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Pair Plasma Dominance in the 3C 279 Jet on Parsec Scales

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Abstract

We have investigated whether a pc-scale jet of 3C 279 is dominated by a normal plasma or an electron–positron plasma. By analyzing Very Long Baseline Interferometry data between 1983 and 1990, and utilizing the theory of synchrotron self-absorption, we have derived the lower limits for the proper electron number density. Comparing the lower limit with another independent constraint for the electron density that is deduced from the kinetic luminosity, we find that the core and components C3 and C4 are likely dominated by an electron–positron plasma.

Key words: Galaxies: active — Galaxies: radio — Quasars: individual (3C 279)

1. Introduction

One of the central problems of extragalactic astronomy concerns the composition of the relativistic jets of plasma that stream from the nuclei of quasars and active galaxies. The two main candidates are a 'normal plasma' consisting of protons and relativistic electrons (for numerical simulations of shock fronts in a VLBI jet, see Gómez et al. 1993, 1994a,b), and a 'pair plasma' consisting only of relativistic electrons and positrons (for theoretical studies of two-fluid concept, see Sol et al. 1989; Despringre, Fraix-Burnet 1997). Distinguishing between these possibilities is crucial for understanding the physical processes that occurr close to the central 'engine' (presumably a supermassive black hole) in the nucleus.

VLBI is uniquely suited to study the matter content of parsec-scale jets, because other observational techniques cannot image at milliarcsecond resolution and must resort on indirect means of studying the active nucleus. Reynolds et al. (1996) analyzed historical VLBI data of the M87 jet at 5 GHz (Pauliny-Toth et al. 1981) and concluded that the core is probably dominated by an $e^{\pm}$ plasma. In the analysis, they utilized the standard theory of synchrotron self-absorption to constrain the magnetic field B [G] and the proper electron number density $N_{\rm e}^*$ [cm^{-3}] of the jet, and derived the following constraint for the core to be optically thick for self-absorption: $N_{\rm e}^* B^2 > 0.5$. Extending the work by Reynolds et al. (1996), Hirotani et al. (1998) investigated the matter content of the 3C 345 jet on parsec scales, and demonstrated that its five components (C2–C5,C7) are likely to be dominated by a pair plasma. Recently, studying the circularly polarized radio emission from the jet of an optically violent variable quasar, 3C 279, Wardle et al. (1998) revealed that its parsec-scale jet is composed of a pair plasma. To reinforce this important conclusion, it is desirable to investigate the composition by an independent method.

On these grounds, we applied the same method as that developed by Reynolds et al. (1996) and Hirotani et al. (1998) to the 3C 279 jet on parsec scales. In the next section, we briefly describe the method used to address the matter content of an AGN jet. We next discuss our application of the method to 3C 279 jet in section 3. In the final section, we discuss the validity of the assumptions

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Table 1. Table of coefficients.

α	-0.25	-0.50	-0.75	-1.00
$b(\alpha)$	1.8	3.2	3.6	3.8
$d(\alpha)$	0.93	1.79	4.12	11.6
$e(\alpha)$	2.27×10^4	3.42×10^5	1.08×10^7	5.75×10^8

that have been made in this paper. We use a Hubble constant of $H_0 = 75h$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ throughout this paper for computing physical sizes. For 3C 279, $z = 0.538$; therefore, 1 mas corresponds to $4.9h^{-1}$ pc. The spectral index α is defined by $S_\nu \propto \nu^\alpha$.

2. Constraints on Magnetic Flux and Particle Densities

In this paper, we model the components in an AGN jet with redshift z as homogeneous spheres of angular diameter θ_d [mas], containing a tangled magnetic field B [G] and relativistic electrons which give a synchrotron spectrum with optically thin index α and maximum flux density S_m [Jy] at frequency ν_m [GHz]. We can then compute the magnetic field density as follows (Ghisellini 1992):

$$B = 10^{-5} b(\alpha) S_\mathrm{m}^{-2} \nu_\mathrm{m}^5 \theta_\mathrm{d}^4 \frac{\delta}{1+z}, \tag{1}$$

where δ is the beaming factor, defined by

$$\delta \equiv \frac{1}{\Gamma(1-\beta\cos\varphi)}, \tag{2}$$

where $\Gamma \equiv 1/\sqrt{1-\beta^2}$ is the bulk Lorentz factor of the jet component moving with velocity βc, and φ is the orientation of the jet axis to the line of sight. The coefficient $b(\alpha)$ is given in Ghisellini (1992) and presented in table 1 for user convenience. Both Γ and φ can be uniquely computed from δ and $\beta_\mathrm{app} c$, the apparent velocity of the component, as follows:

$$\Gamma = \frac{\beta_\mathrm{app}^2 + \delta^2 + 1}{2\delta}, \tag{3}$$

$$\varphi = \tan^{-1}\left(\frac{2\beta_\mathrm{app}}{\beta_\mathrm{app}^2 + \delta^2 - 1}\right). \tag{4}$$

