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LETTERS

Launching jets from accretion belts

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Abstract We propose that sub-Keplerian accretion belts around stars might launch jets. The sub-Keplerian inflow does not form a rotationally supported accretion disk, but it rather reaches the accreting object from a wide solid angle. The basic ingredients of the flow are a turbulent region where the accretion belt interacts with the accreting object via a shear layer, and two avoidance regions on the poles where the accretion rate is very low. A dynamo that is developed in the shear layer amplifies magnetic fields to high values. It is likely that the amplified magnetic fields form polar outflows from the avoidance regions. Our speculative belt-launched jets model has implications on a rich variety of astrophysical objects, from the removal of common envelopes to the explosion of core collapse supernovae by jittering jets.

Key words: stars: jets — (stars:) binaries: accretion discs — (stars:) supernovae: general — accretion, accretion disks

1 INTRODUCTION

Jets are known to be launched by accretion disks around compact objects (e.g., Livio 2011), such as supermassive black holes in active galactic nuclei, X-ray binaries, young stellar objects (YSOs), and in planetary nebulae (e.g., Sahai & Nyman 2000). In many of these objects the jets are observed and resolved. Here we propose a mechanism to launch jets by objects that are embedded inside optically thick gas, and in most cases cannot be observed. In such cases the gas originates from regions close to the compact object, and in some cases does not have large enough specific angular momentum to form an accretion disk. Instead, the accreted gas forms a sub-Keplerian inflow with density increasing toward the equator of the compact object. We term this flow an accretion belt. We are particularly motivated to shed light on the possibility that jets are launched by accretion belts around main sequence (MS) stars that undergo a spiraling-in motion inside the large envelope of a giant star; i.e., common envelope evolution. In such a situation the mechanism of jet launching should not involve an extended accretion disk. As such, we also relax the assumption that large scale magnetic fields exist in the accreted gas.

Many jet launching models are based on the operation of large scale magnetic fields, i.e., those with coherence scale larger than the radius of the disk at the considered location (e.g., Zanni & Ferreira 2013, Narayan et al. 2014 and references therein). Some models do not rely on the magnetic fields of the accreting compact object, but rather assume an outflow from an extended disk region with large scale magnetic fields (e.g., Konigl & Pudritz 2000; Shu et al. 2000; Ferreira 2002; Krasnopolsky et al. 2003; Ferreira & Casse 2004; Murphy et al. 2010; Sheikhnezami et al. 2012; Tzeferacos et al. 2013; Sheikhnezami & Fendt 2015).

We note the following properties that support our approach of not basing our mechanism on large scale magnetic fields. First, the strong dynamo that operates in accretion disks is likely to modify the structure of the large scale magnetic fields (e.g. Hujeirat et al. 2003). Second, Ferreira (2013) concluded that launching models that describe steady state jets cannot spin down protostars to the observed values of roughly 10% of their break-up speed. By contrast, unsteady models are better candidates for the removal of energy and angular momentum from the disk. Our proposed mechanism for jet launching in sub-Keplerian accretion flows is based on unsteady behavior of the magnetic fields. Our proposed mechanism incorporates reconnection of magnetic field lines that takes place in many sporadic events in the accretion belt, much like magnetic activity that occurs on the solar surface. These events, we propose in this study, eject mass along the polar directions and lead to the formation of jets.

We aim at two cases in particular: (1) The case where an MS star is spiraling-in inside the envelope of a giant star. The MS star can accrete mass from the envelope at a rate of the order of the Eddington limit. The specific angular momentum of the accreted gas, $j_{\rm acc}$, might be in many cases below that required to form a Keplerian accretion disk around the MS star, $j_{\rm Kep}$, but still be non-negligible, $j_{\rm acc} \approx 0.1 - 1 j_{\rm Kep}$ (Soker 2004). (2) Accretion onto a newly born neutron star (NS) in a core collapse supernova (CCSN). In some CCSNe the accreted gas might possess a rapidly varying non-negligible value of the specific angular momentum, but is not sufficient to form a Keplerian accretion disk (Gilkis & Soker 2015b,a; Papish et al. 2015a). Both scenarios are quite difficult for observational validation.

Incorporating ingredients from accretion disks formed at high accretion rates, we build the belt-launched jets model. The basic ingredients of the model are described in Section 2, and the dynamo is discussed in Section 3. The implications for some specific astrophysical objects are discussed in Section 4 which also contains our summary.

