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Binary black holes in nuclei of extragalactic radio sources

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Abstract. If we assume that nuclei of extragalactic radio sources contain a Binary Black Hole system, the 2 black holes can eject VLBI components and in that case 2 families of different VLBI trajectories will be observed. An important consequence of the presence of a Binary Black Hole system is the following: the VLBI core is associated with one black hole and if a VLBI component is ejected by the second black hole, one expects to be able to detect the offset of the origin of the VLBI component ejected by the black hole not associated with the VLBI core. The ejection of VLBI components is perturbed by the precession of the accretion disk and the motion of the black holes around the gravity center of the BBH system. We modeled the ejection of the component taking into account the 2 perturbations and we obtained a method to fit the coordinates of a VLBI component and to deduce the characteristics of the BBH system, i.e. the ratio T_p/T_b where T_p is the precession period of the accretion disk and T_b the orbital period of the BBH system, the mass ratio M_1/M_2, the radius of the BBH system R_{bin}. We applied the method to component S1 of 1823+568 and to component C5 of 3C 279 which presents a large offset of the space origin from the VLBI core. We found that 1823+568 contains a BBH system which size is $R_{bin} \approx 60\ \mu as$ and 3C 279 contains a BBH system which size is $R_{bin} \approx 378\ \mu as$. We were able to deduce the separation of the 2 black holes and the coordinates of the second black hole from the VLBI core, this information will be important to make the link between the radio reference frame system deduced from VLBI observations and the optical reference frame system deduced from GAIA.

Key words. Compact radio sources – Binary Black Hole systems – Astrometry

1. Introduction

VLBI observations of compact radio sources show that the ejection of VLBI components does not follow a straight line but undulates. These observations suggests a precession of the accretion disk. To explain the precession of the accretion disk, we will assume that the nucleus of radio sources contains a binary black hole system (BBH system) .

A BBH system produces 2 main perturbations of the VLBI ejection due to:

1. the precession of the accretion disk,
2. the motion of the two black holes around the gravity center of the BBH system.

The presence of a BBH system, induces several consequences, which are:

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1. the 2 black holes can have accretion disks with different angles with the plane of rotation of the BBH system and can eject VLBI components; in that case we will observe two different families of trajectories, a good example of a source showing 2 families of trajectories is 3C 273 which components C5 and C9 follow 2 different type of trajectories,
2. if the VLBI core is associated with one black hole and if the ejection of the VLBI component comes from the second black hole, there will be an offset between the VLBI core and the origin of the ejection of the VLBI component; this offset will correspond the radius of the BBH system.

We model the ejection of the VLBI component using a geometrical model taking into account the two main perturbations due to the BBH system.

We determine the free parameters of the model comparing the observed coordinates of the VLBI component with the calculated coordinates of the model.

Two different cases can happen when we try to solve this problem, namely:

1. either the ejection from the VLBI component occurs from the VLBI core or the offset is smaller than 3 times the smallest error bars of the component coordinates,
2. the ejection from the VLBI component occurs with an offset larger or much larger than 3 times the smallest error bars of the component coordinates.

We will call the first case, Case I. An example of Case I is provided by the fit of the component S1 of 1823+568 using Mojave data.

We will call the second case, Case II. It is much complicated that the first one, because the observed coordinates contain an unknown offset which is very large compare to the error bars. An example of Case II is provided by the fit of the component C5 of 3C 279 using Mojave data.

Modelling ejection of VLBI components using a BBH system has been developed in previous articles, (Britzen et al. 2001) in the case of 0420-014, and (Lobanov & Roland 2005) in the case of 3C 345 and (Roland et al. 2008) in the case of 1803+784, and the fit of components S1 of 1823+568 and C5 of 3C279 is done in (Roland et al. 2012).

