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Recent results in γ-ray astronomy with the ARGO-YBJ detector

Tristano Di Girolamo[1,a] on behalf of the ARGO-YBJ collaboration

[1] *Università "Federico II" and INFN - Napoli, Complesso Monte S. Angelo, Via Cintia, Napoli, Italy*

Abstract. The ARGO-YBJ air shower detector has been in stable data taking for five years at the YangBaJing Cosmic Ray Laboratory (Tibet, P.R. China, 4300m a.s.l.) with a duty cycle > 86% and an energy threshold of a few hundreds of GeV. With the scaler mode technique, the minimum threshold of 1 GeV can be reached. In this paper recent results in γ-ray astronomy will be presented, including those from 4.5 years of observations of the blazar Mrk 421 in common with the Fermi satellite.

1 The detector

The ARGO-YBJ experiment is located at Yangbajing (Tibet, P.R. China, 4300 m a.s.l.) and consists of a single layer of Resistive Plate Counters (RPCs) on a total area of about 110×100 m^2. The detector has a modular structure, the basic module being a cluster (5.7×7.6 m^2), made of 12 RPCs. Each RPC is read by 80 strips (6.75×61.8 cm^2) which are the space pixels, logically organized in 10 independent pads (55.6×61.8 cm^2) which are individually acquired and represent the time pixels of the detector [1]. The detector carpet is connected to two different DAQ systems, which work independently: in shower mode, for each event the location and timing of each detected particle is recorded, allowing the reconstruction of the lateral distribution and of the arrival direction; in scaler mode, the counting rate of each cluster is measured every 0.5 s, with little information on the space distribution and arrival direction of the detected particles. The trigger of the shower mode was $N_{pad} \geq 20$ in a time window of 420 ns, with a rate of 3.5 kHz. In the scaler mode, for each cluster four scalers recorded the rate of counts $\geq$ 1, $\geq$ 2, $\geq$ 3 and $\geq$ 4 in a time window of 150 ns. The corresponding measured rates are, respectively, ~40 kHz, ~2 kHz, ~300 Hz and ~120 Hz [2]. The experiment has been taking data with its full layout from November 2007 to February 2013. The detector pointing accuracy, angular resolution and absolute energy calibration have been determined studying the deficit in the cosmic ray flux due to the Moon [3].

2 Sky survey

The ARGO-YBJ detector surveyed the northern hemisphere, in the declination band from -10° to 70°, at energies above 0.3 TeV. With an integrated sensitivity down to 0.24 Crab unit (depending on the declination) after five years of data taking, six sources were detected with a statistical significance S>5 standard deviations (s.d.), and five excesses are reported as potential (S>4 s.d.) γ-ray emitters. The list of excess regions, with their corresponding significances and TeV associations, is in table 1 [4]. In the rest of this section, a selection of results concerning the detected sources will be presented.

[a] e-mail: tristano.digirolamo@na.infn.it

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Table 1. List of ARGO-YBJ excess regions with corresponding statistical significances S and TeV associations. All significances are given for $N_{pad} \geq 20$ except that of ARGO J1841-0332, which is for $N_{pad} \geq 100$ (for $N_{pad} \geq 20$ the significance is S=3.4 s.d.).

ARGO-YBJ Name	S (s.d.)	TeV Association
ARGO J0409-0627	4.8	
ARGO J0535+2203	20.8	Crab Nebula
ARGO J1105+3821	14.1	Mrk 421
ARGO J1654+3945	9.4	Mrk 501
ARGO J1839-0627	6.0	HESS J1841-055
ARGO J1907+0627	5.3	HESS J1908+063
ARGO J1910+0720	4.3	
ARGO J1912+1026	4.2	HESS J1912+101
ARGO J2021+4038	4.3	VER J2019+407
ARGO J2031+4157	6.1	MGRO J2031+41
		TeV J2032+4130
ARGO J1841-0332	4.2	HESS J1843-033

The differential energy spectrum obtained for the Crab Nebula in the range 0.3-20 TeV can be described by the power law $dN/dE = (5.2 \pm 0.2) \times 10^{-12}(E/2\ TeV)^{(-2.63\pm0.05)}$ photons cm^{-2} s^{-1} TeV^{-1}, and it is consistent with results from other experiments [5]. The light curve over five years, with a binning of 200 days, is compatible with a steady emission with a probability of 0.07. An analysis with data collected in 4.5 years of observations in common with Fermi/LAT and divided in bins of 200 days gives a Pearson correlation coefficient $r = 0.56\pm0.22$. Because of the small statistical significance of these results, no flux variability correlated with Fermi/LAT can be claimed.

