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Formation of magnetohydrodynamic jets: flares as triggers of internal shocks

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Abstract. We investigate how the overall jet formation process is affected by a variation in the accretion disk magnetic flux profile and/or the existence of a central stellar magnetosphere using axisymmetric magnetohydrodynamic (MHD) simulations. These simulations evolve from an initial, hydrostatic equilibrium state in a force-free magnetic field configuration. Two different simulation setups will be considered. In the first approach the role of the disk magnetic flux profile and disk mass loss profile is investigated concerning the jet collimation degree. Our results suggest (and quantify) that in general outflows launched from a very concentrated region close to the inner disk radius tend to be un-collimated. In the second approach, jet formation is numerically investigated from a magnetic field configuration consisting of a stellar dipole superposed by a disk field. The central dipole is found to de-collimate the disk wind considerably. Reconnecting flares are launched by the interaction of the disk and stellar magnetic field and may change the overall mass flux in the outflow by a factor of two. We apply the energetics and time scales of our numerical flare model to XRB sources.

Key words. accretion – accretion disks – magnetohydrodynamics: MHD methods: numerical – stars: formation – stars: magnetic fields – stars: mass loss – stars: winds, outflows – ISM: jets and outflows

1. Introduction

Astrophysical jets are highly collimated beams of high velocity material, observed in a variety of astronomical sources - among them young stellar objects (YSO), micro-quasars (MQs, XRBs), or active galactic nuclei (AGN). Somewhat less collimated beams of comparatively lower speed are usually called outflows. The current understanding of jet formation is that these outflows are launched by *magnetohydrodynamic* (MHD) processes in the close vicinity of the central object – an accretion disk surrounding a protostar or a compact object (Blandford & Payne 1982; Pudritz et al. 2007).

The geometrical setup of a stellar dipolar magnetic field surrounded by an accretion disk carrying its own magnetic flux is a frequent astrophysical scenario which seem to be realized in young stars, cataclysmic variables, high-mass and low-mass X-ray binaries, and other micro-quasar systems.

Numerical simulations of MHD jet formation are an inevitable tool to understand the underlying physical processes. Furthermore, the jet-launching region can be resolved numerically, but not observationally. These simulations can be distinguished in those taking into account the evolution of the disk structure and others considering the disk surface as a fixed-in-time boundary condition for the jet. Both approaches are somewhat complementary, each of them having their pros and cons.

The first approach allows to directly investigate the mechanism lifting matter from the disk into the outflow (Uchida & Shibata 1984; Miller & Stone 1997; Goodson et al. 1999; Casse & Keppens 2002; Romanova et al. 2002; Meliani et al. 2006). This approach is computationally expensive and still somewhat limited by spatial and time resolution. Also, the disk model underlying the jet formation simulations is usually rather basic. Studying the acceleration and collimation of a disk/stellar wind requires essentially to follow the jet dynamical evolution for i) very long time ii) on a sufficiently large grid with iii) appropriate resolution. For such a goal, the second approach is better suited (Ustyugova et al. 1995; Ouyed & Pudritz 1997; Krasnopolsky et al. 1999; Fendt & Cemeljic 2002; Kigure & Shibata 2005; Fendt 2006, 2009; Porth & Fendt 2010). Of course, the mass flux ratio of jet and disk cannot be determined by such an approach. The case of superposed stellar/disk magnetic field is rarely treated in simulations, although the first models were discussed already in Uchida & Low (1981). Simulations of a dipole with aligned vertical disk field are presented by Miller & Stone (1997); Matt et al. (2002). The stellar field has important impact on the jet formation process as enhancing the magnetic flux, adding a central pressure, and providing excess angular momentum for the launching region.

2. Disk jets and stellar magnetospheres

In the following we discuss several aspects which consider the jet formation process in presence of a central stellar magnetic field.

