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THE PERTINENCE OF JET EMITTING DISCS IN MICROQUASARS THEORY AND COMPARISON TO OBSERVATIONS

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Abstract. Jet Emitting Disc (JED) has dynamical properties quite different from both the standard and advection dominated discs. It also exhibits three different thermal equilibrium branches at a given radius: two stable (cold and hot) and one intermediate unstable. The hot solution has all the characteristics of the so-called "hot corona" generally invoked in XrB sytems in the Low/Hard states. We detail the energetics and radiative expectations of our model and show their good agreement with those observed in Cygnus X-1 in terms of jet power, jet velocity and spectral emission.

Keywords: X-rays: binaries, accretion, accretion disks, magnetic fields: MHD

1 Introduction

Jet emitting discs (JED herafter) were originaly studied by Ferreira & Pelletier (1993) in their magnetized accretion ejection structures model (MAES herafter). This model was developed so as to treat both the accretion disc and the jet it generates consistently. The idea is the same as in earlier studies of magneto-centrifugally launched disc winds (Blandford & Payne 1982). However, in the MAES, the solution starts from the midplane of the resistive MHD disc and evolves outwards in the ideal MHD wind/jet. This differs drastically from other studies where the disc was only treated as a boundary condition, hence forbidding any precise quantication of the effect of the MHD wind on the disc.

The resolution of the thermal equilibrium of a JED gives three branches, a cold and hot ones, both thermally and viscously stable and an intermediate unstable one. The hot branch, that would be observationally very similar to ADAFs, corresponds to the JED solution discussed in this paper and applied to Cyg. X-1 (Petrucci et al. 2010, hereafter P10). Thus JEDs could account for most of the successes of the ADAFs, while explaining jet formation (see Ferreira's talk, this proceeding).

1.1 JED Physical properties and global energy budget

Since a JED undergoes mass loss, the disc accretion rate is written as

$$\dot{M}_a(R) = \dot{M}_{a,out}\left(\frac{R}{R_{out}}\right)^{\xi} = \dot{m}\dot{M}_{Edd} \tag{1.1}$$

where ξ measures the local disc ejection efficiency (Ferreira & Pelletier 1993), $\dot{M}_{out}$ the accretion rate at the disc outer radius R_{out} and $\dot{M}_{Edd} = L_{Edd}/c^2$ the Eddington accretion rate. The ejection efficiency ξ is equivalent to the p exponent used in ADIOS models (Blandford & Begelman 1999). But, in strong contrast to the latter, it is not *assumed* but computed as a function of the disc parameters as a trans-Alfvénic regularity condition (see Ferreira 1997 for more details).

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The disc's aspect ratio in a gas supported disc is $\varepsilon = H/R = c_s/v_K$, namely the ratio of the isothermal sound speed to the Keplerian speed $v_K = \Omega_K R$. The radial profiles of the accretion velocity u_o, particle density $n = \rho_o/m_p$, gas pressure P_{gas}, and vertical magnetic field B_z in the JED midplane are given by

$$u_o = -u_r = m_s c_s = m_s\, \varepsilon\, \Omega_K R \tag{1.2}$$

$$n = \frac{\dot{M}_a(R)}{4\pi m_p \Omega_K R^3 m_s \varepsilon^2} \tag{1.3}$$

$$P_{gas} = \rho_o c_s^2 = \frac{\dot{M}_a(R)\Omega_K}{4\pi R m_s} \tag{1.4}$$

$$B_z = \left(\frac{\mu}{m_s}\right)^{1/2} \sqrt{\frac{\mu_o \dot{M}_a(R)\Omega_K}{4\pi R}} \tag{1.5}$$

where we have introduced two dimensionless parameters, the sonic Mach number $m_s = u_o/c_s$ and the disc magnetization $\mu = \mu_o^{-1} B_z^2/P$.

The global energy budget in an accretion-ejection structure is

$$P_{acc} = P_{JED} + P_{jets} = P_{rad} + P_{adv} + P_{jets} \tag{1.6}$$

The total accretion power P_{acc} released in a quasi-Keplerian accretion disc writes as

$$\begin{aligned} P_{acc} &= \frac{GM\dot{M}_a(R_{in})}{2R_{in}} - \frac{GM\dot{M}_a(R_{out})}{2R_{out}} \\ &= \frac{GM\dot{M}_{a,out}}{2R_{in}} \left[\left(\frac{R_{in}}{R_{out}}\right)^{\xi} - \frac{R_{in}}{R_{out}} \right] \end{aligned} \tag{1.7}$$

