KILOPARSEC-SCALE JETS IN FR I RADIO GALAXIES AND THE $\gamma$-RAY BACKGROUND

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ABSTRACT

We discuss the contribution of kiloparsec-scale jets in FR I radio galaxies to the diffuse $\gamma$-ray background radiation. The analyzed $\gamma$-ray emission comes from inverse-Compton scattering of starlight photon fields by the ultrarelativistic electrons whose synchrotron radiation is detected from such sources at radio, optical, and X-ray energies. We find that these objects, under the minimum-power hypothesis (corresponding to a magnetic field of 300 $\mu$G in the brightest knots of these jets), can contribute about one percent to the extragalactic $\gamma$-ray background measured by EGRET. We point out that this result already indicates that the magnetic fields in kiloparsec-scale jets of low-power radio galaxies are not likely to be smaller than 10 $\mu$G on average, as otherwise the extragalactic $\gamma$-ray background would be overproduced.

Subject headings: galaxies: active — galaxies: jets — gamma rays: theory — radiation mechanisms: nonthermal

1. INTRODUCTION

Observations by the EGRET instrument on board the Compton Gamma-Ray Observatory have established the presence of isotropic extragalactic background radiation in the 100 MeV–10 GeV photon energy range, with an integrated flux $F (\gamma \geq 100 \text{MeV}) \lesssim 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ and a curved (concave) spectrum (Sreekumar et al. 1998; Strong et al. 2004). It has been argued (Dermer & Schlickeiser 1992; Stecker et al. 1993; Padovani et al. 1993; Salamon & Stecker 1994; Setti & Wolter 1994; Chiang et al. 1995; Erlykin & Wolfendale 1995; Stecker & Salamon 1996; Chiang & Mukherjee 1998; Weferling & Schlickeiser 1999; Mucke & Pohl 2000) that the bulk of this emission most likely originates from unresolved blazars, whose properties are similar to those detected by EGRET (von Montigny et al. 1995; Hartman et al. 1999). However, as the internal parameters and cosmological distribution of EGRET-like blazar sources are not precisely known, the origin of the diffuse $\gamma$-ray background is still being debated, and new classes of objects emitting GeV photons can be analyzed in this context (e.g., Loeb & Waxman 2000; Gabici & Blasi 2003).

Here we discuss the issue of high-energy $\gamma$-ray emission from the kiloparsec-scale jets in FR I radio galaxies, and in particular its contribution to the $\gamma$-ray background radiation as measured by EGRET. Our study is stimulated by recent results from the Chandra X-Ray Observatory, which have shown that X-ray jet emission is common in FR I sources (Hardcastle et al. 2001, 2002, 2003, 2005; Harris et al. 2002a, 2002b; Kataoka et al. 2003; Kraft et al. 2002; Marshall et al. 2002; Wilson & Yang 2002; Worrall et al. 2001, 2003). The established synchrotron origin of this X-ray emission (see all the references above) implies that the kiloparsec-scale jets in FR I radio galaxies will, at some level, be sources of high- and very high energy $\gamma$-ray emission due to the inverse-Compton scattering of ambient (galactic) photon fields by the synchrotron-emitting electrons. This problem was discussed by Stawarz et al. (2003) and considered in more detail for the specific case of the radio galaxy M87 by Stawarz et al. (2005). The aim of our study—which is an extension of the previous analysis—is twofold, namely, an estimate of the aforementioned contribution (taking into account effects of absorption and subsequent reprocessing of $\gamma$-ray photons by infrared-to-ultraviolet background radiation) and discussion of the constraints on the jet parameters that can be imposed in this way.

The paper is organized as follows. In the next section we describe the ingredients of the model developed to estimate the contribution of kiloparsec-scale FR I jets to the $\gamma$-ray background. In §3 we present the results and discuss briefly the possibility of the direct observation of $\gamma$-rays from these sources. General discussion and the main conclusions are also presented in §3. Throughout the paper we assume a cosmology with $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, and $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$.

