ARE CENTAURUS A AND M87 TeV GAMMA-RAY SOURCES?

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ABSTRACT

In this Letter, we identify Cen A and M87, two nearby Fanaroff-Riley class I (FR I) radio galaxies with high-energy–peaked BL Lac (HBL)–like objects by investigating their spectral energy distributions (SEDs). The SED peak of Cen A at \( \sim 150 \) keV, which was generally believed to be the peak of inverse Compton emission as in the case of 3C 273, is found to be actually the peak of synchrotron emission. The synchrotron emission of M87 peaks in the far-UV band. We summarize the properties of \( \gamma \)-ray–loud blazars, especially those of TeV BL Lac objects, and generalize them to HBL-like FR I radio galaxies according to the unified scheme of BL Lac objects and FR I radio galaxies. We infer that Cen A may have a peak in its Compton component power output at \( \sim 1 \) TeV and that M87 may have a Compton emission peak at \( \sim 0.1 \) TeV. For Cen A, the estimated TeV \( \gamma \)-ray flux during outburst is \( F(0.25-30 \) TeV) = \( 6.4 \times 10^{-9} \) erg cm\(^{-2}\) s\(^{-1}\), and for M87, \( F(0.25-30 \) TeV) = \( 1.1 \times 10^{-11} \) erg cm\(^{-2}\) s\(^{-1}\). Both fluxes are detectable by TeV detectors available today, and hence Cen A and M87 are TeV \( \gamma \)-ray source candidates. By investigating the long-term variability, we predict that Cen A will undergo an outburst in the near future and will be detectable at the TeV \( \gamma \)-ray energy range using the CANGAROO and the German-French-Italian experiment HESS TeV \( \gamma \)-ray telescopes.

Subject headings: BL Lacertae objects: general — galaxies: individual (Centaurus A, M87) — gamma rays: theory — radiation mechanisms: nonthermal — X-rays: galaxies

1. INTRODUCTION

Up to now, five active galactic nuclei (AGNs) in total have been discovered to be TeV (\( E > 0.3 \) TeV) \( \gamma \)-ray sources. All of them are nearby BL Lac objects, namely, Mrk 421 (\( z = 0.031 \); Punch et al. 1992), Mrk 501 (\( z = 0.034 \); Quinn et al. 1996), 1ES 2344+514 (\( z = 0.044 \); Catanese et al. 1998), PKS 2155–304 (\( z = 0.117 \); Chadwick et al. 1999), and 3C 66A (\( z = 0.444 \); Nesphor et al. 1998). BL Lac objects and flat spectrum radio quasars (FSRQs) constitute a rare and extreme blazar class of AGNs that is characterized by strong and rapid variability, high polarization, and apparent superluminal motion. These extreme properties are generally interpreted as a consequence of nonthermal emission from a relativistic jet oriented close to the line of sight (Blandford & Königl 1979). According to unified schemes, BL Lac objects are intrinsically the same as Fanaroff-Riley class I (FR I; Fanaroff & Riley 1974) radio galaxies, while FSRQs are the same as FR II radio galaxies (e.g., Urry & Padovani 1995).

Besides the above five TeV \( \gamma \)-ray–loud blazars, 66 blazars have been detected to date as GeV \( \gamma \)-ray sources by the EGRET experiment on board Compton Gamma Ray Observatory (CGRO; Mukherjee et al. 1997; Mattox et al. 1997; Hartman et al. 1999; Sreekumar et al. 1999). The \( \gamma \)-ray emission of blazars indicates a double-peaked structure in the overall spectral energy distribution (SED; Ulrich, Maraschi, & Urry 1997 and references therein; Fossati et al. 1998), suggesting two broad spectral components. The first component is generally interpreted as being a result of synchrotron emission, and the second is believed to be inverse Compton emission of the same electron population (e.g., Ulrich et al. 1997; Urry 1999). According to the different peak frequencies, BL Lac objects are divided into two subclasses, namely, the low-energy–peaked BL Lac (LBL) objects, which have synchrotron peaks in IR/ optical, and high-energy–peaked BL Lac (HBL) objects, which have synchrotron peaks in the UV/soft X-ray range. All of the above TeV \( \gamma \)-ray blazars are HBL objects (the radio-selected BL Lac object 3C 66A has \( \alpha_\gamma = 0.74 < 0.80 \); Fossati et al. 1998), while almost all GeV \( \gamma \)-ray sources are LBL objects and FSRQs.