2 BASIC INGREDIENTS

A geometrically-thin Keplerian accretion disk is connected to the accreting body, if it is not a black hole and if the accreting body's magnetic field is not too strong, via a thin high-shear layer termed the boundary layer (e.g., Regev 1983; Regev & Bertout 1995). The matter in the boundary layer expands to higher latitudes along the surface of the accreting body. Inogamov & Sunyaev (1999) built a model for cases of high accretion rates onto NSs, and proposed that the meridional spreading brings the accreted mass close to the poles. In that model, the luminosity from the spreading layer, or belt, reaches a maximum some distance from the equatorial plane. The accreted gas spins-down to the rotational velocity of the accreting body through a turbulent friction that exists in the spreading layer (Inogamov & Sunyaev 1999, 2010). This type of flow is depicted in the right side of Figure 1. The left side of Figure 1 schematically presents the flow structure proposed in the present study.

Two comments can be made here regarding Figure 1. (1) In this study we consider cases where a Keplerian disk does not form, at least not initially. It is true that when the thermal and/or magnetic pressures are considered the angular velocity of the gas in the disk is slightly sub-Keplerian. For example, simulations for jets-launching disks have slightly sub-Keplerian disks (e.g., Casse & Keppens 2002; Zanni et al. 2007). However, we consider cases where the magnetic and thermal pressures are not sufficient to allow an accretion disk at early times. Later, after the initial magnetic field has been amplified and viscosity has transferred angular momentum outward, an accretion disk might be formed. If an accretion disk does form, then the launching of jets becomes even more likely. Here we take the pessimistic case that an accretion disk does not form. (2) Because of the sub-Keplerian angular momentum, away from the accreting star, the flow is not influenced much by the rotation. For example, for an MS star orbiting inside a giant star, the accretion might be described by Bondi-Hoyle-Lyttleton accretion. For an NS accreting from a collapsing core, the flow can be spherical on a large scale. However, when the angular velocity is sub-Keplerian but non-negligible, very close to the surface of the star the gas is concentrated toward the equatorial plane. In the polar regions the density of the inflowing gas is very low.

It is not possible to directly apply the results of Inogamov & Sunyaev (1999) to the cases we study here (listed in Sect. 1). We study MS stars accreting at very high rates, a process that is different from accretion onto an NS. For example, radiation pressure might not be as important as in accretion onto an NS. In the flow structure onto a newly born NS in a CCSN, cooling is mainly via neutrinos, and not by photon emission. The flow structures we discuss here are more complicated, and 3D numerical studies will be required to simulate such flows. The study of Inogamov & Sunyaev (1999) nontheless suggests that an energetic wide accretion belt can be formed on the surface of the accreting body, and that turbulence is expected in such a belt.

Neglecting magnetic fields, Inogamov & Sunyaev (1999) find that the meridional extent of the hot part of the spreading layer (the belt) $\theta_\star$ is approximately given by

$$\sin\theta_\star \approx \frac{\dot{M}_{\rm acc} v_K^2}{2L_{\rm edd}}, \tag{1}$$

where $L_{\rm edd}$ is the Eddington luminosity limit, $\dot{M}_{\rm acc}$ is the accretion rate and v_K is the Keplerian velocity on the surface of the accreting body. One can find that for accreting rates larger than about $10^{18}\ {\rm g\ s^{-1}} \simeq 10^{-8} M_\odot\ {\rm yr}^{-1}$ onto an NS with a mass of $M_{\rm NS} \approx 1.4\, M_\odot$ and a radius of $R = 12\ {\rm km}$, the spreading layer extends to the polar regions. Here, we also apply Equation (1) to accretion onto an MS star. We find that for the spreading layer to reach the polar region of an accreting solar-like star, the accretion rate should be larger than approximately $10^{-3} M_\odot\ {\rm yr}^{-1}$. Such accretion rates can be achieved during the common envelope evolution.

We note that Equation (1) was developed for a belt formed by an accretion disk. Here we investigate cases where no geometrically-thin accretion disk is formed, but rather the accreted gas streams from a wide angle, with an avoidance region near the poles. In addition, Equation (1) does not take into account magnetic activity. The magnetic activity leads to mass ejection from the polar regions, and maintains that region open to an outflow (see below).