Secondly, in order that a jet component may become optically thick for synchrotron self-absorption, the following constraint must be satisfied (Hirotani et al. 1998):

$$N_\mathrm{e}^* B^{-\alpha+1.5} > 10^{-4} d(\alpha) \frac{(1+z)^2 h}{z(1+z/4)} \frac{\sin\varphi}{\theta_\mathrm{d}} \times \left(\frac{1+z}{\delta}\right)^{-\alpha+1.5} \nu_\mathrm{m}^{-\alpha+2.5}, \tag{5}$$

where the coefficient $d(\alpha)$ is tabulated in table 1. Substituting equation (1) into (5), we obtain the lower limit of N_e^*,

$$N_\mathrm{e}^{*(\min)} = e(\alpha) \frac{(1+z)^2 h \sin\varphi}{z(1+z/4)} \theta_\mathrm{d}^{4\alpha-7} \nu_\mathrm{m}^{4\alpha-5} \times S_\mathrm{m}^{-2\alpha+3} \left(\frac{\delta}{1+z}\right)^{2\alpha-3}. \tag{6}$$

The coefficient $e(\alpha)$ is also tabulated in table 1.

We can judge whether the possibility of normal plasma dominance is excluded, by comparing $N_\mathrm{e}^{*(\min)}$ with N_e^* derived from the kinetic luminosity, L_kin [erg s^{-1}]. L_kin is expressed in terms of N_e^* as follows:

$$L_\mathrm{kin} = \pi R^2 \beta c N_\mathrm{e}^* \Gamma(\Gamma-1)[\langle\gamma_-\rangle m_\mathrm{e} + \langle\gamma_+\rangle m_+] c^2, \tag{7}$$

where $\langle\gamma_-\rangle$ and $\langle\gamma_+\rangle$ refer to the averaged Lorentz factors of electrons and positively charged particles, respectively; m_+ designates the mass of the positive charge. In a pure pair plasma for instance, we obtain $\langle\gamma_+\rangle = \langle\gamma_-\rangle$ and $m_+ = m_\mathrm{e}$, while in a normal plasma, we obtain $\langle\gamma_+\rangle = 1$ and $m_+ = m_\mathrm{p}$, where m_p is the rest mass of a proton.

For a pure pair plasma, solving equation (7) for N_e, we obtain

$$N_\mathrm{e}^{*(\mathrm{pair})} = 1.1 \times 10^3 \left[\frac{(1+z)^2 h}{z(1+z/4)}\right]^2 \frac{L_{47}}{\theta_\mathrm{d}^2 \beta\Gamma(\Gamma-1)\langle\gamma_-\rangle}, \tag{8}$$

where $L_{47} = L_\mathrm{kin}/(10^{47}\mathrm{erg\,s^{-1}})$. Supposing $\langle\gamma_-\rangle \approx 10$ [for a detailed argument, see e.g., equation (5) of Reynolds et al. 1996], we obtain

$$N_\mathrm{e}^{*(\mathrm{pair})} \approx 110 \left[\frac{(1+z)^2 h}{z(1+z/4)}\right]^2 \frac{L_{47}}{\theta_\mathrm{d}^2 \beta\Gamma(\Gamma-1)}. \tag{9}$$

On the other hand, for a normal plasma, equation (7) gives an electron density of $0.01 N_\mathrm{e}^{*(\mathrm{pair})}$. Therefore, the possibility of normal plasma dominance can be excluded, if $0.01 N_\mathrm{e}^{*(\mathrm{pair})} \ll N_\mathrm{e}^{*(\min)} < N_\mathrm{e}^{*(\mathrm{pair})}$; the former inequality is equivalent to $N_\mathrm{e}^{*(\mathrm{pair})}/N_\mathrm{e}^{*\min} \ll 100$. The discussion presented in this section can be applied to arbitrary components or cores of parsec-scale AGN jets.