Additional magnetic flux. In comparison to the situation of a pure disk magnetic field, the stellar magnetic field adds substantial magnetic flux to the system. For a polar field strength B_0 and a stellar radius $R_{\rm TTS}$ resp. $R_{\rm NS}$, the large-scale stellar dipolar field

$$\begin{aligned} B_{\rm p,\star}(r) &\simeq 40\,{\rm G}\left(\frac{B_0}{1\,{\rm kG}}\right)\left(\frac{r}{3\,R_{\rm TTS}}\right)^{-3} \\ &= 40\,{\rm kG}\left(\frac{B_0}{1\,{\rm MG}}\right)\left(\frac{r}{3\,R_{\rm NS}}\right)^{-3} \end{aligned} \qquad (1)$$

is to be compared to the disk poloidal magnetic field which could be provided either by dynamo action or by advecting the ambient interstellar field. Equipartition arguments suggest a maximum disk magnetic field of

$$\begin{aligned} B_{\rm p,disk} &< B_{\rm eq}(r) = 20\,{\rm G}\,\frac{1}{\sqrt{\alpha}}\left(\frac{\dot{M}_{\rm a}}{10^{-6}\,M_{\odot}/{\rm yr}}\right)^{\frac{1}{2}} \\ &\times \left(\frac{M_\star}{M_\odot}\right)^{\frac{1}{4}}\left(\frac{H/r}{0.1}\right)^{-\frac{1}{2}}\left(\frac{r}{10\,R_\odot}\right)^{-\frac{5}{4}} \\ &= 2\,{\rm MG}\,\frac{1}{\sqrt{\alpha}}\left(\frac{\dot{M}_{\rm a}}{10^{-8}\,M_{\odot}/{\rm yr}}\right)^{\frac{1}{2}} \\ &\times \left(\frac{M_\star}{2M_\odot}\right)^{\frac{1}{4}}\left(\frac{H/r}{0.1}\right)^{-\frac{1}{2}}\left(\frac{r}{5\,R_{\rm NS}}\right)^{-\frac{5}{4}}, \end{aligned} \qquad (2)$$

where the first part refers to the protostellar case and the second one for a compact star. The stellar magnetic dipole will not remain closed, but will partly inflate and open up due to shear between the foot points of the poloidal magnetic field lines on star and disk (e.g. Uchida & Shibata 1984; Fendt & Elstner 2000; Matt & Pudritz 2005). The additional Poynting flux that threads the disk may support jet launching by MHD forces. The stellar field may also serve as an additional energy source for the jet kinetic energy, thus implying a greater asymptotic jet speed (Michel scaling; Michel 1969; Fendt & Camenzind 1996).

Additional magnetic pressure. The stellar magnetic field also provides an additional central magnetic pressure which may result in a de-collimation of the overall outflow. The central stellar magnetic field may launch a strong stellar wind which will remove stellar angular momentum. Such an outflow will interact with the surrounding disk wind. If true, observed jets and outflows from stellar sources may consist of two components – the stellar wind and the disk wind. Note that so far this argument is "ad-hoc" and numerical simulations are needed to figure out the actual dynamical evolution (see below). Simulations of stellar MHD winds have been provided by Matt & Pudritz (2005, 2008).

Angular momentum exchange by the stellar field. In the scenario of magnetic "disk locking", the stellar field which threads the disk will re-arrange the global angular momentum budget. If the star looses angular momentum to the disk, both disk accretion and outflow formation is affected. In this case the angular momentum is transferred by the dipolar field. It is deposited close to the inner disk radius, not farther out than the last closed field line. Therefore, the matter in this region may be accelerated to slightly super-Keplerian rotation which has two interesting aspects. (i) Due to the super-Keplerian speed this disk material could be easily expelled into the corona by magneto-centrifugal launching (Blandford & Payne 1982; Ferreira 1997) and form a disk wind. (ii) The excess angular momentum will stop accretion unless it is removed by some further (unknown) process. A disk outflow launched from the very inner part of the disk can be an efficient way to do this.

