On the Components of Large Extended Extragalactic Radio Sources

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ABSTRACT

Extragalactic radio source components are radio-emitting lobes and jets. If the nature of these sources is understood, appreciation of their evolution through their ambient media will be enhanced. In this work, we have used analytical methods to describe propagation dynamics of these radio source components. Result shows that observed source size $(\mathcal{D})$ depends on the age of the source (t), lobe internal pressure (p_l), ambient medium density (η), and observing angle (ϕ) according the relation, $\mathcal{D} \approx t\left(\frac{p_l}{\eta m_h}\right)^{0.5} \sin\phi$, where m_h is mass of hydrogen nucleus. The implication of this relation is that the radio lobes are domiciled beyond the confines of the host galaxies (i.e. located within the intergalactic media), while the converse is the case for the radio jets.

(Keywords: radio sources, ambient density, radio jet, radio lobe, source age, galaxies)

INTRODUCTION

Extragalactic radio sources (EGRS) are examples of active galaxies. They are located outside the Milky Way galaxy. They are known to radiate more power in the radio frequencies than in the optical frequencies. This is defined by the ratio of the two flux densities, $S_{5\,\mathrm{GHz}}/S_{6\times10^5\,\mathrm{GHz}} > 10$ [1]. They are made up of radio galaxies, radio-loud quasars and BL Lacertae objects [2–4]. Radio morphological structures of these sources usually take the form of two opposite sided relativistic jets that connect the base of the accretion disk to two radio-emitting lobes that straddle the central core, believed to be the central engine [2] (Figures 1 and 2). This central core is thought to be more or less coincident with the nucleus of the host galaxy [3, 5-7]. In some sources, the lobes contain hotspots believed to be the termination points of the jets [3, 5-7] (Figures 1 and 2).

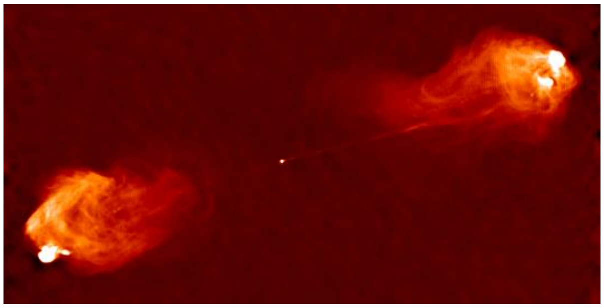

Figure 1: Cygnus A – An EGRS.
Source: Wkipedia

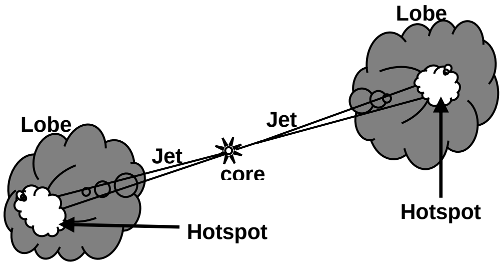

Figure 2: The Structure of a Typical EGRS.
Source: the author.

It is worthy to note that presence of jets in radio sources simply suggests presence of gaseous ambient media [5]. A number of hydrodynamic simulations of jet propagations have been performed to examine their physical state [5–6]. These studies show that jet materials have smaller masses than those of the ambient medium.

In this work, we use analytical methods with some plausible assumptions to obtain a mathematical model that may explain the dynamics of these radio sources.

COMPONENTS' PROPAGATION

In the standard beam model for EGRS, jets of relativistic plasma are ejected from the parent galaxy which plough their way through the ambient medium until they terminate with strong shocks (hotspots) which are thermalized to form lobes [6]. The evolution of a radio source component is therefore expected to depend (among other factors) on the power supplied by the core to the jet, the source age, and the nature of the ambient medium through which it propagates.

We may write lobe velocity kinematically as:

$$v_l dt = d\mathcal{D}_n \qquad (1)$$

where dt is the time frame at which the source grows to the size $d\mathcal{D}_n$ and v_l is lobe velocity. Assuming elastic collision between jet and lobe (and a head-on collision, in which all the velocities lie along the same line; i.e. angular difference between the direction of initial velocity and direction of final velocity is zero), we have from energy conservation principle that:

$$m_j v_{j1}^2 + m_l v_{l1}^2 = m_j v_{j2}^2 + m_l v_{l2}^2 \qquad (2)$$

where m_l = mass of lobe.
m_j = mass of jet that takes part in the collision with the lobe.
v_j = velocity of jet.
v_l = velocity of lobe.

The subscripts "1" and "2" represent "before" and "after" collisions, respectively.

