M87 as a misaligned Synchrotron-Proton Blazar

A. Reimer,[1] R.J. Protheroe,[2] and A.-C. Donea[2,3]
(1) Institut für Theoretische Physik, Lehrstuhl IV: Weltraum- & Astrophysik, Ruhr-Universität Bochum, D-44780 Bochum, Germany
(2) Department of Physics and Mathematical Physics, The University of Adelaide, Adelaide, SA 5005, Australia
(3) Astronomical Institute of the Romanian Academy, Bucharest, 75212, Romania

Abstract

In the framework of the unified model for radio-loud Active Galactic Nuclei (AGN) the Fanaroff-Riley (FR) class 1 radio galaxy M87 is a misaligned blazar of BL Lac type. Its unresolved nuclear region is a strong non-thermal emitter of radio to X-ray photons that have been interpreted as synchrotron radiation. The recent detection of TeV-photons by the HEGRA-telescope array, if confirmed, would make it the first radio galaxy detected at TeV-energies. We discuss the emission from the core region of M87 in the context of the hadronic Synchrotron-Proton Blazar (SPB) model, and place constraints on the model's parameter space consistent with this HEGRA-detection. Model fits to M87's non-simultanous spectral energy distribution (SED) predict the peak power of the γ-ray component at $\sim$100 GeV at a level comparative to the low-energy hump. This makes M87 a promising target for e.g. H.E.S.S., VERITAS and MAGIC.

1. Introduction

Speculations that M87 could be a nearby ($\sim$16 Mpc) powerful accelerator of ultra-high-energy cosmic rays (UHECRs) has triggered many γ-ray instruments to search for high energy emission from this source. Until recently, when the HEGRA team published the first (though tentative) detection of $>$ 730 GeV photons at the 4σ level [1], only upper limits were available at γ-ray energies [5, 8, 13]. This detection has motivated us to refine our previous SPB-model predictions for γ-rays from M87 [12]. Here we concentrate on M87's core emission.

2. Modeling the SED of M87 and predictions

Variability in the core region has been observed in the radio/optical band up to X-ray energies. E.g. Chandra monitoring in 2002 [6] revealed a flux increase of about 20% within 46 days that places a limit on the source size of $R \simeq 0.1$pc.

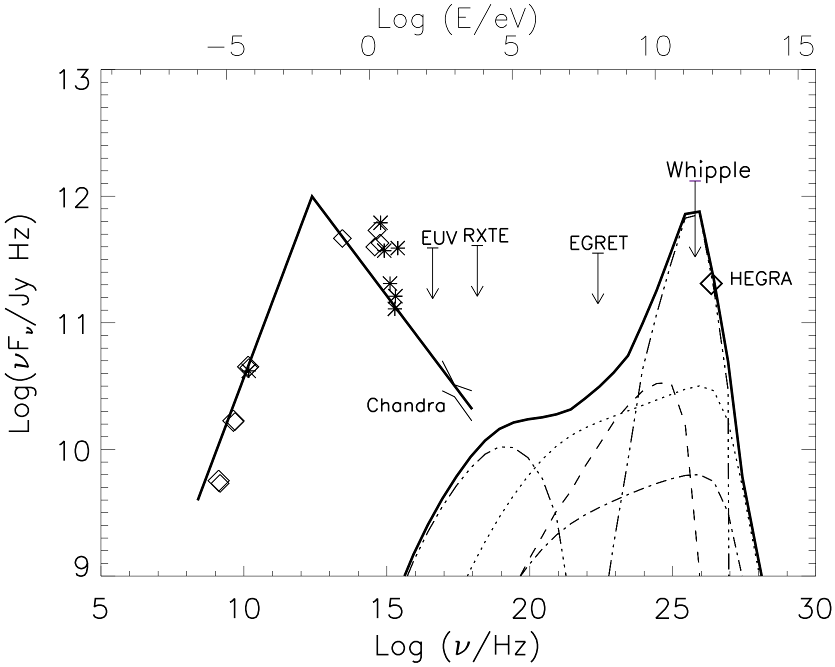
pp. 2631–2634

The most stringent upper limit on R is provided by cm/mm intercontinental VLBI-images with a superb linear resolution of ∼0.01 pc (e.g. [7]). HST data [4] show features within the first arcsec of the jet moving at subluminal speed while at larger distances from the core superluminal motion is observed. The upstream knot closest to the core has an apparent speed of 0.63±0.23c which we use here to constrain the beaming factor for the nuclear emission. For a jet angle of 10^o-40^o as suggested from VLA and HST proper motion studies [3, 4] Doppler factors $D = 1.5 \ldots 3$ are in accord with the apparent bulk speed (we adopt $D = 2$ here).