The torque on the star by the accretion of disk matter is $\tau_{\rm acc} = \dot{M}_{\rm acc} \, (G M_\star r_{\rm in})^{1/2}$ (e.g. Matt & Pudritz 2005; Pudritz et al. 2007),with the disk accretion rate $\dot{M}_{\rm acc}$, the stellar mass $M_\star$ and the disk inner radius $r_{\rm in}$ inside the co-rotation radius. For "disk locking", the star may be braked-down by the magnetic torque due to stellar field lines connecting the star with the accretion disk outside the co-rotation radius. The differential magnetic torque acting on a disk annulus of dr width is $d\tau_{\rm mag} = r^2 B_\phi B_z dr$. However, while B_z may be derived by assuming a central dipolar field, the induction of toroidal magnetic fields (electric currents) is model dependent.

Non-axisymmetric effects from a tipped magnetic dipole. A central dipolar field inclined to the rotation axis of star and disk may strongly disturb the axisymmetry of the system. In extreme cases this may hinder jet formation at all, while weaker non-axisymmetric perturbation may lead to warping of the inner disk, and thus a precession of the outflow launched from this area. A rotating inclined dipole also implies a time-variation of the magnetic field which may lead to a time-variation in the mass flow rates for both the accretion disk and the outflow.

Investigations of the warping process by Pfeiffer & Lai (2004) using numerical simulations show that the warp could evolve into a steady state precessing rigidly. Disks can be warped by the magnetic torque that arises from the a slight misalignment between the disk and star's rotation axis (Lai 1999). This disk warping mechanism may also operate in the absence of a stellar magnetosphere as purely induced by the interaction between a large-scale magnetic field and the disk electric current and, thus, may lead to the precession of magnetic jets/outflows (Lai 2003).

3. MHD simulations: disk jets with of different magnetic flux profiles

Here we discuss simulations of jet formation where jets are form from pure disk winds (for details see Fendt 2006; Pudritz et al. 2006). The physical grid size corresponds to $(r \times z) = (150 \times 300)\, r_{\rm in}$.

We start from a force-free initial field distribution in hydrostatic equilibrium. The simulation evolves under the boundary condition of a fixed mass inflow from the accretion disk into the outflow. However, we run various models, covering a wide range of disk magnetic field profiles and disk wind mass flux profiles, parameterized by a power law, $B_{\rm p,wind}(r) \sim r^{-\mu}, \rho_{\rm wind}(r) \sim r^{-\mu_\rho}$. Both quantities can be combined in the disk wind magnetization parameter (Michel 1969), $\sigma_{\rm wind} \sim B_{\rm p}^2 r^4 \Omega_F^2 / \dot{M}_{wind} \sim r^{\mu_\sigma}$. We quantify the collimation degree by comparing the axial and lateral mass fluxes (see Fendt & Cemeljic 2002; Fendt 2006). Figure 1) shows the degree of collimation measured by the parameter ζ is plotted against the power law exponent of the disk wind magnetization μ_σ. The main result is that steep magnetization profiles, resp. the disk magnetic field profiles, are unlikely to generate highly collimated outflows. However, flat profiles which generally lead to a higher jet colli-

