Dynamics of a high-mass microquasar jet under the influence of stelar wind

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Abstract: A high-mass microquasar is a binary system formed by a massive star and a compact object orbiting around it. This compact object can emit a particle jet that will be hit by the star's wind and affected by the rotation of the object around the star.
In this work, our first goal was to determine the trajectory of the jet taking into account all these effects. We did this by modeling a simulation of the trajectory with the formulae from a previous article on this topic.
Once we determined the trajectory, we studied how some of the parameters of the system affect the trajectory of the jet, and we did so by making 3 changes to our system. First, we changed the distance between the two bodies, then the intensity of the wind coming from the star and to finish we also changed the speed at which the jet propagated.
After studying the resulting graphics, we concluded that when changing the size of the system, the bigger the system is, the less it is affected by the wind. This is because when we increase the size of the system, so does the period of rotation due to Keppler's third law, which results in a decrease in tangential speed of the compact object that reduces the bending of the jet. We have, however, a strange behaviour for certain values of the size of the system where the bending is less than some bigger systems, and this is probably due to compensation of the forces or something else taking effect there.
The intensity of the wind makes the jet to bend a lot more if the wind is more intense, as it will be receiving a stronger force from the wind.
The speed of the jet makes that the faster jet is more affected by the wind, because the interaction between the two fluids, the jet and the wind, is stronger, causing it to bend more.

I. INTRODUCTION

In the Universe, we can find many objects and systems that emit jets of particles. If these jets reach us, we can analyze them in order to understand properties of its origin, and to know more about the object that emitted them.
In this project, we will focus in the study of a jet from a high-mass microquasar (HMMQ). An HMMQ is a binary system consisting of a massive star and a compact object (CO) rotating around it and accreting matter from the star.
Because of this mass accretion, the CO will sometimes emit a jet of particles, which will be our subject to study. In a non moving object and without wind, this jet would just propagate in a straight line unless it were to interact with some other object along its way. However, in our system it is not that simple, because we have both the rotation around the star and the wind from the star that will bend the jet. This interaction between the jet and the wind has been studied previously in some articles like [1] and [2], and we also have examples from real systems like Cygnus X-3, studied in detail in [3]. We could also find some more examples of studied systems, but they all end up showing that the structure of the jet will be helical shaped.

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Our first objective for this study will be to try to replicate this result with a mathematical model based on some of the formulae and parameters known from other studies, in order to see if we can replicate it. Once the model is completed and gives a good trajectory, we have a great tool at our disposal in order to study this kind of systems.
Our second objective will be to make some changes to the initial system, in order to see how certain parameters influence this trajectory.
The way to work will be as follows:
In Section II, we will be setting up the model. We will determine the parameters we are going to use, and implement the formulae that show how the wind and the rotation interact with the jet. All these parameters and formulae will come from different papers about this topic. Then, we will consider the changes in the parameters that we want to do, based on what we consider that will modify the trajectory of the jet the most. We will have a total of 3 variations: The size of the system, the intensity of the wind and the speed of the jet. We will be analysing each of them independently.
Then in Section III we will show the graphic of the initial model, and the ones with the different variations, and see how each of them behaves and the differences between them.
In Section IV we will end by analyzing the results obtained, to see if we can interpret them based on the formulae of our model and how this changes have modified the forces applied to the jet.

We are hoping to be able to replicate the original trajectory, and to find some interesting information from this modifications we have chosen to study.

II. JET DYNAMICS

A. Model creation

To create the model of the jet, we have to study how it behaves and how is it affected by the different forces in the system. In order to create this model, we will be using most of the formulae of the wind-jet interaction from here [1].
Before starting with the model we will look at the parameters used in this calculation, which we can find in Table I. We will be using a quite generic system, with an O-type star in the main sequence as the center. We can find the parameters for a star like this one in [4]. An important parameter will be the Mass-loss rate, which is the amount of matter that is lost from the star in form of wind, and it can be obtained from [5].

Parameter	Value
Stelar luminosity (L_*)	10^{39}erg s^{-1}
Mass-loss rate ($\dot{M}_w$)	10^{-6}M$_\odot$ yr^{-1}
Terminal wind speed (v_∞)	2×10^8cm s^{-1}
β-law exponent (β)	0.8
Jet luminosity (L_j)	5×10^{36}erg s^{-1}
Jet half-opening angle (θ_j)	0.1 rad
Orbital separation (a)	3×10^{12}cm
Starting height (z_0)	2×10^{10}cm
Orbital period (T)	4 days
Jet Lorentz factor (γ_j)	1.3
Star radius (R_*)	7.4×10^{11} cm

TABLE I: Parameters used for the calculations of the model.

