Artificial γ-ray imaging of a galactic, relativistic astrophysical jet

T Smponias¹, T S Kosmas¹

¹ Theoretical Physics Section, University of Ioannina, 45110, Greece
E-mail: hkosmas@uoi.gr

Abstract. The jet in a microquasar stellar system is simulated with a relativistic hydrocode (PLUTO) and then it is imaged, in the γ-rays wave band, with a line-of-sight method, including both emission and self-absorption. A synthetic image is produced which allows to better estimate the system’s physical properties. The calculation procedure in our method has been simplified by exploiting the ability to de-couple the hydrodynamical from the radiative quantities in the computations.

1. Introduction

Microquasars (MQ) are a class of X-ray binaries comprising a close binary stellar system, where a collapsed object (neutron star or black hole) orbits together with a main sequence companion, in close proximity. An accretion stream carries matter from the main sequence star towards the compact object, leading to the formation of an accretion disk around the collapsed star [12]. The main reason for the formation of the disk is conservation of angular momentum, which prevents matter, originally part of a rotating star, to fall directly to the compact object, thus losing angular momentum instantaneously. From the close vicinity of the black hole, or neutron star for that purpose, twin relativistic jets are ejected, fed by accretion disk matter [12] and pointed perpendicular to the plane of the accretion disk.

The jets in MQ are sometimes highly relativistic e.g. GRS 1915+105 [4], or mildly relativistic, like SS433 ([1],[10],[3]). In some cases, apparent superluminal motion is also exhibited (e.g. GRS 1915+105). The jet ejection can be episodic, or a more continuous flow. Strong correlations tend to appear among emissions in different wavelengths, during various phases of system behaviour [9].

In the present work we concentrate on emission from the MQ jet of SS433, an object that has been repeatedly observed over the past three and a half decades. The basic features of the system are very briefly summarized below. The system consists of a main sequence supergiant and a collapsed stellar remnant, orbiting at close distance with a period of around 13 days. Relativistic (0.26c) jets are precessing around an axis inclined at 79 degrees in relation to the direction to the Earth, the precession angle being roughly 20 degrees and the precession period about 160 days [3]. The jets have been verified, from optical spectroscopy, to mainly consist of proton flow ([1], [3]), yet no definite such data exist as of today for other MQ systems (see however [6]).

The ejected plasma can be approximately treated as a fluid flow, assuming a mild magnetic field permeats the jet matter [5]. The field provides a coupling of the jet particles at smaller
Figure 1. A 3-D density plot of the jet moving through the stellar wind, with a resolution of 300*500*300 (XYZ respectively) cartesian homogeneous grid. The accretion disk wind in the model has been crossed by the jet and matter from it can be seen left over around the jet base. The spatial scale ($10^{10}$ cm per unit length) is the same for all axes.

Figure 2. A plot of the γ-ray intensity (z-axis, arbitrary units) of the artificial image (formed on x-y plane) of the jet system, at the same time instant as in Fig. 1. A small amount of self-absorption has been included, in a simplified manner (proportional to the local emission coefficient at each point). Fast and dense matter contributes the most to emission, while absorption is maximum where the column density is largest.

scales, therefore making possible a macroscopically continuous flow, where the jet plasma now behaves as an ideal gas. This approximation opens the possibility of modelling the jet with numerical hydrodynamics codes, allowing the investigation of physical conditions in the jet. Trial and error leads to a set of initial/boundary conditions (IBC’s) that, when inserted into the models, lead to synthetic images that are then compared to actual observed properties. If a match is achieved, then this means that the initial input (IBC) was correct.

This paper attempts to model a microquasar jet using a 3-dimensional (3D) relativistic hydrodode and then, a line-of-sight (LOS) radiative transfer code [13] that produces artificial γ-ray synthetic images of the hydrocode model system. Meanwhile, the emission and absorption coefficients for creating the synthetic images are provided by a separate routine, written in Mathematica [14], in order to deal with the complexity of the relevant mathematical expressions.
2. Methods
2.1. Calculating the emission and absorption coefficients
In order to calculate the -self-absorbed- emission from the simulated jet and its surrounding winds, one needs to obtain the $\gamma$-ray emission and absorption coefficients at every location. This can be achieved through the solution of the equation of radiative transfer, along multiple parallel lines of sight intersecting the volume of the jet-wind system. The full details of this calculation shall be found in [14], based on the formalism of [16], [7], [15] and [13]. More specifically, the one dimensional (no scattering sideways) equation of radiative transfer is solved for each LOS. This equation, in the case of time independent radiative transfer, and also in the absence of sideways scattering reduces to:

\[
[\Omega \cdot \nabla + k_\nu]I_\nu = j_\nu.
\]

