MHD jets around galactic objects

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Abstract. We present a self-similar, steady-state model describing both a magnetized accretion disc and a magnetohydrodynamic jet. We focus on the role of a hot corona in such a structure. This corona enables the disc to launch various types of jets. By considering the energy conservation, we also present a diagnostic of the luminosity of the magnetized disc, which could explain some observational signatures of galactic objects.

Keywords: MHD, accretion disc, galactic objects

1. The disc-jet connection

In the Universe, jets of matter are observed around almost every kind of systems where plasma accretes onto a central object. The central object can be a young protostar, a compact galactic object or a supermassive black hole. The jet velocity is always found to be a few times the escaping velocity of the central object (e.g., Livio, 1997). The most successful model, accounting for all known properties of observed jets, relies on a large scale magnetic field anchored on an accretion disc (Blandford & Payne, 1982). The field extracts the disc angular momentum, thereby allowing accretion, and accelerates a fraction of disc material to high speeds. Moreover, the magnetic field confines the accelerating jet matter, leading to a cylindrical collimation of the jet. Hereafter, such systems are called Magnetized Accretion-Ejection Structures (MAES).

In a MAES, the bipolar magnetic field pinches the disc. Thus, the only force able to counteract both the magnetic and gravitational forces, within the disc, is the vertical plasma pressure gradient. As a consequence, the mass loading in the jet depends critically on this vertical equilibrium. This equilibrium is the connection between the accretion motion and the jet. A more detailed explanation of this phenomenon is displayed in Casse & Ferreira (2000a).

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2. Entropy generation

In all previous studies dealing with magnetized accretion disc steadily launching jets, the energy equation was simply disregarded. It was replaced by the assumption of isothermal or adiabatic magnetic surfaces. In the turbulent disc however, some physical mechanisms (convection, turbulent thermal conductivity) could provide a non-local energy transport, more efficient than by photons. We can mimic these effects by the following equation

$$\rho T \frac{dS}{dt} = Q$$

where $Q$ is the difference between local heating and cooling rates of the plasma. This function $Q$ is prescribed according to the energy conservation (Casse & Ferreira, 2000b). In a steady-state framework, this equation can be written as

$$Q = \frac{\gamma}{\gamma - 1} \frac{k_B}{m_p} \rho u_p \cdot \nabla T - u_p \cdot \nabla P.$$

where $T$ is the temperature, $P$ the plasma pressure, $u_p$ the poloidal velocity of matter and $\gamma$ the polytropic index of plasma. Because the gradient of plasma characteristics are almost vertical in a thin disc, one can see that entropy generation will have a strong impact on the vertical mass flux when the poloidal velocity is vertical (i.e. in the corona taking place at the disc surface). In the disc, the entropy generation will be advected with the flow onto the central object.

This is an important point since advection-dominated accretion flows (ADAF) only occurs in thick or slim discs ($h/r > 0.3$). Here, most of the entropy is generated in the disc atmosphere and taken in the jet, allowing the disc to be thin. Using this approximate form of the energy equation, we solve the full set of MHD equations from the disc midplane (resistive MHD regime) to the jet asymptotics (ideal MHD regime).

3. Global energy conservation

The global energy conservation enables us to know that the power released by accretion $P_{acc}$ is shared between the total jet power $P_{jet}$ (MHD Poynting flux, kinetic energy and enthalpy) and the disc luminosity $L_D$. We measure the amount of entropy generated with a parameter $f$ whose value is determined by the disc turbulence ($0 < f \leq 1$). It is noteworthy that, according to the amount of entropy, the
\[ M_* = 10 \, M_\odot \]
\[ \dot{M}_{\text{ac}} = 10^{-7} \, M_\odot / \text{yr} \]
\[ r_i = 3 \, R_s \]

Figure 1. Poloidal cross-section of MAES. In grey are shown the logarithmic temperature levels, the solid lines are the logarithmic plasma density levels (\( \log n_H = 12, 12.5, 13, 15 \) for left pannel and \( \log n_H = 9, 10, 11, 15 \) for right pannel). The denser level is closer to the disc. The dashed lines represent plasma streamlines coming from the disc to the jet. The poloidal magnetic field lines are not displayed here but are strictly parallel, in the jet, to the poloidal streamlines, according to MHD equations. The left figure displays a structure that might be able to describe the X-ray low/hard state of some microquasars (see Fender et al., 1999). The right pannel could correspond to a X-ray high/soft state.

