Gamma ray and infrared emission from the M87 jet and torus

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The existence of intrinsic obscuration of Fanaroff-Riley I objects is a controversial topic. M87, the nearest such object, is puzzling in that although it has very massive central black hole it has a relatively low luminosity, suggesting it is in a dormant state. Despite of its proximity to us (16 Mpc) it is not known with certainty whether or not M87 has a dusty torus.

Infrared observations indicate that if a torus exists in M87 it must have a rather low infrared luminosity. Using arguments from unification theory of active galactic nuclei, we have earlier suggested that the inner parsec-scale region of M87 could still harbour a small torus sufficiently cold such that its infrared emission is dwarfed by the jet emission. The infrared emission from even a small cold torus could affect through photon-photon pair production interactions the escape of 100 GeV to TeV energy gamma rays from the central parsec of M87.

The TeV gamma-ray flux from the inner jet of M87 has recently been predicted in the context of the Synchrotron Proton Blazar (SPB) model to extend up to at least 100 GeV (Protheroe, Donea, Reimer, 2002). Subsequently, the detection of gamma-rays above 730 GeV by the HEGRA Cherenkov telescopes has been reported. We discuss the interactions of gamma-rays produced in the inner jet of M87 with the weak infrared radiation expected from a possible dusty small-scale torus, and show that the HEGRA detection shows that the temperature of any torus surrounding the gamma-ray emission region must be cooler than about 250 K. We suggest that if no gamma-rays are in future detected during extreme flaring activity in M87 at other wavelength, this may be expected because of torus heating.

§1. Introduction

M87 is usually classified as a Fanaroff-Riley Class I (FRI) radio galaxy having a relativistic jet[1] pointing at $\sim 30°$ to the line of sight.[2] Despite of its proximity to us ($\sim$16 Mpc[3]) it is not known with certainty whether or not M87 has a dusty torus. However, it does appear to have a deficiency of dust at pc scales compared to other galaxies of its class,[4] and this may suggest that the supply of dust in M87 is scarce. Non-observations of polarized emission from the core[5] suggests that we see the nucleus through a depolarizing layer which may be ionized gas filling the torus.

Chandra X-ray observations of the nucleus of M87 show that the accretion flow has low radiative efficiency[6] which would not appear to favour a standard accretion disk (α-disk), and therefore it is likely that the inflowing gas settles into an advection-dominated accretion flow (ADAF).[7,6,8] As a consequence, the heating of any dusty torus would be currently inefficient. Strong mid-infrared emission was not detected from the centre of M87,[9,10] suggesting either that there is no torus, or that the dust cannot settle easily into a 'standard' well-defined large-scale torus configuration. Corbin et al.,[11] have obtained HST WFPC2 images of M87, and from these they did not exclude the possibility of an outer radius of a torus, if present, being smaller that 50 pc.

The existence of the intrinsic obscuration of FRIs is a controversial topic (see Whysong & Antonucci[12] and references therein). Chiaberge et al.[13] suggest that FRIs (including M87) with detected optical fluxes could lack tori, or have geometrically very thin tori which allow the optical emission to be seen. On the other hand, Gambill et al.[14] suggested that at least some FRIs show excess X-ray absorption, possibly a signature of a molecular torus obscuring the core. In addition, several FRI objects show incontestable proof of having toroidal dust structures: Centaurus A,[15,12] 3C270,[16] 3C218.[17,18]

The presence of a broad line region in M87 is undeniable as the Lyα line has observed[19] a width of 3000 km s^{-1}, providing direct evidence that BLR clouds are active in M87. Either the NLR or BLR may contribute to the observed depolarization of the radio flux.[5] Donea & Protheroe[20] have discussed the coexistence of BLR and tori in active galactic nuclei (AGNs) in the context of unification theories of AGN and their implications for TeV emission from jets. In this context, it is hard to accept that M87 completely lacks a dusty component. M87 might still have sufficient dust around the nucleus such that its infrared emission may affect gamma-ray escape.[21] The putative torus of M87 probably differs from a standard quasar torus by being smaller, probably cooler, having a wide opening angle ($\phi \geq 30°$) and a large density gradient in the dust. Such a torus would be quite different from the large tori with external radii of $\approx 100 - 200$ pc assumed to populate quasars. The limits imposed in modelling this torus come from the fact that the infrared flux must not exceed the detected mid-IR flux detected. In Section 3 we will discuss the geometry of the torus in details.

