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FRII RGs: jet dynamics and episodic behaviour

C. Konar[1]* and M. J. Hardcastle[2]

[1]*Academia Sinica Institute of Astronomy and Astrophysics, NTU Campus, Roosevelt Rd, Taipei-10617, Taiwan*
[2]*School of Physics, Astronomy and Mathematics, University of Hertfordshire, College Lane, Hatfield, UK*

Abstract. Radio galaxies are episodic in nature. In our recent work, our study of jet properties and their dynamics in different episodes of activity has revealed various hitherto unknown aspects of the extragalactic jets. We discover that the injection spectral indices are similar in the two different episodes for most of the episodic radio galaxies in our sample. We argue that in order to produce the similar injection indices in two episodes (i) the jet power in different episodes have to be similar and (ii) the Lorentz factor of the spine of the jet should be > 10. We further argue from particle acceleration physics that (iii) the jet fluid is made of electron-positron plasma and (iv) the inner jets of double-double radio galaxies are capable of forming hotspots even when propagating through the tenuous, nonthermal electron-positron plasma of the outer cocoon without any thermal matter in it. The episodic nature of the FR II radio galaxies we have studied appears to be unrelated to AGN feedback on the ambient medium.

Keywords : galaxies: active – radio continuum: general – acceleration of particles

1. Introduction

Morphologically, Radio Galaxies (RGs) are of two types: Fanaroff-Riley type I (FR I) and type II (FR II) (Fanaroff & Riley 1974). FR II RGs are characterised by highly collimated jets and compact hotspots at the outer ends of the lobes, whereas FR I jets are not so collimated and have no hotspots. Here we confine ourselves to FR II jets, in which the jet fluid flows relativistically up to the jet termination point. RGs are often

*email: chiranjib.konar@gmail.com

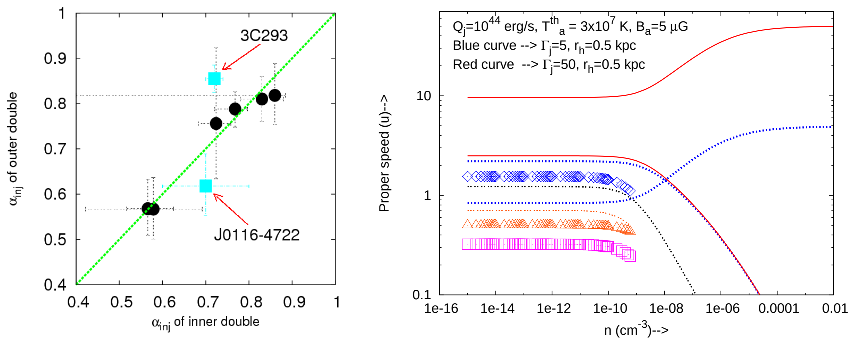

Figure 1. Left panel: inner vs. outer injection index plot. Right panel: The variation of proper speed of the hotspot motion ($u_{\rm h}$) as measured in the host-galaxy frame and the upstream jet bulk motion as measured in the hotspot frame ($u_{\rm j,hs} = \Gamma_{\rm j,hs}\beta_{\rm j,hs}$) as a function of the number density ($n_{\rm p}$) of protons in the ambient medium. Some of the parameters used to draw the curves are annotated in the plot. The curves that fall and saturate as $n_{\rm p}$ decreases show the variation of $u_{\rm j,hs}$ with $n_{\rm p}$. The curves that rise (except the double-dotted black curve) as $n_{\rm p}$ decreases show the variation of $u_{\rm h}$. The black double-dotted curve shows the variation of the Alfvén speed. The orange triple-dotted curve is the sound speed in the absence of magnetic field (only in the ultrarelativistic regime). The other symbols indicate the variation of the magnetosonic waves mainly in the 'pure nonthermal ambient medium', which are as follows: blue diamonds, the speed of the fast magnetosonic wave; orange triangles, the speed of the intermediate magnetosonic wave; and pink squares, the slow magnetosonic wave. These are published in Konar & Hardcastle (2013).

episodic. When we find the observational signature of two consecutive episodes of jet activity with a single host galaxy, we call it a Double-Double Radio Galaxy (DDRG). In this paper, we highlight (i) our study of FR II jet dynamics and (ii) how the study of jet dynamics of the inner and outer doubles of DDRG FR IIs can throw lights in solving many decades-old *open problems* related to RG and jets.

2. Observational results

Our spectral ageing analysis of a small sample of 8 DDRGs (hereafter, DDRG sample), compiled from Konar et al. (2006), Konar et al. (2012); Konar et al. (2013) and Jamrozy et al. (2007), revealed that (i) the injection spectral indices (hereafter, injection indices) are similar in the two episodes of jet activity (see Fig. 1) for our sample sources, (ii) the duration of quiescent phase ranges from 10^5 to 10^7 yr and (iii) there is a strong correlation between the injection index and jet power for a small sample of FR II RGs (hereafter, FR II sample) which includes the DDRG sample also. These samples are described by Konar & Hardcastle (2013). These results have important implications in understanding the jet dynamics and cause of episodic behaviour.