If we take a look at our system, the jet is emitted from the CO, so its origin position is the one of the CO. We will set the xz plane to match the origin position, and we will have the CO at distance a in the x axis from the star if we take the origin of coordinates at the center of the star, and we will be using a non-inertial reference frame in rotation. We will be making all of the calculations for a segment of the jet, which will start at a height z_0. We can see a sketch of the initial system in Fig. 1.
The segment of the jet will propagate at a constant γ_j, which goes in a vertical direction at the beginning and will change its orientation based on the momentum caused by the various forces of the system. So, at the beginning, the momentum of the segment is only in the z coordinate and is defined by:

$$P_z = \dot{P}_j dt = [L_j\gamma_j\beta_j/c(\gamma_j-1)]dt \tag{1}$$

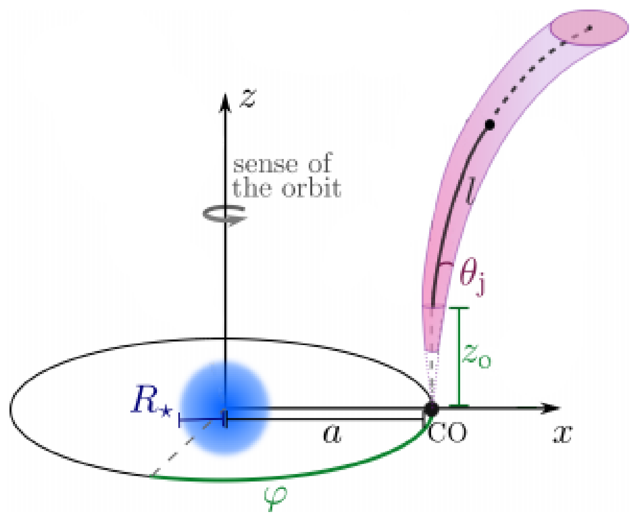

FIG. 1: Sketch of the system and the jet emitted by the CO, adapted from a sketch in [1]. It shows the CO orbiting with a radius a of the star, the sense of the orbit and a representation of the jet.

Once the jet starts expanding and the segment moves, it starts being affected by the different forces in the system, which basically are the force of the wind and the Coriolis force from the rotation of the CO, which can be expressed with:

$$\begin{aligned} F_r &= S_*\rho_w v_w^2 cos(\theta), \\ F_\phi &= \rho_w S_\phi min(4\pi(r-a)/T, 2\pi r/T)^2 \\ F_z &= S_*\rho_w v_w^2 sin(\theta), \end{aligned} \tag{2}$$

Where ρ_w=$\dot{M}_w/4\pi v_w d_*^2$ is the density of the segment, $v_w = v_\infty(1-R_*/r)^\beta$ is the velocity of the wind when it reaches the segment, and $d_* = ||r||$ is the distance between the star and the segment. This calculation of the velocity is what is known as the β-law, which we can see in [6] and [7], which also provide us some of the parameters from Table I. A part form these two papers, another very interesting one take a look at is [8] which also makes use of this β-law and does so in a system very similar to the one we have chosen.
S_* and S_ϕ are referring to the section of the segment perpendicular to the x and ϕ direction respectively and θ is the angle of the jet with the z coordinate.
These forces then will be added to the previous momentum in each direction, to create the momentum for the next iteration. With this new momentum, we can calculate the position of the segment for the next time differential, and after this movement we can start again calculating the new forces and keep doing iterations until we have enough data to make a graphic representation of the trajectory.

B. Modifications

Once we have computed the model based on this equations, we will try some modifications in order to see how the trajectory depends on some of the parameters. We will be making 3 modifications to our system:

1. We are going to change the size of the system, which basically means changing the value of a. However, when doing so we have to take into consideration Kepler's third law of planetary motion, which states that for a circular orbit the following relation applies between T and a.

$$T^2/a^3 = 4\pi^2/GM = ctt. \tag{3}$$

So, when we change the radius of the system, we will also have to change its rotation period according to this proportion.

2. The second property we will be changing is the intensity of the wind coming from the star, in order to have a strong wind and a weak wind to compare them. And how is a wind considered strong or weak? If we look at [2], we will see that they define a χ_j coefficient (4), which is a relation between the intensity of the wind and the jet. This coefficient can be used to calculate the bending angle of the jet.

$$\chi_j = \frac{\theta_j \dot{P}_W}{4\pi \dot{P}_j} = \frac{\theta_j \dot{M}_w v_w (\gamma_j - 1)c}{4\pi \gamma_j \beta_j L_j} \tag{4}$$

We will make it easier, and instead of having to calculate two situations, one for a strong wind and the other for a weak wind, we will make the star's mass-loss rate very big or very small, while keeping the jet the same, to make sure we have a strong wind and a weak wind respectively. We will also take the mass-loss rate we had at the beginning as an intermediate value.

