Why there are no jets from cataclysmic variable stars

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Abstract. We argue that the recent thermal model of jet launching by young stellar objects, when applied to a system containing disk-accreting white dwarfs, naturally explains the otherwise astonishing absence of jets in cataclysmic variable stars. Thermal launching is possible when the accreted material is strongly shocked due to large gradients of physical quantities in the boundary layer (or at the inner boundary of a truncated disk) and then cools on a time scale longer than its ejection time from the disk. In our framework the magnetic fields are weak, and serve only to recollimate the outflow at large distances from the source, or to initiate the shock, but not as a jet-driving agent. Using criteria for shock formation and mass ejection, we find the mass accretion rate above which jets can be launched from boundary layers around accreting white dwarfs to be $\dot{M}_{\text{WD}} \gtrsim 10^{-6}\text{M}_{\odot}\text{y}^{-1}$, which explains the absence of jets in cataclysmic variable stars and their presence in other white-dwarf accreting systems such as super-soft X-ray sources, symbiotic stars and classical novae.

1. Introduction

It is widely believed that accretion with angular momentum leads to ejection of jets. This belief is based on observations of jets in Young Stellar Object (YSOs), Low-Mass and High-Mass X-ray Binaries (LMXBs & HMXBs) and Active Galactic Nuclei. Cataclysmic Variables (CVs), however, are a blatant exception from the presumed universality of the accretion – jet connection. However, CVs are not an exception from a more general, supposedly universal, relation between accretion and “ejection”. Indeed, although no jets have ever been observed in CVs, some of them emit winds. For example, P Cygni profiles in resonant UV lines are observed in some very luminous CVs such as the nova-like stars and dwarf novae at outburst maximum. These winds are too cold to be ejected by a thermal mechanism and are most probably driven by radiative line pressure with some help of magnetic fields (see e.g. Proga, these proceedings). But they are winds, even if slightly collimated, but not jets.

The presence of a white dwarf in the center of an accretion flow cannot be considered to be responsible for this jet-blowing impotence since jets are observed in other accreting white-dwarf systems such as Super Soft X-ray Source (SSXS), symbiotic stars and novae. Fast, $\sim 1000 - 5000 \text{ km s}^{-1}$, collimated outflows have been observed in some SSXSs, RX J0513.9-6951, RX J0019.8+2156 and RX J0925.7-4758 (see references in Soker, & Lasota 2004, hereafter SL04) and sym-
Biotic systems are also known to blow jets (Sokoloski, et al. 2004; Brocksopp, et al. 2004, and references therein). Also the fast nova V1494 Aql produced high velocity $\sim 2800 \text{ km s}^{-1}$ jets during its decline from outburst maximum (Iijima, & Esinoglu 2003; Retter, 2004). SSXSs, symbiotic systems and classical novae differ from CVs by much higher accretion rates and the presence of an additional source of energy produced by thermonuclear reactions. Although novae are CVs undergoing a thermonuclear runaway for the purpose of the present investigation we will separate them from the other members of this class of binaries. Livio (2000) speculated that this latter difference might account for lack of jets in CVs, however, without providing a physical explanation.

Recently we (SL04) have shown that this difference is naturally explained if jets in accreting white-dwarf systems are produced by a thermal mechanism. As discussed below, magnetic fields would play a role in jet formation but this would be rather auxiliary, the main thrust being provided by thermal pressure.

2. Too small discs?

First we will consider another suggestion by Livio (2000) according to whom the absence of jets in CVs might be related to the small size of their accretion discs. The argument is based on numerical jet models of poloidal collimation (see e.g. Ogilvie, & Livio 1998) in which the vertical component of the magnetic field varies as

$$B_z \sim r^{-1}$$

and the jet opening angle is

$$\theta \sim \left( \frac{R_{\text{in}}}{R_{\text{out}}} \right)^{1/2}.$$  \hspace{1cm} (2)

When discs extend down to the smallest possible circular orbit, CV discs are much less extended than those of LMXBs simply because a $\sim 10M_{\odot}$ black hole is much smaller than a white dwarf. However, observations and models suggest that LMXB discs are often truncated, in particular during jet launching (see e.g. Fender, Belloni, & Gallo 2004). In this case the two types of systems might have similar disc sizes.