2. The model

2.1. Introduction: The two-fluid model

We will describe the ejection of a VLBI component in the framework of the two-fluid model (Sol & al. 1989; Pelletier & Roland 1989, 1990; Pelletier & al. 1992). The two-fluid model assumes :

1. The outflow consists of an $e^{\pm}$ plasma (hereafter *the beam*) moving at highly relativistic speed (with corresponding Lorentz factor $\gamma_b \leq 30$) surrounded by an $e^{-}-p$ plasma (hereafter *the jet*) moving at mildly relativistic speed $v_j \leq 0.4 \times c$.
2. The magnetic field lines are parallel to the flow in the beam and the mixing layer, and are toroidal in the jet.

The $e^{-}-p$ jet carries most of the mass and the kinetic energy ejected by the nucleus. It is responsible for the formation of kpc-jets, hot spots and extended lobes. The relativistic $e^{\pm}$ beam moves in a channel through the mildly relativistic jet and is responsible for the formation of superluminal sources and their γ-ray emission.

2.2. The general perturbation of the VLBI ejection

We assume that the black hole ejecting the VLBI component is the origin of the coordinates and is called black hole 1. The coordinates of the moving components are

$$
\begin{aligned}
x_c = & [R_o(z)\cos(\omega_p t - k_p z(t) + \phi_o) \\
& + x_1 cos(\omega_b t - k_b z(t) + \psi_o) - x_1 \cos(\psi_o)] \\
& exp(-t/T_d)\ , \qquad (1)
\end{aligned}
$$

$$
\begin{aligned}
y_c = & [R_o(z)\sin(\omega_p t - k_p z(t) + \phi_o) \\
& + y_1 \sin(\omega_b t - k_b z(t) + \psi_o) - y_1 \sin(\psi_o)] \\
& exp(-t/T_d)\ , \qquad (2)
\end{aligned}
$$

$$z_c = z_c(t)\ . \tag{3}$$

Details can be found in (Roland et al. 2008).

The differential equation governing the evolution of $z_c(t)$ can be obtained through the definition of the speed of the component, namely

$$v_c^2 = \left(\frac{dx_c(t)}{dt}\right)^2 + \left(\frac{dy_c(t)}{dt}\right)^2 + \left(\frac{dz_c(t)}{dt}\right)^2\ , \tag{4}$$

where v_c is related to the bulk Lorentz factor by $v_c/c = \sqrt{(1-1/\gamma_c^2)}$.

Using (1), (2) and (3), we find from (4) that dz_c/dt is the solution of the equation

$$A\left(\frac{dz_c}{dt}\right)^2 + B\left(\frac{dz_c}{dt}\right) + C = 0\ . \tag{5}$$

The calculation of the coefficients A, B and C can be found in Appendix I of (Roland et al. 2008).

Equation (5) admits two solutions corresponding to the jet and the counter-jet.

As (Camenzing & Krokenberger 1992), we call θ the angle between the velocity of the component and the line of sight we have

$$cos(\theta(t)) = \left(\frac{dy_c}{dt} sin\ i_o + \frac{dz_c}{dt} cos\ i_o\right)/v_c\ . \tag{6}$$

The Doppler beaming factor δ, characterizing the anisotropic emission of the moving component, is

$$\delta_c(t) = \frac{1}{\gamma_c\left[1-\beta_c cos(\theta(t))\right]}\ , \tag{7}$$

where $\beta_c = v_c/c$.

Solving (5), we determine the coordinate $z_c(t)$ of a point source component ejected relativistically in the perturbed beam. Then, using (1) and (2), we can find the coordinates $x_c(t)$ and $y_c(t)$ of the component. In addition, for each point of the trajectory, we can calculate $\cos\theta$ from (6) and δ_c from (7).

When the coordinates $x_c(t)$, $y_c(t)$ and $z_c(t)$ have been calculated, they can be transformed to $w_c(t)$ (West) and $n_c(t)$ (North) coordinates.

The radio VLBI component has to be described as an extended component along the beam. Let us call n_{rad} the number of points for which we integrate to model the component. The coordinates of the VLBI component are

$$W_c(t) = \left(\sum_{i=1}^{n_{rad}} w_{ci}(t)\right)/n_{rad}\ , \tag{8}$$

$$N_c(t) = \left(\sum_{i=1}^{n_{rad}} n_{ci}(t)\right)/n_{rad}\ . \tag{9}$$

and can be compared with the observed coordinates of the VLBI component. Details can be found in (Roland et al. 2008).