3. The third property we will be changing is the Lorentz factor of the jet, which determines the speed at which the jet moves. We will compare two situations: a relativistic jet with γ_j=1.3, and a non relativistic one with γ_j=1.005, to see if the speed of the particles in the jet has a great impact in the trajectory.

III. RESULTS

Once the model is complete and functional, we can start compiling results and study how the different properties of the system can affect the evolution of the jet.
To do so, we are going to divide the results in four sections: In the first one, we are going to see the evolution of the jet under the conditions we determined before, which we will call "original conditions". In the other 3, we are going to see the changes in the jet trajectory when we change 3 of the system's variables.

A. Jet evolution

First, we are going to see how the jet evolves under this "original conditions".
We can see in Fig.2 that the jet follows the shape of a helix which keeps growing in its radius as it ascends. The rotation will be opposed to the direction of the orbit of the CO, so in our case, the rotation of the trajectory is clock-wise.

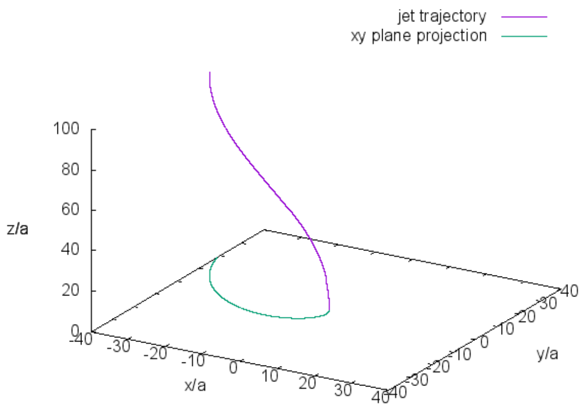

FIG. 2: Evolution of the jet under the effect of the wind. The jet rotates clockwise in an helical shape which is bigger as it goes higher. The model has been calculated up to a jet length of around 300 times a, but it is a little bit reduced in this image so the initial behaviour can be seen better.

Now that we know how the system looks like in our starting conditions, we can proceed to make the different changes and see how the new trajectory behaves.

B. Change in the system's size

First, we are looking at how changing the size of the system affects the trajectory. As we said in the previous section, this will involve changing the radius, and also the rotation period, because of Kepler's third law. We will be checking different trajectories ranging from a radius of 10^{11}cm to 10^{14}cm as we can see in Fig. 3.

We can see some interesting trajectories in this graphic. We have the light blue line that shows the trajectory for $a = 3 \times 10^{12}$cm, which is the same from our original system, and then we can see that both the one with $a = 10^{11}$cm and the one with $a = 10^{13}$cm have a very similar trajectory, but with a smaller relative movement (the values of the graphic are divided by a, so we are not shown the size of the trajectory, but the size relative to the distance between the star and the CO). Last, we have the red line of $a = 10^{14}$cm, where we can see the trajectory is not represented completely, but we can already notice that it will have a much bigger trajectory that the others.

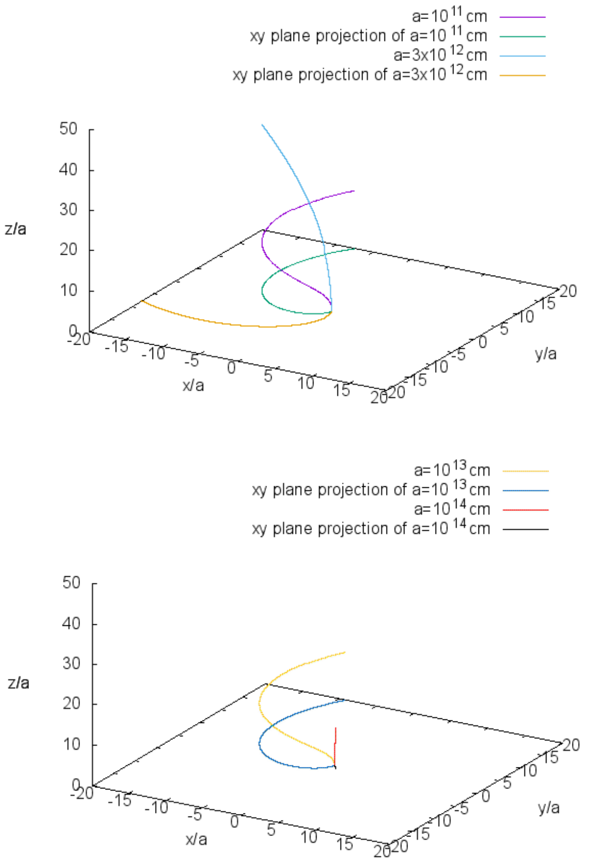

FIG. 3: Evolution of the jet under the variation of the system size. In the first graphic we have the 2 smaller systems and in the second one we have the 2 bigger ones. We can see that both the graphic for $a = 10^{13}$ and $a = 10^{11}$ are very similar, and the other ones show bigger trajectories. The projection of $a = 10^{14}$cm is barely visible, as this trajectory has almost not bent.