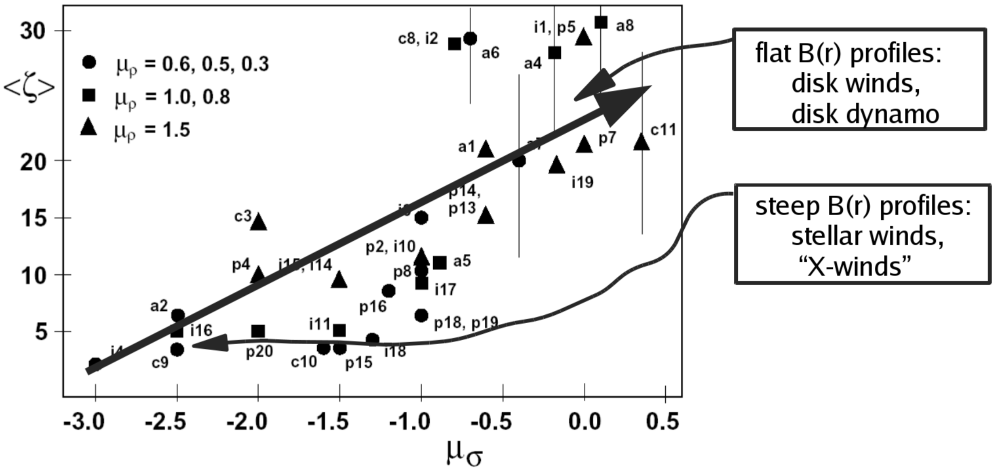

Fig. 1. Time evolution of the axial mass flux close to the upper boundary. The mass flux changes during the initial evolution (sweep-out of the initial corona), but also during the flaring events.

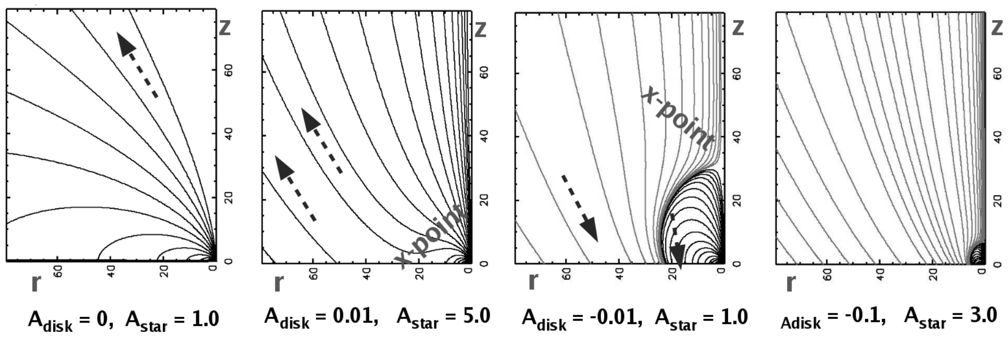

Fig. 2. Initial magnetic field distribution for star-disk jet formation simulations, shown are poloidal magnetic field lines. Arrows indicate the magnetic field direction. Note the different location of the X-points. Different strength and orientation of the superposed stellar and disk magnetic field component, $A_{\rm disk} = 0.0, 0.01, -0.01, -0.1$, resp. $A_{\rm star} = 1.0, 5.0, 1.0, 3.0$ (from left to right). Note that here we show the left hemisphere (rotation axis directs upwards).

mation degree, tend to be unstable, i.e. do not establish a steady state.

Thus, result may indicate that transient jet features arise from accretion disks with flat magnetic flux profiles. transient jet features.

4. MHD simulations: outflows from disk-star magnetospheres

Here we present results of MHD simulations considering the co-evolution of a stellar magnetosphere and a disk magnetic field where both field components are fed by a mass flux from the underlying boundary condition - representing the stellar surface and the accretion disk. The field direction of both components can be aligned or anti-aligned. Similar configurations were considered by Uchida & Low (1981) and were recently reconsidered in the form of reconnection X-winds Ferreira et al. (2006).

In our model we apply cylindrical coordinates (r, ϕ, z), and divide the equatorial in three parts - the stellar surface with $r < r_\star = 0.5 r_{\rm in}$,

