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Are jets in symbiotic stars driven by magnetic fields?

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Abstract. We compare two scenarios to launch jets – formation by MHD processes or formation by thermal pressure in the boundary layer (BL) – with respect to their compatibility with observational data of jets in symbiotic stars, especially in the well studied jet source MWC 560. Finally, we discuss points of further research to be done.

Key words. ISM: jets and outflows – binaries: symbiotic

1. Introduction

Although jets are ubiquitous phenomena in many different astrophysical objects as young stellar objects where they are driven by protostars, symbiotic stars (white dwarfs), X-ray binaries (neutron stars and stellar mass black holes) and active galactic nuclei (supermassive black holes), their formation is relatively unclear.

The mass loss rate of the jet is found to be connected to the mass accretion rate of the underlying disc found in most objects (e.g. Livio 1997). Therefore the necessary components seem to be well known and common to all objects. A more careful investigation of one specific class of objects should promise new insights also for the mechanisms in the other classes. From the observational point of view, one needs observations with a high spatial resolution and kinematic informations from regions as near as possible to the jet source. These aspects make the class of symbiotic stars ideal testbeds.

Symbiotic stars are interacting binaries with orbital periods in the range of years. These systems show outbursts similar to classical novae. The stellar component is a cool red giant (RG), the hot component a white dwarf (WD) with temperatures of 50 000–200 000 K. Both stars show mass loss through supersonic winds. Wind material from the RG is captured by the WD to form an accretion disc. The accretion then causes thermonuclear explosions of the WD surface leading to an increase in luminosity followed by jet emission. Jets are detected in 10 out of almost 200 symbiotic stars (Brocksopp et al. 2004) and this process was directly observed in CH Cygni (Taylor et al. 1986). Other famous systems are R Aquarii and MWC 560. While the first two objects are seen at high inclinations, the jet axis in MWC 560 is practically parallel to the line of sight.

Another class of accreting WDs are cataclysmic variables (CV) which are *very close* WD binaries with a low mass main sequence star as companion. The mass transfer is due to Roche lobe overflow, not due to wind accretion. The short timescales in these systems make them the best understood accreting systems. Remarkably, they show no jet emission. Further related objects are supersoft X-ray sources, in which the temperature and pressure in the boundary layer (BL) of the WD are in the correct range to maintain steady nuclear burning on the WD surface.

In jet formation models presented so far, the magnetic field seems to play a key role. The first analytical work studying magneto-centrifugal acceleration along magnetic field lines threading an accretion disc was done by Blandford & Payne (1982). They have shown the braking of matter in azimuthal direction inside the disc and their acceleration above the disc surface by the poloidal magnetic field components. Toroidal components of the magnetic field then collimate the flow. Numerous semi-analytic models extended the work of Blandford & Payne (1982), either restricted to self-similar solutions and their geometric limitations (e.g. Pudritz & Norman 1986; Vlahakis & Tsinganos 1998, 1999; Ferreira & Casse 2004) or with non-self-similar solutions (e.g. Camenzind 1990; Pelletier & Pudritz 1992; Breitmoser & Camenzind 2000).

Another approach is to use time-dependant numerical MHD simulations to investigate the formation and collimation of jets. In most models, however, a polytropic equilibrium accretion disc was regarded as a boundary condition (e.g. Krasnopolsky et al. 1999, 2004; Anderson et al. 2004; Goodson et al. 1999). The magnetic feedback on the disc structure is therefore not calculated self-consistently. Only in recent years were the first simulations including the accretion disc self-consistently in the calculations of jet formation presented (e.g. Casse & Keppens 2002, 2004; Kato et al. 2004).

Due to the fact, that strong magnetic fields have been detected so far only in one symbiotic system (Z Andromedae, Sokoloski & Bildsten 1999), the jet formation by magneto-centrifugal forces exclusively seems to be insufficient. Radiative launching can be excluded due to too small radiation fields. A new possibility to accelerate plasma close to the central object was proposed involving SPLASHs (*SPatiotemporal Localized Accretion SHocks*) in the BL (Soker & Regev 2003). Locally heated bubbles expand, merge and accelerate plasma to velocities larger than the local escape velocity. Soker & Lasota (2004) applied this model to disk-accreting white dwarfs to explain the absence of jets in CV. They have found a critical accretion rate of $\sim 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$ below which no jets should be present. This scenario was introduced only in analytic estimates.

