VERITAS Observation of M 87

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The giant radio galaxy M 87 is located at a distance of ~ 16 Mpc and harbors a supermassive black hole in its center. The structure of its relativistic plasma jet is resolved at radio, optical and X-ray wavelengths. M 87 belongs to the class of active galactic nuclei (AGN) and is one of the few extragalactic TeV γ-ray source not belonging to the class of blazars. M 87 is also detected by Fermi in the GeV energy range. This makes it a unique laboratory for the study of the jet substructures and the morphology of the non-thermal emission processes. In spring 2010 a major flare was observed at TeV energies, and was sampled by VERITAS and Fermi with unprecedented accuracy. The results of the VERITAS observations will be discussed.

1. Introduction

The search for γ-rays from radio galaxies is important for the understanding of the dynamics and structure of jets in active galactic nuclei (AGN). Even though radio galaxies are AGN with jets, their jet is not oriented toward the observer and therefore the radiation produced by the jet is not Doppler-boosted towards higher energies and luminosities, making them more challenging to detect in the very high energy (VHE: $E > 100$ GeV) regime. The discovery of VHE γ-rays from the radio galaxy M 87 by the HEGRA collaboration [1], detected later by VERITAS [2], and from NGC 5128 (Centaurus A) by the HESS collaboration [3] has shown that non-blazar AGN can produce very energetic photons from non-thermal processes.

Radio galaxies are classified into two main families based on the morphology of their radio emission [4], whether it is core dominated (FR I) or lobe dominated (FR II), with differences in the radio energetics and in the discrete spectral properties [5]. The large number of features that FR I radio galaxies share with BL Lac type blazars suggests a possible unification between the two sub-classes of AGN, in which FR I radio galaxies are BL Lac objects observed at larger jet viewing angles [6].

Evidence for synchrotron emission in radio to X-ray energies from both the extended structures and the core is well explained by relativistic particles moving in a beamed relativistic jet [7]. A commonly considered mechanism for HE-VHE (HE: high energy, 100 MeV < $E < 100$ GeV) radiation is the synchrotron-self-Compton (SSC) process [8], where the optical and UV synchrotron photons are up-scattered by the same relativistic electrons in the jet. Predictions concerning the inverse Compton (IC) component have long been established for the γ-ray emission [2] and frequency-dependent variability [10]. Besides leptonic scenarios, several models also consider a hadronic origin for non-thermal emission in jets. Accelerated protons can initiate electromagnetic cascades or photomeson processes [11], or directly emit synchrotron radiation and produce γ-rays through collisions with ambient gas [14, 15].

Modelling the blazar jet emission with a homogeneous SSC mechanism may imply particularly high Lorentz factors, $\Gamma \gtrsim 50$, with consequent high Doppler factors and small beaming angles $\theta \simeq 1^\circ$ [10]. Such a small beaming angle is in conflict with the unification scheme according to which FR I radio galaxies and BL Lac objects are the same kind of object observed at different viewing angles. Moreover, these high values for the Doppler factor are in disagreement with the small apparent velocities observed in the sub-parsec region of the TeV BL Lac objects Mrk 421 and Mrk 501 [12]. These considerations suggest a more complicated geometry, for example a decelerating flow in the jet with a consequent gradient in the Lorentz factor of the accelerated particles and a smaller average $\Gamma$ [18]. As a result of this gradient, the fast upstream particles interact with the downstream seed photons with an amplified energy density, because of the Doppler boost due to the relative Lorentz factor $\Gamma_{\text{rel}}$. The IC process then requires less extreme values for the Lorentz factor and allows larger values for the beaming angle. In a similar way, a jet spine-sheath structure consisting of a faster internal spine surrounded by a slower layer has been also suggested for the broadband non-thermal emission of VHE BL Lac objects [11]. An inhomogeneous jet with a slow component may explain the HE-VHE emission observed in radio galaxies at larger angles ($\theta_{\text{layer}} = 1/\Gamma_{\text{layer}} \sim 20^\circ$). Observation of the VHE component from radio galaxies is therefore significant for the AGN jet modeling. In this work an overview of the observations of radio galaxies by VERITAS is presented.

2. The VERITAS Instrument

The VERITAS detector is an array of four 12-m diameter imaging atmospheric Cherenkov telescopes located in southern Arizona [20]. Designed to de-
tect emission from astrophysical objects in the energy range from 100 GeV to greater than 30 TeV. VERITAS has an energy resolution of $\sim 15\%$ and an angular resolution (68% containment) of $\sim 0.1^\circ$ per event at 1 TeV. A source with a flux of 1% of the Crab Nebula flux is detected in $\sim 25$ hours of observations, while a 5% Crab Nebula flux source is detected in less than 2 hours. The field of view of the VERITAS telescopes is $3.5^\circ$. For more details on the VERITAS instrument and the imaging atmospheric-Cherenkov technique, see [21].