Although TeV \( \gamma \)-ray observations have already significantly affected our understanding of BL Lac objects and the unified scheme (e.g., Catanese & Weecks 1999), the sample of TeV blazars is still small. Much observational and instrumental work has been devoted to searching for new TeV blazars (Roberts et al. 1999; Urry 1999; Catanese & Weecks 1999 and references therein; Aharonian et al. 2000). As Bai & Lee (2001) pointed out, according to the unified scheme of FR I radio galaxies and BL Lac objects, the SED of the jet-related emission of FR I radio galaxies should also exhibit double-peaked structure and some of them should be HBL-like. Although the relativistic boosting is week or even negative in FR Is, some nearby HBL-like FR I radio galaxies may be loud enough to be detectable in the TeV energy range. If this turns out to be true, it will not only enlarge the sample of TeV sources but also provide a new approach for the study of radio galaxies. Moreover, TeV observations of nearby FR I radio galaxies will provide a test of the unified scheme.

Cen A (NGC 5128) is the prototype of FR I radio galaxies, at a distance of 3.4 Mpc (\( z = 0.0008 \)) with two strong X-ray jets (e.g., Kraft et al. 2000). It is the only GeV \( \gamma \)-ray source not belonging to the blazar class (Sreekumar et al. 1999). M87 (3C 274, Virgo A, NGC 4486; \( z = 0.0043 \)) is a well-studied FR I radio galaxy with the brightest optical jet. It shows most of the characteristics of BL Lac objects, with the jet oriented at 30°–35° to our line of sight (Tsvetanov et al. 1998 and references therein).

In this Letter we present evidence showing that Cen A and M87 are HBL-like FR I radio galaxies and that both of them are probably loud enough to be detectable at the TeV energy range during outburst.

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2. PROPERTIES OF γ-RAY–LOUD BL LAC OBJECTS

The γ-ray–loud BL Lac objects (FSRQs similar to LBL objects) have some common properties that imply physical similarities among different objects. It is believed that γ-ray emission from TeV BL Lac objects is dominated by the synchrotron self-Compton (SSC) process. Within the present uncertainties, the low-frequency side of each of the two peaks of TeV BL Lac objects can be described by the same spectral index (Tavecchio, Maraschi, & Ghisellini 1998), consistent with the SSC model. Besides the property of double-peaked SEDs mentioned in § 1, γ-ray–loud blazars have the following properties that should also be shared by HBL-like FR I radio galaxies, according to the unified scheme:

1. In the context of the SSC model, the relation between the peak frequencies of the synchrotron component ν_s and the Compton component ν_c is ν_s/ν_c ∝ γ_{peak}, where γ_{peak} is the characteristic electron energy (Urry 1999). For TeV BL Lac objects, the averaged upshifting factor of the Compton peak relative to the synchrotron peak is \( \sim 10^{8} \pm 1 \), i.e.,

\[
\frac{\nu_c}{\nu_s} \approx 10^{8} \pm 1.
\]

For example, Mrk 421 has a synchrotron emission peak at or slightly above 10^{37} Hz and a Compton peak just below 1 TeV (Urry 1999), yielding ν_s/ν_c \approx 10^5. The synchrotron peak of Mrk 501 occurs in the range 2–100 keV (Catanese et al. 1997; Pian 1998) and is a strong GeV component in the TeV energy range (Fossati et al. 1998) and is a strong GeV component in the TeV energy range (Fossati et al. 1998).

During the high state, the five TeV blazars all have a Compton luminosity \( L_c \), comparable to or slightly less than the synchrotron luminosity \( L_s \), i.e., \( L_c/L_s \sim 1 \). Assuming this is also valid for candidate TeV sources, we obtain

\[
\frac{\nu_c f_c(\nu_c)}{\nu_s f_s(\nu_s)} = \frac{\nu_s f_s(\nu_s)}{\nu_s f_s(\nu_s)}.
\]

According to the SSC model, the Compton component has the same spectral shape as the synchrotron component. Thus, with equation (3) and the spectral index of the synchrotron component, the TeV γ-ray flux of a candidate can be estimated as

\[
F_\gamma \approx \frac{\nu_c f_c(\nu_c)}{\nu_s f_s(\nu_s)} \left[ \frac{\nu_s^{1-n_{\gamma}} - \nu_c^{1-n_{\gamma}}}{(1-\alpha_c)\nu_c^{1-n_{\gamma}} + (1-\alpha_c)\nu_c^{1-n_{\gamma}}} + \frac{\nu_c^{1-n_{\gamma}} - \nu_s^{1-n_{\gamma}}}{(1-\alpha_s)\nu_s^{1-n_{\gamma}} + (1-\alpha_s)\nu_s^{1-n_{\gamma}}} \right],
\]

where \( \nu_1 (\nu_s \leq \nu_c) \) and \( \nu_2 (\nu_s \geq \nu_c) \) are the energy thresholds of a TeV γ-ray detector, and \( \alpha_s \) and \( \alpha_c \) are spectral indices of the synchrotron component below and above \( \nu_c \), respectively.

