ON THE MAGNETIC FIELD IN THE KILOPARSEC-SCALE JET OF RADIO GALAXY M87

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ABSTRACT

Several low-power kiloparsec-scale jets in nearby radio galaxies are known for their synchrotron radiation extending up to optical and X-ray photon energies. Here we comment on high-energy γ-ray emission of one particular object of this kind, i.e., the kiloparsec-scale jet of the M87 radio galaxy, resulting from Comptonization of the starlight photon field of the host galaxy by the synchrotron-emitting jet electrons. In our analysis, we include the relativistic bulk velocity of the jet, as well as the Klein-Nishina effects. We show that upper limits to the kiloparsec-scale jet inverse Compton radiation imposed by the HESS and HEGRA Cerenkov Telescopes—which detected a variable source of very high energy γ-ray emission within 0.1 (~30 kpc) of the M87 central region—give us an important constraint on the magnetic field strength in this object, namely, that the magnetic field cannot be smaller than the equipartition value (referring solely to the radiating electrons) in the brightest knot of the jet, and most likely, is even stronger. In this context, we point out a need for the amplification of the magnetic energy flux along the M87 jet from the subparsec to kiloparsec scales, suggesting the turbulent dynamo as a plausible process responsible for the aforementioned amplification.

Subject headings: galaxies: individual (M87) — galaxies: jets — galaxies: magnetic fields — radiation mechanisms: nonthermal

1. INTRODUCTION

Because of the pure nonthermal nature of the multiwavelength emission of extragalactic jets, many of the jets’ parameters are basically unknown. Intensity of the jet magnetic field is the exemplary unknown in all jet models. The situation is even less clear on large scales (>1 kpc) than on small (subparsec and parsec) scales, as typically the observed spectrum of large-scale jets consists of the synchrotron emission alone, without synchrotron self-absorption features or the inverse Compton (IC) component. Therefore, the usual approach is to assume energy equipartition between the large-scale jet magnetic field and synchrotron radiating electrons, thus obtaining $B_{\text{eq}} \sim 10^{-6}$ to $10^{-3}$ G. The standard justification for the equipartition assumption is that the IC X-ray emission detected from a number of hot spots and lobes in powerful radio sources often (although not always) yields $B \approx B_{\text{eq}}$ (see, e.g., Kataoka & Stawarz 2004 and references therein). This, however, cannot really be taken as a proof for the magnetic field–radiating electrons energy equipartition in the case of the jet flows, as the physical processes responsible for the evolution of radiating particles and magnetic field within terminal shocks and extended lobes can differ substantially from the respective processes that take place within large-scale jets themselves (see, e.g., a discussion on the magnetic field structure within the hot spots and lobes by Blandell & Rawlings 2000).

Unfortunately, the X-ray emission recently detected from a number of large-scale quasar jets (e.g., Schwartz et al. 2000; Siemiginowska et al. 2002, 2003; Sambruna et al. 2004) cannot give us a definite answer on the magnetic field intensity in these objects. First, it is not well established if this X-ray emission is synchrotron or inverse Compton in origin (see a discussion in Stawarz 2003). Second, poorly constrained relativistic bulk velocities of the large-scale jets influence the inferred values of the jet parameters in both cases significantly. As a result, one can only say that if the X-ray emission of large-scale quasar jets is indeed due to the IC scattering of the cosmic microwave background radiation (Tavecchio et al. 2000), then it is possible to find a value of the jet Doppler factor that allows energy equipartition between the magnetic field and the radiating electrons (or even equipartition between magnetic field energy and the total particle’s bulk energy; Ghisellini & Celotti 2001) in a certain object. This, however, does not mean that the energy equipartition is fulfilled. In fact, Kataoka & Stawarz (2004) argued that in a framework of the IC hypothesis the more plausible interpretation leads to subequipartition magnetic field within the large-scale quasar jets. We note that the analysis of jet dynamics suggests that the powerful quasar jets are most likely matter-dominated, at least on the large scales (see, e.g., Sikora et al. 2005 and references therein). Still, other models involving Poynting flux–dominated outflows (Blandford 2002) cannot be rejected without uncertainty.