Since M87 has a large central mass, and by considering aging arguments[8,22] it could harbour a nucleus comprising of two or more black holes. For a binary black hole system a dusty torus could form with a clumpy structure with rather diluted polar dust caps filling the space between the jet and the equatorial belt of the torus.[23,24]

We shall discuss the implications of the existence of such a patchy, or clumpy, small-scale torus in M87 for observing gamma-rays from the inner jet. At the distance of M87 absorption by photon-photon pair production on the intergalactic infrared background can be neglected below 1 TeV. We suggest that the detection or non-detection of gamma-ray fluxes from M87 can provide useful information about tori in FRIs. However, if an ADAF is present in place of a standard accretion disk, as seems likely in M87, its radiation field may also contribute to the optical depth for escape of gamma-rays from regions of the jet close to the black hole.

§2. Modeling the spectral energy distribution of M87

In this section we summarize the main results from modeling the high energy gamma-ray emission from the inner jet of M87. The origin of the high-energy component of the SEDs of AGNs, starting at X-ray or γ-ray energies and extending in some cases to TeV-energies, is uncertain. Using a leptonic model, Bai & Lee[2] suggested that M87 could emit detectable gamma rays with an inverse-Compton emission peak at 0.1 TeV. In the context of hadronic models, the spectrum of gamma-ray emission
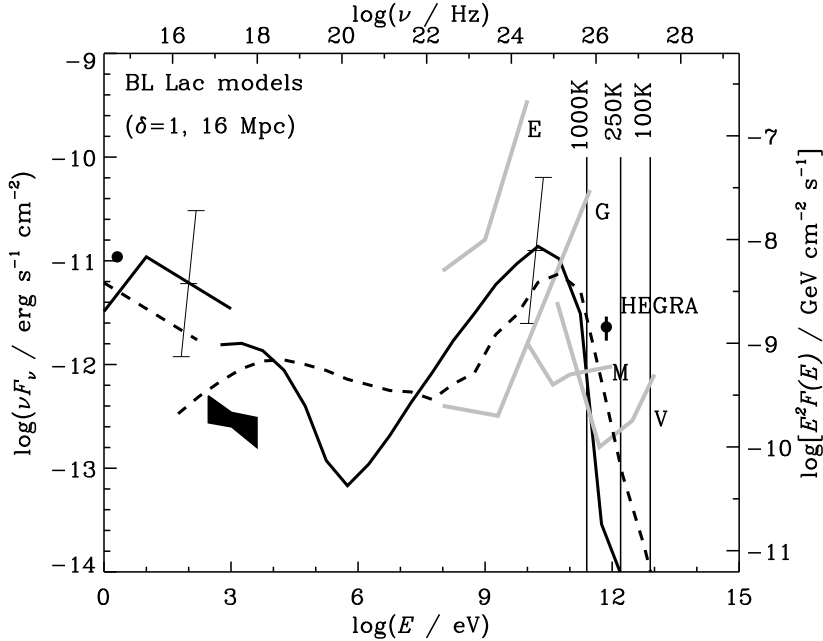
Fig. 1. Predicted high energy component of the spectral energy distribution[30] (SED) of the nucleus of M87 assuming it to be a mis-aligned HBL (solid curves) or LBL (dashed curve). The broken power-laws on the left show the electron synchrotron radiation which provides the target photons for proton interactions; the curves on the right show the predicted X-ray to gamma-ray flux. Error bars attached to solid curves correspond to uncertainty due to the Doppler factor of M87 which we taken to be in the range $0.67 \leq \delta \leq 1.5$. The sensitivities of the EGRET (E), GLAST (G), MAGIC (M) and VERITAS (V) gamma ray telescopes are indicated, as well as the HEGRA observation.[26] Non-simultaneous data from M87 unresolved nuclear jet emission refs.[27), 10), 32] Vertical lines show the cut-off energies for photon-photon pair production for γ-rays from the inner jet interacting with IR photons from the assumed torus with the temperatures indicated.