3. Particle acceleration and composition of jet fluid

An important questions is 'What is a realistic model for the particle acceleration phenomenon at the hotspots of FR II RGs?' We have shown in our recent paper (Konar & Hardcastle 2013) that the model of Kirk et al. (2000) is fully consistent with our observational results. This model deals with the particle acceleration at the relativistic MagnetoHydroDynamic (MHD) shock in a fluid with completely tangled magnetic field which is dynamically important.

It is believed that the particles are further accelerated at the Jet Termination Shocks (JTS, i.e, hotspots). We argue that if the jet fluid is an electron-proton plasma then by Drury's suggestion (Drury 1983) of 'selectivity of injection', the protons, being heavier, would be accelerated with more energy and in greater numbers at the JTS before being injected into the lobes. So in the lobes, if they are in equipartition at all, the magnetic field should be in equipartition with the electrons and protons together. However, in such a situation, the magnetic field would essentially be in equipartition with the protons as they are energetically dominant, which is contrary to observations (Croston et al. 2005). Hence, we rule out significant numbers of protons in the jet fluid and suggest that the jet fluid is made of pair plasma.

4. Jet dynamics

The momentum carried through the jet is transferred to the ambient medium and the working surface (hence the hotspot) moves outwards due to that. The hotspot motion is governed by ram pressure balance at the working surface. For typical densities of the thermal ambient media around RGs the hotspot motion is non-relativistic. However, the inner hotspots of DDRGs can move relativistically (see Konar & Hardcastle (2013) for observational evidence). So, we need a relativistic ram pressure balance equation, given by

$$\beta_{\rm hs} = \frac{1}{1 + \sqrt{\frac{\beta_{\rm j} c A_{\rm h}}{Q_{\rm j}} w_{\rm a}}}\beta_{\rm j}, \tag{1}$$

where $\beta_{\rm hs}$ and $\beta_{\rm j}$ are the hotspot velocity and jet bulk velocity in the HG frame, $A_{\rm h}$ is the area over which the jet momentum flux is distributed, c is the speed of light, $Q_{\rm j}$ is the jet power and $w_{\rm a}$ is the relativistic enthalpy density of the ambient medium surrounding the jet and lobes (see Konar & Hardcastle (2013) for the derivation of this equation). Our theoretical study of ram pressure balance shows that for plausible values of the parameters occurring in equation (1), (i) the motion of the inner hotspots is supersonic relative to the first magnetosonic wave (hereafter, first wave) of the cocoon matter and (ii) the bulk speed of the jet fluid relative to the hotspot frame is faster than the first wave of the jet fluid, even if the cocoon matter and the jet fluid are ultra-relativistic non-thermal plasma. We conclude that the inner jets can form JTSs as well as bow shocks under typical observed conditions of DDRGs.

5. Physical explanation of the results

The particle acceleration model of Kirk et al. (2000) is the most realistic one for the hotspots. So, a possible relation described by a curve (in the plane of power-law index vs. upstream speed of the jet fluid in JTS frame) of the kind shown in Fig. 4 of their paper, but with an appropriate value of $\sigma_{\rm j}$ (i.e., $\sigma_{\rm j}$ at equipartition) with a very high Lorentz factor ($\Gamma_{\rm j} > 10$) flow of jet fluid, combined with adiabatic loss and higher synchrotron losses due to higher magnetic field at the hotspots of high power sources, can explain the injection index−jet power correlation as well as the similarity of injection index in two different episodes. Also, we notice that for our FR II sample, there is no obvious correlation between the injection spectral index and the redshift of those sources. This enables us to conclude that jet power−spectral index correlation is the primary one, and not the redshift-spectral index correlation that has been discussed in earlier work. The quiescent phase of our DDRG sample is $10^5 - 10^7$ yr which is much smaller than the cooling time of the typical ambient thermal medium of these DDRGs. This implies that any feedback loop between the supermassive black hole and the thermal ambient medium cannot be responsible for the episodic jet activity of these sources.

6. Conclusions

The particle acceleration model of Kirk et al. (2000) is consistent with the particle acceleration at the hotspots implied by observations. This model can explain our observational results presented in section 2. Moreover, we have tackled several decades-old problems which are as follows: 1) the jet fluid is made of e^-e^+ plasma (we have given a completely new physical argument), 2) the inner jets in a DDRG can form hotspots while propagating through tenuous e^-e^+ plasma (which is contrary to usual expectation), 3) Similar injection indices in two DDRG episodes imply similar jet powers in the two episodes (we show this for the first time), 4) we have concluded that $\Gamma_{\rm j} > 10$ to explain the similarity of injection index in two episodes (this is surprising but consistent with jet related X-ray as pointed out by Hardcastle (2006)), 5) The $\alpha_{\rm inj} - Q_{\rm jet}$ correlation is the primary one and not the $\alpha_{\rm inj} - z$ correlation (we provide a plausible physical interpretation of this correlation for the first time). These results are published in Konar & Hardcastle (2013).

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