Contrary to the large-scale quasar jets, the synchrotron origin of the X-ray emission of the kiloparsec-scale flows in low-luminosity radio galaxies is well established (see Stawarz 2003 and references therein). In addition, the two-sidedness of the FR I radio structures suggests much lower bulk velocities of these jets compared to their powerful quasar-hosted analogs. All of these constraints give the unique opportunity to more accurately estimate magnetic field intensity within some nearby FR I jets by studying their inevitable IC γ-ray emission. Unfortunately, because of the insufficient sensitivity of the present γ-ray detectors, such analysis can be performed only for the closest FR I sources.

Stawarz et al. (2003) considered very high energy (VHE) γ-ray emission produced by the kiloparsec-scale jets in nearby low-power radio galaxies of the FR I type. Optical and X-ray emission recently detected from a number of such objects indicate that these jets are still relativistic on the kiloparsec scale and that they contain ultrarelativistic electrons with energies up to...
to 100 TeV (see a discussion in Stawarz 2003). Therefore, some of the nearby FR I jets can be, in principle, VHE γ-ray emitters as a result of the IC scattering off ambient photon fields that, at kiloparsec distances from the active nuclei, are expected to still be relatively high. For example, following Tsiari & Mathews (1995), we found that the bolometric energy density of the stellar emission at 1 kpc from the center of a typical luminous elliptical galaxy is, on average, $U_{\text{bol,star}} \approx 10^{-9}$ ergs cm$^{-3}$ (which can be compared with the local value of the cosmic microwave background radiation, $U_{\text{CMB}} \approx 4 \times 10^{-13}$ ergs cm$^{-3}$). In the particular case of radio galaxy M87, Stawarz et al. (2003) showed that Comptonization of such starlight radiation within the kiloparsec-scale jet (its brightest knot A) by the synchrotron-emitting electrons in the equipartition magnetic field can possibly account for the TeV emission detected by the HESS Cerenkov Telescope from the direction of that source (Aharonian et al. 2003). However, subsequent observations of M87 by the Whipple Telescope (Leo Bohac et al. 2004) gave only upper limits for its emission at the 0.4–4 TeV photon energy range, suggesting, although not strictly implying, variability of the VHE γ-ray signal. Such variability, clearly confirmed by the most recent HESS observations that established the presence of a variable (on the timescale of years) VHE γ-ray source within 0.1–30 kpc of the M87 central region (Beilicke et al. 2005), questions the possibility that the extended kiloparsec-scale jet is responsible for the 3–4σ detections of M87 by the HEGRA and HESS telescopes. On the other hand, the upper limits imposed in this way put interesting constraints on the magnetic field within the M87 large-scale jet, an issue that is of general importance in astrophysics (see, e.g., the recent monograph on the cosmic magnetic fields by Vallée 2004), and in particular in the physics of extragalactic jets (De Young 2002).

Here we comment in more detail on the high-energy γ-ray emission of the M87 kiloparsec-scale jet, resulting from the IC scattering on the stellar photon field. We take into account a relativistic bulk velocity of the emitting region, as well as the Klein-Nishina regime of the electron-photon interaction. We emphasize an important aspect of the presented model: IC scattering of the starlight emission by the synchrotron-emitting electrons is inevitable and involves neither the unknown target photon field nor the additional unconstrained source of the ultrarelativistic high-energy electrons. In particular, following our previous approach presented in Stawarz et al. (2003), we “reconstruct” the electron energy distribution from the known broadband synchrotron spectrum of a given jet region and then estimate the IC flux for the known target photon field. Therefore, our discussion is independent of any model of particle acceleration. This constitutes an important difference with the other models proposed in the literature in the context of the VHE γ-ray emission of M87 system (Pfrommer & Ensslin 2003; Reimer et al. 2004).

The paper is organized as follows. In § 2 we present the formalism used in order to evaluate the high-energy γ-ray emission of knot A in the M87 jet. In § 3 we compare the estimated fluxes with the observations reported in the literature. In § 4 we discuss implications of the obtained lower limit on the magnetic field to the theoretical models of FR I structures and the M87 jet in particular. General conclusions are presented in the last § 5.

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4 We note that the energy density of the starlight photons dominates over the energy densities of the other photon fields in the jet comoving frame, in particular over the energy density of the synchrotron photons (Stawarz et al. 2003).