3. Application to 3C 279 Jet

Let us apply the method described in the previous section to the 3C 279 jet on parsec scales and investigate the matter content. 3C 279 was the first source found to show superluminal motion (Cotton et al. 1979; Unwin et al. 1989, 1998). The expansion velocity of the jet components was reported to be $\beta_\mathrm{app} h \approx 2.8/0.75 = 3.7$ for C3 and C4 (Carrara et al. 1993).

The values of α, ν_m, and S_m of several components have been reported in the literature. Unwin et al.

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Table 2. Magnetic field and electron densities of components.

Component	D	C3	C4	C4
Epoch	1983.10	1983.10	1989.26	1990.17
ρh [mas]	0.0	1.23/0.75[a]	1.18/0.75[b]	1.26/0.75[b]
$\beta_{\rm app} h$	2.2/0.75[a]	2.2/0.75[a]	2.8/0.75[b]	2.8/0.75[b]
$\nu_{\rm m}$ [GHz]	13.0[a]	6.8[a]	11 ± 2[c]	11 ± 2[c]
$S_{\rm m}$ [Jy]	6.2[a]	9.4[a]	$4.38 \pm .36$[b]	$4.61 \pm .21$[b]
α	-1.0[a]	-1.0[a]	-0.9[b]	-0.9[b]
$\theta_{\rm d}$ [rad]	0.75[a]	0.95[a]	$0.55 \pm .22$[b]	$0.66 \pm .11$[b]
$\delta_{\rm eq}$[c]	2.5	9.5	$4.6^{+10.7}_{-2.6}$	$3.2^{+1.7}_{-1.0}$
$\Gamma_{\rm eq}$[c]	3.2	5.3	$3.9^{+4.5}_{-0.1}$	$3.9^{+0.7}_{-0.2}$
$\varphi_{\rm eq}$ [rad][c]	0.40	0.060	$0.21^{+0.15}_{-0.18}$	$0.31^{+0.04}_{-0.13}$
B [G][c]	0.19	0.031	$0.086^{+0.064}_{-0.052}$	$0.11^{+0.03}_{-0.03}$
$N_{\rm e}^{*({\rm min})}$ [cm^{-3}][c]	350	14	100^{+18}_{-93}	150^{+40}_{-100}
$N_{\rm e}^{*({\rm pair})}$ [cm^{-3}][c]	$450 L_{47}$	$8.4 L_{47}$	$480^{+20}_{-380} L_{47}$	$340^{+120}_{-160} L_{47}$
$N_{\rm e}^{*({\rm pair})}/N_{\rm e}^{*({\rm min})}$[c]	$1.3 L_{47}$	$0.59 L_{47}$	$4.8^{+36.2}_{-3.3} L_{47}$	$2.2^{+7.7}_{-0.6} L_{47}$
$N_{\rm e}^{*({\rm pair})}/N_{\rm e}^{*({\rm min})}$ $(h=0.67)$[d]	$0.20 L_{47}$	$1.8 L_{47}$	$0.95^{+10.0}_{-0.75} L_{47}$	$0.36^{+1.40}_{-0.13} L_{47}$
$N_{\rm e}^{*({\rm pair})}/N_{\rm e}^{*({\rm min})}$ $(h=1.33)$[e]	$0.43 L_{47}$	$1.3 L_{47}$	$1.4^{+7.8}_{-0.8} L_{47}$	$0.72^{+2.30}_{-0.14} L_{47}$
$e^{\pm}$ dominated?	**likely yes**	**likely yes**	**likely yes**	**likely yes**

[a] From Unwin et al. (1989).
[b] From Carrara et al. (1993). They gave $\nu_{\rm m} \sim 11$ GHz and $\alpha = -0.9$ above their equation (1). In addition, $S_{\rm m}$ are $\theta_{\rm d}$ listed in their table 2.
[c] The values for $H_0 = 75$ km s^{-1} Mpc^{-1} are presented. $L_{47} \equiv L_{\rm kin}/10^{47}$erg s^{-1} (see text).
[d] The values for $H_0 = 50$ km s^{-1} Mpc^{-1} are presented for comparison.
[e] The values for $H_0 = 100$ km s^{-1} Mpc^{-1} are presented for comparison.