2. THE MODEL

Below we describe the procedure used to estimate the $\gamma$-ray emission from a “typical” kiloparsec-scale jet in a FR I radio galaxy. We assume that all of these objects have similar properties, and that the detection rate of their brightest knots at optical and X-ray frequencies depends solely on the amount of relativistic beaming (Sparks et al. 1995; Scarp & Urry 2002; Jester 2003). Within this approach, we find the “universal” electron energy distribution in the brightest knots of these jets by fitting a broken power law to the radio–to–$X$–ray synchrotron continua of the collected jet sources. Next, we compute the $\gamma$-ray emission due to inverse-Compton (IC) scattering of the reconstructed universal electron energy distribution on the starlight radiation of the host galaxies (Stawarz et al. 2003, 2005). We include both
the Klein-Nishina effects and the relativistic bulk velocity of the emitting plasma in the analysis. We also present the adopted approach in relating the γ-ray output of the jets with the total radio luminosities of the analyzed sources, and hence the γ-ray luminosity function (GLF) of kiloparsec-scale FR I jets with the radio luminosity function (RLF) of low-power radio galaxies (Willott et al. 2001). Finally, we briefly describe the adopted model for the absorption of the emitted high-energy γ-ray photons by the infrared-to-ultraviolet metagalactic radiation field (MRF), taking into account evolution of the background photon field up to high redshifts (Kneiske et al. 2002, 2004) and also repro processing of the absorbed γ-ray photons to lower energies by the cascading processes.

2.1. Jet γ-Ray Emission

We collate data for all FR I radio galaxies with detected X-ray jets. We restrict our analysis to the brightest knots in these jets, which are placed at ~1 kpc from the galactic nuclei, thus obtaining a list of 11 sources. Table 1 summarizes the input parameters for the considered knots, i.e., the radio fluxes $S_r$ measured at $\nu_r = 5$ GHz, the optical fluxes $S_o$ (if available) at $\nu_o = 5 \times 10^{14}$ Hz, and the X-ray fluxes $S_X$ at $h\nu_X = 1$ keV photon energies. We fit broken power laws to the radio–X-ray continua of the analyzed knots with spectral indices $\alpha_r$ and $\alpha_X$ measured directly from the data or, when large uncertainties are encountered, with the adopted median values $\alpha_r = 0.75$ and $\alpha_X = 1.2$. We assume a spherical geometry of radius 26 pc for all knots, which corresponds to an angular radius of 0′3 at the distance of M87 (see in this context Kataoka & Stawarz 2005). The obtained values of the break frequencies in the synchrotron spectra, $\nu_{br}$, as well as the equipartition magnetic field computed for no relativistic beaming, $B_{eq}(1)$, are also given in Table 1, together with the median equipartition magnetic field computed for no relativistic beaming, $B_{eq}(1)$, which are placed at 1 kpc from the galactic center of M87 (in this context Kataoka & Stawarz 2005). We assume a characteristic frequency of the starlight emission of $\nu_{star} = 10^{14}$ Hz and a bolometric starlight energy density at ~1 kpc from the galactic center of $U_{star} = 10^{-9}$ ergs cm$^{-3}$, both as measured in the host-galaxy rest frame (see Stawarz et al. 2003). The starlight radiation energy density then dominates the other photon fields in the jet rest frame, in particular, the energy density of the synchrotron photons, by more than an order of magnitude for knot synchrotron luminosities $\lesssim 10^{42}$ ergs s$^{-1}$ and other parameters as discussed in the paper.