The blazar Mrk 421 was observed by ARGO-YBJ and the Fermi satellite during a 4.5 year period of common operation time, from August 2008 to February 2013 [6]. Thanks to long-term multiwavelength observations, the variable emission of this source and the correlations among flux variations in different wavebands were investigated. The TeV flux is clearly correlated with the X-ray flux, while only partially with the GeV flux. Seven large flares, of which five in X-rays and two at GeV energies, and one X-ray outburst were identified and used to study the variation of the Spectral Energy Distribution (SED) with respect to two steady phases. The behaviour of the GeV γ-rays allows the classification of SEDs into three different groups. Adopting a simple one-zone synchrotron self-Compton model, we find that in two out of three groups electrons are injected with a power-law spectral index $\sim$-2.2, as expected from relativistic diffuse shock acceleration, while in the remaining group the spectrum is harder ($\sim$-1.8). The variations of the states may be due to environment properties (first two groups) or to the acceleration process itself (last group).

In a location consistent with MGRO J2031+41, Fermi/LAT detected a complex extended source, attributed to the emission by a "cocoon" of freshly accelerated cosmic rays which fill the cavities carved by stellar winds and ionization fronts from young stellar clusters [7]. After reanalysing the complete ARGO-YBJ data set, subtracting the contribution of the overlapping TeV sources and using a larger region to evaluate the excess map (since Fermi/LAT observations revealed a large extended source), ARGO J2031+4157 resulted with an extension $\sigma_{ext} = 1.8^\circ \pm 0.5^\circ$, consistent with that of the Cygnus Cocoon as measured by Fermi/LAT, i.e., $\sigma_{ext} = 2.0^\circ \pm 0.2^\circ$ [8]. The spectrum also shows a good connection with that determined by Fermi/LAT in the 1-100 GeV energy range. Therefore, ARGO J2031+4157 is identified as the counterpart of the Cygnus Cocoon at TeV energies.

3 Diffuse γ-rays from the Galactic plane

The events collected by ARGO-YBJ have been analysed to determine the diffuse γ-ray emission in the Galactic plane at longitudes $25^\circ < l < 100^\circ$ and latitudes $|b| < 5^\circ$ [9]. This analysis was carried out in the energy range connecting the region explored by Fermi/LAT with that investigated by Milagro. In particular, the analysis was focused on two selected regions of the Galactic plane, i.e., $40^\circ < l < 100^\circ$ and $65^\circ < l < 85^\circ$ (the Cygnus region), where Milagro observed an excess with respect to what predicted by current models.

In the Galactic region $40^\circ < l < 100^\circ$, $|b| < 5^\circ$, after masking the discrete sources and subtracting the residual contribution, an excess with a statistical significance of 6.1 s.d. above the background is found. The spectral analysis provides the three fluxes shown in Figure 1 (left), whose fit with a power law gives a spectral index -2.90 ± 0.31, and the corresponding flux at 1 TeV is compatible with the extrapolation of the Fermi/LAT model for the Diffuse Galactic Emission (Fermi-DGE). On the other hand, the first measurement of the diffuse TeV (integral) flux from the Galactic plane made by Milagro revealed a "TeV excess" in the diffuse γ-ray spectrum with respect to expectations [10]. This Milagro measurement, converted into differential flux, is only 34% greater than the value expected from the extrapolation of the Fermi-DGE, and within the experimental uncertainties (see triangle with error bars in left plot of Figure 1). Moreover, considering that the Milagro result does not take into account the contributions from the Cygnus Cocoon (not yet discovered at the time of the measurement) and from overlapping point and extended sources, the discrepancy with the Fermi/LAT predictions is almost cancelled out. Therefore, the full set of measurements with ground-based detectors is in agreement with direct observations by Fermi/LAT, and the evidence of any "TeV excess" is ruled out.

