On the interaction of jets with stellar winds in massive X-ray binaries.

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We present the first three-dimensional simulations of the evolution of a microquasar jet inside the binary-star system. The aim is to study the interaction of these jets with the stellar wind from a massive companion and the possible locations of high-energy emission sites. We have simulated two jets with different injection power in order to give a hint on the minimum power required for the jet to escape the system and become visible in larger scales. In the setup, we include a massive star wind filling the grid through which the jet evolves. We show that jets should have powers of the order of $10^{37}$ erg/s or more in order not to be destroyed by the stellar wind. The jet-wind interaction results in regions in which high energy emission could be produced. These results imply the possible existence of a population of X-ray binaries not detected in the radio band due to jet disruption inside the region dominated by the stellar wind.

Keywords: Microquasars; X-ray binaries; relativistic jets

1. Introduction

The powerful jets of X-ray binaries (XRB; i.e. microquasars) are produced close to a compact object, a black hole or a neutron star, through ejection of material accreted from the companion star. The interaction of jets with the stellar wind in the binary region has to be taken into account as a possible source of strong shocks and/or jet disruption in the case of a massive companion star. The occurrence of collisionless shocks can lead to efficient particle acceleration (see Ref. [1]), resulting in significant non-thermal emission of synchrotron and inverse Compton origin and, possibly, from proton-proton collisions (see Ref. [2] and references therein).

In Ref. [3] (PBR08 from now on) the authors performed two-dimensional (2D) numerical simulations in order to show how the strong wind of an OB star can influence the jet dynamics at scales similar to the orbital separation ($\sim 0.2$ AU). Simulations in two dimensions of a hydrodynamical jet interacting with an homo-
geneous (i.e. not clumpy) stellar wind were performed in cylindrical (axisymmetric) and planar (slab) symmetry. The results showed that a strong recollimation shock is likely to occur at jet heights $\sim 10^{12}$ cm, which could lead to efficient particle acceleration and explain the TeV emission seen in several high-mass X-ray binaries (LS 5039, LS I +61 303, Cygnus X-1, see Refs. [4], [5] and [6]). It was also found that jet disruption could occur for jet kinetic luminosities as high as $L_j \sim 10^{36}$ erg s$^{-1}$ because of jet instabilities produced by the act of the strong and assymetric wind. Such a $L_j$-value is $\sim 0.1 - 1\%$ the Eddington luminosity, typical for an X-ray binary with persistent jets (see Fig. 1 in Ref. [7]). This implies that the stellar wind in high mass microquasars could play a role not only for feeding accretion, but also for high-energy radiation and jet suppression at the binary system scales. To carry this research further, we have performed three-dimensional (3D) simulations of hydrodynamical jets interacting with a strong stellar wind. We find, confirming previous results, that even jets with $L_j > 10^{36}$ erg s$^{-1}$ may be disrupted, since the lower wind-jet momentum transfer in 3D as compared to 2D is balanced by the development of helical Kelvin-Helmholtz (KH) instabilities. Our findings also point to the presence of a strong recollimation shock that could efficiently accelerate very energetic particles.

2. Numerical Simulations

2.1. Set-up

We have performed 3D simulations of two fast supersonic hydrodynamical jets with $L_j = 10^{35}$ (Jet 1) and $10^{37}$ erg s$^{-1}$ (Jet 2), and injection velocity $1.66 \times 10^{10}$ cm s$^{-1}$. The medium in which the jets propagate is an isotropic wind (as seen from the star) of mass loss rate $10^{-6}$ $M_\odot$ yr$^{-1}$ and (constant) velocity $2 \times 10^8$ cm s$^{-1}$, typical for an O-type star (see Section 2 and Table 1 in PBR08). The initial jet densities are different, being $\rho_1 = 0.088 \rho_a$ and $\rho_2 = 8.8 \rho_a$, where $\rho_a = 3 \times 10^{-15}$ gr cm$^{-3}$ is the stellar wind density. The initial jet temperature is $T_j \approx 10^{10}$ K, Mach number is $M_j = 16.6$ and pressure $P_{j,1} = 70.8$ dyn cm$^{-2}$ and $P_{j,2} = 7.1 \times 10^3$ dyn cm$^{-2}$. The star is located at a distance of $2 \times 10^{12}$ cm from the base of the jet, in a direction perpendicular to the jet axis. Hereafter, we will use coordinate $z$ for the direction of propagation of the jet, $x$ for the direction connecting the jet base and the star, and $y$ for the direction perpendicular to both.

We have used a finite-difference code, named Ratpenat, which solves the 3D equations of relativistic hydrodynamics written in conservation form. Ratpenat has been parallelized using a hybrid scheme with both parallel processes (MPI) and parallel threads (OpenMP) inside each process (see Ref. [8] for further details). The simulations have been performed in Mare Nostrum, at the Barcelona Supercomputing Centre (BSC) using up to 128 processors. The numerical grid box expands transversally $20 R_j$ (jet radii) on each side of the jet axis (making a total of $40 R_j$), and 10 $R_j$ per node (4 processors). The numerical resolution of the simulation is of 4 cells per initial jet radius. This means that the final box is $160 \times 160 \times 1280$ cells.
An extended grid is used in the transversal direction, with 80 cells, which brings the outer boundary 80 $R_j$ farther from the axis. The resolution is relatively low due to the amount of computational time needed to perform the simulations. However, as the jets initially expand, the effective resolution at the distances of interest, say $\sim 10^{12}$ from the base, is $\sim 16$ cells per jet radius.

We implicitly assume that the magnetic field has no dynamical influence in the evolution of the jet, that the wind is continuous and homogeneous during the time of the simulations and that the compact object is at the same orbital position during this time ($10^{2} - 10^{3}$ s compared to orbital times $T > 10^{5}$ s).