3. Cen A and M87 as TeV Source Candidates

As mentioned in § 1, BL Lac objects are divided into HBL and LBL objects according to the peak locations in the SEDs. Further studies show that for LBL objects the X-rays are inverse Compton emission, while X-rays in HBL objects are an extension of synchrotron emission at lower energies (Padovani & Giommi 1996; Fossati et al. 1998). In the following subsections we will...
show that X-rays in Cen A and M87 consist of synchrotron emission and thus are HBL objects.

3.1. Cen A

Figure 1 shows SEDs of Cen A, M87, and Mrk 501 based on several observations in the literature. The X-ray spectral index of the Cen A nucleus in 2–10 keV was found to be less than 1 (Turner et al. 1997; Miyazaki et al. 1996), and hence log (νfν) is a monotonously rising function of log ν. Between 10 and 100 keV, the spectral index is 0.7–0.8 (Miyazaki et al. 1996; Bond et al. 1996; Wheaton et al. 1996; Kinzer et al. 1995), but less than 1, with a monotonously rising SED of Cen A in this energy range. The SED of Cen A continuously rises below ~150 keV where the spectrum breaks, and then the SED goes down continuously to the MeV and even GeV energy range (see Fig. 1). As in the case of blazars, this hump represents one of the two radiation components, and the radiation mechanism of this component is the same as that of X-rays.

Steinle et al. (1998) and Kinzer et al. (1995) pointed out that the spectra of Cen A show interesting similarities to those of jet-aligned blazars (McNaron-Brown et al. 1995) and in particular to those of the well-studied quasar 3C 273 (Johnson et al. 1995; Lichti et al. 1995); both show spectral breaks in the soft γ-ray regime, and both have intensity-independent power-law shapes below the break. For 3C 273, the peak in the soft γ-ray regime is a Compton peak, so Steinle et al. (1998) and Kinzer et al. (1995) regarded the peak of Cen A at ~150 keV as a Compton peak.

However, based on the observations by ROSAT and ASCA, Turner et al. (1997) found that the spectrum of the jet of Cen A is actually consistent with the spectrum of the nuclear continuum and that the spectrum of the jet is flatter than that expected as a result of an inverse Compton scattering of radio photons but is consistent with that predicted by a simple synchrotron model. Recent Chandra observations also indicated that X-rays from the jet of Cen A comprise synchrotron emission (Birk & Lesch 2000). Therefore, the peak at ~150 keV is not the Compton peak but the synchrotron peak, as in the case of Mrk 501 (see Fig. 1). The peak frequency of Cen A is variable, which is also similar to the behavior in TeV blazars. Observations by CGRO OSSE in 1991–1994 revealed peak frequencies of ~150 keV (Kinzer et al. 1995), while Miyazaki et al. (1996) reported a peak frequency of 180 keV, based on Welcome-1 observations.

The peak of the Compton component of Mrk 501 is at ~1 TeV, so that of Cen A is probably also at ~1 TeV. During the outburst state, the flux density at 100 keV is ~11 × 10^-3 photons cm^-2 s^-1 keV^-1 (see Fig. 5 in Bond et al. 1996), and the synchrotron peak flux density is f_ν,ν=100keV = 2.1 × 10^-29 ergs cm^-2 s^-1 Hz^-1, assuming a spectral index of 0.7. According to equation (4), with αν = 0.7 and αν = 1.3, the estimated TeV flux in 0.25–30 TeV for Cen A is

\[ F(0.25–30 \text{ TeV}) = 6.4 \times 10^{-9} \text{ ergs cm}^{-2} \text{ s}^{-1}, \]

which is about 10 times brighter than that of Mrk 501 in the 1997 outburst, suggesting that Cen A can be a strong TeV γ-ray source during outburst.

3.2. M87

The radio–to–X-ray SED of M87 is very smooth, like that of a typical BL Lac object (Tsvetanov et al. 1998; see Fig. 1). If it is really a misaligned BL Lac object, the radio to X-ray hump should be the synchrotron component, and X-rays are also synchrotron emission, suggesting that M87 is an HBL object. Einstein and ROSAT observations show that the X-ray emission from the jet of M87 is probably the high-frequency tail of the radio to optical synchrotron spectrum, although other origins (thermal or inverse Compton) for the X-rays cannot be ruled out completely (Biretta, Stern, & Harris 1991; Neumann et al. 1997). The EUVE observations of M87 are consistent with the spectral cutoff in the spectrum of the jet in M87 as suggested by Meisenheimer, Roeser, & Schloetelburg (1996), which further supports the idea that the EUV and X-ray emission of the jet is synchrotron radiation (Berghöfer, Bowyer, & Korpela 2000). Reynolds et al. (1999) also identify M87 with an HBL object, by combining Rossi X-Ray Timing Explorer hard X-ray (4–15 keV) observations with ROSAT data and inferring that the X-ray spectra of the M87 core and jet must be steep, like those of HBL objects.