Indeed, taking for the outer disc radius $R_{\text{out}} = 0.9R_{\text{lL}}$, where $R_{\text{lL}}$ is the mean Roche-lobe radius (see e.g. Frank, King, & Raine 2002, for the formula), one obtains for the ratio of the CV to LMXB putative jet opening angles

$$\frac{\theta_{\text{CV}}}{\theta_{\text{BH}}} \approx 7.5 \left( \frac{M_{\text{BH}}}{M_{\text{WD}}} \right)^{1/3} \left( \frac{M_{\text{BH}}}{10 M_{\odot}} \right)^{-1/2} \left( \frac{R_{\text{WD}}}{5 \times 10^8 \text{cm}} \right)^{1/2} \left( \frac{R_{\text{in}}}{3R_{\text{S}}} \right)^{-1/2}$$  \hspace{1cm} (3)

where $R_{\text{S}} = 2GM/c^2$ is the Schwarzschild radius and we assumed a 1 M$_{\odot}$ white dwarf. Since jets are observed during hard/low states when (according to a popular scenario) $R_{\text{in}} \sim 100R_{\text{S}}$, the extent of the disc of a jet-launching LMXB could be comparable to that of a typical CV which makes the small disc argument not very compelling. One should add that although CVs discs can also be truncated, one expects jet to be launched at high accretion rates at which the accretion disc would reach down to the white dwarf surface.
3. Thermal launching

In jet models magnetic fields may play a dominant role in three types of processes: in triggering the jet ejection events, e.g., by causing instabilities in the disk, in accelerating the jets (as in the classic “centrifugal wind” mechanism, first proposed by Blandford, & Payne 1982) and finally in collimating the jets (e.g. Heyvaerts, & Norman 1989). Since models containing all these three elements fail to account for the absence of jets in CVs one is justified in trying to replace at least one of them by a different mechanism. SL04 showed that depriving the magnetic field of its accelerating role and replacing it by the action of the thermal pressure not only offers a natural explanation of the absence of jets in CVs but also accounts for the presence of jets in other white-dwarf systems such as classical novae, SSXSSs and symbiotic stars.

SL04 based their argument on the model of thermal pressure acceleration proposed by Torbett, (1984) and Torbett, & Gilden (1992) recently developed and extended by Soker, & Regev (2003) to explain strongly collimated outflows in YSOs. In this jet model magnetic fields are weak, and might serve only to re-collimate the outflow at large distances from the source and might trigger disturbances in the boundary layer (BL) where the disk adjust itself to the conditions at the surface of the accreting star.

Soker, & Regev (2003) found two conditions necessary for the jet thermal launching model to work. The first condition is that the strongly shocked gas in the BL cools slowly so that the thermal pressure have enough time to accelerate the jet’s material. The second condition requires that weakly shocked blobs in the BL expand and disturb it in such a way that a strong shock develops. SR03 term such strong shocks ‘spatiotemporally localized (but not too small!) accretion shocks’, or SPLASHes.

3.1. Ejection condition

The characteristic radiative cooling time in the BL is equal to the photon diffusion time

\[ t_{\text{cool}} = H^2 \frac{\rho \kappa}{c}, \]  

(4)

where \( H \) is the vertical scale height, \( \rho \) the density, \( \kappa \) the opacity, and \( c \) the speed of light, whereas the ejection time is given by the dynamical time

\[ t_{\text{ej}} = \frac{H}{\sqrt{2} v_K}, \]  

(5)

where \( v_K = \sqrt{GM/R} \), where \( R \) is the distance to the disc’s center.

