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Gamma Ray Astronomy with ARGO-YBJ

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Abstract. The ARGO-YBJ experiment (YangBaJing, Tibet, P.R. China) is an extensive air shower detector made of a single layer of Resistive Plate Counters (RPCs) covering a surface of about 6700 m^2, consisting of a continuous central carpet 74 × 78 m^2 wide and an external guard ring with coarse coverage. The full coverage approach (93% of active area in the central carpet) and the high altitude location (4300 m a.s.l.) allow ARGO-YBJ to work with an energy threshold as low as a few hundred GeV. ARGO-YBJ can detect showers within a primary energy range partially overlapping that of Čerenkov Telescopes, with the advantages of a larger field of view and a duty cycle close to 100%. These features make ARGO-YBJ suitable for monitoring the γ-ray sky, detecting unexpected events such as flaring episodes in Active Galactic Nuclei and very high energy emission from Gamma Ray Bursts.
In this paper we report some ARGO-YBJ results in γ astronomy, in particular the observations of the Crab Nebula and of the flaring activity of Markarian 421.

Key words. Gamma Ray Astronomy – Crab Nebula – Mkn421

1. Introduction

Observations of cosmic γ-ray sources in the 1- 100 GeV region region have to be made using satellite-born telescopes because of the Earth's atmosphere opacity to γ-rays; above a few hundred GeV the steep decrease of the flux limits the sensitivity of satellite-based experiments and calls for indirect ground-based detection: the incident γ-ray is not directly detected. Instead, the extensive air shower (EAS) of charged particles it produces by interaction with atmosphere nuclei is observed. Two detection techniques are used in ground-based γ astronomy: the EAS arrays sample the electromagnetic component of the shower at a given observation level, while the Imaging Atmospheric Čerenkov Telescopes (IACTs) detect the Čerenkov light produced throughout the shower development by the EAS charged particles. These two techniques have complementary advantages and drawbacks: IACTs are usually preferred to EAS arrays because of their great sensitivity and low energy threshold, but they suffer the limitations of a small field of view (few degrees) and low duty cycle, being data acquisition restricted to clear, moonless nights. Like the traditional EAS arrays, ARGO-YBJ has the advantages of a large field of view, allowing sky monitoring in a wide declination band ($-10^o < \delta < 70^o$ given the ARGO-YBJ latitude), and of an almost continuous duty cycle, only limited by main-

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tenance needs; but ARGO-YBJ is a cut above being able to work in an energy range partially overlapping that of IACTs, thanks to the mountain location and to the full coverage technique.

2. The ARGO-YBJ detector

ARGO-YBJ is an EAS detector dedicated to the study of cosmic rays and γ radiation, optimized to work at TeV energies, with an energy threshold of a few hundred GeV for γ-rays and a sensitivity extending to PeV energies. ARGO-YBJ is a modular detector, the basic unit being the *cluster* (5.7×7.6 m^2), made up of 12 RPCs (1.225×2.850 m^2)(Aielli et al. 2006). Signals from each RPC are piched up by 10 electrodes 55.6×61.8 cm^2 wide, called *pads*, which provide the space-time pattern of the shower front with a time resolution of ~ 1.8 ns. Each pad is segmented into 8 strips which count the number of particles hitting the pad. The full detector is composed by 153 clusters, corresponding to a total active surface of ~ 6700 m^2: a central full coverage carpet made up of 10×13 cluster is enclosed by a sampling guard ring in order to enlarge the active area and improve the capability of tagging the internal events (whose core falls inside the central carpet) and the external ones (with a core location outside the carpet and for which ARGO-YBJ is sampling a peripheral corner).

In the so-called shower mode, ARGO-YBJ records all the events triggering at least N_{trig} pads in the central carpet within a coincidence window of 420 ns. The arrival time and the spatial coordinates of each fired pad are used to reconstruct the shower core position and the arrival direction of the primary particle (Di Sciascio et al. 2007). The current threshold is set to $N_{trig} = 20$, corresponding to a trigger rate of ~ 3.6 kHz.

3. Gamma Ray Astronomy results

The analysis procedure used when studying γ-ray sources is the following: a $20^o \times 20^o$ sky map in celestial coordinates (right ascension and declination) with $0.1^o \times 0.1^o$ bin size, centered on the source location, is filled with the detected events. The estimation of the cosmic ray background, which is crucial in order to calculate the excess of γ-rays coming from the source, is made with the time swapping method (Alexandreas et al. 1992): N fake events per detected event are generated by replacing the original arrival time with a different one randomly drawn from a 3 hours set of data taking. With the time swapping procedure, the right ascension of the event changes, while the declination remains fixed. The statistical uncertainty in the background map generated using these fake events can be kept sufficiently small by using 10 fake events per real event.