In Sect. 2, we give general estimates based on observations of the well studied jet in MWC 560. After that we calculate the magnetic field near the white dwarf required for jet formation by MHD processes in Sect. 3. In Sect. 4, we list different ways with which a magnetic field in MWC 560 could be detected. Finally a discussion is given.

2. General estimates

As observed by Schmid et al. (2001) and as used to simulate the jet nozzle in Stute et al. (2005), the parameters of the jet in MWC 560 are

- the velocity $v_{\mathrm{jet}} = 1000\ \mathrm{km\,s^{-1}}$;
- the number density $n_{\mathrm{jet}} = 5 \times 10^6\ \mathrm{cm}^{-3}$, which is equal to a mass density $\rho_{\mathrm{jet}} = 8.4 \times 10^{-18}\ \mathrm{g\ cm^{-3}}$; and
- the jet radius $R_{\mathrm{jet}} = 1$ AU.

Using the equations

$$\begin{aligned}\dot{M}_{\mathrm{jet}} &= \pi R_{\mathrm{jet}}^2 m_{\mathrm{H}} n_{\mathrm{jet}} v_{\mathrm{jet}}\\ \dot{P}_0 &= \dot{M}_{\mathrm{jet}} v_{\mathrm{jet}}\\ L_{\mathrm{jet}} &= \frac{1}{2}\dot{M} v_{\mathrm{jet}}^2 = \frac{1}{2}\pi R_{\mathrm{jet}}^2 m_{\mathrm{H}} n_{\mathrm{jet}} v_{\mathrm{jet}}^3,\end{aligned}$$

this specifies

- the mass outflow rate $\dot{M}_{\mathrm{jet}} = 9.33 \times 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$;
- the momentum discharge $\dot{P}_0 = 5.93 \times 10^{25}\ \mathrm{g\ cm^{-1}\ s^{-2}}$; and
- the kinetic jet luminosity $L_{\mathrm{jet}} = 2.93 \times 10^{33}\ \mathrm{erg\ s^{-1}}$.

This luminosity can be provided by several different mechanisms:

- by the (insufficient) luminosity of the white dwarfs
$$\begin{aligned}L_{\mathrm{WD}} &= 4\pi R_*^2 \sigma T^4\\ &= 3.5 \times 10^{30} \left(\frac{R_*}{7\times 10^8\ \mathrm{cm}}\right)^2 \left(\frac{T}{10^4\ \mathrm{K}}\right)^4 \mathrm{erg\,s^{-1}};\end{aligned} \qquad (1)$$
- the accretion power of the disk (and almost the same amount coming from a BL) of a rotating magnetized WD
$$\begin{aligned}L_{\mathrm{acc}} &= \frac{G M_* \dot{M}}{R_*} = 1.19 \times 10^{35} \left(\frac{M_*}{M_\odot}\right)\\ &\times \left(\frac{R_*}{7\times 10^8\ \mathrm{cm}}\right)^{-1} \left(\frac{\dot{M}}{10^{-8}\ M_\odot\ \mathrm{yr}^{-1}}\right) \mathrm{erg\,s^{-1}};\end{aligned} \qquad (2)$$
- or the magnetic luminosity (Camenzind 1997)
$$\begin{aligned}L_{\mathrm{mag}} &= \frac{1}{2}\Omega_* R_*^3 B_{\mathrm{p}} B_\varphi = 4.76 \times 10^{34}\\ &\times \left(\frac{\Omega_*}{\mathrm{h}^{-1}}\right) \left(\frac{R_*}{7\times 10^8\ \mathrm{cm}}\right)^3 \left(\frac{B_{\mathrm{p}}}{\mathrm{MG}}\right) \left(\frac{B_\varphi}{\mathrm{MG}}\right) \mathrm{erg\,s^{-1}}.\end{aligned} \qquad (3)$$

The flux in the UV band was measured as $10^{-9}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$ (Maran et al. 1991) and the UV luminosity – which is likely to be equal to the accretion power of the disk and the boundary layer – is then

$$L_{\mathrm{UV}} = 1.2 \times 10^{35} \left(\frac{d}{\mathrm{kpc}}\right)^2 \mathrm{erg\,s^{-1}}. \qquad (4)$$

With a derived distance of 2.5 kpc, this suggests a minimal accretion rate of $6.3 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ and therefore an ejection efficiency of 14%.

