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Beam Trajectories in the Intracluster Medium

L. Zaninetti[1] and H. M. Van Horn[2]

[1] Dipartimento di Fisica Generale, Via Pietro Giuria 1 ,10125 Torino, Italy email: zaninetti@to.infn.it

[2] Department of Physics and Astronomy, University of Rochester Rochester , NY 14627

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ABSTRACT

Context. We show that a simple kinematic model, which combines ram pressure bending or variable jet velocity with precession and variable orientation of the observer relative to the trajectory of a galaxy through the intracluster medium, can yield a wide range of morphological types of twin-jet systems.
Aims. In particular the transition from "C"-shaped sources to "S"-shaped sources can be understood as a consequence of different parameter choices within this simple model.
Methods. To be written
Results. To be written

Key words. Key words : jets of galaxies - jets of quasars

1. Introduction

Extended radio sources often exhibit long, radio emitting " tails. " The simplest hypothesis consistent with these features is that they are a " fossil record " traced in the intergalactic medium by jets emitted from a moving galaxy (Miley et al. (1972)). If the flow direction of the jet is changed by ram pressure due to interaction with the intergalactic medium, a "C"-shaped form may be produced, such as that of 3C 83.1B/NGC 1265 (Owen et al. (1978)). Alternatively the jet velocity may decrease as a result of expansion or of changes within the source of the jet itself. In addition to these effects, precession of the jet axis (cf. Gower et al. (1982) and references therein) can lead to significant changes in the apparent structure of the radio tails. For example the "S"-shaped structure of 2300-189 (Hunstead et al. (1984)) is most naturally understood as a consequence of this effect. The rich morphology of extragalactic radiosources (cf. Miley (1980)) suggests that the interplay between variable jet direction or velocity and precession can lead to remarkably complex appearances of radio sources as projected on the sky.

The purpose of this paper is to demonstrate that a wide range of morphological types can indeed be produced by a simple kinematic model involving combinations of variable

Send offprint requests to: L.Zaninetti

jet direction or velocity , precession of the jet axis, and angle of orientation of the observer relative to the trajectory of the galaxy. In particular we show that different choices of these parameters can produce a transition from "C"-shaped to "S"-shaped sources. Some of these effects have previously been studied by Gower et al. (1982). Although their calculations are relativistic while ours are not, they have made the unnecessary restrictive assumptions (i) that the observer's line of sight is normal to the axis of precession of the jet and (ii) that the velocity of the jet is constant. Our calculation relaxes both of these assumptions.

2. Ram pressure bending plus precession

We consider a two-sided jet emitted with velocity $\boldsymbol{U}_0$ and -$\boldsymbol{U}_0$ from the galaxy which is itself moving through the intracluster medium (ICM) with velocity $\boldsymbol{V}_g$ along a trajectory perpendicular to the axis of the jet. While the orientations of most radio jets appear to be correlated with the orientations of the rotation axes of the galaxies from which they originate, this is not universally true (Heckman et al. (1985)), and in any case there is no obvious physical reason for supposing a correlation with the direction of motion of the galaxy. Our assumption that the axis of the jet is perpendicular to the trajectory of the galaxy is not essential and will be relaxed in subsequent work. In the rest frame of the galaxy, the ICM appears to be flowing past the galaxy with velocity -$\boldsymbol{V}_g$. The ram pressure resulting from the interaction with this flow bends the jet away from the direction of motion of the galaxy (cf. Odea (1985); Odea & Owen (1986) for a general review). For our present purposes , it is sufficient to approximate the form of the curved jet as a semicircle :

$$R_c = \sqrt{x^2 + y^2 + z^2} \quad , \tag{1}$$

where R_c is the radius of curvature, and

$$z = z_0 + V_g t \quad , \tag{2}$$

is the position of the galaxy at time t.

