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Short term and multi-band variability of the active nucleus of IC 310

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Abstract. The MAGIC Telescopes detected the active galaxy IC 310 at very high energies (VHE, > 100 GeV) during observations of the Perseus cluster in 2009 and 2010. This source had originally been classified as a head-tail radio galaxy. By contrast, recent high-resolution radio images obtained with the VLBA reveal the blazar-like structure of IC 310 on parsec scales. This object is also investigated in terms of its variability at X-ray and gamma-ray energies. Studies of the multi-band flux variability at different time periods are presented. The spectral evolution seems to be different in the VHE gamma-ray and X-ray bands.

Keywords: Active Galactic Nuclei: individual (IC 310); gamma-rays: observations; gamma-ray telescopes; Radio galaxies

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IC 310: THE PARSEC SCALE JET OF A γ -RAY LOUD OBJECT

The nearby galaxy IC 310 (S0, $z = 0.01898$), which is located in the Perseus cluster of galaxies, exhibits an active nucleus, which was recently detected at high energies above 30 GeV with *Fermi*-LAT [1] as well as at very high energies above 260 GeV with the MAGIC Telescopes [2]. X-ray observations with *XMM-Newton* showed non-thermal emission originating from a point-like source [3]. This particular object is known in literature as a head-tail radio galaxy [4, 5].

Head-tail radio galaxies, usually found in clusters of galaxies, are characterized by the fact that their jet direction is determined by the galaxy motion through the intra-cluster medium (ICM). The “head” marks the bow shock from the interaction of the jet with the ICM, and the “tail” corresponds to the redirected extended jet. Analysis of archival VLBA data of IC 310 (taken in May 2011) presented in [6] revealed the parsec-scale

radio structure at a wavelength of 3.6 cm. We found a one-sided core-jet structure, which we interpret as blazar-like, oriented along the same position angle as the kiloparsec scale radio structure. Doppler favoritism is consistent with a small angle of $< 38^\circ$ between the jet axis and the line-of-sight. In order to study the parsec-scale jet structure, we included IC 310 in the ongoing MOJAVE measurements (blazar monitoring at 15 GHz with VLBA). Flux density measurements with the Effelsberg 100 m Telescope in July 2011 and January 2012 shows a steep spectrum below 10 GHz. This is presumably dominated by kpc-scale radio emission. Above 10 GHz the spectrum starts to flatten at a flux density level of ~ 115 mJy. Flux variability is also detected at these frequencies.

OBSERVATIONS OF THE PERSEUS CLUSTER WITH THE MAGIC TELESCOPES

The Perseus cluster was observed with the MAGIC Telescopes from October 2009 to February 2010 in the so-called wobble mode, i.e. pointing alternatively to two positions 0.4° away (along the RA axis) from the cluster center (NGC 1275). Since IC 310 is located 0.6° from the cluster center, it appeared as an off-axis source during these observations. The position of the source is 0.25° and 1° away from the camera center in the two wobble positions, respectively. In [2] only data of the closest wobble position were used to determine the light curve and spectrum. Here, we applied an improved analysis using the data from both wobble positions with different effective area, thus providing more accurate results. The daily-binned light curve above 300 GeV obtained from 33 individual nights clearly shows variability. A constant fit to the flux ($\Phi_{CstFit} = (2.52 \pm 0.37) \times 10^{-12} \text{ cm}^{-2}\text{s}^{-1}$) has a χ^2 -test value of 102.03 for 32 degrees of freedom, corresponding to a probability of 2.21×10^{-9} . Three nights show a flux $> 4\sigma$ (standard deviations) above the constant flux fit: November 16, 2009 (MJD=55150.9), January 8, 2010 (MJD=55203.9) and February 9, 2010 (MJD=55235.8). The mean flux of these three nights is $(1.60 \pm 0.17) \times 10^{-11} \text{ cm}^{-2}\text{s}^{-1}$ more than six times higher than the constant fit flux. Further observations carried out between August 2010 and February 2011 resulted in a non-detection. The derived integral upper limit of $F^{\text{U.L.}}(> 300 \text{ GeV}) = 1.2 \times 10^{-12} \text{ cm}^{-2}\text{s}^{-1}$ is three times lower than the mean flux measured between October 2009 to February 2010 [7].