The resulting intrinsic IC luminosity, $L_s(\epsilon)$, consists of a power-law continuum $\propto \epsilon^{-0.75}$ at photon energies $\epsilon < 1$ GeV, a break region between 1 and 100 GeV due to both the transition between the Thomson and the Klein-Nishina regimes and a break in the electron energy distribution, and finally a steep power law for $\epsilon \gtrsim 100$ GeV (see Fig. 1). With a maximum electron energy of $E_{\max} = 10^8$ assumed hereafter, the maximum IC photon

### Table 1: Parameters for the Brightest Knots of the X-Ray–detected FR I Jets

| Name   | $z$   | $d_L$ (Mpc) | $\alpha_r$ | $\alpha_X$ | $S_r$ (mJy) | $S_X$ (mJy) | $\log \nu_{br}$ (Hz) | $B_{eq}(1)$ ($\mu$G) | $\log L_{IC}$ (ergs s$^{-1}$) | $\eta$ | References |
|--------|-------|-------------|------------|------------|-------------|-------------|----------------------|-----------------------|------------------------|--------|------------|
| 3C 15  | 0.073 | 326         | 0.85       | 1.2        | 1.2         | 1.6         | 14.16                | 877                   | 42.0                   | 0.035  | 1          |
| NGC 315| 0.0165 | 71          | 0.90       | 1.2        | 1.2         | 1.6         | 16.37                | 392                   | 40.6                   | 0.047  | 2          |
| 3C 31  | 0.0169 | 72          | 0.55       | 1.2        | 1.2         | 1.6         | 13.57                | 334                   | 40.8                   | 0.02    | 3          |
| B 0206 | 0.0369 | 60          | 0.50       | 1.2        | 1.2         | 1.6         | 13.30                | 474                   | 41.1                   | 0.033  | 4          |
| 3C 66B | 0.0215 | 92          | 0.60       | 1.2        | 1.2         | 1.6         | 13.84                | 374                   | 41.3                   | 0.011  | 5          |
| 3C 129 | 0.0208 | 89          | 0.75       | 1.2        | 1.2         | 1.6         | 16.19                | 196                   | 41.1                   | 0.001  | 6          |
| B2 0755| 0.0428 | 187         | 0.75       | 1.2        | 1.2         | 1.6         | 15.20                | 637                   | 41.1                   | 0.091  | 4          |
| M84    | 0.00354 | 15          | 0.65       | 1.2        | 1.2         | 1.6         | <30                  | 136.5                 | 39.9                   | 0.002  | 7          |
| M87    | 0.00427 | 18          | 0.70       | 1.2        | 1.2         | 1.6         | 15.29                | 510                   | 41.3                   | 0.024  | 8, 9       |
| Cen A  | 0.00081 | 3.4         | 0.75       | 1.2        | 1.2         | 1.6         | 16.17                | 125                   | 40.8                   | 0.0005 | 10, 11     |
| 3C 296 | 0.0237 | 102         | 0.60       | 1.2        | 1.2         | <10         | 14.02                | 358                   | 41.0                   | 0.015  | 12         |

Notes.—$z$: redshift of the source; $d_L$: luminosity distance to the source adopting $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, and $\Omega_X = 0.73$. $\alpha_r$: radio spectral index at 5 GHz, $S_r$: radio flux density at 5 GHz in mJy, $\alpha_X$: X-ray spectral index at 1 keV, $S_X$: X-ray flux density at 1 keV in mJy, $
u_{br}$: break frequency of the synchrotron emission in Hz, $B_{eq}(1)$: the equipartition magnetic field computed for no relativistic beaming in $\mu$G, $L_{IC}$: total luminosity of the source at 5 GHz in ergs s$^{-1}$, and $\eta$: ratio between 5 GHz luminosity of the knot and total 5 GHz luminosity of the source. Total radio luminosities are taken from Liu & Zhang (2002) and converted to the adopted cosmology and an observing frequency of 5 GHz.

