6 cycles of inflation and reconnection. Our simulations often show 30-50 cycles of inflation and reconnection.

Kurosawa and Romanova (2012) have calculated spectra from modeled conical winds and accretion funnels combining the 3D MHD simulations with 3D radiative transfer code TORUS. They have shown that conical winds may explain different features in the hydrogen spectral lines, in the He I line and also a relatively narrow, low-velocity blue-shifted absorption components in the He I $\lambda 10830$ which is

often seen in observations (Kurosawa et al. 2011). Further, the 3D MHD+3D radiative transfer codes have been used to model the young star V2129 Oph, where the parameters of the star including the surface magnetic field distribution are known (Alencar et al. 2012). The spectrum in several Hydrogen lines was calculated and compared it with observed spectrum. A good match was obtained between the modeled and observed spectra (Alencar et al. 2012).

4 Lopsided jets and outflows from discs

There is clear evidence, mainly from Hubble Space Telescope (HST) observations, of the asymmetry between the approaching and receding jets from a number of young stars. The objects include the jets in HH 30 (Bacciotti et al. 1999), RW Aur (Woitas et al. 2002), TH 28 (Coffey et al. 2004), and LkH α 233 (Perrin and Graham 2007). Specifically, the radial speed of the approaching jet may differ by a factor of two from that of the receding jet. For example, for RW Aur the radial redshifted speed is ~ 100 km/s whereas the blueshifted radial speed is ~ 175 km/s. The mass and momentum fluxes are also significantly different for the approaching and receding jets in a number of cases. It is possible that the observed asymmetry of the jets could be due to differences in the gas densities on the two sides of the source. However, it is more likely that the asymmetry of the outflows arises from the asymmetry of the star's magnetic field. Substantial observational evidence points to the fact that young stars often have *complex* magnetic fields consisting of dipole, quadrupole, and higher order poles misaligned with respect to each other and the rotation axis (Jardine et al. 2002; Donati et al. 2008). Analysis of the

plasma flow around stars with realistic fields have shown that a significant fraction of the star's magnetic field lines are open and may carry outflows (Gregory et al. 2006).

The complex magnetic field of a star will destroy the commonly assumed symmetry of the magnetic field and the plasma about the equatorial plane. MHD simulations by Lovelace et al. (2010) fully support the qualitative picture suggested in the sketch in Figure 1 of Lovelace et al. (2010). The idea of mixing of even and odd symmetry magnetic fields about $z = 0$ to get lopsided outflows was proposed earlier by Wang et al. (1992). The time-scale during which the jet comes from the upper hemisphere is set by the evolution time-scale for the stellar magnetic field. This is determined by the dynamo processes responsible for the generation of the field. Remarkably, once the assumption of symmetry about the equatorial plane is dropped, the conical winds alternately come from one hemisphere and then the other *even* when the stellar magnetic field is a centered axisymmetric dipole (Lovelace et al. 2010). Fendt and Sheikhnezhani (2013) likewise found that symmetric magnetic field configurations produced asymmetric outflows if there were thermal asymmetries in the disc. The time-scale for the 'flipping' is the accretion time-scale of the inner part of the disc which is expected to be much less than the evolution time of the star's magnetic field.

We have revisited the problem of the asymmetry of the jets and outflows using a new axisymmetric code with a high-resolution stretched-grid (Dyda et al.: Bipolar MHD Outflows from T Tauri Stars, in preparation). The star has a radius of 1 in our simulation units, and the first 30 grid cells have lengths $\delta R = 0.1$. At larger R , the cell lengths are given recursively by $\delta R_{i+1} = 1.025\delta R_i$. Similarly, in the Z -direction, the first 30 grid cells above and below the equatorial plane have lengths $\delta Z = 0.1$. At larger $|Z|$, the cell lengths are given recursively by $\delta Z_{j+1} = 1.025\delta Z_j$. This grid gives high resolution in the region occupied by the disc and by the jet. Here, we present sample results with a simulation region of 135×216 ($R \times Z$) cells. Figure 5 shows a sparse version of this grid.

The initial magnetic field is taken to be a superposition of a dipole field centered in the star described by the flux function

$$\Psi_D = \frac{\mu R^2}{(R^2 + Z^2)^{3/2}}, \quad (8)$$

and a Zanni-type distributed field in the disc,

$$\Psi_Z = \frac{4}{3} B_0 r_0^2 \left(\frac{r}{r_0} \right)^{3/4} \frac{m^{5/4}}{(m^2 + Z^2/R^2)^{5/8}} \quad (9)$$

(Zanni et al. 2007), where μ is the magnetic moment of the star, B_0 is a reference value for the disc field, and m is a dimensionless parameter which controls the initial disc field geometry.