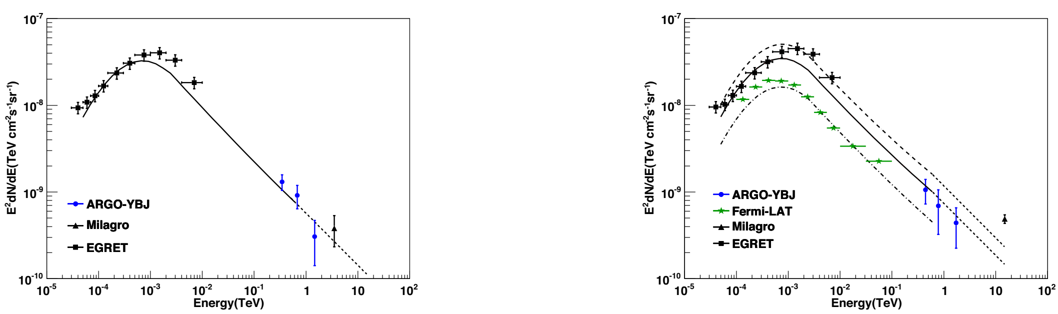

Figure 1. Energy spectrum of the Galactic diffuse γ-ray emission. The EGRET data (squares), showing a "GeV excess", are likely due to instrumental effects. The Fermi/LAT data (stars) were obtained in the region $72^\circ < l < 88^\circ$, $|b| < 15^\circ$. The different lines indicate the energy spectra expected from the Fermi-DGE (with index -2.6, which also rules their extensions) in the different sky regions investigated by the detectors (details are given in [9]). Left: region $40^\circ < l < 100^\circ$, $|b| < 5^\circ$. Right: region $65^\circ < l < 85^\circ$, $|b| < 5^\circ$

In the Galactic region $65^\circ < l < 85^\circ$, $|b| < 5^\circ$, after masking the discrete sources and the Cygnus Cocoon and subtracting the residual contribution, an excess of 4.1 s.d. is left. The SED of γ-ray emission is shown in the right plot of Figure 1 together with the spectra expected from the Fermi-DGE in the different sky regions investigated by the detectors. Milagro measured the diffuse γ-ray emission from the region $65^\circ < l < 85^\circ$, $|b| < 2^\circ$ at a median energy of 15 TeV [11], obtaining the flux reported as a filled triangle in the same plot. For comparison, the long-dashed line shows the expected energy spectrum for this region according to the Fermi-DGE. The Milagro flux results about 75% higher than the Fermi-DGE, suggesting the presence of an excess. The spectral analysis of

ARGO-YBJ data provides the three fluxes shown in the right plot of Figure 1, whose fit with a power law gives a spectral index -2.65 ± 0.44, and the corresponding flux at 1 TeV is about 10% lower than the extrapolation of the Fermi-DGE. These data do not show any excess at energies around 1 TeV which corresponds to the excess found by Milagro. Again, this discrepancy can be explained taking into account that the contribution of all the discrete γ-ray sources was not completely removed from the Milagro data. Finally, the harder spectrum in the Cygnus region compared with that measured in the whole region $40° < l < 100°$, $|b| < 5°$ may suggest the presence of young cosmic rays accelerated by a nearby source.

4 Search for Gamma Ray Bursts in scaler mode

In scaler mode, the energy threshold for photons is about 1 GeV, lower than the highest energies detected by satellite experiments. Moreover, the modular structure of the ARGO-YBJ detector allowed the collection of data during the different mounting phases. Therefore a search for emission from Gamma Ray Bursts (GRBs) in coincidence with satellite detections started in November 2004, when the Swift satellite was launched [12]. Until February 2013 a sample of 206 GRBs was analysed, 24 of them with known redshift z. This is the largest sample of GRBs investigated with a ground-based detector at high energies. Since no significant signal was found in the data, for each GRB fluence upper limits in the 1-100 GeV energy range were determined at 99% c.l. assuming two different power law spectra: a) the index measured by satellite detectors in the keV-MeV energy range; b) the conservative differential index -2.5. For case a), when double power law spectral features have been identified, the higher energy index has been used. Therefore, we obtain ranges of upper limits between the values corresponding to the two spectral assumptions, while a single value results if the low energy spectrum is a cutoff power law, and thus only case b) is considered. For the set of 24 GRBs with known redshift, the fluence upper limits are as low as $\sim 3 \times 10^{-5}$ erg/cm^2 and are the only ones set at GeV energies. For a subset of these GRBs, the upper limits show that the low-energy spectrum cannot be extended to the GeV region and some additional features occur in the keV-MeV range. For GRB090902B the upper limit can be compared with the fluence extrapolated from Fermi/LAT observations in the same energy range [13], which results lower by a factor $\sim$3. More results and details about this search are given in [14].

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