The background and the event maps are smoothed: every bin is filled with the content of all bins having an angular distance less than an opening window whose value - estimated in Iuppa et al. (2009)- depends on the pad multiplicity of the events used to fill the maps. The source map is obtained by subtracting the background map from the event map; finally, the excess statistical significance in standard deviations is calculated for each bin.

3.1. The Crab Nebula

The Crab Nebula, a pulsar plus pulsar wind nebula, is the *standard candle* for γ-ray astronomy, being the strongest steady source, visible from both hemispheres. At the ARGO-YBJ location the Crab culminates at a zenith angle $\theta_c = 8.1^o$ and is visible every day for 5.8 hours with $\theta < 40^o$. The Crab has been observed from November 2007 to March 2009 for a total of 424 on-source days.

To evaluate the energy spectrum - assumed to follow a power law $dN/dE = kE^{-\alpha}$ - the events have been grouped in 3 N_{pad} windows: 40-99,100-299,$\geq$300. The number of expected events for different values of k and α has been estimated by simulating a source following the Crab path. The best fit to the experimental rates (128 ± 24, 17.9 ± 6.3 and 9.2 ± 2.3 events/day respectively) is given by the spectrum $dN/dE = (3.7 \pm 0.8) \times 10^{-11} E^{-2.67 \pm 0.25}$ photons cm^{-2} s^{-1} TeV^{-1} (Marsella et al. 2009), in agreement with previous observations by other detectors (see fig. 1). The median energies for the 3 multiplicity windows - obtained by means of

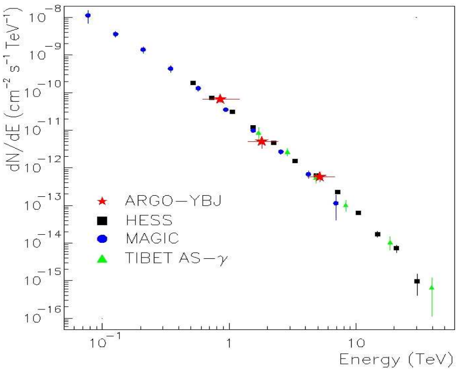

Fig. 1. Energy spectrum of the Crab Nebula estimated by ARGO-YBJ (red stars) compared with results published by other detectors: H.E.S.S. (black squares), MAGIC (blue circles) and TIBET-ASγ (green triangles).

Monte Carlo simulations - are 0.85, 1.8 and 5.2 TeV respectively.

3.2. Flaring activity of Markarian 421

The blazar Mkn421 was the first extragalctic source detected at $E > 500$ GeV and it is the closest Active Galactic Nucleus (AGN) ($z = 0.031$) detected at Very High Energies (VHE, $E > 100$ GeV) up to date. Flaring activity of Mkn421 at different variability time scales has been observed. The simultaneous detection of the flaring activity at different wavelengths can provide unique information about the radiation processes at the source. A set of simultaneous measurements covering 12 decades of energies, from optical to TeV γ-rays, was performed by different detectors during the first half of June 2008, when two strong flaring episodes occurred: the first one on June 3-8, and the second one, larger and harder, on June 9-15. Using the multi frequency observations up to TeV energies, (Donnarumma et al. 2008) derived the spectral energy distribution (SED) for June 6. The double hump structure they found is consistent with the Synchrotron Self Compton (SSC) model: X-rays are attributed to synchrotron radiation from high energy electrons accelerated in the jet, while VHE photons are due to inverse Compton scattering off the synchrotron photons. The authors predicted for the second flare a VHE flux about a factor 2 larger with respect to the first one, reaching a value of about 3.5 Crab units at $E > 400$ GeV. Unfortunately their multiwavelength analysis did not include VHE observations for the second flare, as IACTs were blind after June 8 because of the moonlight. ARGO-YBJ can complete this multifrequency observation: the results reported in the following are described with more details in Vernetto et al. (2009).