In the sub-Keplerian inflow scenario, the accreted gas has an average specific angular momentum of $j_{\rm acc} < j_{\rm Kep}$, where $j_{\rm Kep} = (GMR)^{1/2}$ is the Keplerian specific angular momentum on the surface of the accreting object with mass M and radius R. A parcel of gas with such an angular momentum cannot be accreted to the surface of the star

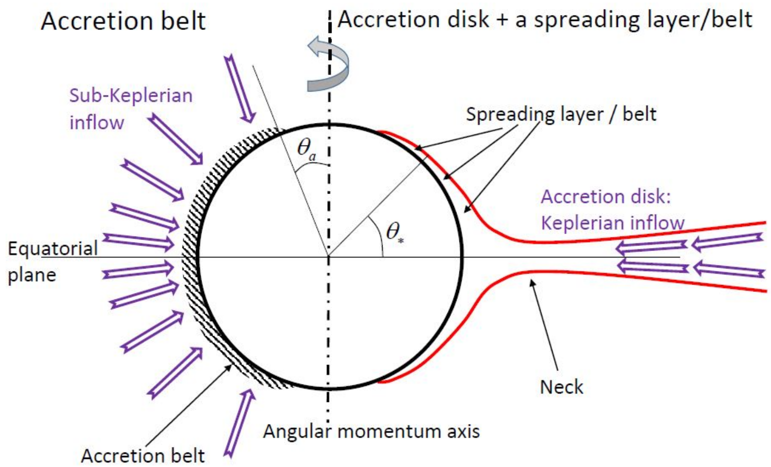

Fig. 1 The flow structure studied here is presented schematically in the left side of the figure. It has some similarities with the spreading layer, which was proposed by Inogamov & Sunyaev (1999) and is presented in the right side. The meridional extent of the hot part of the spreading layer $\theta_\star$ is described by Eq. (1). The region forming the angle of avoidance θ_a is given by Eq. (2).

within an angle θ_a from the poles. θ_a is given by (Papish et al. 2015a)

$$\theta_a = \sin^{-1}\sqrt{\frac{j_{\rm acc}}{j_{\rm Kep}}}. \tag{2}$$

This is termed the avoidance angle.

In Section 3 we speculate that the extended belt formed in the sub-Keplerian accretion flow can launch jets. We suggest there that the strong radial shear due to the powerful differential rotation, together with the turbulence, amplifies magnetic fields through the dynamo action. MHD effects, such as reconnection of magnetic field lines and dragging gas in the polar directions via magnetic stress of field lines that are anchored to the accreted gas, then launch a polar-collimated outflow. The point to make here is that in the case of a belt formed by an accretion disk it is expected that more mass will be launched by the accretion disk than by the belt. In the sub-Keplerian wide inflow case, most, or even all, of the outflowing gas is launched by the belt.

The amplification of magnetic fields affects the opening angle as given in Equation (2). (1) Reconnection of the magnetic field lines ejects gas through the two opposite polar avoidance regions. This activity, which leads to the formation of an outflow and high magnetic pressure region, might increase the opening angle in the inflowing gas. (2) Winding of the magnetic field lines frozen to the polar outflow channels rotational energy to kinetic energy of the outflow. The magnetic tension of the magnetic field lines might further increase the opening angle. Overall, the opening angle increases with the specific angular momentum of the accreted gas, and might be further increased by magnetic activity.

The basic ingredients of the belt-launched jets scenario are presented in Table 1 along with those of jets launched by accretion disks. Our proposed launching mechanism does not require large scale magnetic fields and does not require a thin Keplerian disk. The most important ingredient is the operation of a dynamo, the belt dynamo.

3 THE BELT DYNAMO

There are several approaches to estimate the amplification of magnetic fields in sheared layers in stellar interiors, both in convective and non-convective regions. In the present preliminary study we perform one calculation that applies to a non-convective region. We then argue that in a convective region of the accretion belt the amplification will be even more efficient.

Spruit (2002) described the analytic grounds for quantifying the magnetic fields created in non-convective layers in a differentially rotating star. The differential rotation stretches poloidal field lines into toroidal fields. Magnetic instabilities in the amplified toroidal magnetic fields replace the role of convection in creating more poloidal magnetic fields from the toroidal fields. This process, which is relatively slow in the stellar interior, is expected to be more efficient in a more rapidly spinning belt. The turbulent regions of the belt are even more efficient in amplifying the magnetic field. We now show that even in the non-turbulent regions of the belt the dynamo can still be effective.

Due to the strong differential rotation (shear) occurring in the belt, the radial component of the field, B_r, is twisted into the azimuthal direction, B_ϕ, so that after a few rotations it becomes the dominant component. Its strength increases linearly with time, until it becomes unstable. The amplitude of the dynamo-generated field in the