Here we discuss M87 in the framework of the SPB model [9, 10] in which relativistic protons, whose particle density N'_p follows a power law spectrum $\propto \gamma_p'^{-\alpha_p}$ (restricted here to $\alpha_p = 2$) in the range $2 \leq \gamma'_p \leq \gamma'_{\rm p,max}$ (primed quantities are in the jet frame), interact with the synchrotron radiation field produced by the primary relativistic electrons (e^-) via meson photoproduction and Bethe-Heitler pair production, and more importantly, with the strong ambient magnetic field, emitting synchrotron radiation ($\pi^\pm$ and $\mu^\pm$ also emit synchrotron radiation). The relativistic primary e^- radiate synchrotron photons that manifests itself in the blazar SED as the synchrotron hump, and serves as the target radiation field for pγ interactions, and for the subsequent pair-synchrotron cascade which develops as a result of $\gamma\gamma$ pair production in the highly magnetized blob. The acceleration rate is $d\gamma'_p/dt' = \eta e c^2 B'$ where $\eta \leq 1$ describes the efficiency. The maximum proton energy is limited by the balance between energy gain and loss rates.

The data of the synchrotron spectrum from the primary e^- imply a break at either a few 10^{12}Hz [11] or $\sim 10^{14}$Hz Fig. 1 shows examples of parameter sets using a break in the target photon spectrum at 0.01 eV and 1 eV, that represent the data satisfactorily. They predict the main high energy power output at ∼100 GeV to be due to either $\mu^\pm/\pi^\pm$- or p-synchrotron radiation, depending on whether the primary e^- synchrotron component peaks at high or low energies, respectively. The power output in the high energy domain is predicted to be roughly equal to the power output in the low energy hump. Because of M87's proximity absorption of γ-rays in the cosmic background radiation field is expected to have minimal effect on the spectrum below $\sim$ 50 TeV. The HEGRA-detection at $>$ 730 GeV places an important constraint on the models: protons must be accelerated to very high energies above $\geq 10^{10}$GeV which can only be explained if proton acceleration is extremely efficient ($\eta \approx 1$). We therefore expect M87, if a misaligned SPB, could be an important source of UHECRs (e.g. [12]).

The recently commissioned Cherenkov telescopes VERITAS, MAGIC and the southern H.E.S.S. array (though at large zenith angles $> 35^o$) should easily be able to detect M87. The predicted integral fluxes $>$ 100 GeV for both models are $\sim 3 \times 10^{-11}$cm^{-2} s^{-1}. We have used A. Konopelko's simulator for the H.E.S.S. response (http://pluto.mpi-hd.mpg.de/∼konopelk/WEB/simulator.html) to estimate the necessary observation time for acceptable detections. A 10 h observation