References.—(1) Kataoka et al. 2003; (2) Worrall et al. 2003; (3) Hardcastle et al. 2002; (4) Worrall et al. 2001; (5) Hardcastle et al. 2001; (6) Harris et al. 2002b; (7) Harris et al. 2002a; (8) Marshall et al. 2002; (9) Wilson & Yang 2002; (10) Kraft et al. 2002; (11) Hardcastle et al. 2003; (12) Hardcastle et al. 2005.
energy is $\epsilon \approx 50$ TeV. Note that the energy density of the jet magnetic field in the emitting plasma rest frame (denoted by primes), $U_0 B = B_{\text{eq}}^2 / 8 \pi \approx 3.6 \times 10^{-9}$ ergs cm$^{-3}$, is roughly comparable with the energy density of the starlight radiation, $U_{\text{star}} = \Gamma_j U_{\text{star}} \approx 9 \times 10^{-9}$ ergs cm$^{-3}$, and hence the intrinsic IC luminosity is roughly comparable with the synchrotron luminosity. In particular, by integrating over the IC photon energy range, $L_\gamma = \int_{\epsilon_{\text{min}}}^{\epsilon_{\text{max}}} L_\gamma (\epsilon) \, d\epsilon$, we find that

$$L_\gamma \approx \left( \frac{\epsilon}{0.01} \right) L_{\text{tot}}$$

for $\epsilon_{\text{min}} = 100$ MeV and $\epsilon_{\text{max}} = 300$ GeV. Due to the specific spectral shape of the intrinsic IC emission, with a maximum at 1–100 GeV, the above relation is expected to be correct for $\epsilon_{\text{min}} < 100$ MeV and $\epsilon_{\text{max}} > 300$ GeV as well. Obviously, the observed IC emission will be modified by the effects of absorption and subsequent reprocessing of high-energy $\gamma$-ray photons on the diffuse cosmic background radiation fields, as described below.

### 2.2. Absorption and Reprocessing of $\gamma$-Ray Photons

High-energy $\gamma$-ray photons produced at cosmological distances are likely to be absorbed by the diffuse cosmic background radiation due to photo-photon annihilation (Nikishov 1962; Gould & Schreder 1966; Stecker et al. 1992). The absorbed $\gamma$-rays are then reemitted at lower energies due to IC radiation of the created electron-positron pairs in the cascading process (Aharonian & Atoyan 1985; Protheroe 1986; Zdziarski 1988; Protheroe & Staney 1993; Aharonian et al. 1994; Kel’Ner et al. 2004). Among other implications, this process is of significant interest in studying the contribution of cosmologically distant sources to the $\gamma$-ray background (Coppi & Aharonian 1997; T. Kneiske et al. 2005, in preparation). A crucial point in the analysis of the attenuation of high-energy $\gamma$-rays emitted by cosmologically distant objects is, however, the knowledge of spectral shape of the MRF in the infrared-to-ultraviolet photon energy range, which is responsible for the $\gamma$-ray absorption/reemission, and of its evolution up to high redshifts (see Primack et al. 1999). This is a complicated problem, since the direct measurements of the MRF at infrared wavelengths are difficult (see Hauser & Dwek 2001 and references therein). We note that careful analysis of the spectra of TeV-emitting blazars constitutes a very promising (although not direct and, in addition, restricted to redshifts $z < 1$) method for constraining unknown parameters of the MRF (e.g., Staney & Franceschini 1998; Renault et al. 2001; Aharonian et al. 2002; Costamante et al. 2004; Dwek & Krennrich 2005).

Here we adopt a model proposed by Kneiske et al. (2002, 2004), which under a minimum of parameters and assumptions follows the evolution of the MRF from redshift $z = 5$ to 0, fulfilling all the observational constraints on the MRF in the infrared-to-optical band at the present epoch. This forward-evolution model based on optical and infrared galaxy surveys considers emission from stars, gas, and dust in optically selected galaxies as well as in luminous and ultraluminous infrared galaxies (LIGs/ULIGs). The contribution of LIGs is essential, since the number of stars formed in this object is comparable to the one in optically selected galaxies, and their contribution to the infrared-to-ultraviolet metagalactic radiation field is about 50%. We note that in a framework of the adopted model the UV background is underestimated at redshifts $z > 3$ by a factor of 2–4. With this for the MRF, we derive the optical depth for $\gamma$-ray absorption (including the effects...
of re-emission) as a function of redshift and γ-ray photon energy, \( \tau_{\gamma\gamma}(\epsilon, z) \) (\cite{T. Kneiske et al. 2005, in preparation}) and compute the observed absorbed IC flux of the selected FR I jets,