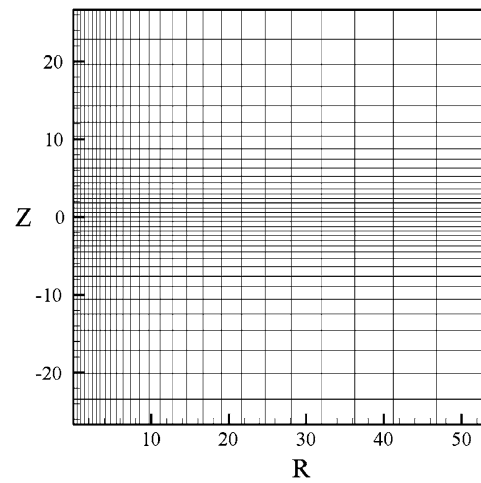


Figure 5 Diluted picture of new high-resolution mesh used to study lopsided jets and outflows. The actual mesh has 5-times as many cells in the R -direction and 6-times as many cells in the Z -direction.

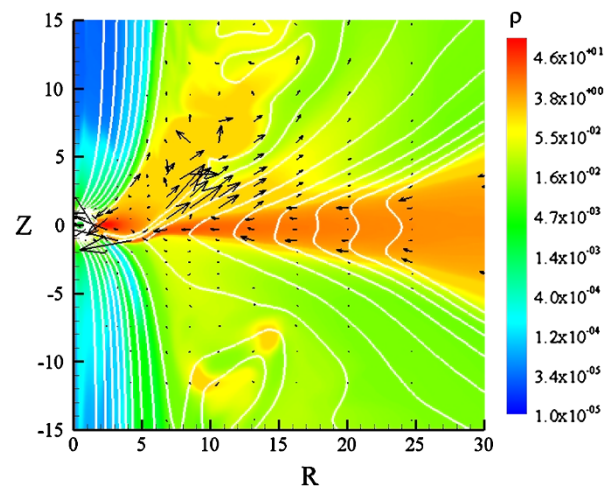


Figure 6 Lopsided outflow from the disc-magnetosphere boundary at a time corresponding to 203 rotation periods of the disc at the corotation radius r_{cr} , which is twice the star's radius r_* . The initial magnetic field, which is symmetric about $z = 0$, is the sum of the stellar dipole (Eq. (8)) and the disc field (Eq. (9)), where the dipole and disc fields are parallel and equal in magnitude at $r = 4.4r_*$ and $z = 0$. The color background shows the density and the white lines the poloidal projection of the magnetic field lines. The arrows inside the disc (the orange region) are the poloidal velocity vectors, while the arrows external to the disc show the momentum density ρv .

Figure 6 shows a zoomed-in view of results from the new stretched-grid code for an episode of lopsided jet formation for a case where the dipole field of the rotating star is parallel to the disc field in the disc midplane. The outflow from the top side of the disc is at super escape speed veloc-

ities with the result that the mass outflow is predominantly from the top side of the disc. During the duration of the run (203 rotation periods of the disc at the corotation radius), the poloidal flux of the disc field advects inward and accumulates in the low-density axial blue region in the figure. In this region there are magnetically collimated Poynting flux outflows of energy and angular momentum in the $\pm z$ directions.

5 Conclusions

Detailed magnetohydrodynamic simulations have established that long-lasting outflows of cold disc matter are ejected into a hot, low-density corona from the disc-magnetosphere boundary in the case of both slowly and rapidly rotating stars. The main results are the following:

For slowly rotating stars a new type of outflow - a conical wind - has been discovered. Matter flows out forming a *conical wind* which has the shape of a thin conical shell with a half-opening angle $\theta \sim 30^\circ$. The outflows appear in cases where the magnetic flux of the star is bunched up by the inward accretion flow of the disc. We find that this occurs when the turbulent magnetic Prandtl number (the ratio of viscosity to diffusivity) $\mathcal{P}_m > 1$, and when the viscosity is sufficiently high, $\alpha_v \gtrsim 0.03$.