The synchrotron peak of M87 lies between 10^{23} and 10^{16} Hz (see Fig. 1). According to equation (1), the Compton component of M87 may peak at ~0.1 TeV. The flux of the core and jet of M87 in the EUVE Deep Survey bandpass is 16.25 μJy (using a core/jet flux ratio of ~1.5) with a spectral index of the UV to X-ray power-law spectrum of α ≈ 1.4 (Berghöfer et al. 2000; Harris, Biretta, & Junor 1997). According to equation (4), the estimated TeV flux (0.25–30 TeV) for M87 is

\[ F(0.25–30 \text{ TeV}) = 1.1 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}, \]

which is comparable to that of Mrk 501 in 1995, suggesting that M87 may be a TeV γ-ray–loud FR I radio galaxy.

4. DISCUSSION AND CONCLUSIONS

Cen A was observed with the CANGAROO 3.8 m TeV γ-ray telescope from 1995 March to April but was not detected (Rowell et al. 1999). There was no X-ray observation for Cen A in 1995, but using the observations before 1995 we can infer that Cen A was in the low state during 1995. Between 1992 and 1995 Cen A was very faint, and there was no trend toward outburst in 1995 (see Fig. 5 in Bond et al. 1996). Thus, the TeV
flux of Cen A was below the detection limit of the CANGAROO telescope. Grindlay et al. (1975) reported that Cen A was detected in the TeV energy range during 1972–1974. Since the detection has not been repeated (Israel 1998), it appears that no one has included Cen A in the list of known TeV γ-ray AGNs. However, from 1972 to 1976, Cen A underwent a large outburst in the X-ray energy range (see Fig. 4 in Turner et al. 1997 or Fig. 5 in Bond et al. 1996) and probably underwent an outburst in the TeV energy range at the same time, so the detection of Cen A by Grindlay et al. (1975) is considered to be authentic.

At present, the CANGAROO 10 m telescope is the only TeV γ-ray telescope that can be used to observe the southern object Cen A. In the future, Cen A can be observed by CANGAROO III and the German-French-Italian experiment HESS in Namibia. The long-term X-ray light curve of Cen A shows that the period of outburst is 5–6 yr (see Fig. 5 in Bond et al. 1996), which is typical for radio-loud AGNs (Smith & Nair 1995). The recent observation by the Chandra X-Ray Observatory in 1999 shows that Cen A is in the low state at present (Kraft et al. 2000). Thus, it is expected that Cen A may undergo an outburst in the near future. The long-term light curve also shows that Cen A did not undergo any large outburst since 1986, so the coming outburst may be a large one. In addition, according to equation (1) the Compton component of Cen A may also peak as high as ~100 TeV. It may thus be strong enough to be detectable even in the PeV energy range during outburst.

The Hubble Space Telescope has recorded that the flux from the M87 optical nucleus varies by a factor of ~2 on timescales of ~2.5 months (Tsvetanov et al. 1998). A difference by a factor of 5 in the flux detected by Spacelab 2 and Ginga indicated that the hard X-ray from the M87 core also varied violently (Guainazzi & Molendi 1999), which suggests that the variability in M87 around peak frequency is similar to that in TeV blazars. EGRET has observed M87 but has not detected any GeV γ-rays (Sreekumar et al. 1996), which may indicate that M87 does not have a peak in its Compton component at the GeV energy range, which is consistent with our result. M87 was observed at TeV energies many years ago but was not detected. At that time the TeV detectors were not sensitive (the Crab Nebula was not detected either), and the observations gave only upper limits, \( F(0.4 \text{ TeV}) < 8.3 \times 10^{-11} \text{ photons cm}^{-2} \text{s}^{-1} \) (Cawley et al. 1985) and \( F(0.21 \text{ TeV}) < 1.2 \times 10^{-10} \text{ photons cm}^{-2} \text{s}^{-1} \) (Weekes et al. 1972; see Fig. 1). M87 has not yet been observed by any modern TeV γ-ray telescopes. It can be observed using powerful TeV γ-ray telescopes, such as Whipple and HEGRA.

In summary, the X-rays from Cen A and M87 are synchrotron emission rather than inverse Compton emission, and hence these nearby FR I radio galaxies are HBL-like objects. In particular, Cen A is similar to Mrk 501 with its synchrotron component peaking at very high energies, which was once thought to be nonsynchrotron radiation (Skibo et al. 1994; Kinzer et al. 1995; Steinle et al. 1998). According to the unified scheme of BL Lac objects and FR I radio galaxies and assuming that the properties of the known TeV BL Lac objects are common for all TeV AGNs, we predict that Cen A may have a peak in its Compton component power output at ~1 TeV and that M87 may have a Compton emission peak at ~0.1 TeV, both having TeV γ-ray flux detectable by TeV γ-ray detectors available today.

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