\[
S_\gamma(\epsilon) = \frac{(1 + z) L_\gamma ((1 + z) \epsilon)}{4 \pi d_L^2} \exp\left[-\tau_{\gamma\gamma}(\epsilon, z)\right].
\] (3)

Figure 1 shows a comparison between the unabsorbed and the absorbed IC fluxes from kiloparsec-scale jets located at different redshifts, \( z = 0.03, 0.1, 1.0, \) and \( 4.0 \) (for \( L_\gamma = 10^{41} \) erg s\(^{-1}\)). As illustrated, only a relatively small part of the IC flux is absorbed by the MRF in the 0.1–10 GeV photon energy range, and hence our analysis of the contribution of kiloparsec-scale FR I jets to the γ-ray background radiation is not greatly affected by the inevitably somewhat arbitrary nature of the adopted MRF model.

### 2.3. γ-Ray Luminosity Function

We take the radio luminosity function—i.e., the number of sources per unit comoving volume per unit (base 10) logarithm of the source luminosity—characterizing low-power radio sources (including “classical” FR I radio galaxies and FR II radio galaxies with weak/absent emission lines) in the form

\[
\rho_W(L, z) = \frac{dN}{dV d \log L} = \begin{cases} 
\rho_0 \left(\frac{L}{L_{cr}}\right)^{-\alpha} \exp\left(-\frac{L}{L_{cr}}\right) (1 + z)^f, & z < z_{cr}, \\
\rho_0 \left(\frac{L}{L_{cr}}\right)^{-\alpha} \exp\left(-\frac{L}{L_{cr}}\right) (1 + z_{cr})^f, & z \geq z_{cr},
\end{cases}
\] (4)

as discussed by Willott et al. (2001). We adopt the values of the five free parameters of \( \rho_W(L, z) \) as determined from 3CRR, 6C, and 7CRS samples for a \( \Omega_M = \Omega_\Lambda = 0 \) and \( H_0 = 50 \) km s\(^{-1}\) Mpc\(^{-1}\) cosmology by Willott et al. (2001), model C therein. Then we convert this RLF to the modern cosmology adopted here, and convert the total radio luminosity to the IC jet luminosity \( L_\gamma \) according to equation (2). Hence, we obtain the γ-ray luminosity function for the jets in FR I radio galaxies, which can be written in the form

\[
\rho(L_\gamma, z) = \kappa(z) \rho_W(L_\gamma, z),
\] (5)

where \( \log \rho_0 = -7.523 \) (where \( \rho_0 \) is in Mpc\(^{-3}\)), \( \alpha = 0.586 \), \( \log L_{cr} = 43.062 \) (where \( L_{cr} \) is now the critical intrinsic γ-ray luminosity of the jet in ergs s\(^{-1}\)), \( z_{cr} = 0.71 \), and \( k = 3.48 \). The function \( \kappa(z) \) expresses the transformation of the comoving volume elements between different cosmological models,

\[
\kappa(z) \equiv \frac{dV_W}{dV} \frac{d\Omega}{d\Omega_{dz}}.
\] (6)

We note that

\[
\frac{dV_W}{d\Omega_{dz}} = \frac{c^3 z^2 (2 + z)^2}{4H_0^2 (1 + z)^3}, \quad \text{with} \quad H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1},
\] (7)

and

\[
\frac{dV}{d\Omega_{dz}} = \left(\frac{c}{H_0}\right)^3 E^{-1}(z) \left[ \int_0^z \frac{dz'}{E(z')} \right]^2, \quad \text{with} \ E(z) = \sqrt{\Omega_M (1 + z)^3 + \Omega_\Lambda},
\]

\[
H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}, \quad \Omega_M = 0.27, \quad \text{and} \quad \Omega_\Lambda = 0.73.
\] (8)

