

## MAGIC and multi-wavelength observations of the radio galaxy NGC 1275

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**Abstract:** The massive radio galaxy NGC 1275 at the center of the Perseus cluster is regularly observed with the MAGIC telescopes since 2009. The observation campaign (in stereoscopic mode) between August 2010 and February 2011 leads to the first detection of the source in very high energy (VHE,  $>100$  GeV)  $\gamma$  rays. NGC 1275 is one of the few non-Blazar AGNs detected in this domain which is highly dominated by BL Lac objects. The proximity and the relatively large angle between the jet axis and the line of sight allow to resolve inner-jet structures with radio interferometry and to test non-thermal emission model for larger viewing angles. NGC 1275 is then a good laboratory to locate the  $\gamma$ -ray emission region and understand acceleration process at work in AGNs. Here we present the long term monitoring of NGC 1275 with MAGIC as well as with *Fermi*-LAT (in GeV band), KVA (optical) and VLBA (15 GHz). The multiwavelength lightcurves show a correlation between  $\gamma$ -ray, optical and a radio component of the inner-jet. We reconstructed the broad band spectral energy distributions (SED) of the source during two separated MAGIC campaigns which both lead to the detection of NGC 1275 in VHE. We applied a one-zone Synchrotron Self Compton model with a small Doppler factor ( $\sim 2$ ) which can fit the SEDs and reproduces the optical/gamma correlation. Finally, we will discuss the validity of this simple model and the implication of our results for the AGN physics.

**Keywords:** radio galaxy,  $\gamma$  ray astronomy, AGN, NGC 1275, MAGIC, *Fermi*-LAT, KVA

### 1 Introduction

NGC 1275, the dominant central galaxy of the Perseus cluster, hosts a well know active galactic nuclei (AGN) with a radio emission dominated by a very bright compact source (3C 84). The core-dominated morphology with asymmetrical jets at kpc scale [1] and pc scale [2] looks like a Fanaroff-Riley type I (FR I) radio galaxy. The faint counter jet measured with Very Long Baseline Interferometry (VLBI) suggests a viewing angle between the jet axis and the line of sight of  $\theta_v=30^\circ-55^\circ$  in the core region [2, 3, 4]. The flux and morphology of the core radio emission are variable. Recent observations showed that an outburst is on-going since 2005 [5]. At sub-pc scale, a new component appeared near the nucleus in 2007 and keeps growing in flux as it goes away from the nucleus.

NGC 1275 is one of the few non-blazar (jet not pointing toward the observer) AGNs detected in  $\gamma$ -ray band up to very high energy (VHE,  $>100$  GeV). It was discovered first in the 100 MeV–100 GeV band with *Fermi*-LAT after the first four months of all-sky survey in 2008 [6], and at VHE with MAGIC during the stereoscopic observation carried out between August 2010 and February 2011 [7]. Only two other AGNs with a visible radio counter jet are known as VHE  $\gamma$ -ray emitters: M 87 and Cen A. They

are all FR I radio galaxies which are seen in the AGN unified schemes as misaligned version of BL Lac objects. The  $\gamma$ -ray emission of BL Lacs, which are the most common extragalactic VHE sources, is generally understood as Synchrotron-Self-Compton (SSC) emission from high energy electrons in the jet. These three radio galaxies represent then a unique opportunity to study non-thermal emission model of AGN (such as SSC model) for larger viewing angles and test the AGN unified schemes.

The NGC 1275 flux measured with *Fermi*-LAT is seven times higher than the *CGRO*-EGRET upper limit [8] over the period 1991-2000. This imply a strong variability of the source which could be connected to the recent renewing activity in radio. Subsequent *Fermi*-LAT observations confirmed the variability, revealing variation time-scale as quick as a week [9, 10]. The angular resolution of  $\gamma$ -ray observatory is too low to locate the  $\gamma$ -ray emission region within the galaxy, but temporal correlation between the  $\gamma$ -ray flux and radio sub-structure light curves (LC) could pinpoint the  $\gamma$ -ray emitting region location.

In this work, we study contemporaneous multiwavelength observations of the NGC 1275 AGN emission. We analyzed the MAGIC data taken in stereoscopic mode from October 2009 to February 2011 as well as *Fermi*-LAT data, X-ray Chandra data, optical data of KVA and NOT,

and radio data of the MOJAVE program at VLBA from the same observation period.