SPECTRAL ENERGY DISTRIBUTION FROM X-RAY TO VHE

For the spectral analysis, we split the MAGIC data set into two samples corresponding to different γ -ray emission states. We define a “high state” containing the three nights with a higher flux level (MJD 55150.9, 55203.9 and 55235.8, $t_{\text{eff}} = 4.5$ h) and a “low state” including all the other nights between October 2009 and February 2010 ($t_{\text{eff}} = 38.8$ h). The reconstructed spectrum between 123 GeV to 8.1 TeV can be well described by a simple power law for both emission states:

$$\frac{dN}{dE} = f_0 \times \left(\frac{E}{1 \text{ TeV}} \right)^\Gamma \left[\frac{10^{-12}}{\text{cm}^2 \text{ s TeV}} \right]. \quad (1)$$

FIGURE 1. *Left panel:* Measured spectral energy distribution of IC 310 in the X-ray band in different time periods: *Chandra* ObsID: 5596 (2005), *XMM-Newton* (2003), *Chandra* ObsID: 5597 (2004) and *Swift-XRT* (2007). *Left bottom panel:* χ^2 result of fits. *Right panel:* Measured (filled squares) and deabsorbed (open squares) spectral energy distribution for IC 310 obtained by MAGIC in high and low state together with their fit result. For comparison, we show the result reported in [2] (triangles).

We corrected the IC 310 spectra for the absorption due to the Extragalactic Background Light (EBL) according to the model by [8]. Due to the low redshift of IC 310 ($z = 0.0189$), the effect of the absorption is relatively modest, reducing the flux above 1 TeV by 15-20%, while steepening the spectral index by 0.1. For the intrinsic spectra we obtained $f_0 = 5.14 \pm 0.28_{\text{stat}} \pm 0.90_{\text{syst}}$ and $\Gamma = -1.85 \pm 0.11_{\text{stat}} \pm 0.20_{\text{syst}}$ for the “high state” and $f_0 = 0.741 \pm 0.045_{\text{stat}} \pm 0.14_{\text{syst}}$ and $\Gamma = -1.81 \pm 0.13_{\text{stat}} \pm 0.20_{\text{syst}}$ for the “low state”. The results are shown in the right panel of Fig. 1. No significant change in the spectral index is observed between the high and low states.

The three year data taken by *Fermi*-LAT resulted in the detection of IC 310 above 10 GeV with a test statistic of 27.0 (4.5σ). The integrated flux N between 10 and 500 GeV is measured to be $(6.9 \pm 3.3) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$. The spectrum in this energy band can be fitted by a pure power law formula with a spectral index of $\Gamma = (-1.3 \pm 0.5)$. In addition we analyzed archival X-ray data from *XMM-Newton* taken in 2003, two *Chandra* observation in 2004 and 2005 and one *Swift-XRT* observation from 2007 (see Fig. 1, left). We found variability at X-ray energies in flux as well as in the spectral index. The spectral energy distribution (SED, shown in Fig. 2) from X-ray to VHE shows the results from two *Chandra* observations, the *Fermi*-LAT three-year data, the 2nd *Fermi* catalog and the MAGIC high and low state distribution.

CONCLUSIONS

We presented selected results from a multi-wavelength study of the TeV emitting object IC 310. VLBA observations of IC 310 revealed a core-dominated radio emission of the AGN. We interpret the radio emission as originating from the central blazar-like engine rather than being produced by interactions with the ICM. Blazar-like behavior is seen at X-ray energies by flux and spectral index variability presented here as well as in daily VHE flux variability.

FIGURE 2. *Left panel:* Daily light curve above 300 GeV measured by the MAGIC Telescopes between October 2009 and February 2010. The dashed line shows the constant flux fit. *Right panel:* Spectral energy distribution. Shown are analysis results of archival data taken by *Chandra* 2005 (upper butterfly) and *Chandra* 2004 (lower butterfly). The open triangle and the upper limits are obtained from *Fermi*-LAT second source catalog. Also shown are the results (full triangles) for the high energy analysis above 10 GeV by *Fermi*-LAT. The MAGIC results (EBL corrected, model by [8] used) for the high and low state are marked as full squares and full circles, respectively. The intrinsic luminosity is given at the right axis.

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