The power P_{adv} is advected onto the central object along with the accreting material scales. P_{jets} is the sum of the total (kinetic, potential, and internal) energy flux advected by the outflowing plasma and the MHD Poynting flux leaving the disc surfaces. Since we are mainly interested in powerful jets, the latter contribution dominates, and it can be shown that (see P10):

$$P_{jets} \simeq b P_{acc} \tag{1.8}$$

Consequently, given the above expressions, the total JED power P_{JED} and JED luminosity P_{rad} are given by

$$P_{JED} = P_{acc} - P_{jets} = (1-b)P_{acc} \tag{1.9}$$

$$P_{rad} = P_{JED} - P_{adv} = (1-b)P_{acc} - P_{adv}. \tag{1.10}$$

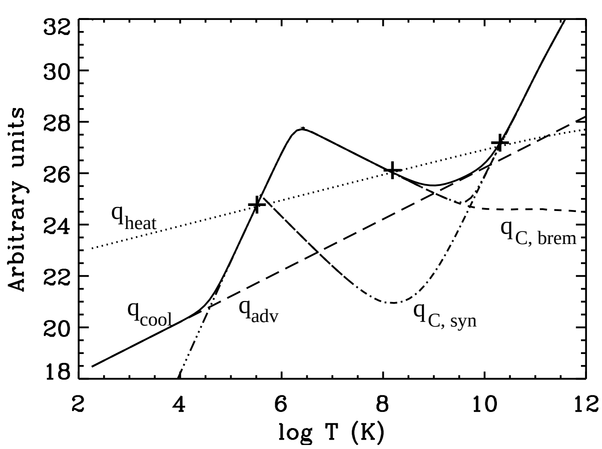


Fig. 1. Thermal balance of a jet emitting disc (JED) at $r = 6$ for $\dot{m}$ =0.001 and $m = 10$. The underlying JED structure has a jet power parameter $b = 0.5$ and an ejection efficiency $\xi = 0.1$. The dotted line is the heating term q_{heat}, the dot-dot-dot-dashed line the radiative cooling term q_{rad}, and the long dashed line is the advective term q_{adv}. The Comptonized bremsstrahlung $q_{C,brem}$ (short dashed) and the Comptonized synchrotron $q_{C,sync}$ (dot-dashed) radiative terms are also shown. The solid line corresponds to $q_{rad} + q_{adv}$ and the solutions of Eq. (2.1) are indicated by crosses.

The jet power parameter b is thus a crucial parameter as it controls the power sharing between the jet and the disc. Since it is generally found in the range 0.5-0.99 (see P10), JEDs considered here are engines converting accretion power into ejection power with high efficiency. To get the fraction of the power P_{rad} that is actually radiated away, however we need to compute the JED thermal balance. This is explained in the next section.

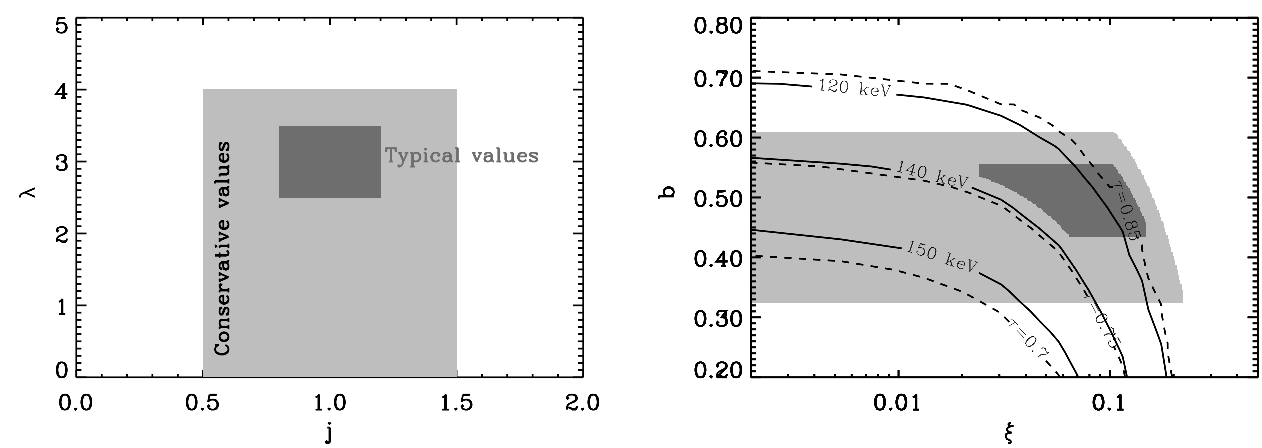
2 JED thermal balance

The equation governing the internal energy of the accretion flow writes as

$$q_{heat} = q_{rad} + \underbrace{P\nabla.\mathbf{u} + \nabla U.\mathbf{u}}_{q_{adv}} \tag{2.1}$$

where q_{heat} is the heating power density, q_{rad} the sum of all radiative cooling terms, P the total plasma pressure, $\mathbf{u}$ the flow velocity, U its internal energy and q_{adv} the advection term. Equation (1.9) directly provides the radial JED volumetric heating rate in a disc ring of height $2H$, radius R and extent dR i.e. $q_{heat}(R) = \frac{1}{4\pi RH}\frac{dP_{JED}}{dR}$.