C. Change in the wind's intensity

Now we are looking at how changing the intensity of the wind created by the star affects the trajectory. As stated in the previous section, we have 3 types of wind, a weak wind, a medium wind and a strong wind. We need to remember that this intensities also depend on the speed of the jet, as we saw in (4), so a change in this speed could mean a change in the type of wind. For this reason we will keep the jet the same and only change the wind.

We can see in Fig. 4 that for the strong wind, the jet is really affected, and its movement is greater in the xy plane than the z direction. For the medium wind, we have our original trajectory, which is more vertical than before, but still has a lot of deviation by the wind. For the weak wind, we can see that the movement is almost fully vertical, with little movement in xy plane.

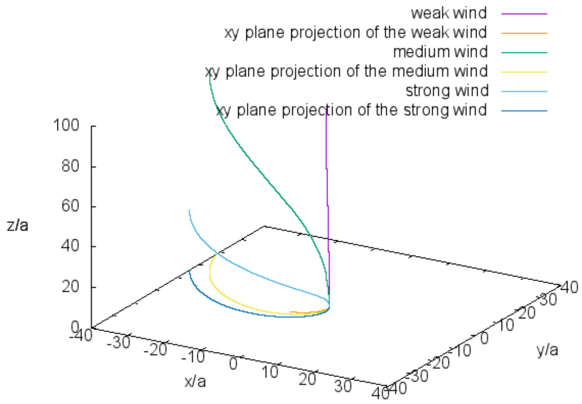

FIG. 4: Evolution of the jet under the variation of the wind intensity. We see that the jet bends more for stronger winds, but the projections at the xy plane follow a similar path.

D. Change in the jet's speed

Last, we are changing the speed of the jet. For this change, we just studied 2 different examples, which would be a relativistic jet (γ_j=1.3) and a non-relativistic one (γ_j=1.005).

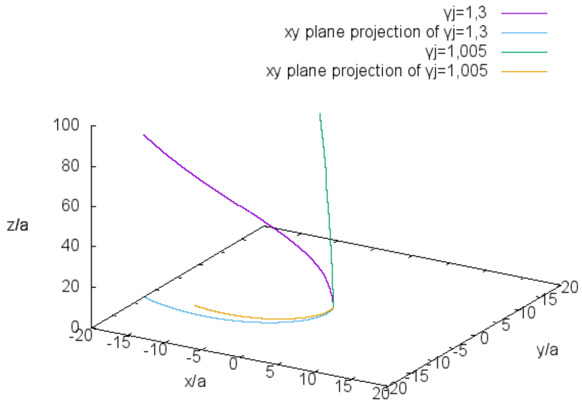

FIG. 5: Evolution of the jet under the variation of the jet speed. We see that for γ_j=1.3 the jet bends a lot, while for γ_j=1.005 the jet hardly bends. The trajectory on the xy plane is quite similar.

If we look at Fig. 5, we can see that the relativistic jet is more affected by the wind and has more horizontal movement than the non relativistic one.

IV. CONCLUSIONS

- **Jet trajectory**
  We have checked that the trajectory of the original jet is like it was stated in some other papers: it follows a helical structure with a growing radius, and also the direction of the rotation is opposite to the one of the CO.

- **System size**
  When we change the size of the system, we are not only changing its radius, but we are also changing its period of rotation due to Keppler's third law. Effectively, what we are doing is to change the tangential velocity of the CO. When we are increasing the size of the system, the period also increases, so we have less tangential velocity. This will make that the bigger the system, the less the jet will be affected by the rotation. However, when we keep reducing the size, we see that at around a=3×10^{12}cm, the jet if being less affected that in some bigger systems, but if we keep making them small it becomes more affected again. This is probably due to the fact that the two forces, the wind and the rotation, may cancel out some of their effects, of maybe there is something else that also changes giving this results.

- **Wind intensity**
  The effect of the change in the intensity of the wind is easier to understand. We know that the impact of the wind on the jet is one of the main reasons for it to bend, so a system with more intense winds will have a more bent jet, like we see in the results.

- **Jet speed**
  The effect of the speed of the jet can be better understood if we look at the jet and the wind like two fluids that interact with each at the moment of impact. If the jet is faster, the section of the jet we are considering is bigger, so the surface of interaction between both is larger, and this causes that the jet bends more.

Acknowledgments

I would like to start by thanking my advisor Valentí Bosch-Ramon for all the guidance and help that he has given to me during all this project, and for all the knowledge that I have gained from working with him. I would also like to thank all my colleagues and friends who have helped me in the moments when I needed it, and my family, for always being by my side supporting me in everything I have done.

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