## 2 Observation and data analysis

### 2.1 TeV $\gamma$ ray: MAGIC

MAGIC is a system of two 17 m-diameter imaging atmospheric Cherenkov telescopes located at the Roque de los Muchachos observatory in the Canary Island of La Palma. Since fall 2009 the MAGIC telescopes are carrying out stereoscopic observations of NGC 1275. Here we report the result of the first two observational campaigns performed between October 2009 and February 2010 ( $\sim 45.3$  h), and August 2010 and February 2011 ( $\sim 53.6$  h). Both campaigns were carried out in stereoscopic mode, but under different global trigger configurations. The former campaign (Camp. 1) happened partially during the commissioning phase of the second telescope (MAGIC-II). It was performed in the so-called soft-stereo trigger mode, with the first telescope (MAGIC-I) trigger working in single mode and the second telescope (MAGIC-II) recording only events triggered by both telescopes. In the latter campaign (Camp. 2) observations were instead taken in the standard full-stereo trigger mode. Both surveys were performed at low zenith angles ( $< 35^\circ$ ) in the false-source tracking (wobble) mode [11], pointing at  $0.4^\circ$  from NGC 1275. These campaigns resulted in the discovery of VHE  $\gamma$ -ray emission from NGC 1275 [7] and from another radio galaxy of the Perseus cluster named IC 310 [12, 13].

The data analysis was performed using the standard software package MARS [14] with an analysis energy threshold of 100 GeV. The background is estimated from mirror regions corresponding to the source position in the camera during the other wobble pointing positions. While the standard Monte Carlo simulations were used for the analysis of Camp. 2 data [7], the data analysis of the first campaign required new dedicated simulations in order to fully take into account the non-standard trigger condition.

After the application of standard quality checks, 39.0 h (Camp. 1) and 45.7 h (Camp. 2) of data were selected to derive the results presented here. A  $\gamma$ -ray signal above 100 GeV is detected independently for both campaigns at  $6.1\sigma$  and  $6.6\sigma$  for Camp. 1 and Camp. 2 respectively.

The monthly LC of NGC 1275 above 100 GeV is shown in top panel of Fig. 1. While Camp. 2 LC is well consistent with a constant flux ( $\chi^2/n_{dof} = 7.4/4$ , probability = 0.29), a hint of variability can be derived for the first campaign. Indeed, a constant flux fit yields a  $\chi^2/n_{dof} = 22.9/4$  (probability =  $1.3 \times 10^{-4}$ ), corresponding to a significance for a monthly variable emission of  $3.65\sigma$ .

The differential energy spectra between 65 and 650 GeV corresponding to the two observational campaigns are shown Fig. 2. They can be described by a simple power-law:

$$\frac{dF}{dE} = f_0 \left( \frac{E}{100 \text{ GeV}} \right)^\Gamma, \quad (1)$$

with a photon index of  $\Gamma = -4.0 \pm 0.5_{stat} \pm 0.3_{syst}$  and a normalization constant at 100 GeV  $f_0 = (5.0 \pm 0.9_{stat} \pm 1.1_{syst}) \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$  for Camp. 1, and  $\Gamma = -4.1 \pm 0.7_{stat} \pm 0.3_{syst}$  and  $f_0 = (3.1 \pm 1.0_{stat} \pm 0.7_{syst}) \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$  for Camp. 2.

### 2.2 GeV $\gamma$ ray: *Fermi*-LAT

The Large Area Telescope (LAT) is a pair conversion telescope, on board *Fermi* Gamma-ray Space Telescope, designed to cover the energy band from 20 MeV to 300 GeV. The observation used here comprises all scientific data obtained between August 4, 2008 and February 21, 2011. We use the ‘‘Source’’ class events [15] with a zenith angle cut of  $100^\circ$ . In our analysis, the lower energy bound is set at 100 MeV and Science Tools version v9r27p1 and Instrumental Response Functions P7SOURCE\_V6 were used. The early portion of the data here coincides with the early LAT observations of NGC 1275 presented in literatures [6, 9, 10].