In addition to this translational motion, we wish to include the effect of precession of the jet axis. For simplicity, we assume that the axis of the jet is perpendicular to the axis of precession, and we take the precession rate ω to be constant. Thus, if ψ is the angle between the x-axis and the axis of the jet, we have

$$\psi = \psi_0 + \omega t \quad . \tag{3}$$

The angular velocity of precession, ω, can in principle be determined from the measurable parameters of the model :

$$\omega = \frac{V_g}{R_c} \Delta\psi \quad , \tag{4}$$

where $\Delta\psi = \psi - \psi_0$. In particular, if we write $R_3 = R_c/1Kpc$ and $V_3 = V_g/10^3 Km\, s^{-1}$, we obtain

$$\omega = \frac{V_3 \Delta\psi}{R_3} \quad \frac{rad}{Myrs} \quad . \tag{5}$$

We wish also to observe the resulting pattern formed by the jet from an arbitrary orientation. The jets seen in nature are observed from many different angles, and it is important

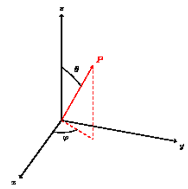

Fig. 1. Orientation of the observer relative to the jet- emitting galaxy. The galaxy moves along the z-axis, and the two -sided jet is assumed to lie in the x-y plane and to precess with uniform angular velocity ω about the direction of motion of the galaxy.

to appreciate the great variety which perspective alone can give to a single shape. The orientation of the direction of observation in the rest frame of the galaxy is shown in Fig. 1.

Here the z-axis is the direction of motion of the galaxy, the jet is emitted from the galaxy parallel to the x-y plane at an angle ψ relative to x-axis, and the direction of observation is oriented at an angle ϕ relative to the x-axis and at a latitude θ relative to the x-y plane. In Figs 2, 3, 4, and 5 we show the striking variety of forms which can be produced from a simple combination of ram pressure bending plus precession. Fig. 2 shows the view looking down along the z-axis. The "S"-shaped form of the jets produced by the precession of the beam axis through an angle of 90^0 is evident. Without the precession, and looking along the x-axis rather than the z-axis, this figure would have appeared as a semicircle. ("C"-shaped figure). Evidently, a combination of ram pressure bending plus precession can produce a transition between these two observed forms of radiosources. The effect of changes in the angle at which the simulated radio source is observed is illustrated in Figs. 3, 4, and 5. In all cases the same system is shown , but from quite different perspectives. The changes in aspect of even this simple system are quite dramatic.

3. Decreasing jet velocity plus precession

We next consider the case of a jet with variable velocity but with no ram pressure bending. The assumed geometry is the same as for the case considered in the previous section, but we now compute the form of the curved jet directly instead of approximating it as a semicircle.

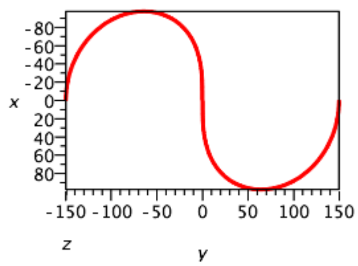

Fig. 2. Two sided-jet together with precession. Jet and counter jet originate at (x,y,z) = (0,0,0). The observer is at Euler angles [0,0,0]. The units of R, V_g and ω are arbitrary.

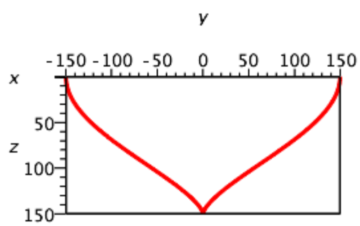

Fig. 3. The same as Figure 2 but the observer is at Euler angles [0,-90,0].

The variation of velocity along the jet depends strongly upon the adopted model. Perhaps the simplest case is that of free expansion of a turbulent jet. In this case, the jet velocity is inversely proportional to the projected radial distance from the origin of the jet (Landau (1987)). For our case, the jet velocity is therefore given by

$$v_\rho = \frac{U_0 \rho_0}{\rho} \quad , \tag{6}$$

where $\rho = \sqrt{x^2 + y^2}$, and U_0 is the initial velocity of the jet at the injection radius ρ_0 (in cylindrical coordinates coaxial with the trajectory of the emitting galaxy). For this case, the trajectory of the jet therefore given by the parametric equations (2),(3) and (7) :

$$\rho^2 = \rho_0^2 + 2 U_0 \rho_0 \frac{\Delta z}{V_g} \quad . \tag{7}$$

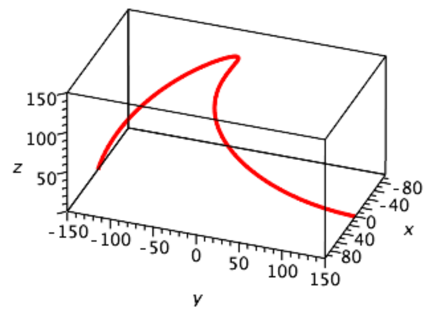

Fig. 4. The same as Figure 2 but the observer is at Euler angles [20,60,0].