The final form of \( \rho(L_\gamma, z) \)—shown in Figure 2 (top) for redshifts \( z = 0.001, 1, \) and \( 2 \) (dotted, dashed, and solid lines, respectively) as a function of total IC jet luminosity \( L_\gamma \). Bottom: Cumulative number density of low-power radio sources as a function of redshift, for \( L_{\text{low}} = 10^{38}, 10^{39}, \) and \( 10^{40} \) ergs s\(^{-1}\) (solid, dashed, and dotted lines, respectively) and \( L_{\text{high}} = 10^{44} \) ergs s\(^{-1}\).

The final form of \( \rho(L_\gamma, z) \) shown in Figure 2 (top) for redshifts \( z = 0.001, 1, \) and \( 2 \)—then gives the number of low-power radio sources per unit comoving volume (in Mpc\(^3\)) per unit (base 10) logarithm of the intrinsic IC jet luminosity \( L_\gamma \) (in ergs s\(^{-1}\)). We note that a similar approach to the luminosity function was adopted by Celotti & Fabian (2004), who discussed the extended X-ray emission of FR I radio galaxies (due to IC scattering of the cosmic microwave background radiation by radio-emitting electrons) in the context of deep X-ray surveys.

Figure 2 (bottom) also shows the cumulative number density of the low-power radio sources considered here,
the other hand, the number of high-luminosity sources in the population considered here, i.e., sources with a total radio power exceeding Fanaroff-Riley critical luminosity (roughly \( L_{\text{crit}} = 10^{42} \text{ ergs s}^{-1} \)), is negligible when compared to the number of lower luminosity (“classical” FR I) objects. In other words, the adopted upper cutoff in the GLF, \( L_{\text{high}} = 10^{44} \text{ ergs s}^{-1} \), can also be safely assumed in the following calculations. We finally note in this context that X-ray jets with properties similar to the classical FR I X-ray jets are indeed discovered in radio galaxies of intermediate power and morphology (e.g., 3C 15; Kataoka et al. 2003).

3. RESULTS AND DISCUSSION

The \( \gamma \)-ray emission due to inverse Compton (IC) scattering of starlight photons in the kiloparsec-scale jets of FR I radio galaxies is relatively weak, accounting for only a small fraction of the direct EGRET measurement in the 0.1–10 GeV photon energy range, consistent with the analysis presented by Cillessen et al. (2004). We note that for an EGRET sensitivity of \( 5.4 \times 10^{-8} \) photons cm\(^{-2}\) s\(^{-1}\), corresponding to a 5 \( \sigma \) detection in a one-year all-sky survey (Bloom 1996), the “typical” FR I kiloparsec-scale jet as considered here could be eventually detected only if its luminosity distance is roughly \( d_L < 100(L/10^{44} \text{ ergs s}^{-1})^{1/2} \) Mpc. It does not mean, however, that the FR I jets cannot be associated with some unidentified EGRET sources, as the inverse Comptonization of this and other photon fields (especially within the inner portions of the outflows) in some particular FR I objects can result in \( \gamma \)-ray signals exceeding Fanaroff-Riley critical luminosity (roughly \( L_{\text{FR I}} \)) in, e.g., T. Kneiske et al. (2005, in preparation), blazar sources can account for the bulk of the extragalactic \( \gamma \)-ray background. This indicates that the magnetic fields in the analyzed jet regions is not likely to be much smaller on average than the equipartition value, as otherwise the contribution of the considered objects would be uncomfortably high. Note that the IC jet luminosity scales roughly as \( L_{\gamma} \propto B^{-2} \), and hence a magnetic field as low as \( 10 \mu G \) would cause overproduction of the diffuse \( \gamma \)-ray background by the FR I jets on their own. Therefore, weak magnetic fields in the brightest kiloparsec-scale knots in FR I jets can be excluded (see in this context Stawarz et al. 2005, for the case of M87 jet).