The resulting jet is magnetically-driven ("cold" jet \( f \sim 0 \)) or magneto-thermally-driven ("hot" jet \( f \sim 1 \)). The energy conservation becomes (Casse & Ferreira, 2000b)

\[ 2L_D = (1 - f)P_{\text{diss}} = P_{\text{acc}} - 2P_{\text{jet}} \]

where \( P_{\text{diss}} \) is the viscous and ohmic heating integrated all over the disc. One can easily see that if most of heat is deposited as entropy in the corona, a thin magnetized disc could launch jets and have a weak luminosity. Assuming the disc to be optically thick, we can calculate its luminosity \( L_D \) and effective temperature \( T_{\text{eff}} \), namely

\[
\frac{L_D}{L_{\text{EDD}}} \simeq 0.36 \left( \frac{1 - f}{1 + \Lambda} \right) \left( \frac{\dot{M}_{\text{ac}}}{10^{-7} M_\odot/\text{yr}} \right) \left( \frac{M_*}{10M_\odot} \right) \left( \frac{3R_s}{r_i} \right) \\

kT_{\text{eff}} \simeq 1 \text{keV} \left( \frac{1 - f}{1 + \Lambda} \right)^{\frac{4}{7}} \left( \frac{\dot{M}_s(r)}{10^{-7} M_\odot/\text{yr}} \right)^{\frac{1}{7}} \left( \frac{M_*}{10M_\odot} \right)^{-\frac{1}{7}} \left( \frac{r}{3R_s} \right)^{-\frac{3}{7}}
\]
where we have assumed the external radius $r_e$ of the MAES to be much larger than the internal radius $r_i$ ($R_s = 2GM_*/c^2$ and $L_{Edd}$ is the Eddington luminosity). The parameter $\Lambda$ is the ratio of the magnetic to the viscous torque at the disc midplane and depends on the local MHD turbulence (Casse & Ferreira, 2000a).

An important consequence arises from these estimates. Indeed a magnetized disc driving jets could be less luminous than a standard accretion disc, even with $f \simeq 0$ (no corona). This will be the case if the turbulence is such that the magnetic torque is larger than the viscous one, the disc will be darker but keeping almost the same effective temperature.

In a stationary MAES, the characteristic timescale for jet launching is only a few dynamical timescales, i.e. roughly one second around a stellar black hole. So both low and high state of microquasars (e.g. Mirabel et al., 1998, Fender et al., 1999) might be described by two different MAES. Indeed the high state exhibits a strong thermal emission in X-rays (soft X-rays emitted from the disc, $f \rightarrow 0$) and a very small radio emission that could be accounted by a very tenuous, cold jet (or no jet at all). At the opposite, the low state is characterized by a non-thermal emission in hard X-rays (associated with a corona) and a “radio” jet. This low state might be obtained with a MAES where most of the heat is not released as radiation by the optically thick disc but shared between coronal losses and thermal energy sent into the jet ($f \rightarrow 1$). The resulting jets are hot and dense, and may be associated with a radio and infra-red emissions. In Figure 1, we display these two MAES. Anyway, a disc instability allowing the MAES to shift between these two states remains to be found. Also, to clearly validate this scenario, a modelisation of spectrum emitted from MAES must be performed and compared to observations. The authors would like to thank Rob Fender for fruitful discussions.

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