Figure (1) shows the different heating, cooling, and advection terms as functions of the temperature for a given black hole mass, JED radius, and accretion rate. The resolution of the thermal equilibrium gives three branches of solutions, indicated by crosses on the figure. The hottest one corresponds to the JED solution discussed in this paper (a more detailed discussion of the other solutions is postponed to a future work). It is a hot, optically thin, thermally and viscously stable disc solution that behaves radiatively in the same way as the LHAF solutions studied by Yuan (2001) (see also Yuan et al. 2006 for a discussion on hot one-temprature accretion flows). The major difference concerns the underlying dynamics of our JED solutions, which self-consistently include the presence of powerful self-collimated jets.



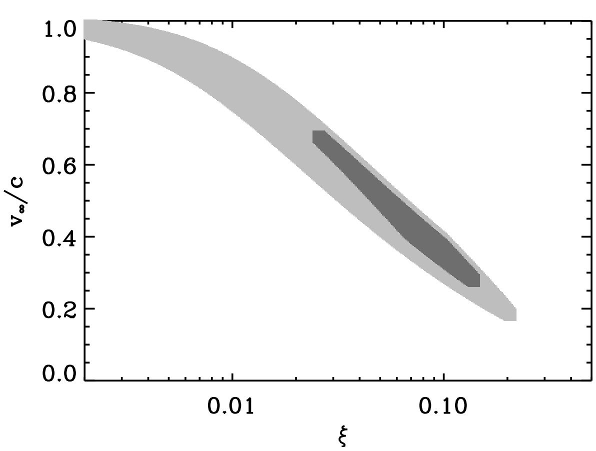


Fig. 2. Top-left: the parameter space $j-\lambda$ allowed by the observations. **Top right**: Observational constraints translated into our JED parameter space $\xi - b$. Overplotted are the contours of temperature (solid lines) and optical depth (dashed lines) for an accretion rate of 1-2% Edd., typical of Cyg X-1. **Bottom-left**: terminal jet velocity V_∞/c as function of the disc ejection efficiency ξ

3 Comparison to Cygnus X-1

The energetics of the jets and the X-ray corona of Cygnus X-1 have been investigated recently by Malzac et al. (2009 herafter M09). Observations constraint the ratio $j = P_{jets}/L_h$ of the total jet kinetic power to the typical X-ray luminosity in the hard state as well as the ratio λ of the soft to hard radiative efficiencies to be in the ranges (M09):

$$0.45 \leq j = \frac{P_{jets}}{L_h} \leq 1.5 \text{ and } \lambda = \frac{L_s}{\dot{M}_s}\frac{\dot{M}_h}{L_h} \leq 4 \tag{3.1}$$

These observational constraints on j and λ can be easily translated into constraints on our JED parameters b and ξ, where $P_{jets} \simeq bP_{acc}$ and $\dot{M}_a(R) \propto R^{\xi}$.

The top left panel of Fig. (2) displays the domain in the observed parameter space $j - \lambda$ allowed by the observations. The top right panel shows the same constraints but translated into our JED parameter space $\xi - b$. Our treatment of the disc thermal balance allows us to estimate the expected temperature and optical depth within a JED. Contours of these two quantities at a radius of 10 R_G are overplotted in the top-left panel of Fig. (2), the solid lines representing the temperature while the dashed lines the optical depth. The black hole mass is taken equal to 10 $M_\odot$ and the total luminosity is about 1% of the Eddington luminosity. This corresponds to the typical luminosity of Cyg X-1 close to the hard-to-soft state transition. The ratio of the outer to inner JED radii is fixed to 100 but our results do not strongly depend on this parameter. Interestingly, the temperature ranges between 120 and 140 keV and the optical depth $\tau \simeq 0.7 - 0.9$, which are not so far, given the simplicity of our thermal balance computation, from the values deduced from sophisticated fits of Cyg X-1 in the hard state

Finally the bottom-left panel of Fig. (2) shows V_∞/c as a function of b and ξ. The generally accepted values (i.e. the dark grey area in Fig. 2) provide a range in V_∞/c between 0.3 and 0.6 in good agreement with observations. This is remarkable as it arises from another independent observational constraint.

The accretion and ejection properties of JEDs agree with the observations of the prototypical black hole binary Cygnus X-1. The JED solutions are likely to be relevant to the whole class of microquasars.

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