5 We follow the notation with the primed quantities measured in the jet comoving frame and the bare ones, if given, in the observer rest frame, with the exception of the magnetic field intensity $B$ as well as electron Lorentz factors $\gamma$, which always refer to the emitting plasma rest frame.
$V'K'_\ell = 1.8 \times 10^{40} \delta^{-3.65} B^{-1.65}$. Note that the above expressions apply either if knot A is a moving blob or a stationary shock (see a discussion in Sikora et al. 1997).

### 2.2. Starlight Photon Field

For the target starlight photons at the position of knot A we assume roughly isotropic distribution in the galactic rest frame and strongly anisotropic in the jet rest frame because of the relativistic jet velocity. We take the characteristic observed frequency of the optical-NIR bump due to the elliptical host of M87 as $\nu_{\text{star}} = 10^{14}$ Hz (see, e.g., Müller et al. 2004). We also evaluate the appropriate starlight energy density at the position of knot A directly from the observations of the M87 host galaxy.

Young et al. (1978) showed that the distribution of stars in the M87 host galaxy agrees with the King model for the distances >1″–2″ from the active center, while at the smaller scales an additional population of massive stars from the central cusp was present because of a supermassive black hole perturbing central region of the galaxy (see also Macchetto et al. 1997). Let us therefore consider the starlight of the “unperturbed” population of the evolved stars, for which the emissivity can be approximated by

$$j_{\text{star}}(r) = j_0 \left[1 + \left(\frac{r}{r_0}\right)^2\right]^{-3/2} \quad \text{for} \quad r < r_0, \quad (5)$$

where $r$ is the radius as measured from the central galaxy, $r_0$ is the core radius for the galaxy, and $r_s$ is the appropriate tidal radius. We normalize this distribution to the luminosity density profile $\rho_0(r) = 4\pi j_{\text{star}}(r)$ in the I band, as given by Lauer et al. (1992). For the parameters $\rho_0(1 \text{kpc}) = (3-4)\times10^{-22}$ ergs s$^{-1}$ cm$^{-3}$, we obtain $j_0 \approx (3-4)\times10^{-2}$ ergs s$^{-1}$ cm$^{-3}$. The intensity of the starlight emission in a given direction specified by the azimuthal angle $\zeta \equiv \cos^{-1} \kappa$ can be obtained by integrating the stellar emissivity along a ray,

$$I_{\text{star}}(r, \kappa) = \int_{-\infty}^{l_{\text{max}}} j_{\text{star}}(\sqrt{r^2 + l^2 + 2rl\kappa}) \, dl, \quad (6)$$

where the outer boundary of the host galaxy is

$$l_{\text{max}} = -r\kappa + \sqrt{r^2 - r^2 + r^2\kappa^2}, \quad (7)$$

as discussed in Tsai & Mathews (1995). By further integrating over the solid angle, one can find the required value for the starlight energy density at a given position $r$ from the core,

$$U_{\text{star}}(r) = \frac{2\pi}{c} \int_{-1}^{1} I_{\text{star}}(r, \kappa) \, d\kappa \quad (8)$$

(see Tsai & Mathews 1995, eq. [26]). With all the parameters as discussed in this section, we obtain the I-band stellar energy density $U_{\text{star}}(1 \text{kpc}) \approx 10^{-10}$ ergs cm$^{-3}$.

There are several reasons why the above estimate should be considered as a safe lower limit. First, the obtained value refers to the I-band energy density and not to the bolometric one. We also do not include any effects of photon absorption by gas or dust. Second, in the analysis above, contribution from the additional population of massive stars from the central cusp was neglected. Also, the 2 kpc long M87 jet is surrounded by the filaments of the optically emitting cluster gas (e.g., Sparks et al. 2004), which additionally contributes to the intensity of the optical radiation around knot A. Finally, we note that synchrotron emission produced within knot A—peaked in the jet rest frame at similar frequencies to the stellar emission, although characterized by much broader energy distribution and much lower energy density than the starlight photon field—may be important for the IC emission of the highest energy electrons, increasing total IC flux at highest photon energies.