2.3. The parameters of the model

The free parameters of the model are:

- i_o the inclination angle,
- ϕ_o the phase of the precession at $t = 0$,
- $\Delta\Xi$ the mean direction of the source in the plane of the sky,
- Ω the opening angle of the precession cone,
- R_o the maximum amplitude of the perturbation,
- T_p the precession period of the accretion disk,
- T_d the characteristic time for the damping of the beam perturbation,
- M_1 the mass of the black hole ejecting the radio jet,
- M_2 the mass of the secondary black hole,
- γ_c the bulk Lorentz factor of the VLBI component,
- ψ_o the phase of the BBH system at $t = 0$,
- T_b the period of the BBH system,
- t_o the origin of the ejection of the VLBI component,
- V_a the propagation speed of the perturbations,
- n_{rad} is the number of steps to describe the extension of the VLBI component along the beam,
- ΔW and ΔN the possible offsets of the origin of the VLBI component.

Practically the problem we have to solve is a 15 free parameters problem. See details in (Roland et al. 2012).

3. Results

From the fit of the coordinates of the component S1 of 1823+568, the main characteristics of the final solution of the BBH system associated with 1823+568 are:

- the radius of the BBH system is $R_{bin} \approx 60$ $\mu as \approx 0.42$ pc,
- the VLBI component S1 is not ejected by the VBLI core and the offsets of the observed coordinates are $\Delta W \approx +5$ μas and $\Delta N \approx 60$ μas,
- the ratio T_p/T_b is $8.88 \leq T_p/T_b \leq 9.88$,
- the ratio M_1/M_2 is $0.095 \leq M_1/M_2 \leq 0.25$,
- the inclination angle is $i_o \approx 4.0$,
- the bulk Lorentz factor of the VLBI component is $\gamma_c \approx 17.7$.

From the fit of the coordinates of the component C5 of 3C 279, the main characteristics of the final solution of the BBH system associated with 3C 279 are:

- the radius of the BBH system is $R_{bin} \approx 378$ $\mu as \approx 2.4$ pc,
- the VLBI component C5 is not ejected by the VLBI core and the offsets of the observed coordinates are $\Delta W \approx +375$ μas and $\Delta N \approx +50$ μas,
- the ratio T_p/T_b is $T_p/T_b \approx 65$,
- the ratio M_1/M_2 is $2.02 \leq M_1/M_2 \leq 2.10$,
- the inclination angle is $i_o \approx 8.4$,
- the bulk Lorentz factor of the VLBI component is $\gamma_c \approx 18.2$.

Details of the fits are given in (Roland et al. 2012).

4. Discussion and conclusion

Let us mention that the precession of the accretion disk can be explained using a single rotating black hole (Lens-Thirring effect). However, a spinning black hole and a BBH system have completely different consequences. In the case of a BBH system, one has an extra perturbation of the ejected component due to the motions of the black holes around the gravity center of the BBH system, one can expect to observe two different families of trajectories (if the two black holes eject VLBI components) and an offset of the origin of the ejected component if it is ejected by the black hole which is not associated with the VLBI core.

The observations used have been done at 15 GHz and the smallest error bars are ≈ 40 μas. In the case of 1823+568, we are able to detect a BBH system which radius is $R_{bin} \approx 60$ μas. The fit provides in addition to the size of the BBH system, the coordinates of the second black hole. As indicated in (Britzen et al. 2001) and from VLBI observations in the first few mas, probably all extragalactic radio sources contain a BBH system. As GAIA will provide positions of extragalactic radio sources within ≈ 25 μas the link between the GAIA reference frame from optical observations of extragalactic radio sources and the reference frame obtained from VLBI observations will have to take into account the complex structure of nuclei of extragalactic radio sources because with a resolution of ≈ 25 μas, probably all these sources will appear as double sources and the radio core, obtained from VLBI observations, and the optical core obtained by GAIA will not be necessarily the same.

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