Winds from the disc-magnetosphere boundary have been proposed earlier by Shu and collaborators and referred to as X-winds (Shu et al. 1994). In this model, the wind originates from a small region near the corotation radius r_{cr} , while the disc truncation radius r_t (or, the magnetospheric radius r_m) is only slightly smaller than r_{cr} ($r_m \approx 0.7r_{cr}$, Shu et al. 1994). It is suggested that excess angular momentum flows from the star to the disc and from there into the X-winds. The model aims to explain the slow rotation of the star and the formation of jets. In the simulations discussed here we have obtained outflows from both slowly and rapidly rotating stars. Both have conical wind components which are reminiscent of X-winds. In some respects the conical winds are similar to X-winds: They both require *bunching* of the poloidal field lines and show outflows from the inner disc; and they both have high rotation and show gradual poloidal acceleration (e.g., Najita and Shu 1994).

The main differences are the following: (1) The conical/propeller outflows have *two components*: a slow high-density conical wind (which can be considered as an analogue of the X-wind), and a fast low-density jet. No jet component is discussed in the X-wind model. (2) Conical winds form around stars with *any rotation rate* including very slowly rotating stars. They do not require fine tuning of the corotation and truncation radii. For example, bunching of field lines is often expected during periods of enhanced or unstable accretion when the disc comes closer to the surface of the star and $r_m \ll r_{cr}$. Under this condition conical winds will form. In contrast, X-winds require

$r_m \approx r_{cr}$. (3) The base of the conical wind component in both slowly and rapidly rotating stars is associated with the region where the field lines are bunched up, and not with the corotation radius. (4) X-winds are driven by the *centrifugal force*, and as a result matter flows over a wide range of directions below the 'dead zone' (Shu et al. 1994; Ostriker and Shu 1995). In conical winds the matter is driven by the *magnetic force* (Lovelace et al. 1991) which acts such that the matter flows into a *thin shell* with a cone half-angle $\theta \sim 30^\circ$. The same force tends to collimate the flow.

For rapidly rotating stars in the propeller regime where $r_m > r_{cr}$ and where the condition for bunching, $\mathcal{P}_m > 1$, is satisfied we find two distinct outflow components (1) a relatively low-velocity conical wind and (2) a high-velocity axial jet. A significant part of the disc matter and angular momentum flows into the conical winds. At the same time a significant part of the rotational energy of the star flows into the magnetically-dominated axial jet. This regime is particularly relevant to protostars, where the star rotates rapidly and has a high accretion rate. The star spins down rapidly due to the angular momentum flow into the axial jet along the field lines connecting the star and the corona. For typical parameters a protostar spins down in 3×10^5 years. The axial jet is powered by the spin-down of the star rather than by disc accretion. The matter fluxes into both components (wind and jet) strongly oscillate due to events of inflation and reconnection. Most powerful outbursts occur every 1-2 months. The interval between outbursts is expected to be longer for smaller diffusivities in the disc. Outbursts are accompanied by higher outflow velocities and stronger self-collimation of both components. Such outbursts may explain the ejection of knots in CTTs every few months.

When the artificial requirement of symmetry about the equatorial plane is dropped, MHD simulations reveal that the conical winds may alternately come from one side of the disc and then the other even for the case where the stellar magnetic field is a centered axisymmetric dipole (Lovelace et al. 2010; Fendt and Sheikhezami 2013; Dyda et al.: Bipolar MHD Outflows from T Tauri Stars, in preparation).

In recent work we have studied the disc accretion to rotating magnetized stars in the propeller regime using a new code with very high resolution in the region of the disc. In this code *no* turbulent viscosity or diffusivity is incorporated, but instead strong turbulence occurs due to the magneto-rotational instability. This turbulence drives the accretion and it leads to episodic outflows. The effective (α_v, α_η) values due to the turbulence arising from the magneto-rotational instability (MRI) are found to be ~ 0.1 . These values are much larger than the numerical viscosity and diffusivity values due to the finite grids used which are $\lesssim 0.01$. Note however that the characterization of the turbulence by α -values is a rough approximation.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

RL and MR were principal investigators of this research and drafted this manuscript. PL performed the simulations and analysis of the conical winds and axial jets. SD performed the simulations and analysis of the lopsided jets and disc outflows. All authors read and approved the final manuscript.

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Acknowledgements

The authors thank GV Ustyugova and AV Koldoba for the development of the codes used in the reviewed simulations. This research was supported in part by NSF grants AST-1008636 and AST-1211318 and by a NASA ATP grant NNX10AF63G; we thank NASA for use of the NASA High Performance Computing Facilities.

Received: 26 February 2014 Accepted: 2 June 2014

Published online: 11 September 2014

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doi:10.1186/s40668-014-0003-5

Cite this article as: Lovelace et al.: On the origin of jets from disc-accreting magnetized stars. *Computational Astrophysics and Cosmology* 2014 **1**:3.

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