At the ARGO-YBJ location, Mkn421 culminates at $\theta_c = 8.1^o$ and is observable every day for 6.38 hours with $\theta < 40^o$. Mkn421 has been observed from 2007 December 13 to 2008 December 31, for a total of 325 on-source days; the observed flux is variable with time, peaking in March-June 2008. The energy spectrum has been determined using the method described for the Crab Nebula, with data from 2008 February 11 to September 5, when the X-ray flux showed the most intense flares; the signal significance in this period is 6.1 σ. The extinction of γ-rays by the Extragalactic Background Light (EBL) has been accounted for by multipying the power law spectrum with the exponential factor $e^{-\tau(E)}$ given by Primack et al. (2005). The best fit to data is given by the spectrum $dN/dE = (7.46 \pm 1.70) \times 10^{-11} E^{-2.51\pm0.29} e^{-\tau(E)}$ photons cm^{-2} s^{-1} TeV^{-1}. The median energies for the 3 multiplicity windows are 0.84, 1.74 and 4.2 TeV respectively.

The observed γ-ray luminosity appears to be corelated with that in X-rays, as expected from the SSC model. A detailed analysis of the VHE emission during the June 2008 flares has been performed. The ARGO-YBJ sensitivity does not allow the measurement of a few Crab units flux in only one day, so it has been integrated over 3 days. The detection significance is 3.2 σ for $N_{pad} \geq 100$ during the period June 11-13, corresponding to the maximum emission of the second flare. The signal significance increases to 4.2 σ by applying some quality cuts to the events. Regarding the first flare, data were integrated over the period June 5-7, obtaining a signal significance of ~ 2 σ, increasing to 3.0 σ using the data selection criteria. The event rates measured as a function of the minimum pad multiplicity for

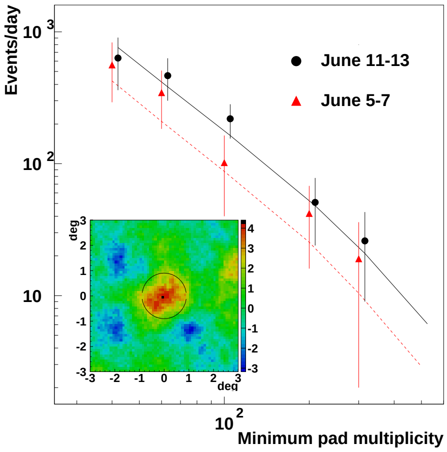

Fig. 2. Event rates observed by ARGO-YBJ as a function of the event minimum pad multiplicity on June 5-7 (red triangles) and June 11-13 (black circles). The red dashed and the solid black lines represent the expected rates according to the Donnarumma et al. model for the same two periods. The inset represents the sky map around Mkn421 on June 11-13, obtained for events with $N_{pad} \geq 100$. The circle in the figure corresponds to the applied smoothing window (0.9^o). The colour scale represents the statistical significance of the signal.

the two flares, shown in fig. 2, are consistent with the SEDs predicted by Donnarumma et al. (see fig. 3). The energy spectrum of the second flare was estimated following the already described method. Assuming a source spectrum given by the theoretical SED, the median energies in the 3 N_{pad} windows are 0.9, 1.4 and 2.4 TeV.

4. Conclusions

The ARGO-YBJ detector has been completely installed and is in stable data taking operations from November 2007 with a duty cycle > 90%.

More than one year of Crab Nebula data has been analysed; the energy spectrum obtained is in agreement with observations by other experiments.

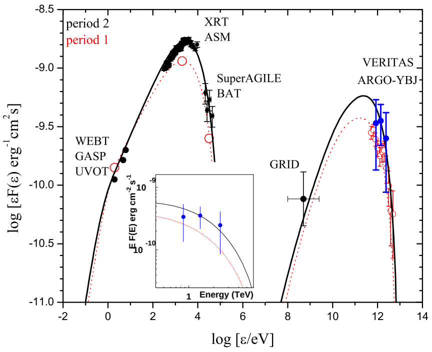

Fig. 3. SED measured by ARGO-YBJ on June 11-13 (blue circles) together with results from other experiments, obtained during the first flare (red open circles) and the second one (black circles). The red dashed and the black solid curves represent the SEDs modeled by Donnarumma et al. for the two flares. The inset shows a zoom on ARGO-YBJ data.

Mkn421 has been continuously monitored by ARGO-YBJ during 2008, showing a VHE flux close to the Crab Nebula level from February to September, and decreasing afterwards. Two strong flares in June 2008 have been observed in a multifrequency campaign from optical to TeV energies. ARGO-YBJ measured the spectrum of Mkn421 above 0.9 TeV during the second flare completing the multifrequency observations. For the first time an EAS array was able to detect γ-ray flaring activity at sub-TeV energies in a few days period.

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