Using the the mass conservation equation \( \dot{M} = 2\pi R^2 H \rho v_r \), taking for the radial velocity \( v_r \sim \alpha (H/R)^2 v_K \) and and taking into account the strong shock density-contrast condition one obtains

\[ \frac{t_{\text{cool}}}{t_{\text{ej}}} \simeq \frac{\dot{M} \kappa}{\pi c \alpha^2 R} \simeq 1.3 \left( \frac{H/R}{0.1} \right)^{-2} \left( \frac{\alpha}{0.1} \right)^{-1} \left( \frac{\dot{M}}{10^{-7} M_\odot Y^{-1}} \right) \left( \frac{\kappa(\rho,T)}{\text{cm}^2 \text{g}^{-1}} \right) \left( \frac{R}{R_\odot} \right)^{-1}. \]  

(6)
Therefore for accreting white dwarfs \( R \approx 0.01R_\odot \) the condition \( t_{\text{cool}} \gtrsim t_{\text{ej}} \) is satisfied for

\[
\dot{M}_s \gtrsim 2 \times 10^{-9} \left( \frac{H/R}{0.1} \right)^2 \left( \frac{\alpha}{0.1} \right) M_\odot \text{yr}^{-1},
\]

which is satisfied for the nova-like stars and dwarf novae at maximum, i.e. for CVs at highest accretion rate. However, in these systems one observes only winds, not jets.

### 3.2. Strong shock condition

The model assumes that hundreds of small blobs are formed in the sheared BL (section 2 of Soker, & Regev 2003). The blobs occasionally collide with each other, and create shocks which cause the shocked regions to expand in all directions. If the shocked regions continue to expand out into the path of yet more circulating blobs, stronger shocks may be created, as was proposed by Pringle, & Savonije (1979) to explain the emission of X-rays out of disk BLs in dwarf novae. For the shocked blobs to expand, the radiative cooling time of individual blobs, \( t_{\text{cool}} \approx \ell^2 \kappa T_b / c \), must be longer than their adiabatic expansion time \( t_{\text{ad}} = \ell / c_s \), where \( \ell \) is the size of an expanding blob, and \( T_b \) the post-shock blob's temperature.

This condition also leads to a minimum value for the mass accretion rate (Soker, & Regev 2003, eq. 12 in SL04)

\[
\dot{M}_b \gtrsim 4.2 \times 10^{-5} \frac{1}{\kappa \rho_b} \left( \frac{\alpha}{0.1} \right) \left( \frac{R_j}{R_\odot} \right) M_\odot \text{yr}^{-1},
\]

where \( R_j \) is the radius from where the jet is launched. For accreting white dwarfs the weak-shock temperature \( T_b \approx 5 \times 10^7 \text{K} \). Therefore also in this case \( \kappa = 0.4 \text{cm}^2 \text{g}^{-1} \) (SL04). The strong-shock formation condition for accreting white dwarfs is

\[
\dot{M}_{\text{WD}} \gtrsim 10^{-6} \left( \frac{\alpha}{0.1} \right) M_\odot \text{yr}^{-1}.
\]

This is roughly two to three orders of magnitude larger than the maximal accretion rate in CVs (the accretion rate of nova-like stars and dwarf novae at maximum is always \( \lesssim 10^{-8} M_\odot \text{yr}^{-1} \)). The condition (9) provides therefore an explanation for the absence of jets in CVs.