(1)

where $I_\nu$ is the local intensity, at frequency $\nu$, $\Omega$ is the solid angle, $j_\nu$ denotes the local emission coefficient and $k_\nu$ the local absorption coefficient. Along a line of sight that subtends a solid angle $\Delta\Omega$, the above expression becomes

\[
\Delta\Omega \cdot \frac{dI_\nu}{dl} = j_\nu - k_\nu I_\nu
\]

(2)

The two indices are, in general, dependent on the properties of the jet matter. Consequently, in order to calculate the emission from a given system, such as the microquasar jet, one also needs the description of the geometrical and dynamical conditions of the system in question. The emission and absorption coefficients for $\gamma$-rays are obtained from the proton-proton interaction for emission and from a number of processes ($\gamma$-$\gamma$ interaction with ambient soft photons $\gamma\gamma \rightarrow e^+e^-$, photopion production $\gamma N \rightarrow \pi_i \gamma$, photopair production $\gamma N \rightarrow Ne^+e^-$) for absorption [15]. A simplified absorption process, with the relevant coefficient set proportional to the emission coefficient, shall be considered for this paper.

2.2. Numerical hydrodynamic simulations using the PLUTO code
The jet was represented as a 3-dimensional relativistic flow of ideal gas within the framework of the PLUTO code [11], originating from the vicinity of the compact object and then crossing the accretion disk wind and the stellar wind of the companion. The domain of the simulation is Cartesian XYZ with a resolution of 300*500*300 for this specific run. The algorithm used (piecewise-linear method: [8], [2]) includes linear interpolation in cells and a dimensionally split method of characteristic tracing to advance the solution in time at each cell interface. The simulation is let to evolve until the jet, injected at the one side of the computational box, begins to exit from the other side. Although the binary companion lies outside the domain, its stellar wind is still present, with a $\frac{1}{r^2}$ inverse dependence on the distance from the (not-included-yet assumed-to-exist at a specific but remote location) companion star. The accretion disk wind is represented in a simplified manner, using a cylindrical shape wind construct, with a density decreasing as proportional to $\frac{1}{y^2}$, where $y$ is parallel to the jet precession axis.

2.3. Line of sight integration
In order to calculate the emission and absorption of $\gamma$-rays from the jet and from the surrounding winds, line of sight integration is performed. The 3-dimensional volume of a snapshot from the hydrocode, is transferred, in the form of 3-D data arrays, to the imaging program (LOS code) in IDL. Then, the data volume is crossed by many parallel lines of sight (LOS’s), all set parallel to a preset direction, i.e. oriented towards the Earth. Each LOS constitutes a 1-D vector array, whose elements are selected from the 3-D array, as the LOS path is drawn through the volume. The emission and absorption coefficients, $\epsilon_\nu$ and $\kappa_\nu$ respectively, are also calculated along the
way. Finally, when a LOS has been completed, its elements forming a 1-D array, the equation of radiative transfer (no sideways scattering is allowed) is solved along the given LOS, using the obtained emission and absorption coefficients. The result, for each LOS, is the intensity from that LOS and it is assigned as the radiative intensity of the pixel where the LOS meets the plane of observation, i.e. the plane where the synthetic image is formed. This way, each pixel of the artificial image is assigned the intensity from a LOS.

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3. Results

A computer simulation study of the SS433 jet was performed, using the PLUTO hydrocode and the in-house radiative transfer codes ([13], [14]). The size of the computational grid for PLUTO was set to 300*500*300 equal sized cells, while the imaging was performed at a resolution 5 times less (60*100*60). The jet speed is set to $u=0.26c$ and the jet enters the grid at the center of the xz plane. The accretion disk wind and stellar companion wind are represented in the model as ambient matter, that is traversed by the jet on its way outwards, along the positive Y-direction. In Figure 1 we can see a snapshot of the jet density, where the jet has crossed the accretion disk wind matter, part of which is now piling up around the jet base.

Then, the model system was artificially imaged, in $\gamma$-rays, using the LOS code (Figure 2). The emission coefficient was set to be proportional to the hydrodynamical density $\rho$, times the square of the local velocity $u^2$, at each point, while the absorption coefficient was simply set proportional to the emission coefficient, as a first attempt to include the absorption. As can be seen, the fast moving matter contributes more to the emission. The absorption, on the other hand, is generally stronger where the column density is higher (i.e. where the LOS has to cross more matter along its way through the system).

4. Conclusions

The simplified emission and absorption model used here is based on the fact that in the formalism of Ref. [15] the hydrodynamical quantities can be de-coupled from the radiative ones, during the calculation of $\gamma$-ray emission. Therefore, the same radiative calculation can be applied all over the model system and then the result should be multiplied by the density, velocity, etc. This approximation, however, is not always (e.g. for neutrino emission) valid.

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