from the nucleus of M87 has been predicted using the SPB model by Protheroe et al.[30] by treating M87 as a mis-aligned BL Lac object. The SPB model[25] employs hadronic interactions in relativistic jets and the high-energy radiation is produced through photomeson production, proton and muon synchrotron radiation, and subsequent pair-synchrotron cascading in the highly magnetized environment. In the case of BL Lacs internal photon fields (i.e. produced by synchrotron radiation from the co-accelerated electrons at the radio to UV or X-ray frequencies) serve as the target for pion photoproduction. Protheroe et al.[30] have shown that, M87 could be either a high-frequency peaked (HBL) or a low-frequency peaked (LBL) BL Lac object, and predicted the gamma-ray emission (see Fig 1) from the nuclear jet to extend up to at least 100 GeV. Subsequently the HEGRA Collaboration reported the detection of gamma rays above 730 GeV with luminosity $\sim 10^{41}$ erg/s,[26] consistent with that predicted.[30] Future telescopes with higher sensitivity (see Fig. 1) such as GLAST and MAGIC, and possibly VERITAS, should be able to measure the spectrum in detail.

The difference in the shapes of the high energy hump of the SED when M87

is modelled as a mis-aligned LBL or HBL is due the nature of the proton interactions and interactions of particles and radiation produced as secondaries. If M87 is modelled as a mis-aligned LBL (dashed curve in Fig 1) pion photoproduction losses determine the maximum proton energy, and hence the maximum gamma-ray energy which results from the cascades initiated by proton synchrotron radiation and pion decay (including pion and muon synchrotron radiation). In the case of mis-aligned HBL, because of the lower energies of target photons, synchrotron losses determine the maximum proton energy, and synchrotron radiation by muons can become important (see Protheroe et al.[30] for details).

The uncertainties in the Doppler factor of M87 (range considered 0.66 – 1.6) give rise to a much larger uncertainty in the bolometric luminosity (indicated in the theoretical SED by the slanted error-bars). In both cases the predicted neutrino flux is well below detection levels of future neutrino telescopes, however it is possibly that the flux will increases during an extreme flare in the LBL case.

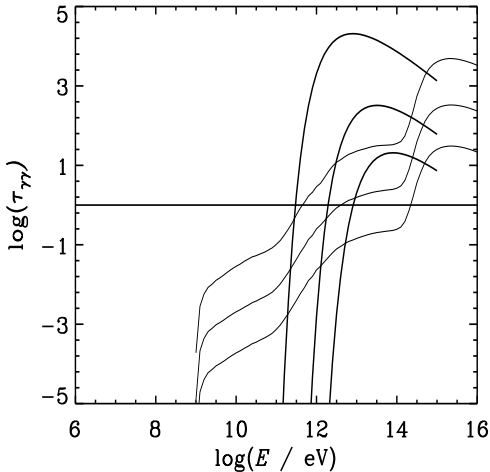## §3. Gamma ray absorption in torus and ADAF fields

Fig. 2. Optical depth for the absorption of GeV–TeV photons travelling along the jet from distance z from the black hole to infinity: in the infrared field of a compact torus with temperature $T = (100, 250, 1000)$ K (thick curves from bottom to top, $z \ll 1$ pc); in the radiation field of an ADAF for $z = (0.001, 0.01, 0.1)$ pc (thin curves from top to bottom).