The second panel of Fig. 1 shows the  $\gamma$ -ray flux ( $E > 100$  MeV) variations of NGC 1275 from September 25, 2009 to February 18, 2011 binned at one week interval. For the analysis, we set the region of interest (ROI) at  $10^\circ$  and all the nearby sources in 2FGL catalog [16] were included in the model of the ROI. In each week time bin, NGC 1275 was significantly detected above the test statistic  $TS > 10$  with a ratio of flux error to flux below 0.5. One can note a general trend of increasing flux towards end of observations, and several episodes of large flares as fast as a week-time scale.

Fig. 2 shows the *Fermi*-LAT SED derived for the two MAGIC-observation campaigns (MJD 55123-55241 for Camp. 1 and MJD 55417-55595 for Camp. 2). Substantial spectral evolution can be seen both in the flux and peak frequencies of the  $\gamma$ -ray emissions.

### 2.3 X-ray: Chandra

In the Chandra public archive we found seven observations performed in the MAGIC observing period (namely Obsid 11713, 11714, 11715, 12025, 12033, 12036, 12037). In NGC 1275 the nuclear X-ray flux is high enough that pileup is potentially a severe problem when dealing with Chandra data (pileup fraction of about 50%). The nucleus was not the primary target of these observations and no observing strategy for minimizing nuclear pileup was actuated (e.g. selecting a sub-array to reduce the nominal frame integration time, etc.). The analysis of these data is very challenging and our result is not yet ready to be released in these early proceedings. Instead we refer to earlier observation focusing on the nucleus [17].

### 2.4 Optical: KVA and NOT

NGC 1275 has been monitored in optical R-band by the Tuorla blazar monitoring program<sup>1</sup> since the autumn of 2009. The observations are performed using KVA 35 cm telescope located at La Palma. The data were reduced using the standard data analysis pipeline and the magnitudes were measured with aperture of  $5''$  between 13.05 and 13.3.

For the calculation of the intrinsic emission from the core, the measured magnitudes are host galaxy subtracted and de-reddened. Additionally the core flux is contaminated by emission lines which must be also subtracted. In order to estimate the contributions of the host galaxy and the emission lines, NGC 1275 was observed with the Nordic Optical Telescope (NOT) on November 15, 2011 using ALFOSC instrument. Five 60 s R-band exposures and two spectra using grism 4 and slit  $1''$  were obtained. Using the methodology of [18] the host galaxy contribution within

1. <http://users.utu.fi/kani/1m>

the used aperture is estimated at  $11.08 \pm 0.55$  mJy. The line contamination is estimated at 0.9 mJy from the spectrum by integrating the observed line flux within the NOT R-band filter. The host and line contaminations are subtracted to derive the core continuum non-thermal flux which is then corrected for galactic extinction using the extinction value from [19]. The measured fluxes are shown together with the multiwavelength LC in Fig. 1. The mean flux over the MAGIC campaigns are  $(4.1 \pm 0.6)$  mJy for Camp. 1 and  $(6.5 \pm 0.6)$  mJy for Camp. 2.

## 2.5 Radio: VLBA (MOJAVE)

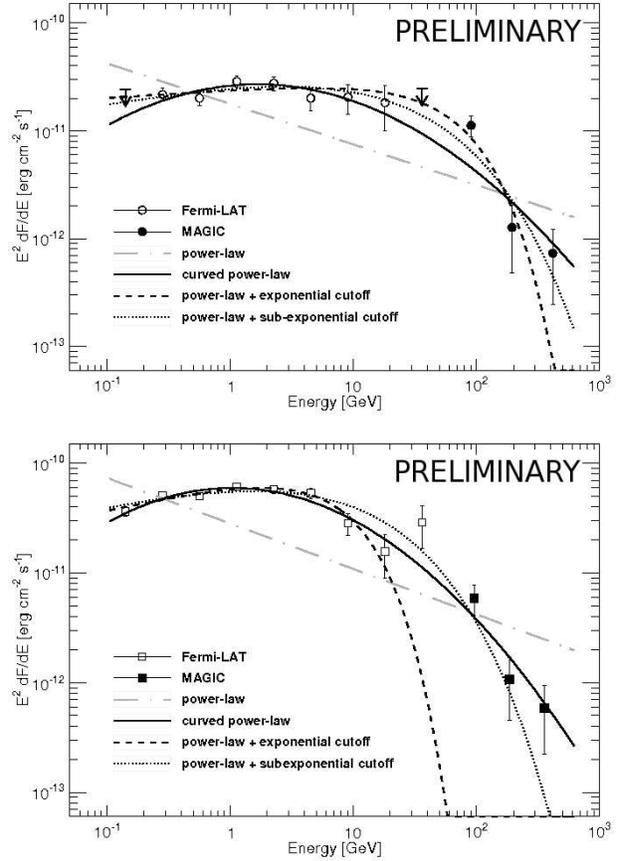
The Very Long Baseline Array (VLBA) is a radio interferometer using ten 25 m-diameter antennas located over the USA between Hawaii and the Virgin Islands, which can achieve angular resolutions down to milli-arcseconds. The MOJAVE program is constantly monitoring a set of bright AGNs in the northern hemisphere, including NGC 1275, at 15 GHz [20]. The calibrated data of the MOJAVE program have been reduced using the NRAO AIPS. In this work, we analyzed five epochs covering the time slot from October 2009 to February 2011. The position and flux density for each component was derived by way of the task JMFIT, which fits a gaussian function to a selected area in the image plane.