Table 1 Jet Launching Cases

Physical parameter	Accretion disk	Accretion Belt
Accretion rate ($\dot{M}_{\rm acc}$)	up to $\approx \dot{M}_{\rm Edd}$	$\gtrsim \dot{M}_{\rm Edd}$
Accreted specific angular momentum ($j_{\rm acc}$)	$\gg j_{\rm Kep}$	$< j_{\rm Kep}$
Angular velocity at launching ($\Omega_{\rm L}$)	$\approx \Omega_{\rm Kep}$	$< \Omega_{\rm Kep}$
Launching area ($D_{\rm L}$)	$\gg R$	$\simeq R$
Magnetic fields	weak to strong	$\boldsymbol{B}$ is amplified locally via dynamo
Jet's energy source	Gravitational energy of accreted gas	Gravitational energy of accreted gas

Notes: The different symbols have the following meanings: R is the radius of the accreting body; $\dot{M}_{\rm Edd}$ is the Eddington accretion limit; $j_{\rm Kep}$ and $\Omega_{\rm Kep}$ are the Keplerian specific angular momentum and angular velocity very close to the surface of the accreting body, respectively.

non-turbulent regions is given by (Spruit 2002)

$$B_\phi = r\,(4\pi\rho)^{1/2}\,\Omega_{\rm belt}\,q^{1/2}\left(\frac{\Omega_{\rm belt}}{N}\right)^{1/8}\left(\frac{\kappa}{r^2 N}\right)^{1/8}, \tag{3}$$

$$B_r = B_\phi\left(\frac{\Omega_{\rm belt}}{N}\right)^{1/4}\left(\frac{\kappa}{r^2 N}\right)^{1/4}, \tag{4}$$

where the density in the belt is estimated from mass conservation of the inflowing gas

$$\rho = \dot{M}\left(4\pi r^2\, v_{\rm in}\right)^{-1}, \tag{5}$$

and $v_{\rm in}$ is the radial inflow speed into the belt, which we take as the free-fall velocity. The temperature of the accreted plasma when it is stopped on the accreting object is calculated from $3/2kT = 1/2\, m_p v_{\rm in}^2$. Here $\Omega_{\rm belt}$ is the angular velocity of the belt and N is the buoyancy (Brunt-Väisälä) frequency that is slightly less than the Keplerian frequency. We can crudely take $N \approx \Omega_{\rm belt}$. The thermal diffusivity is $\kappa = 16\sigma T^3/(3\kappa_R\rho^2 c_p)$, where c_p is the heat capacity per unit mass, κ_R is the opacity and $q = (r\partial_r\Omega_{\rm belt})/\Omega_{\rm belt} \simeq 1-3$ is the dimensionless differential rotation rate.

Because the cooling in an accreting NS in a CCSN is due to neutrinos, we apply Equations (3) and (4) to accreting MS stars. We take an accretion rate of $\dot{M}_{\rm acc} = 10^{-3} M_\odot\,{\rm yr}^{-1}$ onto a solar like star, from which we find the density of the accretion inflow near the surface, and the temperature of the gas in the belt to be $T = 10^6$ K. We find that $\kappa \approx 10^{22}\,{\rm cm}^2\,{\rm s}^{-1}$, and so $[\kappa/(r^2N)]^{1/8} \approx 1$. From Equation (3), we can derive the ratio of the magnetic field energy density to the kinetic and thermal gas energy densities, for an accreting MS star at a rate of $\dot{M}_{\rm acc} \approx 10^{-2} - 10^{-4} M_\odot\,{\rm yr}^{-1}$. For the gas energy density we take $\rho v_{\rm esc}^2/2$, where $v_{\rm esc}$ is the escape velocity from the star

$$\frac{B^2/4\pi}{e_{\rm gas}} \approx 0.2q\left(\frac{\Omega_{\rm belt}/\Omega_{\rm Kep}}{0.3}\right)^2\left(\frac{\Omega_{\rm belt}}{N}\right)^{1/4} \times\left(\frac{\kappa}{r^2 N}\right)^{1/4}.$$

As stated, this is for the non-turbulent part of the accretion belt. As turbulence is expected in the strongly sheared belt, the amplification can be a more efficient process. We conclude that a fraction of $\approx$ few $\times\, 0.1$ of the accreted energy is channeled to magnetic energy. In our proposed scenario the magnetic field lines are further wound and stretched by the rotating belt as they are dragged by the outflowing gas. The magnetic fields reconnect and launch jets.

In claiming that an efficient dynamo can operate in the accretion belt we are encouraged by the recent results of Mösta et al. (2015) who conducted very high resolution simulations of CCSNe with pre-collapse rapidly rotating cores. They show that rapidly rotating material around the newly born NS can tremendously amplify an initial magnetic field, and lead to jets being launched. In their simulations, the turbulent kinetic energy in the accreted gas is converted into electromagnetic energy. The timescale for an e-fold increase in the magnetic field in the accretion disk, $\tau_e \approx 0.5$ ms, is about half an orbital period in the relevant part of the disk. Interestingly, only very-high resolution simulations have been able to demonstrate the tremendous magnetic field amplification. These results are very supportive of the jittering jets model for the explosion of all CCSNe with explosion energies of $\gtrsim 2\times 10^{50}$ erg.