The minimal accretion rate is below the critical accretion rate derived by Soker & Lasota (2004) by a factor of 16. As these authors claim an uncertainty of a factor of ~10 and the remaining factor could naturally arise from our estimates, this should not concern.

Using the observables $\dot{M}$, L_{jet} and $\dot{P}_0$, one can fix in principle the two free parameters χ and Γ of the model of Soker & Regev (2003). These parameters are the fractions of the mass outflow rate due to SPLASHs to the accretion rate and of the initial kinetic energy to the final kinetic energy inside a SPLASH, respectively. Fixing the model highly depends on estimating the right mass accretion rate which, however, is rather difficult.

3. Required magnetic fields in the magnetic jet formation scenario

Let Ψ be a magnetic surface anchored at the inner radius of the accretion disk. Then this surface remains always inside the jet up to large distances. Using the constants of motion along this surface and the jet parameters, one can make detailed estimates following from the scenario.

As magneto-centrifugally driven jets have fast-magnetosonic Mach numbers $M_{\mathrm{fm}} \sim 3$ (e.g. Krasnopolsky et al. 2004), the total magnetic field in the jet should be

$$\sqrt{B_{\mathrm{p,jet}}^2 + B_{\varphi,\mathrm{jet}}^2} = \frac{1}{3}\sqrt{4\pi\rho_{\mathrm{jet}}}\, v_{\mathrm{jet}} = 0.34\ \mathrm{G} \sim B_{\varphi,\mathrm{jet}}, \qquad (5)$$

as the azimuthal component should be dominant inside the jet. With the conservation of current $I = R B_\varphi$, the azimuthal field near the jet source is then

$$B_{\varphi,0} \sim 7.3\ \mathrm{kG}. \qquad (6)$$

As $B_{\varphi,0} \ll B_{\mathrm{p},0}$, the total magnetic field should be by far larger. An upper limit can be found using again Eq. (5), namely $B_{\mathrm{p,jet}} \ll 0.34$ G, and the conservation of flux $\Psi = B_{\mathrm{p}} R^2$, leading to magnetic fields in the range of

$$7.3\ \mathrm{kG} \ll B_{\mathrm{p},0} \ll 155\ \mathrm{MG}. \qquad (7)$$

4. Observing the magnetic field

Following Brocksopp et al. (2004), jets are detected in 10 out of almost 200 symbiotic stars. Remarkably, this is exactly the fraction of magnetized to un-magnetized *isolated* white dwarfs with field strengths larger than 30 kG (Wickramasinghe & Ferrario 2000).

A strong magnetic field, however, has been detected only in one symbiotic system (Z Andromedae, Sokoloski & Bildsten 1999). They interpreted an observed periodic photometric variability as the Keplerian spin period at the magnetospheric radius $r_{\rm mag}$, where the magnetic pressure of the WD's field is comparable to the ram pressure of the accreted material. This radius can be calculated as

$$r_{\rm mag} = \left(\frac{B^4 R^{12}}{32\, G\, M\, \dot{M}^2}\right)^{1/7} = 3.6\times 10^9 \left(\frac{B}{\rm MG}\right)^{4/7} \times\left(\frac{R}{7\times 10^8\,{\rm cm}}\right)^{12/7} \left(\frac{M}{M_\odot}\right)^{-1/7} \left(\frac{\dot{M}}{10^{-8}\,M_\odot\,{\rm yr}^{-1}}\right)^{-2/7}\ {\rm cm}, \tag{8}$$

which leads to a Keplerian period of

$$P = 2\pi\sqrt{\frac{r_{\rm mag}^3}{G\,M}} = 116\left(\frac{B}{\rm MG}\right)^{6/7}\left(\frac{R}{7\times 10^8\,{\rm cm}}\right)^{18/7} \times\left(\frac{M}{M_\odot}\right)^{-5/7}\left(\frac{\dot{M}}{10^{-8}\,M_\odot\,{\rm yr}^{-1}}\right)^{-3/7}\ {\rm s}. \tag{9}$$

In the case of Z And, the measured period was about 28 min (Sokoloski & Bildsten 1999), equivalent to a magnetic field of about 22 MG.