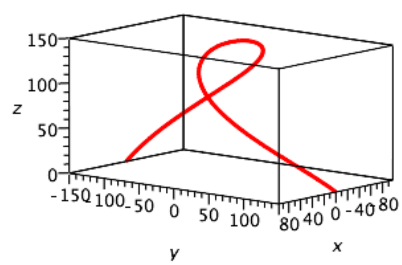

Fig. 5. The same as Figure 2 but the observer is at Euler angles [40,80,0].

Equation (7) shows that the configuration generated by this set of assumptions is a parabola. However, the precessional motion again converts this “C”-shaped figure into an “S”-shaped one.

Examples of the appearance of this system are shown in Figs 6, 7, 8 and 9 , Fig 6 can be compared directly with Fig. 2.

The “S”-shaped form of the projection onto the x-y plane is apparent. More interesting are the views along the x-axis (Fig. 7) and along the y-axis (Fig 8), showing that the same jet configuration can appear as a closed, teardrop-shaped loop or as a cusp, depending on the orientation of the observer. Fig 9 shows a projection from an orientation similar to that illustrated in Fig. 3, and the distorted “S”-shaped figure is apparent in both.

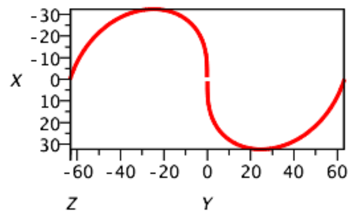

Fig. 6. Two sided-jet together with precession and decreasing velocity. Jet and counter jet originate at (x,y,z) = (0,0,0). The observer is at Euler angles [0,0,0]. The parameter a is given by a = $\rho_0 U_0/V_g$=20.

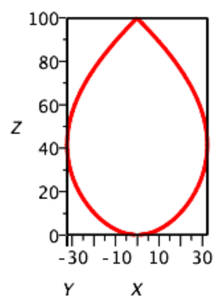

Fig. 7. The same as Figure 6 but now the observer is at Euler angles [0,90,90].

The angular velocity of precession can again be inferred from the observed parameters for this case of ram pressure bending. From (2) and (7) it follows analogously to (5) that

$$\omega = \frac{V_3 \Delta\psi}{\Delta z_3} \quad \frac{rad}{Myrs} \quad , \tag{8}$$

where again $V_3 = V_g/10^3 Kms^{-1}$, and where $\Delta z_3 = (z - z_0)/1Kpc$.

4. Conclusions

We have shown that the combination of either ram pressure bending or variable jet velocity plus precession and viewing angle can produce forms of rather complicated appearance, even for very simple types of input physics. In particular, we have demonstrated that a

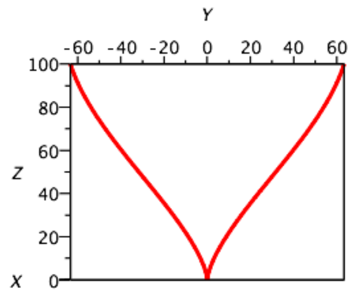

Fig. 8. The same as Figure 6 but now the observer is at Euler angles [0,90,0].

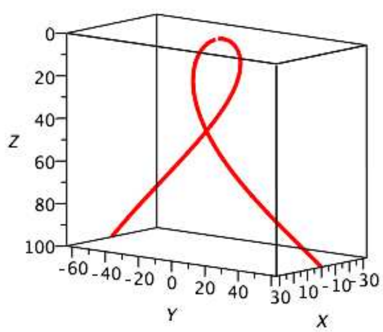

Fig. 9. The same as Figure 6 but now the observer is at Euler angles [40,-80,0].

transition from "C"-shaped to "S"-shaped forms can be produced by suitable combination of these parameters.

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