The morphology of the central region ( $\sim 1$  pc) at 15 GHz, shows three bright components C1, C2 and C3. Generally C1 is understood as being the nucleus core emission. C3 corresponds to the rapidly growing component that recently appeared [5]. The flux densities for each component are shown in last panel of Fig 1. While the flux density of C1 and C2 do not show considerable variability, the intensity of C3 increases throughout all the observational campaign.

## 3 Results

Fig 1 shows the  $\gamma$ -ray LCs of NGC 1275 from October 2009 to February 2011 together with the optical LC of the core continuum and the radio LCs of the three innermost radio components. The clear correlation between the  $\gamma$ -ray flux above 100 MeV and the optical core emission suggests a single emission region. The newborn radio component C3 shows also a similar long-term trend of slowly increasing flux, which makes it a suitable candidate hosting the  $\gamma$ -ray emitting region.

Fig 2 shows NGC 1275  $\gamma$ -ray SED from 100 MeV to 650 GeV measured with *Fermi*-LAT and MAGIC from 2009 to 2011. The SED is clearly bent with a peak at the GeV energy ( $\Gamma=2$ ) and a very steep spectrum above 100 GeV ( $\Gamma=4$ ). The spectral shape is variable in the GeV range but quite stable at VHE. The combined MAGIC-*Fermi* data points can be well fit by a curved power-law (log parabola:  $dF/dE = f_0 (\frac{E}{\text{GeV}})^{-2-\beta \log(E/E_p)}$ ) or a power-law with sub-exponential cutoff ( $\frac{dF}{dE} = f_0 (\frac{E}{\text{GeV}})^\Gamma e^{-\sqrt{E/E_c}}$ ). The SED-peak energy of the curved-power-law fit is  $E_p=2.8 \pm 1.5$  GeV and  $E_p=1.1 \pm 0.2$  GeV for Camp. 1 and Camp. 2, respectively. The sub-exponential cutoff energy is  $E_c=13.1 \pm 4.2$  GeV (Camp. 1) and  $E_c=5.0 \pm 1.6$  GeV (Camp. 2).