Intermittent accretion belts in CCSNe are expected to last for a time of $\tau_b \approx 0.01 - 0.1$ s, as estimated either from the fluctuation in the convective shells of the pre-collapse core (Gilkis & Soker 2015a), or from fluctuations in the post-collapse region around the NS formed by the standing accretion shock instability (Papish et al. 2015a). This timescale is about equal to tens of Keplerian orbits at $\sim$ 20 km from the NS. A belt with a specific angular momentum of $\eta \equiv j_{\rm acc}/j_{\rm Kep}$ has an orbital period on the equator of the newly born NS of $\approx 26(\eta/0.05)^{-1}(r/20\,{\rm km})^{3/2}$ ms. Closer to the poles the period will be shorter. Overall, the accretion belt can last for a timescale that is several times and up to tens times a half orbital period. According to the results of Mösta et al. (2015), this is a sufficiently long time to amplify the magnetic fields. This shows that the sub-Keplerian disk might have sufficient time to substantially amplify the magnetic fields. We conjecture that the strong magnetic fields with the preferred axis of rotation and the avoidance angle (Eq. 2) lead to the launching of two opposite jets in the polar directions, where the ram pressure of the accreted gas is very low.

4 DISCUSSION AND SUMMARY

We conducted a preliminary study that leads us to argue that sub-Keplerian accretion flows onto compact objects can launch jets. The sub-Keplerian accreted gas forms an accretion belt rather than an accretion disk (left side of Fig. 1). Within the avoidance angle θ_a from the polar directions (Eq. (2)) the accretion rate is very low. The dynamo amplification of the magnetic fields within the belt (Sect. 3) can lead to very strong magnetic fields, as can be seen from Equation (6) that gives the ratio of the amplified magnetic field energy density to that in the accreted gas.

We speculate that reconnection of the magnetic field lines can lead to an outflow through the two opposite polar avoidance regions. Winding of the magnetic field lines frozen to the polar outflow can further channel rotational energy to kinetic energy of the outflow. The main differences and common properties of the proposed belt-launched jets scenario compared to those of the common disk-launched jets are presented in Table 1.

Our conclusion is that accretion belts that are formed by sub-Keplerian accretion flows might launch jets. If true, these results might have far reaching implications for the removal of common envelopes by jets. Numerical studies point at a limited efficiency of the common envelope removal by the gravitational energy released during the spiraling-in process (e.g., De Marco et al. 2011; Passy et al. 2012; Ricker & Taam 2012; Ohlmann et al. 2016). It has been suggested that jets can assist in removing the common envelope (e.g. Soker 2014). However, the specific angular momentum of the gas accreted by an MS star spiraling-in inside a giant envelope is sub-Keplerian with $j_{\rm acc} \approx 0.1 - 1 j_{\rm Kep}$ (Soker 2004). A belt is expected to be formed around the MS star during the common envelope phase. Jets that might be launched by the belt, as argued in the present study, can assist in removing the common envelope.

In addition, our results might have implications for CCSN explosion scenarios. The delayed-neutrino mechanism has severe problems in accounting for explosions with kinetic energy of more than about $2 - 5 \times 10^{50}$ erg (Papish et al. 2015b). An intermittent accretion belt is expected to be formed around a newly born NS during the first several seconds of the explosion (Gilkis & Soker 2015b,a; Papish et al. 2015b). If the present results hold for such a flow structure, then the jets can cause the star to explode, up to explosion energies of above 10^{52} erg (Gilkis et al. 2015). We note that because of the stochastic nature of the angular momentum of the accreted mass in many CCSNe, in the jittering jets model the spin of the NS might be inclined with respect to the instantaneous angular momentum of the belt. The effect of this will be studied in future numerical simulations.

In both cases of common envelope removal and CCSN, the origin region of the jets is completely obscured. In cases where the origin of the jets is seen, such as in YSOs, active galactic nuclei and some binary systems, the accretion rate is low and an accretion disk is required to be formed. Here we argue that in cases where the accretion rate is very high, and hence the entire region is heavily obscured, even an accretion belt formed by a sub-Keplerian inflow can launch jets (also see Shiber et al. 2015).

We can summarize our study by stating that the possibility for accretion belts to launch collimated outflows, or jets, opens a rich variety of processes that can account for some puzzles in astrophysics, such as the explosion of massive stars and in some cases the removal of a common envelope.

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