As no oscillations have been detected in MWC 560 so far, the magnetic field near the white dwarf should have lower values in the range of Eq. (7) – of the order of $B = 100$ kG, with which the period would be 16 s and therefore certainly below any observable limit.

Soker & Regev (2003), however, assumed that the magnetic field either inside the jet or near the jet source would undergo fast reconnection which heats up the plasma to temperatures making the gas visible in X-rays. The maximum temperature up to which the gas is heated can be estimated by equipartition (Tanuma et al. 2003) as

$$T_{\rm max} \sim 10^6 \left(\frac{n}{10^6\,{\rm cm}^{-3}}\right)^{-1}\left(\frac{B}{100\,{\rm mG}}\right)^2\ {\rm K}. \tag{10}$$

Inside the jet, the maximum temperature, however, would be negligible. Near the jet source it would be $\sim 7\times 10^7$ K with a density of 1.4×10^{16} cm^{-3} – which corresponds to an accretion rate of 10^{-8} $M_\odot$ yr^{-1} – and a magnetic field of 100 kG. The emissivity in Bremsstrahlung, created by reconnection, would then be 3×10^9 erg s^{-1} cm^{-3} and, multiplied by the volume of the accretion disk affected by the magnetic field $(2\pi R_*)\times(0.1\,R_*)\times(r_{\rm mag}-R_*)$, the total luminosity would be 2.4×10^{35} erg s^{-1}. With again a distance of 2.5 kpc, the flux would be 3×10^{-8} erg s^{-1} cm^{-2}. MWC 560 was not detected by the *ROSAT* all-sky survey, although the flux limit of *ROSAT* is 3×10^{-12} erg s^{-1} cm^{-2} (Cruddace et al. 2002).

A common argument in YSOs to explain the non-detection is absorption by a high column density. As Schmid et al. (2001) and Stute et al. (2005) have found that the number density near the red giant should be of the order of 10^9 cm^{-3} and then be decreasing following a $1/r^2$-law, the total column density in directions with large inclination would be of the order of 10^{22} cm^{-2} which is too low to cause the necessary absorption. The column density of the jet in MWC 560 has similar values (Schmid et al. 2001) leading to the same conclusion. The non-detection therefore sets an upper limit for the magnetic field which is at the lower end of the range of Eq. (7).

5. Discussion

By analytic estimates for the symbiotic star MWC 560, we have tried to decide which of the two main mechanisms – formation by MHD processes or formation by thermal pressure in the boundary layer (BL) – is more reliable to explain the observed parameters of jets in symbiotic stars. This question can not (yet) be answered by observations.

The X-ray observations of MWC 560 giving an upper limit for the magnetic field strength show that is still consistent with the minimal magnetic field required for a magnetic jet formation process. Further X-ray observations are needed to reduce this detection limit and to decide whether the magnetic scenario can be excluded or not. Until very high speed photometric observations are made, also the first way to deduce the magnetic field strength does not reveal any reason against a magnetic jet formation process. At the moment, both mechanisms are still possible.

As the BL scenario was introduced only analytically and the derivation of the model parameters by observation is highly difficult, however, numerical simulations of a compact object with a solid surface accreting matter would be interesting. Then the reliability could be qualitatively and quantitatively checked in different ranges of parameters, which should be interesting not only for symbiotic stars, but also for other kinds of binaries. The effectivity of jet launching by thermal pressure inside the BL should be investigated and dependencies of jet parameters as outflow rate, outflow velocity and jet kinetic luminosity from initial model parameters as e.g. the mass accretion rate should be derived. The authors have started first simulations whose results will be presented soon.

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