### 2.3. Inverse Compton Emission

The high-energy emissivity of knot A due to IC scattering on monoenergetic and monodirectional (in the jet rest frame) starlight photon field, including proper relativistic effects in the Klein-Nishina regime, can be found from the approximate expression given by equation (20) of Aharonian & Atoyan (1981) as

$$[\nu'p'_{\nu'}]_{\text{ic}} = \frac{c\sigma_{\text{T}}}{4\pi} U_{\text{star}}(\nu_{\text{star}})^{1/2} \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} \frac{n_f(\gamma)}{\gamma^2} f(\epsilon', \epsilon_{\text{star}}, \gamma, \mu') \, d\gamma. \quad (9)$$

Here $\epsilon' \equiv h\nu' / m_e c^2$, $\epsilon_{\text{star}} \equiv h\nu_{\text{star}} / m_e c^2$, $\theta' \equiv \cos^{-1} \mu'$ is the scattering angle, and

$$f(\epsilon', \epsilon_{\text{star}}, \gamma, \mu') = 1 + \frac{w'}{2(1 - w')} - \frac{2w'}{\nu'(1 - w')} + \frac{2w'^2}{v'^2(1 - w')^2}, \quad (10)$$

where $w' = (1 - \mu'')\epsilon_{\text{star}} \gamma$ and $w' = \epsilon'/\gamma$. The lower limit of the integral over $\gamma$, given by the condition $f \geq 0$, is

$$\gamma_0 = \frac{\epsilon'}{2} \sqrt{1 + \left(1 + \frac{2}{(1 - \mu')\epsilon' \epsilon_{\text{star}}}\right)^{1/2}}. \quad (11)$$

Hence, using the well-known relativistic transformations $\epsilon_{\text{star}} = \epsilon_{\text{star}} \Gamma$ (where $\Gamma$ is a jet bulk Lorentz factor), $\epsilon' = \epsilon / \beta$, and $\mu' = (\mu - \beta)(1 - \beta \mu)$, one can find the observed IC flux

$$[\nu'p']_{\text{ic}} = \frac{1}{d_L^2} \delta^4 V' \left[\nu'p'_{\nu'}\right]_{\text{ic}}. \quad (12)$$

Note that the IC fluxes evaluated below do not depend on the poorly known volume of the emission region, as normalization of the electron energy distribution to the observed synchrotron emission allows us to find the product $V'K'_{\ell}$, which is then inserted into equation (12).

The above expressions for the IC emissivity are correct only if $\epsilon'/\epsilon_{\text{star}} \gg 1$ and $\gamma \gg 1$, as considered in this paper. For a general case the appropriate formula for $[\nu'p']_{\text{ic}}$ is much more complicated (see Aharonian & Atoyan 1981; Brunetti 2000).

### 2.4. Kinematic Factors

High-jet-counterjet brightness asymmetry for the 2 kpc jet structure in M87 (~450 in the optical energy range), as well as other morphological properties of this object, led Bicknell & Begelman (1996) to conclude that the appropriate bulk Lorentz factor at the position of knot A is $\Gamma \sim 3-5$ and the jet viewing angle $\theta \sim 30°-35°$. Heinz & Begelman (1997) considered
We note that superluminal velocities detected by Hubble Space Telescope downstream of knot HST-1 in the M87 jet (distances 0.05–10 pc from the center; Biretta et al. 1999), as well as the X-ray and optical month-to-year variability of the HST-1 knot emission (Harris et al. 2003; Perlman et al. 2003), suggest even higher values for the jet Doppler factor, albeit characterizing the jet flow upstream with respect to knot A. One should be aware that the high Doppler factor (δ ≳ 3) of the kiloparsec-scale jet in M87 would require a small jet inclination, leading in turn to a decrease of the energy density of the starlight photons at the position of knot A, as the physical distance of this region from the core increases with the decreasing jet viewing angle. These effects introduce, however, only minor changes of the evaluated magnetic field intensity, as it depends rather weakly on the exact value of $U_{\text{star}}$ (for which we take in this paper a very safe lower limit). We note that according to the discussion in Zavala & Taylor (2002), a large jet viewing angle ($\theta \gtrsim 20^\circ$) in the M87 radio galaxy is consistent with a lack of any polarized radio emission from its core explained in terms of obscuration of the active nucleus by a dense, multiphase nuclear disk depolarizing the core emission.