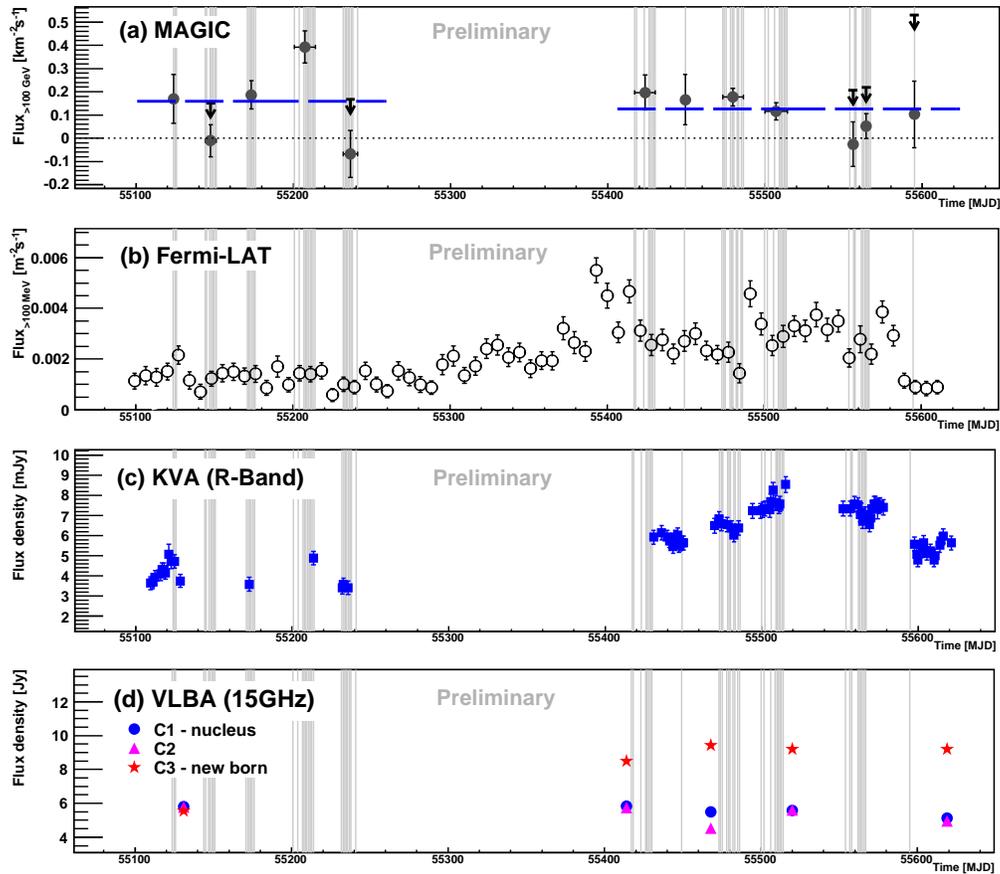


**Fig. 2:** NGC 1275  $\gamma$ -ray SED from 100 MeV to 650 GeV measured with *Fermi*-LAT and MAGIC, together with fit functions of the data. Upper and lower panels correspond to the periods Oct. 2009–Feb. 2010 and Aug. 2010–Feb. 2011 respectively.

## 4 Broad-band emission model

The flux level measured in optical and GeV  $\gamma$ -ray ( $\nu F_\nu > 10^{-11}$  erg cm $^{-2}$  s $^{-1}$ ) is much above the archival X-ray Chandra measurement of 2003 [17]. This hints for a classical double-peaked SED, similarly to the other TeV emitting AGNs (mainly blazars), which then probably arises in the relativistic jet. The available data allow us an excellent description of the high-energy bump of the SED. In particular, it is possible to constrain the peak position with a good accuracy.

The evidence for a common trend between the optical and the  $\gamma$ -ray flux suggests that the non-thermal continuum from NGC 1275 nucleus is dominated by the emission from a single region. We then assume that the emission is coming from a unique uniform spherical region, compact enough to explain the week-scale variability. We can reproduce the SED using a synchrotron self-Compton model (for details see [21]) assuming an electron energy distribution of the form  $N(\gamma) = K\gamma^{-n} \exp(-\gamma/\gamma_c)$ , with a Lorentz factor  $\gamma > \gamma_{\min}$ . The other physical parameters of the model are the magnetic field intensity  $B$ , the source radius  $R$  and the Doppler factor  $\delta$ . The latter parameter is given by  $\delta = 1/[\Gamma(1 - \beta \cos \theta_v)]$ , where  $\Gamma$  is the bulk Lorentz factor of the plasma. The radio counter-jet evidences imply a jet viewing angle  $\theta_v \geq 30^\circ$  which constrains the Doppler



**Fig. 1:** Multi-frequency lightcurves of NGC 1275 from October 2009 to February 2011. The vertical grey lines show the MAGIC observation dates. (a) The MAGIC LC above an energy threshold of 100 GeV uses monthly bins. The thick dashed lines represent the constant fit for both observation campaigns. For data showing an excess  $< 1\sigma$ , 95% confidence level upper limits are calculated assuming a spectral index of  $\Gamma = -4.0$  (black arrows). (b) The *Fermi*-LAT LC above 100 MeV has weekly binning. (c) The KVA R-band LC shows the core continuum flux corrected for galactic extinction. The systematic error induced by the host-galaxy and emission-line subtraction is not included on the shown error bars. (d) The VLBA LCs show the 15 GHz emission from the three innermost components of the radio jet.

factor to be less than  $\delta = 2$ . Taking into account all these constraints we try to fit the SED with our SSC model. The result of this modeling and its implication to the AGN physics will be presented and discussed at the conference.

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