Similarly, from conservation of momentum, we have:

$$m_j v_{j1} + m_l v_{l1} = m_j v_{j2} + m_l v_{l2} \qquad (3)$$

For simplicity, let's assume that the velocity of the lobe before the considered collision is zero. Therefore, (2) and (3) yield:

$$m_j v_{j1}^2 = m_j v_{j2}^2 + m_l v_{l2}^2 \qquad (4)$$

and

$$m_j v_{j1} = m_j v_{j2} + m_l v_{l2} \qquad (5)$$

respectively. Rearranging (4), gives:

$$m_l v_{l2}^2 = m_j\left(v_{j1}^2 - v_{j2}^2\right) \qquad (6)$$

Also, rearranging (5) we obtain:

$$m_l v_{l2} = m_j\left(v_{j1} - v_{j2}\right) \qquad (7)$$

The quotient of (6) and (7) yields:

$$v_{l2} = v_{j1} + v_{j2} \qquad (8)$$

From the last two equations, we have:

$$m_l\left(v_{j1} + v_{j2}\right) = m_j\left(v_{j1} - v_{j2}\right) \qquad (9)$$

This gives:

$$v_{j2} = \left(\frac{m_j - m_l}{m_j + m_l}\right) v_{j1} \qquad (10)$$

Putting this in (8), gives:

$$v_{l2} = v_{j1} + \left(\frac{m_j - m_l}{m_j + m_l}\right) v_{j1} \qquad (11)$$

or

$$v_l = \left(\frac{2m_j}{m_j + m_l}\right) v_j \qquad (12)$$

where v_{l2} and v_{j1} have been replaced with v_l and v_j, respectively. Simplifying further, we obtain:

$$v_l = \mu v_j \qquad (13)$$

where $\mu = \frac{2m_j}{m_j + m_l}$

Putting (13) in (1), we obtain:

$$d\mathcal{D}_n = \mu v_j dt \qquad (14)$$

Considering the source kinematic age, t, (14) becomes:

$$\mathcal{D}_n = \mu v_j t \qquad (15)$$

It is worthy of notation that jet particles decelerate as they collide with the particles of the lobe [3, 5-7]. Therefore, Jet velocity is expected to be greater than lobe velocity. Thus, we have:

$$\mu < 1 \qquad (16)$$

This indicates that mass of jet is less than mass of lobe.

Moreover, “Relativistic Beaming and Orientation Effects”, predicts that the observed linear size ($\mathcal{D}$) of the source and the angle of observation (ϕ) are related by:

$$\mathcal{D} = \mathcal{D}_n \sin\phi \qquad (17)$$

Therefore from (15) and (17), we have:

$$\mathcal{D} = \mu v_j t \sin\phi \qquad (18)$$

Assuming ram-pressure balance between the lobe and the ambient medium, we have [8–9]:

$$p_l \approx \eta m_h v_l^2 \qquad (19)$$

where $\eta =$ particle number density of the source ambient medium.
$m_h =$ hydrogen mass.

Combining (13), (18) and (19), we have:

$$\mathcal{D} \approx t\left(\frac{p_l}{\eta m_h}\right)^{0.5} \sin\phi \qquad (20)$$

This suggestively indicates that the observed source size $(\mathcal{D})$ depends on the source age (t), lobe internal pressure (p_l), ambient particle number density (η), and angle of observation (ϕ).

Furthermore, (19) can be rewritten for the jet to give:

$$p_j \approx \eta m_h v_j^2 \qquad (21)$$

where the parameters have their usual meanings. Combining (17) and (20), intrinsic source size $(\mathcal{D}_n)$ becomes:

$$\mathcal{D}_n \approx t\left(\frac{p_l}{\eta m_h}\right)^{0.5} \qquad (22)$$

Eliminating η from the last two equations yields:

$$\mathcal{D}_n^2 \approx t^2 \frac{p_l}{p_j} v_j^2 \qquad (21)$$

Combining this with (1), we obtain:

$$\left(\frac{v_l}{v_j}\right)^2 \approx \frac{p_l}{p_j} \qquad (22)$$

Therefore, for greater jet velocity $(v_j > v_l)$, jet internal pressure exceeds the lobes. For this to be true, ambient medium density must be higher in jet region than in the region of the lobe. This is expected since the ambient density thins out from the central core to the lobe [10]. This supports the idea that lobes are located outside the host galaxies (i.e., in the intergalactic media) rather than within the host galaxies (i.e., in the interstellar media) [9].

DISCUSSION AND CONCLUSION

In the last section, we have used analytical methods to obtain a relation, $\mathcal{D} \approx t\left(\frac{p_l}{\eta m_h}\right)^{0.5} \sin\phi$, that may describe propagation dynamics of EGRS components through their ambient media. The relation suggests that observed linear size $(\mathcal{D})$ of a typical EGRS depends on lobe internal pressure (p_l), time or age of the radio source (t), source ambient media number density (η), and angle of observation ϕ.

Moreover, from the analyses, we have shown that the obtained relation, $\frac{v_l}{v_j} \approx \frac{p_l}{p_j}$, suggestively implies that since jet velocity is greater than lobe velocity $(v_j > v_l)$, jet internal pressure exceeds the lobe’s internal pressure. However, for this to be true, ambient medium density must be higher in jet region than in the region of the lobe. This is expected since the ambient density thins out from the central core to the region where lobe is located [10]. This supports the idea that lobes are located outside the host galaxies (i.e., in the intergalactic media) rather than within the host galaxies (i.e., in the interstellar media).

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