3. THE RESULTS

Spectral energy distribution of the high-energy γ-ray IC emission of knot A is presented in Figures 1 and 2 for a different magnetic field intensity, two jet viewing angles $\theta = 30^\circ$ and $20^\circ$, and the bulk Lorentz factors $\Gamma = 3$ and 5. The Thomson part of this emission extends up to photon energies of the order of $10^{10} – 10^{11}$ eV. Below we compare the expected IC fluxes for different photon energies to the upper limits imposed by the observations of the EGRET observatory and the ground-based Cerenkov Telescopes HESS, HEGRA, and Whipple.

3.1. EGRET Observations

EGRET observations of the Virgo cluster imply the photon flux $F(>100$ MeV) $< 2.2 \times 10^{-8}$ cm$^{-2}$ s$^{-1}$ (Reimer et al. 2003). When converted to the energy flux density assuming power-law emission with the spectral index $\alpha_e = 0.65$, as expected in the Thomson regime of the IC emission of knot A, this reads as $\nu S_\nu(100$ MeV) $< 2.3 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$.

Figures 3 and 4 show the expected flux of knot A at the observed 100 MeV photon energy as a function of the magnetic field intensity, for the jet viewing angles $\theta = 30^\circ$ and $20^\circ$, and the bulk Lorentz factors $\Gamma = 3$ and 5. The vertical lines indicate the appropriate equipartition value that can be found from the synchrotron spectrum of the knot A,

$$B_{\text{eq}} = 330 \delta^{-5/7} \mu \text{G},$$

as given by Kataoka & Stawarz (2004). Note that the adopted value of $B_{\text{eq}}$ refers to the energy equipartition between the jet magnetic field and ultrarelativistic electrons, with possible contribution from the nonradiating particles neglected. The EGRET observations thus imply $B > 30–100 \mu \text{G}$ for any choice of the kinematic factors considered here, corresponding roughly to $B/B_{\text{eq}} > 0.1–0.5$. This constraint does not necessarily mean a
departure from the magnetic field–radiating particles’ energy equipartition but, interestingly enough, already excludes a class of models involving a very weak jet magnetic field. Note in this context that models postulating “loss-free channel” within the jet (i.e., a reservoir of high-energy electrons residing in the jet regions in which the magnetic field is extremely low, thus enabling the particles to travel along the jet without radiative energy losses) are also excluded. That is because of the dramatic radiative losses suffered by such high-energy electrons when propagating through the intense stellar radiation field of the host galaxy. Such a channel in the context of M87 jet was discussed by Owen et al. (1989).

3.2. Whipple Observations

Whipple observations give the 99% CL upper limit to the VHE γ-ray photon flux of M87 radio galaxy $F(\gamma > 0.4\,\text{TeV}) < 6.9 \times 10^{-12}\,\text{cm}^{-2}\,\text{s}^{-1}$ (Le Bohec et al. 2004). As can be seen in Figures 1 and 2, such an energetic emission from the jet would be produced entirely in the Klein-Nishima regime.

Figures 5 and 6 show the expected photon flux of knot A at the observed photon energies $h\nu_0 > 0.4\,$ TeV, where

$$F(\gamma > h\nu_0) = \int_{\nu_0}^{\infty} \frac{[\nu S_{\nu}]_{\text{ic}}}{h\nu^2} d\nu$$

(14)

(see eq. [12]) as a function of the magnetic field intensity for the jet viewing angles $\theta = 30^\circ$ and $20^\circ$ considered here and the bulk Lorentz factors $\Gamma = 3$ and $5$. The vertical lines again indicate the appropriate equipartition magnetic field. One can see that, independent of the EGRET constraints, the Whipple observations imply magnetic field intensity within the discussed jet region $B > 50–60\,\mu\text{G}$, or in other words $B/B_{\text{Eq}} > 0.2–0.4$.

3.3. HEGRA and HESS Observations

HEGRA observations resulted in a $4\sigma$ detection of high-energy γ-ray flux from the direction of M87 with the photon flux $F(\gamma > 0.73\,\text{TeV}) \approx 0.96 \times 10^{-12}\,\text{cm}^{-2}\,\text{s}^{-1}$ (Aharonian et al. 2003). Recent HESS observations also resulted in marginal

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Fig. 4.—Same as Fig. 3, but for the jet viewing angle $\theta = 20^\circ$.