We calculate the photon-photon pair-production optical depth $\tau_{\gamma\gamma}$ of GeV-TeV photons emitted by the jet of M87 interacting with IR photons from the torus as in Donea & Protheroe.[20] In Section 1 we mentioned that M87 could have an ADAF, and with the jet contributing little to the heating the torus, a compact cold torus would result. We take the inner radius of the torus to be $R_{in} \approx 1$ pc. For an opening angle of at least $\phi \approx 30°$, such that the inner jet could be seen from the observer we infer a maximum height of 1.7 pc of the inner wall of the torus. If the torus cross section is a rectangle with the inner edges cut way at the angle $\phi \geq 30°$, then the torus could be higher at radii larger than 2.5 pc (such that the nucleus remains unobscured). Since the γ-ray emission is assumed to come mainly from the inner jet (distances $z \ll 1$ pc), then it is completely imbedded in the infrared radiation of the torus. In this case the outer radius of the torus is irrelevant, and only the temperature

of its inner wall is important. However, if the γ-rays are produced somewhere above the torus, then the radial extent of the dust should be considered. We take a minimum value for the outer radius of the torus $R_{\text{out}} = 2.5$ pc, and from $R_{\text{out}} \approx 2.5$ pc to 50 pc[11] the dust is considered to have a very patchy configuration. The calculation of the torus emission follows Barvainis[29] where the ultraviolet absorption efficiency of the grains is taken to be unity. A torus heated up to $T \sim 250$ K could account for the observed infrared flux.

Fig 2 shows the γ-γ opacity for γ-rays travelling along the jet axis from $z \ll 1$ pc to infinity in the infrared radiation of a compact torus for three temperatures $T = (100, 250, 1000)$ K. It can be seen that γ-rays with energies above 10 TeV could still be absorbed even when the torus is cold ($T = 100$ K) provided the emission region lies within the torus.

Radiation emitted by an ADAF may also provide target photons for photon-photon pair production. We have taken the geometry of the ADAF to be a disk of inner radius 6 gravitational radii and the outer radius at 1000 gravitational radii, and the ADAF spectrum is taken from Di Matteo et al.[6] The γ-γ opacity for γ-rays interacting with the anisotropic ADAF radiation field is also shown in Fig 2 for three different positions of the emitting region along the jet. As one can see, the TeV emission could be attenuated if the gamma-ray emission region is sufficiently close to the black hole.

§4. Discussion

The gamma-ray flux observed from M87 by HEGRA is for energies above 730 GeV, the flux level is such that with the sensitivity of the HEGRA telescopes it is impossible to determine to what energies the spectrum continues (the predicted fluxes also not extend TeV energies). Nevertheless, given the HEGRA data it is possible to say something about the nature of any torus present. With the emission region well inside the putative torus, one expects a cut-off in the gamma rays spectrum at an energy determined by the torus temperature (vertical lines in Fig 1). The fact that HEGRA has detected gamma-ray emission at 730 GeV confirms that the torus (if it exists) should be cold, with a temperature less than ~ 250 K, consistent with the interpretation of the directly observed infrared flux.[10]

M87 appears to be in a dormant state, and the situation could change drastically during extreme flaring activity, possibly related to spin flip during binary black hole merger,[24] turbulences or a sudden increase in the accretion mass rate. Owen et al.[22] pointed out that M87 could display on-off activity cycles, assuming that there could be a phenomenon which turns off/on the central engine. In this case the small-scale torus could undergo periodic heating during which the torus temperature could rise up to the sublimation temperature ~ 1500 K. This would present any TeV photons produced within the *reactivated* torus escaping (see the top solid curve of Fig 2 corresponding to $T = 1000$ K). Such a reactivation of the nucleus of M87 would affect other radiation fields making them relevant target fields for interaction of particles and radiation within the jet. In this case the SPB model would need to be replaced with a different model, perhaps a proton quasar model[31] in which pion

photoproduction and Bethe-Heitler pair production dominate for energetic protons. In this case, a reduction in the TeV gamma ray flux would be accompanied by an increase in the flux at other wavelength, and also to enhanced neutrino emission, perhaps at a level observable by planned km^3 extensions to the AMANDA neutrino detector. Regular monitoring of M87 in several wavelength bands would be helpful to detect the onset of extreme flaring activity.