2.2. Results

Jet 1 propagates up to $z \simeq 1.6 \times 10^{12}$ cm after $\simeq 1.25 \times 10^{3}$ s. In the beginning of the simulation, the jet expands and generates a thick shear layer with positive velocities in the jet direction. The backflow surrounds and interacts strongly with this outer jet region, generating instabilities that grow in the shear layer. These instabilities are asymmetric in the plane of impact of the wind due to the different pressures in the cocoon on both sides of the jet (see Fig. 1). After expansion, the central region of the jet becomes underpressured with respect to its surroundings and recollimates until the formation of a reconfinement shock. This quasi-steady shock propagates very slowly from $z \simeq 2 \times 10^{11}$ cm to $z \simeq 4 \times 10^{11}$ cm, as the pressure in the cocoon drops (see PBR08). Downstream of the reconfinement shock, the instabilities, which were growing in the shear layer, propagate to the whole section of the jet as the internal jet flow is decelerated and becomes more sensitive to perturbations. This process ends up in the mixing and deceleration of the jet flow at $z \geq 10^{12}$ cm.

Fig. 1 shows two axial cuts of Jet 1 of rest-mass density, along the YZ (upper) and the XZ planes (lower) at the last snapshot. The deviation caused by the wind thrust can be observed in the XZ plane, which is the plane of symmetry of the wind. Fig. 2 shows transversal cuts of axial velocity, logarithm of rest-mass density and tracer $f$ at $z \simeq 1.3 \times 10^{12}$ cm. In this figure, we can see the deformation of the bow-shock caused by the wind thrust. The jet has been entrained, at this axial position, by the wind material $-f_{\max} < 1$, and the maximum velocity in the jet fluid is still relatively fast ($\simeq 1.5 \times 10^{10}$ cm s$^{-1}$), despite the irregular morphology and mixing. Actually, the velocity drops to $v \simeq 10^{10}$ cm s$^{-1}$ after this point. The low velocity of the jet at the end of the simulation, along with its final (destabilized) structure, implies that the jet will be disrupted and will not propagate collimated out of the binary system.

The evolution of Jet 2 is very similar to that of Jet 1 from a qualitative point of view, but this jet propagates up to $z \simeq 2 \times 10^{12}$ cm in just $\simeq 210$ s. The jet expands more at the base because it is initially denser (more overpressured) and the velocity

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*aThe tracer, $f = [0, 1]$, indicates the composition of the fluid, with 0 corresponding to pure wind material, 1 to pure jet material and any value between 0 and 1 indicates the relative amount of jet material in a cell.*
of the jet head is faster. Therefore, the reconfinement shock is stronger and occurs farther downstream (see PBR08). The location of the shock changes with time from \( z \simeq 6 \times 10^{11} \) cm to \( z \simeq 10^{12} \) cm (see Fig. 3). The effect of the wind in the direction of the jet propagation is very small, as seen in Figs. 3 and 4. In the latter, the structure of the bow shock at \( z \simeq 1.5 \times 10^{12} \) cm is observed to be more symmetric than that in Jet 1 (Fig. 2). The development of asymmetric KH instabilities in the shear layer, as in Jet 1, propagates to the whole jet after the reconfinement shock, what triggers helical motions and distortions in the jet. Fig. 4 shows that the jet core is unmixed \((f = 1)\) and that the flow velocity is still as high as that in the injection point. At the end of the simulation, the velocity of the bow-shock ahead of the jet is \( \simeq 8.4 \times 10^9 \) cm s\(^{-1}\), which is close to the initial speed \( \simeq 9 \times 10^9 \) cm s\(^{-1}\).
3. Discussion

Our work shows that the stellar wind from a massive star may cause the disruption of a jet if its power is $\leq 10^{37} \text{ erg s}^{-1}$. The cocoon generated by the jet presents asymmetric properties due to the impact of the wind. The difference in pressure on both sides of the jet triggers helical perturbation modes in the jet, which develop initially only in the shear layer of the jet. After the jet core goes through a strong reconfinement shock, the helical instability propagates to the whole jet. In PBR08, it was shown that such a shock will occur inside the binary region if the temperature of the jet is $T_j < 10^{14} \text{ K}$ when the jet is surrounded by the cocoon, or $T_j < 10^{13} \text{ K}$ when the jet is in direct contact with shocked wind. Reconfinement shocks and those produced in the interaction with the stellar wind (bow-shock and reverse-shock in the wind impact region) are candidate locations for the production of high energy emission. This aspect will be treated elsewhere (Bosch-Ramon, Khangulyan...
A candidate X-ray binary where disruption of the jet could be taking place is LS 5039 (see Ref. [9]), but higher resolution observations are required for a proper probe of the jet-wind interaction region. The presented situation could take place in several high-mass XRBs (HMXB) in the Galaxy. The luminosity function derived in Ref. [10] predicts 3 HMXBs with \( L_X = 10^{35} \text{erg/s} \). Following Ref. [11] a HMXB with a 10 \( M_\odot \) black hole, could produce a jet with kinetic power between \( 10^{35} \) and \( 10^{38} \text{erg/s} \), which is in the range of the simulations performed here. Although Ref. [10] does not offer any specific prediction for \( L_X \leq 10^{35} \text{erg/s} \), extrapolating the given luminosity function, we deduce that there is room for a few (~ 10) sources in our Galaxy in which the jets could be disrupted by the stellar wind.

The possible influence of magnetic fields or an inhomogeneous wind remain to be tested. At present, we compute the evolution of Jet 2 in a decreasing density atmosphere given by the wind, and study the influence that this may have in the position of the recollimation shock and in the growth of instabilities.

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