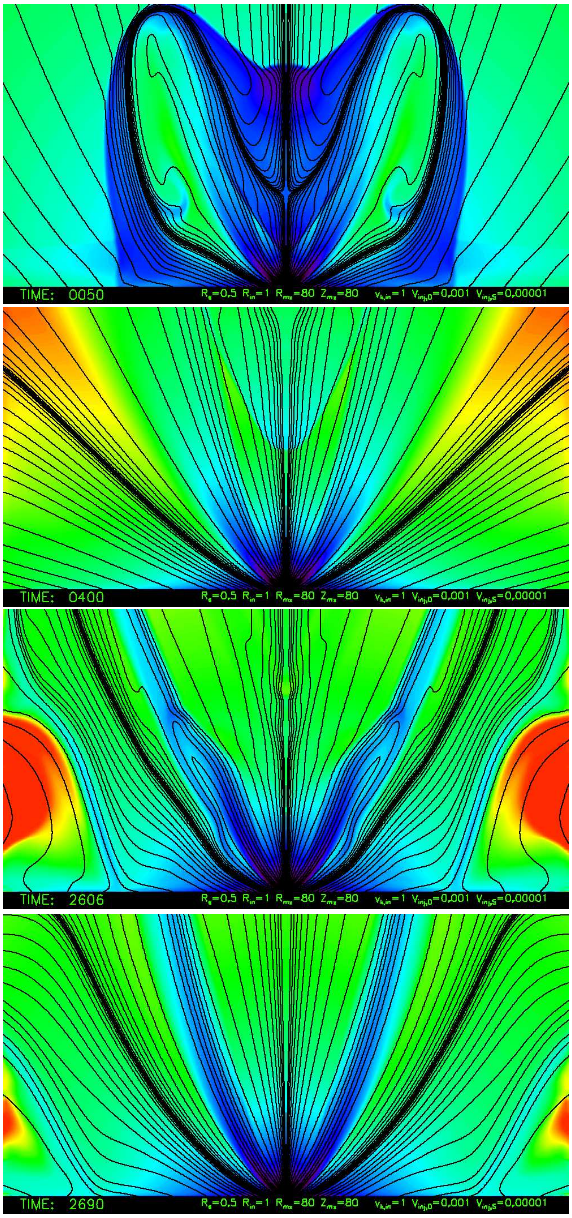

Fig. 3. Time evolution of a star-disk magnetosphere from initial state of Fig. reffig:star-disk-ini, middle. Time step is 50, 400, 2606, 2700 rotations of the inner disk (from top to bottom). Colors show logarithmic density contours, black lines are poloidal field lines (magnetic flux contours).
Note that here we show both upper hemispheres (rotation axis directs upwards).

the accretion disk at radii $r > r_{\rm in} = 1.0$, and also the gap between star and disk. The outflow mass flux consists of a stellar wind contribution and a disk wind contribution. The central star is rotating with a magnetospheric co-rotation radius equal to the disk inner radius. The grid size is $(r \times z) = (80 \times 80)$ inner disk radii which refers to different physical scales when applied to e.g. protostars or XRBs. The initial magnetic field distribution is taken as a superposition of the stellar (dipolar) field and the disk field (force-free potential field),

$$\Psi_{\rm total}(r,z) = A_{\rm disk} f_{\rm disk}(r,z) + A_{\rm star} f_{\rm star}(r,z) \quad (3)$$

(see Fig. 2), where $\Psi_{0,\rm disk}$ and $\Psi_{0,\rm star}$ measure the strength of both components and the functions $f(r,z)$ describe the initial (force-free) magnetic field distribution of both components (Fendt 2009).

Figure 3) shows how the coronal field structure evolves in time for the example simulation with $\Psi_{0,\rm disk} = -0.1$ and $\Psi_{0,\rm star} = 3.0$. In this case, disk magnetic field and stellar dipolar field (along the equatorial plane) are aligned. We evolve the simulations for 2800 rotations at the inner disk radius corresponding to 4 rotations at the outer disk radius. At intermediate time scales (about 700 inner disk rotations) a quasi-stationary state emerges. One clearly sees the de-collimating effect of the central stellar wind component. Note, however, that at this time the outer disk has rotated only about 0.15 times and the coronal structure above the outer disk will further evolve in time and disturb the quasi-steady state. Over the long run such quasi-stationary states may be approached again, what we observed is a cyclic behavior of the opening angle with a periodicity of about 500 (inner disk) rotation periods.