Fig. 5.—Constraints on the jet magnetic field within knot A imposed by the Whipple observations (dotted horizontal lines) for the jet viewing angle $\theta = 30^\circ$ and the jet bulk Lorentz factors $\Gamma = 5$ and $3$ (solid and dashed diagonal lines, respectively). Vertical lines denote the equipartition magnetic field for $\Gamma = 5$ and $3$ (solid and dashed lines, respectively).

Fig. 6.—Same as Fig. 5, but for the jet viewing angle $\theta = 20^\circ$.

Fig. 7.—Constraints on the jet magnetic field within knot A imposed by the HEGRA and HESS observations (dotted horizontal lines) for the jet viewing angle $\theta = 30^\circ$ and the jet bulk Lorentz factors $\Gamma = 5$ and $3$ (solid and dashed diagonal lines, respectively). Vertical lines denote the equipartition magnetic field for $\Gamma = 5$ and $3$ (solid and dashed lines, respectively).
The detection of the M87 system at the 3 – 4 σ level, albeit with photon fluxes $F(>0.73 \text{ TeV}) \approx 0.4 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ in 2003 and $F(>0.73 \text{ TeV}) \approx 0.15 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ in 2004 (Bellmec et al. 2005). This clearly indicates a variability of the high-energy $\gamma$-ray emission of this source, and therefore gives the upper limits for the VHE radiation of knot A.

Figures 7 and 8 show the expected photon flux of knot A at the observed photon energies $h\nu_0 > 0.73 \text{ TeV}$ as a function of the magnetic field intensity, for the jet viewing angles $\theta = 30^\circ$ and $20^\circ$, and the bulk Lorentz factors $\Gamma = 3$ and $5$. The vertical lines indicate the appropriate equipartition magnetic field. The most recent HESS observations therefore imply the magnetic field within knot A is as strong as $B > 300 \mu G$, i.e., $B/B_{eq} > 1$–2, again for any choice of the kinematic factors considered here. Let us emphasize here once again that in evaluating the IC fluxes the safe lower limit on the starlight energy density at the position of knot A was considered. Therefore, in light of the HESS observations one can firmly conclude that a weak sub-equipartition jet magnetic field is excluded in M87.

4. DISCUSSION

Our study indicates that the magnetic field within the brightest knot A of the M87 jet, placed at $\sim 1$–3 kpc from the active nucleus, is $B \approx 300 \mu G \approx B_{eq}$ (if the jet viewing angle is in the range $\theta = 20^\circ$–$30^\circ$ and the jet bulk Lorentz factors $\Gamma = 3$–$5$). On the other hand, the upper limit to the magnetic field intensity within knot A can be found from the upper limit imposed on the magnetic field energy flux, $L_B \approx \frac{1}{2} R^2 c \Gamma^2 B^2 < L_j$, where $L_j \sim \text{few} \times 10^{44} \text{ ergs s}^{-1}$ is the total power of the M87 jet (Owen et al. 2000) and $R \approx 60 \text{ pc}$ is the radius of radio structure at the position of knot A. This gives roughly $B_{max} < 1000 \mu G$.

Now let us discuss a few issues related to the above derived magnetic field lower limit.

4.1. Synchrotron Continuum

The low-energy electrons within knot A, if present, can also IC upscatter the starlight photons to the observed X-ray photon energies. For example, in order to produce 1 keV emission in this process, one has to involve electrons with Lorentz factors $\gamma \sim 50/\delta$. The spectrum of such low-energy electrons is unknown because their synchrotron radio emission ($\nu < 10 \text{ MHz}$) cannot be directly observed. If, however, electron energy distribution of the form given in equation (1) can indeed be extrapolated down to 10 MeV electron energies, the IC energy flux density $\nu S_{\nu}|_{ic} \propto \nu^{1-0.65}$ at $h\nu = 1 \text{ keV}$ is expected to be $\approx 10^{-15}$ to $10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$ for all the parameters as discussed above.