3. Observations

Most of the VERITAS observations of radio galaxies are on the radio galaxy M 87. This AGN is located in the center of the Virgo cluster at a distance of $\sim 16$ Mpc and is currently the brightest detected VHE radio galaxy. M 87 was originally detected with marginal significance by HEGRA at TeV energies [1], and later also by HESS [22], VERITAS [2] and MAGIC [23]. This giant radio galaxy has always been of particular interest because its jet lies at $\sim 20^\circ$ respect to the line of sight and its core and the structure of the jet are spatially resolved in X-ray, optical and radio observations, thus it is an ideal candidate for correlated MWL studies [24].

In 2008 VERITAS coordinated an observational campaign with two other major VHE observatories (MAGIC, HESS), overlapping with VLBA radio observations [25]. Three Chandra X-ray pointed observations have also been performed during the first half of 2008. Multiple flares at VHE have been detected. In X-rays, the inner-most knot in the jet (HST-1) was found in low state, while the core region was in high state since 2000. Progressive brightening of the core region in radio was also seen along the VHE flare development. This is an indication that the $\gamma$-ray emission originates from a region close to the core rather than from more distant regions.

In April 2010, during the seasonal monitoring of M 87, VERITAS detected another flare with peak flux of $\sim 20\%$ of the Crab Nebula flux. During the six-month observation period, M 87 was detected at a level of 25.6$\sigma$ above the background, with an average flux above 350 GeV equivalent to 5% of the Crab Nebula flux. Dedicated analysis in 20-minute bins has been performed on the April 2010 flaring episode. A spectral analysis has been done on three different phases of the flaring episode: the rising phase, the peak and the falling phase. A power-law fit has been applied to each phase, showing a hint of spectral variability: $\Gamma_{\text{rise}} = 2.60 \pm 0.31$, $\Gamma_{\text{peak}} = 2.19 \pm 0.07$, $\Gamma_{\text{fall}} = 2.62 \pm 0.18$. Figure 1 shows the 2010 seasonal light curve and the spectral analysis at different times for the flaring episode that occurred in April 2010.

4. Conclusions

The radio galaxy M 87 is a unique laboratory for studying the acceleration and emission processes around the supermassive black hole of AGNs. Its relatively high brightness in VHE $\gamma$-rays enables to perform cross-correlated MWL observational campaigns and to study variability and spectral evolution features. VERITAS VHE observations have been crucial during past MWL observational campaigns in identifying a close-region to the core as responsible for the $\gamma$-ray emission. During the 2009-2010 observational season, VERITAS detected the strongest flare ever observed in $\gamma$-rays on M 87. This observation enabled for the first time the study of flux and spectral temporal properties on a radio galaxy. Further details on the long-term MWL observational campaign on M 87 are in the process of publication.

Figure 1: (upper plot) VERITAS light curve of the 2010 seasonal monitoring campaign. (lower plot) Spectral analysis for three phases of the April 2010 flaring event: rising phase (circles), peak (squares) and decreasing phase (triangles).

Details on the analysis and results of the 2010 observational campaign on M 87 are presented in a publication currently in the process of peer-review. Results of the extensive multi-year MWL observational campaign on M 87 will be presented soon too.
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References

[1] Aharonian, F., et al. 2003, A&A, 403, L1
[2] Acciari, V. A., et al. 2008, ApJ, 679, 397
[3] Aharonian F. 2009, ApJ, 695, L40
[4] Fanaroff, B. F., Riley, J. M. 1974, MNRAS, 167, 31
[5] Zirbel, E. L., Baum S. A. 1995, ApJ, 448, 521
[6] Urry, C. M., Padovani, P. 1995, PASP, 54, 215
[7] Ghisellini, G., et al. 1993, ApJ, 407, 65
[8] Jones, T. W., O’Dell, S. L., Stein, W. A. 1974, ApJ, 188, 353
[9] Bloom, S. D., Marscher, A. P. 1996 ApJ, 461, 657
[10] Ghisellini, G., George, I. M., Done, C. 1989, MNRAS, 241, 43
[11] Mannheim, K. 1993, A&A, 269, 67
[12] Aharonian, F. 2002, MNRAS, 332, 215
[13] Reimer, A., et al. 2004, A&A, 419, 89
[14] Beall J.H., Bednarek W. 1999, ApJ, 510, 188
[15] Pohl M., Schlickeiser R. (2000), A&A, 354, 395
[16] Krawczynski, H., Coppi, P. S., & Aharonian., F. 2002, MNRAS, 336, 721
[17] Marscher, A. P. 1999, Astropart. Phys., 11, 19
[18] Georganopoulos, M., & Kazanas, D. 2003 ApJ, 589, L5
[19] Ghisellini, G., et al. 2005, A&A, 432, 401
[20] Weekes, T. C., et al., Astroparticle Physics, 2002, 17, 221-243
[21] Perkins, J. S., eConf Proceedings C091122, astro-ph:0912.3841
[22] Aharonian, F., et al., Science, 2006, 314, 1424-1427
[23] Albert, J., et al., ApJ, 2008, 685, L23-L26
[24] Wilson, A. S., & Yang, Y., ApJ, 2002, 568, 133-140
[25] Acciari, V. A., et al., Science, 2009, 325, 444