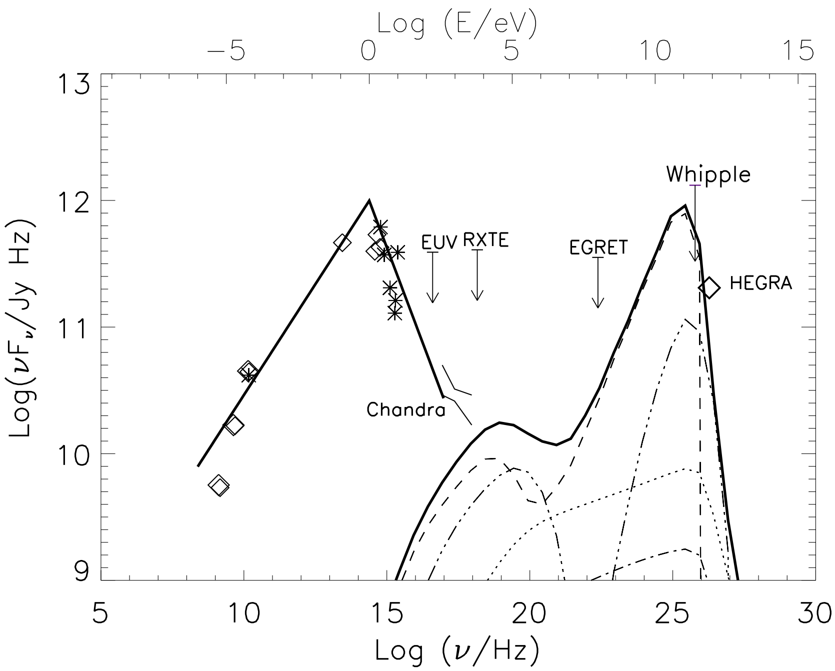


Fig. 1. Non-simultanous SED of M87's core emission in comparison with model 1 (upper figure) and model 2 (lower figure). Data are from [1, 2, 8, 11, 13, 14, 15]; see also ref. in [12]. For both models $B' = 30$ G, $D = 2$, $R' = 2\times10^{15}$cm, $u'_{\rm phot} = 5\times10^{10}$eV cm^{-3}, For Model 1: $u'_p = 21$ erg cm^{-3}, e/p≈6, $L_{\rm jet} \approx 3\times10^{43}$erg/s, $\gamma'_{p,\max} = 2\times10^{10}$, $\eta \approx 1$, and for Model 2: $u'_p = 24$ erg cm^{-3}, e/p≈6, $L_{\rm jet} \approx 4\times10^{43}$erg/s, $\gamma'_{p,\max} = 3\times10^{10}$, $\eta \approx 1$. The target photon field for $p\gamma$ interactions is the primary electron synchrotron photon field, approximated by broken power laws shown on the left of each figure. The total cascade spectrum (solid line) is the sum of p synchrotron- (dashed line), $\mu^\pm/\pi^\pm$ synchrotron- (dashed-triple dot), π^0- (dotted line) and $\pi^\pm$-cascade (dashed-dotted line).

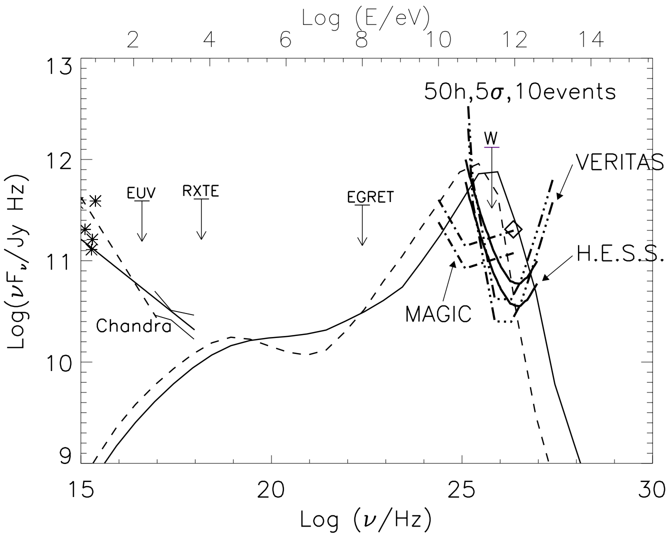


Fig. 2: Model fits 1 (solid line) and 2 (dashed line) in comparison with sensitivities of VERITAS ([16]; dashed-triple-dotted lines), HESS phase I (http://pluto.mpi-hd.mpg.de/∼konopelk/WEB/results.html; thick solid lines), MAGIC (dashed-dotted lines; http://hegra1.mppmu.mpg.de/MAGICWeb) assuming a source photon spectrum $\propto E^{-2.5}$ (thick lower lines) and $\propto E^{-3.5}$ (thick upper lines) at zenith.

at zenith with the phase I (4 telescopes) H.E.S.S. array would give a $6-8\sigma$ detection. Fig. 2 summarizes the minimum fluxes for a 50 h observation on a 5σ level using the H.E.S.S. array, VERITAS and MAGIC in comparison to the predicted fluxes. These predictions are, however, based on a non-simultanously observed SED, i.e. depending on the activity state of M87 they may change significantly.

Acknowledgements: We thank A. Konopelko for providing us with his H.E.S.S. response simulator and fruitful discussions. The research of AR is funded by DESY-HS grant 05CH1PCA/6, and that of RJP and ACD by an ARC Discovery Project grant.

References:

1. Aharonian F. & the HEGRA Collaboration 2003, A&A 403, L1.
2. Berghöfer T.W., S. Bowyer S., Korpela E. 2000, ApJ 535, 615.
3. Biretta J.A., Zhou F., Owen F.N. 1995, ApJ 447, 582.
4. Biretta J.A., Sparks W.B., Macchetto F. 1999, ApJ 520, 621.
5. Götting N. & HEGRA Coll. 2001, Proc. 27th ICRC, Hamburg, vol. 7, 2669
6. Harris D.E., Biretta J.A., Junor W., et al. 2003, astro-ph/0302270.
7. Junor W., Biretta J.A., Livio M. 1999, Nature 401, 891.
8. Lebohec S. & VERITAS Coll. 2001, Proc. 27th ICRC, Hamburg, vol. 7, 2643
9. Mücke A., Protheroe R.J. 2001, Astropart. Phys. 15, 121.
10. Mücke A., Protheroe R.J., Engel R.R., et al. 2003, Astropart. Phys. 18, 593.
11. Perlman E.S., Sparks W.B., Radomski J., et al. 2001, ApJ 561, L51.
12. Protheroe R.J., Donea A.-C., Reimer A. 2003, Astropart. Phys., in press.
13. Reimer O., Pohl M., Sreekumar P., et al. 2003, ApJ 588, 155.
14. Reynolds C.S., Heinz S., Fabian A.C., et al. 1999, ApJ 521, 99.
15. Sparks W.B., Biretta J. A., Macchetto F. 1996, ApJ 473, 254.
16. Weekes T.C. & the VERITAS collaboration 2002, Astropart. Phys. 17, 221.