11th Hel.A.S. Conference
Athens, 8-12 September, 2013
CONTRIBUTED POSTER

Are counterrotating jets possible?

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Abstract: Rotation measurement of jets of T Tauri stars seem to indicate that some jets are rotating in a direction opposite to that of the underlying disk, although it is not yet clear if this affects the totality or part of the outflows. We show that this result is not as surprising as it may seem, and that it emerges naturally from the magnetohydrodynamic (MHD) equations. Specifically, counterrotating jets neither contradict the magnetocentrifugal driving of the flow nor prevent extraction of angular momentum from the disk. The demonstration of this result is shown by combining the ideal MHD equations for steady axisymmetric flows. We also extend this analytical derivation to relativistic jets demonstrating that under rather general conditions counterrotation can take place in such systems too. We illustrate the involved mechanisms by performing MHD simulations in both the newtonian and relativistic framework.

1 Introduction

Many attempts have been made to measure jet rotation in various wavelengths, which is a rather delicate and difficult task. The RW Aur jet has been the most extensively studied such case, with the rotation of the receding optical jet being opposite to that of the underlying disk [1, 2]. Counterrotation has been observed in several other jets. For instance, there is at least one knot (SK1) in HH212 that seems to counterrotate as explained in [3], with new evidence coming from Fe and HII lines. This is also the case for HH111 the observations of which also indicate a counterrotating knot.

Despite the fact that rotation measurement in jets is a difficult task, counterrotation still remains an important open issue, first of all because according to the common view this may contradict the classical magnetocentrifugal outflow driving proposed in [4] for jet launching from a Keplerian disk. Counterrotation is a direct consequence of the velocity variation along the flow as well as of the flux tube geometry. It is shown that the conservation laws are satisfied and specifically that angular momentum flux is constant along the flow.

2 Basic equations and condition for counterrotation

We start from the discussion of the special relativistic case which includes the newtonian framework as a subcase. For steady and axisymmetric flows the integrals of motion (magnetic field angular velocity Ω, total angular momentum to mass flux L, total energy to mass flux μ) take the following form $(c = 1)$: $\Omega = \dfrac{1}{\varpi}\left(V_\varphi - \dfrac{V_\mathrm{p}}{B_\mathrm{p}}B_\varphi\right)$, $L = \xi\gamma\varpi V_\varphi - \dfrac{\varpi B_\varphi B_\mathrm{p}}{4\pi\gamma\rho V_\mathrm{p}}$, $\mu = \xi\gamma - \dfrac{\varpi\Omega B_\varphi B_\mathrm{p}}{4\pi\gamma\rho V_\mathrm{p}}$, where ϖ is the cylindrical distance, V_p and V_φ the poloidal and toroidal components of the three-velocity, B the magnetic field, γ the Lorentz factor, ρ the proper density and ξ the relativistic enthalpy.

By splitting the angular momentum and total energy in the hydro (HYD) and magnetic (MAG) parts we obtain the following expressions: $L = L_\mathrm{HYD} + L_\mathrm{MAG}$, $\quad \mu = \mu_\mathrm{HYD} + \mu_\mathrm{MAG} = \mu_\mathrm{HYD} + \Omega L_\mathrm{MAG}$.

Although the total energy and angular momentum are constant along a field line, energy and angular momentum can be transferred from the electromagnetic field to the plasma and vice versa.

For instance, whenever the flow decelerates or cools adiabatically, the $\mu_{\rm MAG}$ term becomes larger. Consequently, the term $L_{\rm MAG}$ also increases due to their proportionality. Therefore, in order for the total angular momentum to remain constant, the above imply a decrease in the value of the toroidal velocity. Depending on the absolute value of V_φ as well as the decrease in the poloidal velocity and/or the enthalpy, counterrotation can occur. This mechanism refers only to steady flows, however, similar mechanisms can take place locally in time variable jets.

3 Numerical illustration

Here, we present both cases of counterrotation: a) a protostellar time-dependent jet that shows counterrotation locally due to deceleration (Figure 1) and b) a relativistic steady outflow whose enthalpy decreases and the toroidal velocity is reversed (Figure 2). Both are axisymmetric MHD simulations performed with PLUTO [5].

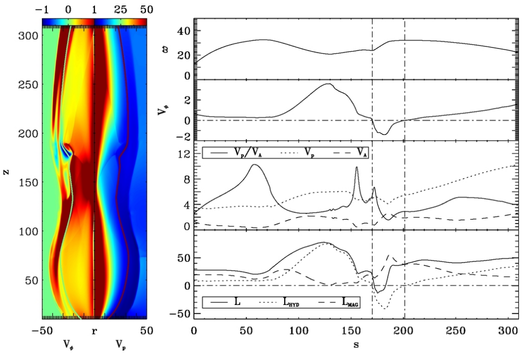

Figure 1: Snapshot of a protostellar jet simulation surrounded by an external medium of constant pressure [6]. On the left panel, the toroidal (left) and poloidal velocities (right) are displayed. The reversal of the rotation corresponds to the darkest zone of the V_φ contours. A specific streamline has been selected (solid line) along which the quantities shown on the right panel are plotted. From top to bottom: the cylindrical radius $\varpi(s)$, the toroidal speed, the poloidal and Alfvén speeds and the poloidal Alfvénic Mach number, the angular momentum flux L and its parts $L_{\rm HYD}$ (dotted line) and $L_{\rm MAG}$(dashed line), as functions of the curvilinear abscissa (s).

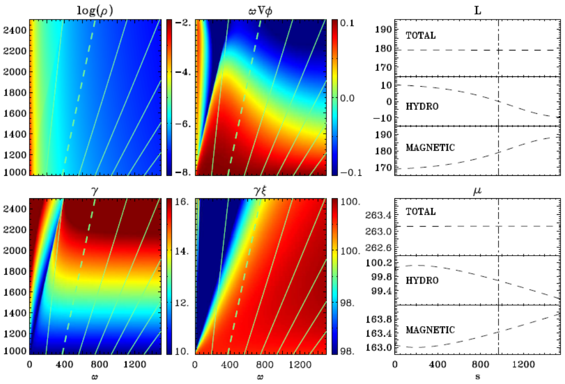

Figure 2: Left and center panels: maps of the proper density top left), Lorentz factor (bottom left), toroidal velocity multiplied by the radius (top center), matter energy part (bottom center), together with the magnetic field lines of a relativistic jet model. Whenever the values of each quantity are outside the plotted range, the colors saturate to the corresponding min/max value. Right panel: The profiles of L (top) and μ (bottom) along the dashed field line indicated on the maps. The total values of the integrals are broken to the hydro and magnetic components. The vertical dot-dashed line shows the location at which counterrotation starts. (Image from [7].)

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