Independent of the alignment, the central dipole does not survive on the large scale. A two-component outflow emerges as stellar wind surrounded by a disk wind. For a reasonably strong disk magnetic flux a collimated jet emerges. If the overall outflow is dominated by a strong stellar outflow the low mass flux disk wind remains un-collimated. The favorable setup to launch a collimated jet from a star-disk magnetosphere is that of a relatively heavy disk wind and high disk magnetic flux.

We also observe that reconnection processes close to the remaining inner dipole leads to sudden flares (see also Goodson et al. 1999)which seem to trigger the large-scale cyclic behavior. The propagation of these flares is very fast, reconnection islands propagate across the jet magnetosphere within a few rotation time steps. In our case the reconnection/flares seem to be triggered by the evolution of the outer disk wind. Even for our very long time-scales the outer disk outflow is still dynamically evolving, thus changing the cross-jet force equilibrium and forcing the inner structure to adjust accordingly. The flare events are accompanied by a temporal change in the outflow mass flux and momentum. Figure 5 shows the mass loss rate in axial direction integrated across the jet. We see two flares with a 10%-increase in the mass flux followed by a sudden decrease of mass flux by a factor of two. This behavior is also seen in the poloidal velocity profile.

Considering the ejection of large-scale flares and the follow-up re-configuration of outflow dynamics, we hypothesize that the origin of jet knots is triggered by such flaring events. Our time-scale for flare generation is of 1000 rotational periods and longer than the typical dynamical time at the jet base, but similar to the observed knots. The flare itself for about 30-40 inner disk rotation times (see Fendt (2009) for a comparison to the Sweet-Parker reconnection time scale which turns out to be of the same order for the simulation parameters applied).

5. Reconnection flares triggering unsteady jets?

Massi & Kaufman Bernado (2008) provide a summary on magnetic field strengths, accretion rate, and jet parameters in micro quasars (MQs) and X-ray binaries (XRBs). For the sources carrying a neutron star in the center (i.e. not a black hole) the flaring model due to disk - star magnetic field interaction discussed above may be applied.

We first need an energy estimate. The maximum magnetic energy density available is $\sim B^2/8\pi$. As typical field strength we take the stellar dipolar field at the inner disk radius (see eq. 1). The volume of the flaring region we estimate as a cylinder with radius of the inner disk

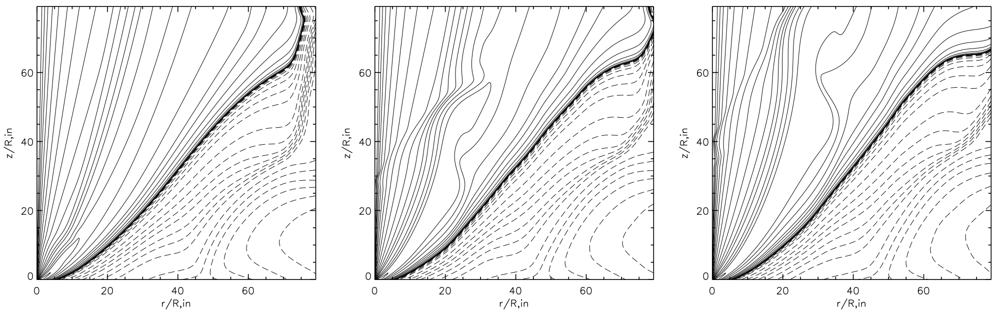

Fig. 4. Poloidal magnetic field evolution during one example flare around t = 1800. Solid and dashed lines indicate the direction of total magnetic flux of the superposed dipolar and disk magnetic field components. Shown are time steps: 1760, 1790, 1810 (from left to right). Note that here we show the right hemisphere (rotation axis directs upwards).