(1989) presented these parameters for D (core) and the C3 component from observations at 5, 11, and 22 GHz, and derived $\theta_{\rm d}$ and the error determined from model-fitting a homogeneous sphere. Subsequently, Carrara et al. (1993) gave those parameters for C4 component at epochs 1989.26 and 1990.17. These parameters are listed in table 2.

To compute $N_{\rm e}^{*({\rm min})}$ from equation (6), we must constrain δ and φ. In order to obtain a severe constraint in $N_{\rm e}^{*({\rm min})}$, we must know the *upper* limit of δ or its appropriate value, calculated based on some reasonable assumptions. Unfortunately, we cannot constrain its upper limit. Nevertheless, assuming energy equipartition between the magnetic field and the radiating particles, we can estimate δ by the so-called equipartition Doppler factor (Readhead 1994),

$$\delta = \delta_{\rm eq}$$

$$\equiv \left\{ \left[\frac{10^3 F(\alpha)}{\theta_{\rm d}} \right]^{34} \left[\frac{2(h/1.33)}{1-1/\sqrt{1+z}} \right]^2 (1+z)^{15-2\alpha} \times S_{\rm m}^{16} (10^3 \nu_{\rm m})^{-35-2\alpha} \right\}^{1/(13-2\alpha)}, \qquad (10)$$

where $F(\alpha)$ is given in Scott and Readhead (1977). The resultant values of $\delta_{\rm eq}$ of each component computed from $\theta_{\rm d}$, $S_{\rm m}$, and $\nu_{\rm m}$, are presented in table 2.

There is much justification in adopting the equipartition Doppler factor. As Güijosa and Daly (1996) pointed out, the $\delta_{\rm eq}$'s of various AGN jets have a high correlation with $\delta_{({\rm min})}$, the minimum allowed Doppler factor derived by comparing the predicted and observed self-Compton fluxes (Marscher 1987; Ghisellini et al. 1992). (If a homogeneous moving sphere emits all of the observed X-ray flux via synchrotron self-Compton process, the δ equals $\delta_{\rm eq}$.) Moreover, the ratio $\delta_{\rm eq}/\delta$ depends weakly on the ra-

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tio u_p/u_B, where u_p and u_B refer to the energy densities of radiating particles (i.e., electrons and positrons) and the magnetic field, respectively. For $\alpha = -0.75$ for instance, we obtain $\delta_{eq}/\delta = (u_p/u_B)^{2/17}$ (Readhead 1994).

Instead of substituting $\delta = \delta_{eq}$ in equation (6), we can actually compute N_e^* from $u_p = u_B$, provided that B is known from equation (1). The results of N_e^* do not significantly differ from $N_e^{*(\min)}$ obtained from equation (6). We thus adopt equation (10) as a good estimate for δ in this paper.

First, let us consider the magnetic field strength B. We can easily see that the core contains the most dense magnetic field compared to the component, as expected. The same tendency can bee seen for N_e^*.

Secondly, we consider $N_e^{*(\mathrm{pair})}$. To investigate this quantity, we must estimate the kinetic luminosity L_{kin} [erg s^{-1}]. For this purpose, we use the observed γ-ray luminosity. Since the observed γ-ray luminosity is comparable to that across all other frequencies (Maraschi et al. 1994; von Montigny et al. 1995), it may be reasonable to suppose that about 10% of the kinetic luminosity is radiated in γ-rays:

$$0.1 L_{\mathrm{kin}} \approx \frac{\Omega}{4\pi} L_\gamma^{(\mathrm{iso})}, \tag{11}$$

where Ω is the solid angle in which γ-rays are beamed; $L_\gamma^{(\mathrm{iso})}$ is the γ-ray luminosity that would be realized if γ-rays were to be radiated isotropically. Substituting $L_\gamma^{(\mathrm{iso})} \approx 10^{47.5}$ erg s^{-1} in the quiescent state of 3C 279, we obtain $L_{\mathrm{kin}} \approx 3 \times 10^{47} \Omega \,\mathrm{erg\,s^{-1}}$.