This is more than an order of magnitude below the energy flux detected by Chandra, $\nu S_{\nu}(1 \text{ keV}) = 3.4 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$ (Marshall et al. 2002). We note that the variability of the X-ray emission of knot A on the timescale of years (Harris et al. 1997) indicates that the X-rays detected from this region are synchrotron in origin.

Wilson & Yang (2002) reported that x-ray spectral indices characterize different parts of the M87 jet that are significantly flatter than the appropriate optical–to–X-ray power-law slopes, although still relatively steep, $\alpha_X > 1$ (but see Wilson & Yang 2004). If real in the case of knot A, such spectral flattenings would be difficult to explain as resulting from the Comptonization of the low-energy electrons (i.e., as an evidence for the transition from the synchrotron to the IC spectral component), according to the discussion above. Hence, they could most probably indicate pileup effects occurring at the high-energy tail of the electron energy distribution emitting synchrotron X-rays. Dermer & Atoyan (2002) showed that similar pileup features can appear in the synchrotron spectra of extragalactic large-scale jets as a result of a decrease of the IC cooling rate of the high-energy electrons in the Klein-Nishina regime. In particular, Dermer & Atoyan (2002) considered cosmic microwave background radiation as the seed photon field for the IC emission, obtaining spectral flattenings of the synchrotron jet continua at the observed X-ray photon energies for a highly relativistic jet. In the case considered here, it is the starlight radiation that dominates the photon energy density within the emitting region ($U_{\text{star}}/U_{\text{CMB}} > 100$), and hence potential pileup effects should be pronounced at lower energies of the emitted synchrotron photons. This already indicates that the X-ray spectral flattenings in the M87 jet—if real—must be produced by another physical mechanism, such as, for example, stochastic particle acceleration processes acting within extended turbulent regions of the jet flows, as discussed by Stawarz & Ostrowski (2002). We note here that Meisenheimer et al. (1996) reported a “marginal but significant” flattening of the optical spectra at the boundaries of some parts of the M87 jet. Such flattenings could result from an efficient acceleration of the high-energy electrons at the jet edges, independent of the X-ray spectra formed closer to the jet central regions.

4.2. Particle Acceleration

Heinz & Begelman (1997), who considered synchrotron and adiabatic energy losses of radiating electrons, showed that a long extension of the optical jet in the M87 radio galaxy (as compared with the propagation length of the synchrotron emitting electrons) can be explained without invoking continuous particle acceleration only if the jet is relativistic ($\Gamma = 3$–$5$) and the jet magnetic field on kilparsec scales is below equipartition ($B \leq 0.2$–$0.7 \mu G$). As discussed in this paper, the latter condition is not likely to be fulfilled, and hence some kind of particle reacceleration acting continuously within the jet is needed. As pointed out by many authors (e.g., De Young 1986), boundary shear layers of the large-scale jets are very likely to be highly turbulent and hence are very likely to be the sites for the efficient second-order Fermi acceleration of the jet particles.6 As

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6 We invoke this physically and mathematically well-described process. However, it stands here for a number of different mechanisms, which are expected to accelerate particles within the jet boundary layer. In this context one can mention reconnection processes in highly perturbed and sheared magnetic fields or small-scale, local oblique/weak shocks formed in regions of forced supersonic turbulence.
discussed further by Stawarz & Ostrowski (2002), the maximum energies the electrons can reach in such a process can be very high (≳TeV), and the resulting electron energy distribution can deviate from a simple power-law behavior at the highest energy range, reflecting conditions within the jet flows. In this scenario, limb-brightenings of the jet are expected. It is therefore interesting to note that the limb-brightenings are indeed observed in some of the FR I jets in radio (M87; Owen et al. 1989), optical (3C 66B and 3C 264; Macchetto et al. 1991 and Crane et al. 1993, respectively) and X-ray (Cen A; Hardecastle et al. 2003). In the case of the M87 jet, however, the optical structure is narrower than the radio structure (Sparks et al. 1996), in addition displaying different polarization patterns when compared to the radio one (which is most likely determined by the boundary shear layer morphology; Perlman et al. 1999). This fact does not necessarily mean that the optically emitting electrons cannot be accelerated predominantly at the jet boundaries, as the turbulent mixing of the jet matter connected with the entrainment processes—important in the case of FR I jets—can play a role in this context (see De Young 2002). The presence of the turbulent mixing layer between the jet and the surrounding medium was also suggested to explain Faraday rotation measures for the small-scale jet in M87 source (Zavala & Taylor 2003). However, further investigation of this problem is impeded because of the little-known jet internal structure.