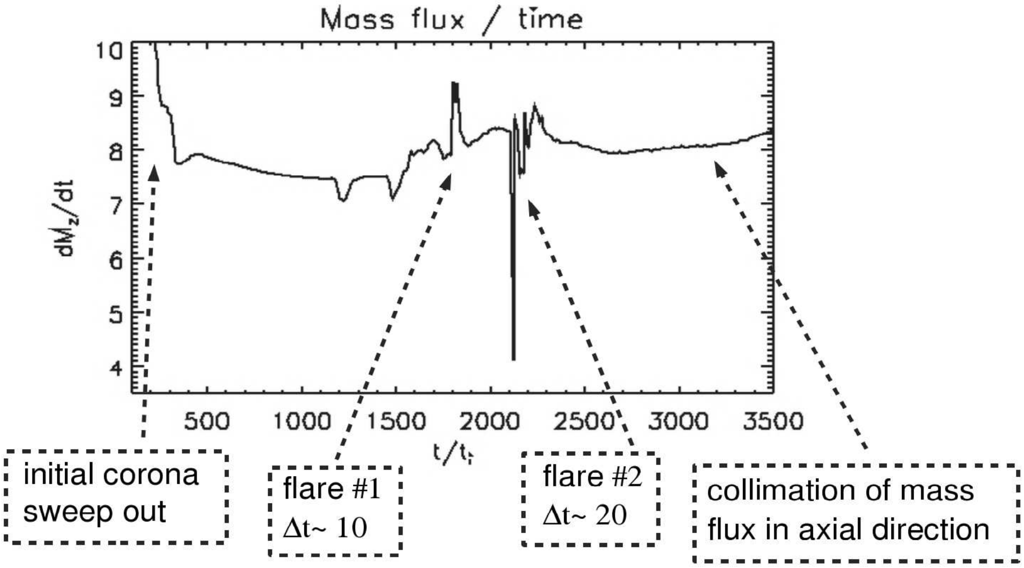

Fig. 5. Time evolution of the axial mass flux close to the upper boundary. The mass flux changes during the initial evolution (sweep-out of the initial corona), but also during the flaring events.

radius $r_{\rm in}$, a height of five disk scale heights, $\Delta z = 5h = 2.5 r_{\rm in}$ (assuming a thick disk model $h \sim 0.5r$), a gauge of $\Delta r = \Delta z$, thus a volume of $\Delta V \simeq 2.5\pi r_{\rm in}^3$. With that the magnetic energy available is about

$$E_{\rm B} = 1.5 \times 10^{34} {\rm erg} \left(\frac{B_0}{10^9 {\rm G}}\right)^2 \left(\frac{r_{\rm in}}{5\, R_{\rm NS}}\right)^{-3} \qquad (4)$$

This corresponds to an upper limit for the flare energy, assuming that a global 3D structure (a cylinder ring is flaring at the same time and that all magnetic energy is transferred. Applying the flare time scale derived from our numerical simulations above the flare luminosity is about $L_{\rm B} \simeq E_{\rm B}/\tau_{\rm flare} \simeq 2 \times 10^{28}$erg/s. Since the dipolar stellar field decays rapidly with radius, reconnection events from radii $\sim 50 R_{\rm NS}$ would provide much less (factor 1000) energy.

This should be compared to typical kinetic jet energies,

$$L_{\rm kin} = 1.5 \times 10^{33} {\rm erg s}^{-1} \left(\frac{v_{\rm jet}}{0.5\,c}\right)^2 \left(\frac{\dot{M}_{\rm jet}}{10^{-3}\dot{M}_{\rm acc}}\right)\left(\frac{\dot{M}_{\rm acc}}{10^{-10} M_{\odot} {\rm yr}^{-1}}\right). \quad (5)$$

This value is clearly beyond the capabilities of a flaring event discussed above. However, one may understand the flare energy transferred to a much smaller mass load, creating a wave riding on the jet stream which higher velocity and triggering a shock wave visible as transient flow. Still the energy provided by the flare seems to be too low considering even a transient flow of, say 10^{-4} of the bulk jet kinetic luminosity. Only if we consider extremely low mass fluxes for the bulk jet, the large-scale reconnection may cause a significant contribution to the kinetic energy propagating along the jet. On the other side, the jet mass flux may in fact be the essential parameter dividing transient from steady jet flows.

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