Acknowledgments

References

1) J.A. Biretta, in The Radio Galaxy M87, ed. H.-J. Röser & K. Meisenheimer (Springer: Berlin), (1999) 159.
2) J.M. Bai and M.G. Lee, Astrophys. J. **549** (2001) L173
3) J.C. Cohen et al. , Astron. J. **119** (2000), 162.
4) W.B. Sparks, J.A. Biretta, F. Macchetto, Astrophys. J. **473** (1996), 254
5) R.T. Zavala ,G.B. Taylor, Astrophys. J. **566** (2002), 9
6) T. Di Matteo, S.W. Allen, A.C. Fabian, A.S. Wilson, Andrew J. Young, Astron. J. **582** (2003), 133
7) R. Narayan, I Yi and R Mahadevan, Nature **375** (1995), 623
8) C.S. Reynolds ,T. Di Matteo, A. C., Fabian , U. Hwang and C.R. Canizares , MNRAS **283** (1996), L111
9) D. Whysong, R. Antonucci, astro-ph/0106381
10) E.S. Perlman, W.B. Sparks, J. Radomski, C. Packham, R.S. Fisher, R. Pina, J.A. Biretta, Astrophys. J. **561** (2001) L51
11) M.R. Corbin , E. O'Neil, M. Rieke, Astron. J. **124** (2002), 183
12) D. Whysong, R. Antonucci, astro-ph/0207385
13) M. Chiaberge, A. Capetti, A. Celloti, A&A **349** (1999), 77.
14) J.K. Gambill, R.M. Sambruna, G. Chartas, et al., accepted A&A (2003), astro-ph/0302265
15) D.M. Alexander , A. Efstathiou, J.H. Hough, et al., MNRAS **310** (1999), 78
16) A.J Barth, A.V. Filippenko, Astrophys. J. **525** (1999) 673.
17) R.M. Sambruna, G. Chartas, M. Eracleous, R.F. Mushotzky,Astrophys. J. **532** (2000), 91
18) Antonucci, R., Tenerife lectures, (2001) astro-ph/0103048.
19) R. Sankrit, K.R. Sembach , & C.R. Canizares, Astrophys. J. **527** (1999), 733
20) A.-C. Donea, R.J. Protheroe, Astroph. Phys. **18** (2003), 377
21) A.-C. Donea, R.J. Protheroe, Proceedings of the conference on Active Galactic Nuclei: from Central Engine to Host Galaxy, meeting held in Meudon, France, July 23-27, 2002, Eds.: S. Collin, F. Combes and I. Shlosman,astro-ph/0301433
22) F.N. Owen, J.A. Eilek and N.E. Kassim Astrophys. J. **ApJ** (543), 200, 611
23) C. Zier , P.L. Biermann , A&A, 377 (2001) 23
24) P.L. Biermann et al., (2002), astro-ph/0211503
25) A. Mücke, R.J. Protheroe, Astropart. Phys **15** (2001), 121
26) HEGRA Collaboration: F. Aharonian, A. Akhperjanian, M. Beilicke, submitted to A&A (2003), astro-ph/0302155
27) J.A. Biretta, C.P. Stern, D.E. Harris, Astron. J. **101** (1991) 1632.
28) "Exploring nature's highest energy processes with the Gamma Ray Large Area Space Telescope" NASA document NP-2000-9-107-GSFC, p29., http://glast.gfsc.nasa.gov/resources/brochures/gsd/
29) V. Barvainis, Astrophys. J. **320** (1987), 537
30) R.J. Protheroe, A.-C. Donea, A. Riemer, Astroph. Phys. **to appear** (2003), .
31) R.J. Protheroe, A.-C. Donea, ICRC, (2003), in preparation
32) A.S. Wilson ,Y. Yang,Astrophys. J. **568** (2002), 133