4.3. Jet Magnetic Field

The comoving energy density of the magnetic field within knot A is roughly limited by \( U_B^{\prime} = B^2/8\pi \geq 3.6 \times 10^{-9} \) ergs cm\(^{-3}\). As discussed above, this value is most likely higher than the energy density of the radiating electrons. This may indicate the energy equipartition between the jet magnetic field and relativistic protons present within knot A, \( U_B^{\prime} \sim U_{\text{rel}, p} \gg U_{\text{rel}, e} \), although rough lower limits obtained in this paper do not enable further quantitative analysis of this issue.

\( VLBI \) measurements often allow one to infer magnetic field structure from the low-frequency spectral break in the radio emission of the (sub) parsec-scale jet modeled in terms of synchrotron self-absorption process. In the case of the M87 jet, this method gives \( B_{\text{VLBI}} < 0.2 \) G at \( R_{\text{VLBI}} \approx 0.06 \) pc (Reynolds et al. 1996). If the magnetic energy flux in a jet is constant, then one should expect magnetic field intensity at the position of knot A to be roughly \( B = (1/\Gamma_{\text{VLBI}}/\Gamma)(R_{\text{VLBI}}/R)B_{\text{VLBI}} \ll 300 \) \( \mu G \), where we put \( \Gamma_{\text{VLBI}}/\Gamma \approx 2 \) and the jet radius at the position of the considered knot \( R \approx 60 \) pc (Owen et al. 2000). Hence, one can conclude that some kind of amplification of the jet magnetic field has to take place between the parsec and kiloparsec scales, although all the estimates presented above should be taken with caution, as some arbitrary assumptions on the jet magnetic field structure were invoked (but see Hughes 2005).

The suggested amplification of the jet magnetic field can take place at the extended shock wave located within knot A (see Medvedev & Loeb 1999). However, another (in some respect more “natural” in this object) possibility is offered by an action of the turbulent dynamo processes discussed in this context by De Young (1980; see also, e.g., Gvaramadze et al. 1988; Urpin 2002). That is because the Kelvin-Helmholtz instabilities inevitably occurring at the edges of the jet are supposed to create large-scale eddies at the flow boundaries, which amplify the jet magnetic field and develop a highly turbulent mixing layer between the jet and the surrounding medium. Such turbulent shear layers play a crucial role in mass entrainment (and thus deceleration) of the FR I outflows (Bicknell 1994), and in acceleration of the jet particles, also influencing polarization properties of the jets (Laing 1980). In a framework of this model, in order to allow for the turbulent dynamo process to proceed at all, the M87 jet has to be dynamically dominated by the (cold) particles on the small scales. On the larger scales the mass entrainment process decelerates the flow gradually, slowly amplifying the jet magnetic field (to the value exceeding at some point the energy equipartition with the radiating electrons) and creating a turbulent boundary layer that spreads into the jet interior. This process is accomplished at \( \approx 1–2 \) kpc from the active center (knot A and beyond), where the jet magnetic field reaches an approximate equipartition with the energy density of the jet particles, while the jet flow itself becomes fully turbulent, disappearing into the outer amorphous radio lobe (see the low-frequency radio maps of M87 by Owen et al. 2000). Again, further discussion of this issue is hindered because of unknown details of the turbulent dynamo process and the jet internal structure.

5. CONCLUSIONS

We discuss how the present upper limits on the high-energy \( \gamma \)-ray emission of the kiloparsec-scale jet in the M87 radio galaxy can be used to estimate magnetic field strength in the brightest knot of the jet. We obtain a “safe” lower limit of \( B > 300 \) \( \mu G \), which indicates a very likely departure from the minimum power condition in the sense that the magnetic field energy density within knot A is higher than the energy density of the radiating ultrarelativistic electrons. We speculate that the high magnetic field in knot A of the M87 jet is due to turbulent dynamo processes related to interaction of the jet with the surrounding medium.

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