As mentioned in the introduction this explanation is strengthened by the fact that white-dwarf systems accreting at rates satisfying Eq. (9) do show jets. In SSXSs white dwarfs accrete at rates of \( 3 \times 10^{-8} - 10^{-6} M_\odot \text{yr}^{-1} \) from a companion, and sustain nuclear burning on their surface (e.g. van den Heuvel, et al. 1992). In symbiotic systems, white dwarfs accrete at high rates from the wind of red giant branch stars or asymptotic giant branch stars. In some of the symbiotic systems which blow jets the white dwarf sustains a quasi-steady nuclear burning, similar to SSXSs; in others, there is no nuclear burning (Brocksopp, et al. 2004). Retter (2004) showed that conditions during the jet ejection by V1494 Aql are consistent with condition Eq. (9). He estimated the accretion rate to be then \( \sim 10^{-6} M_\odot \text{yr}^{-1} \). To be really consistent with our model, the white dwarf
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should be accreting from a disc during jet production. The disc is most probably destroyed during the nova explosion and reforms during the decline. In V1494 Aql the accretion disc would have to be present during the “transition phase”, three months after the maximum. This is rather rapid compared to another fast nova GQ Mus in which the disc reappeared only after a decade when the X-ray source had turned off (Starrfield, et al. 1994), but still another fast nova V1974 Cyg might have shown a disc signature some thirty months after the outburst (Retter, Leibowitz, & Ofek 1997).

4. Discussion and perspectives

The thermal model elucidates why there exists a critical accretion rate necessary for jet launching. This critical rate is well above the maximum rate encountered in CVs and so solves the mystery of their jet quietness. One could argue that this is just a coincidence. The critical value could, for example, correspond to the appearance of a large-scale (poloidal) magnetic field necessary for a Blandford & Payne – type mechanism to work, as proposed by Livio, Pringle, & King (2003). According to these authors, at a critical rate the accretion disc would switch from a standard radiative disc to a state where most of the accretion energy is released in the form of a bulk flow. For the time being no MHD simulation is capable to follow such a process (see the article by Balbus in these proceedings), and the value of the critical accretion rate (if any) can be only matter of speculation. Livio, Pringle, & King (2003) suggested that the inner parts of the nova-like star discs are underluminous because of the transition into an outflow phase. This would imply a critical accretion rate of \( \sim 10^{-8} \text{M}_{\odot} \text{yr}^{-1} \). However, this rate corresponds rather to launching of winds, not of jets, and the mystery of their absence in CVs would be still with us. It should be also noted that the alleged luminosity deficit in the inner disc of nova-like stars could be (at least in part) just an artefact of the disc model used (Smak 1994). In any case the existence of a critical accretion rate for the presence of large-scale poloidal field would not be necessarily in contradiction with our criterion Eq. (9) which is only a necessary condition for jet launching. On the other hand, if the poloidal field is generated at the cost of local energy dissipation thermal jet launching could be problematic.

Finally, our model has the vocation to be universal despite the fact that we use properties of the boundary layer which would not exist when accretion occurs onto black holes or strongly magnetized stars. However, the boundary layer is important only because it is where strong shocks can be produced. The required strong gradients could be also produced in accretion discs by “magnetospheric” MHD even when the central object is a black hole (e.g. Li & Narayan 2004 and references therein). In such a case MHD instabilities, turbulence, or other disturbances may lead to strong shocks; the high post-shock pressure may accelerate gas and form jets and/or winds, e.g., as was shown for non-radiative accretion around a black hole by De Villiers, Hawley, & Krolik (2003).

Scaled to the case of an accreting black hole Eq. (8) becomes

\[
\dot{m} \equiv \frac{\dot{M}}{\dot{M}_{\text{Edd}}} \geq 0.02 \left( \frac{\alpha}{0.1} \right) \left( \frac{0.4 \text{ g cm}^{-2}}{\kappa} \right) \frac{R_i}{R_G},
\]  

(10)
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where $\dot{M}_{\text{Edd}} = \frac{L_{\text{Edd}}}{0.1c^2} = 2.3 \times 10^{-8} (M/M_\odot) M_\odot y^{-1}$ is the Eddington accretion rate. In Soker, & Lasota (2004) we mistakenly claimed that this formula might be relevant to the appearance of steady jets (we Friedrich Meyer for pointing this out at the present conference). It remains to be seen how and when the thermal jet-launching model applies to systems with black hole, but we expect (in preparation) that in the case of microquasars it would be rather relevant to the launching of powerful, high Lorentz-factor jets (e.g. Fender, et al. 2004).

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