There are a few significant features of our analysis. First, the analysis presented here does not depend on any particular model of particle acceleration in the jet, as the energy distribution of the radiating electrons is inferred directly from their synchrotron emission (see Stawarz et al. 2003, 2005). Second, we do not include here the inevitable synchrotron self-Compton process, which would increase the expected IC flux of the jets, especially in the “problematic” (because of the absorption/reprocessing effects) very high energy \( \gamma \)-ray band. Note also that, according to our minimum-assumption approach, we consider the same equipartition value for the kiloparsec-scale jet magnetic field in all FR I jets, which differ in total radio power (and hence most probably in jet kinetic luminosity) by several orders of magnitude. Indeed, for low-power jets one should expect an equipartition magnetic field of less than the 300 \( \mu G \) obtained here for relatively powerful jets from our sample. In other words, we underestimate the IC radiation of such extremely weak but numerous sources. Thus, the evaluated \( \gamma \)-ray emission can be considered as a lower limit only, and so the estimated one percent contribution to the extragalactic \( \gamma \)-ray background can be considered guaranteed, as long as the minimum-power hypothesis for the kiloparsec-scale jets in FR I radio galaxies is correct.

Let us also mention that the presence of bright knots at \( \approx 1 \) kpc from the active centers of FR I radio galaxies is indeed universal (Parma et al. 1987; Laing et al. 1999). These knots are usually called “flaring points,” since their positions always mark the transition in jet collimation and emissivity. Laing & Bridle (2002), who discussed the dynamics of the kiloparsec-scale jet in the FR I radio galaxy 3C 31 in detail, concluded that the flaring points...
are most likely caused by the stationary reconfinement shocks formed due to rapid changes in pressure of the hot ambient gas (see also in this context, e.g., Sanders 1983; Falle & Wilson 1985; Komissarov 1994). Others attribute them to the Kelvin-Helmholtz instabilities, whose nonlinear development can also result in the formation of weak oblique shocks (e.g., Hardee 1979; Bicknell & Begelman 1996; Lobanov et al. 2003). Whatever the case is, the analysis presented here suggests that a weak magnetic field at the position of the flaring points is unlikely. Of course, this conclusion is based on a simplified approach in modeling the IC emission of the kiloparsec-scale FR I jets on average, and the jet parameters used in our analysis are determined from a relatively small sample of the X-ray-emitting objects. However, more sophisticated analyses can be performed only with a larger sample of FR I jets detected at optical and X-ray frequencies.

With the approximate lower limit of 10 μG, the dynamical importance of the magnetic field in kiloparsec-scale FR I jets cannot yet be determined, with additional uncertainty arising from the poorly known total kinetic powers of these outflows. In addition, any possible changes of the magnetic energy flux along the outflows are not constrained in our analysis. Let us only note in this context that modeling of the spectral energy distribution of BL Lac objects—believed to be beamed counterparts of FR I radio galaxies (Urry & Padovani 1995)—usually leads to sub-equipartition magnetic field characterizing the nuclear portion of the low-power jets (e.g., Kino et al. 2002), although the model uncertainties and variety in BL Lac objects’ spectral properties are large. Hence, one can in principle suspect that amplification of the magnetic energy flux along the low-power jets between the subparsec and kiloparsec scales is required by the data, in agreement with the more detailed analysis of M87 (Stawarz et al. 2005). We note that amplification of a mean magnetic energy flux is indeed expected in any conductive plasma containing non-vanishing helicity of turbulent motions or a strong velocity shear, although the general applicability of the simple kinematic dynamo theory—usually considered in this context—to realistic astrophysical situations (like the relativistic outflows discussed here) is not clear (see, e.g., the recent review by Vishniac et al. 2003).

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