Consider the case when isotropic nonthermal electrons in the relativistically moving blobs Thomson-scatter an external isotropic radiation field. Then, the beaming pattern of the γ-rays goes as $f(\Gamma, \varphi) = \delta^{4-2\alpha}(1+\cos\varphi)^{1-\alpha}$ (Dermer 1995). For a fixed value of Γ, f is maximized at $\varphi = 0$ and decreases with increasing φ. When $\alpha = -1.0$ and $\Gamma = 3.0$ for instance (see table 2), $f(3, \varphi)$ declines to $0.1 \times f(3, 0)$ at $\varphi = 0.24$ rad. Even if all of the γ-rays are produced isotropically in the blob frame via SSC [and hence the beaming pattern goes as $\delta^{3-\alpha}$, see equation (2) in Dermer (1995)], the flux decreases to 10% of its maximum (at $\varphi = 0$) at $\varphi = 0.31$ rad. Therefore, Ω will be at most $0.3^2\pi = 0.3$ ster. On these grounds, we estimate the upper limit of kinetic luminosity of 3C 279 to be

$$L_{\mathrm{kin}} \approx 10^{47} \mathrm{erg\,s^{-1}} \tag{12}$$

in this paper. It may be worth comparing this upper limit of L_{kin} with the value of $10^{46.41}$ given by Celotti et al. (1997). They further considered 18 other core-dominated high-polarized quasars to find that 10^{47} is a reasonable estimate as the upper limit of L_{kin} for this class of AGNs. If L_{kin} decreases from this value, the possibility of normal plasma dominance further decreases.

Using L_{kin}, we can compute $N_e^{*(\mathrm{pair})}$ by equation (9). The results of $N_e^{*(\mathrm{pair})}$ are presented in table 2, together with the ratio $N_e^{*(\mathrm{pair})}/N_e^{*(\min)}$. If $1 < N_e^{*(\mathrm{pair})}/N_e^{*(\min)} \ll 100$ is satisfied, the component is likely to be dominated by a pair plasma. Unless L_{pair} is underestimated, $N_e^{*(\mathrm{pair})}/N_e^{*(\min)}$ should be greater than unity.

It follows from table 2 that D, C3, and C4 are likely to be dominated by a pair plasma. Unfortunately, for D and C3, the errors cannot be calculated, because those in ν_m and S_m were not presented in the literature.

4. Discussion

In summary, we have derived a general condition that a homogeneous component is optically thick for synchrotron self-absorption. This condition gives the lower limit of the proper electron number density, $N_e^{*(\min)}$, if it is combined with the surface-brightness condition, which gives the magnetic field. Comparing $N_e^{*(\min)}$ with the density derived from the kinetic luminosity of the jet, we can investigate whether we can exclude the possibility of normal plasma (e^-–p) dominance in an AGN jet in parsec scales. Applying this method to the "superluminal" quasar 3C 279, using the published spectrum data of D, C3, and C4, and adopting the equipartition Doppler factors, we find that all the three components are likely to be dominated by a pair plasma.

If L_{kin} were to become comparable with 10^{48} erg s^{-1}, then the possibility of normal plasma dominance would not be ruled out. However, we conjecture that such a large value of L_{kin} is unlikely, because most of the observed γ-rays flux of 3C 279 is expected to be beamed along the local propagation direction of the jet.

For a normal plasma, the energy distribution of electrons may cut off at higher values, such as $10^2 m_e c^2$. In this case, we have $\langle\gamma_-\rangle \approx 700$ for $\alpha = -0.5$. Thus, the electron density will be $\sim 0.007 N_e^{*(\mathrm{pair})}$, which further lowers the possibility of normal plasma dominance.

Let us finally discuss how the ratio $N_e^{*(\mathrm{pair})}/N_e^{*(\min)}$ depends on the Hubble constant. The results for $H_0 = 50 \,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $H_0 = 100 \,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ are presented in table 2. Note that the functions $N_e^{*(\min)}$ and $N_e^{*(\mathrm{pair})}$ depend on h, not only through the explicit factors in equations (6) and (9), but also through δ, Γ, and φ. Nevertheless, there is no significant difference in their ratio among $h = 0.67$, 1.00, and 1.33 cases. The conclusion of pair plasma dominance for the 3C 279 jet on parsec scales is, therefore, not affected at all by the choice of the Hubble constant.

Although the quasar 3C 279 is a 'famous' source, very limited VLBI data are available to determine the spectral profile of each component. Therefore, multi-frequency si-

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multaneous observations are required to conclusively address the matter content of other components of 3C 279.

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