Gamma ray sources observation with the ARGO-YBJ detector

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ABSTRACT
Since November 2007 the air shower detector ARGO-YBJ is continuously monitoring the gamma ray sky in the declination band from −10° to +70° at energies E > 0.5 TeV.
In this work we present the results of our observations of galactic and extragalactic sources during more than 3 years, focusing our attention on the Crab Nebula, the blazar Mrk 421 and the galactic extended source MGRO J1908 + 06, probably associated to the Fermi pulsar PSR J1907 + 0602.

1. The ARGO-YBJ experiment
ARGO-YBJ is a full coverage air shower detector located at the Yangbajing Cosmic Ray Laboratory (4300 m a.s.l. Tibet, PR China) devoted to the study of gamma rays and cosmic rays. Exploiting the high altitude and the full coverage approach with a high granularity, ARGO-YBJ can detect gamma rays with an energy threshold as low as a few hundred GeV. Due to its large field of view (~2 sr) and the high duty cycle (~86%) it can monitor continuously a large fraction of the sky.

The detector consists of a ~74 × 78 m² carpet made of a single layer of Resistive Plate Chambers (RPCs) with ~93% of active area, surrounded by a partially instrumented (~20%) area up to ~100 × 110 m² (see Fig. 1).

The apparatus has a modular structure, the basic data acquisition element being a cluster (5.7 × 7.6 m²), made of 12 RPCs (2.8 × 1.25 m²). Each RPC is read by 80 strips of 6.75 × 61.8 cm² (the spatial pixels), logically organized in 10 independent “pads” of 55.6 × 61.8 cm² which are individually acquired and represent the time pixels of the detector [1]. In addition, in order to extend the dynamical range up to PeV energies, each RPC is equipped with two large size pad (139 × 123 cm²) to collect the total charge developed by the particle hitting the detector [2]. The full experiment is made of 153 clusters for a total active surface of ~6600 m².

ARGO-YBJ operates in two independent acquisition modes: the shower mode and the scaler mode [3]. In this analysis we refer to the data recorded in shower mode. In this mode, an electronic logic has been implemented to build an inclusive trigger, based on a time correlation between the pad signals, depending on their relative distance [4]. In this way, all the shower events giving a number of fired pads \( N_{pad} \geq N_{trig} \) in the central carpet in a time window of 420 ns generate the trigger.

Since November 2007 ARGO-YBJ is in stable data taking with the trigger condition \( N_{trig} = 20 \), corresponding to a rate of ~3.5 kHz and a dead time of 4%.

2. Detector performances
The time and the location of each fired pad are recorded and used to reconstruct the position of the shower core and the arrival direction of the primary particle [5]. A software method has been developed to perform the time calibration of the 18 360 pads [6].

The angular resolution and the pointing accuracy of the detector have been evaluated by using the Moon shadow, i.e. the deficit of cosmic rays in the Moon direction. The Moon shadow is observed by ARGO-YBJ with a statistical significance of ~9 standard deviations per month [7].

The shape of the shadow provides a measurement of the detector Point Spread Function (PSF), and its position allows the individuation of possible pointing biases. The data have been compared to the results of a Monte Carlo simulating the propagation of cosmic ray in the Earth magnetic fields, the shower development in the atmosphere by using the CORSIKA code [8], and the detector response with a code based on the GEANT package [9].

The measured PSF of cosmic rays has been found in excellent agreement with the Monte Carlo evaluation, confirming the reliability of the simulation procedure (see Fig. 2). Concerning the pointing accuracy, a systematic error of 0.2 towards North
probably due a residual effect in the pad time calibration procedure is under investigation (see Fig. 3, upper panel).

The Moon shadow gives also the possibility to check the absolute energy calibration of the detector, by studying the westward shift of the deficit location due to the geomagnetic field. The observed displacement as a function of the event multiplicity $N_{\text{pad}}$ is in agreement with the simulation (see Fig. 3, lower panel). From this analysis the total absolute energy scale error, including systematics effects, is estimated to be less than 13%.

With the same simulation codes we evaluated the angular resolution for $\gamma$ rays, that results smaller with respect to protons by $\sim 30\text{–}40\%$ depending on $N_{\text{pad}}$ due to the better defined time profile of the showers. In general the PSF can be described by the combination of two Gaussian functions. For events with $N_{\text{pad}} \geq 40$ (200) the radius of the opening angle that maximizes the signal to background ratio is $1.2^\circ (0.6^\circ)$ and contains $\sim 55\%$ of the signal.

3. The Crab Nebula

The Crab Nebula was observed at very high energies (VHEs) for the first time by the Whipple Collaboration in 1989 [10]. Later several experiments confirmed this detection measuring a VHE spectrum extending up to about 80 TeV [11].

The radiation from the Crab Nebula is dominated by a non-thermal emission, attributed to synchrotron radiation from highly relativistic electrons with energies up to $\sim 10^{15}$ eV [12]. The interaction of accelerated electrons with local photon fields (mostly produced by synchrotron emission from the same electron population) produce VHE gamma-rays via the inverse Compton process [11].

At the ARGO-YBJ site the Crab Nebula culminates with a zenith angle of 8° and every day is visible for 5.8 h with a zenith angle less than 40°. The dataset used in this analysis contains all the events recorded from November 2007 to February 2011, with $N_{\text{pad}} \geq 20$, where $N_{\text{pad}}$ is the number of hit pads on the central carpet. No gamma/hadron discrimination is performed on these data. The total on-source time is 5908 h.

The events are used to fill a set of $8^\prime \times 8^\prime$ sky maps in celestial coordinates (right ascension and declination) with $0.1^\prime \times 0.1^\prime$ bin size, centered on the source position, each map corresponding to a defined $N_{\text{pad}}$ interval. We use eight intervals, corresponding to 20–39, 40–59, 60–99, 100–199, 200–299, 300–499, 500–999 and > 1000 $N_{\text{pad}}$. 

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Fig. 1. Layout of the ARGO-YBJ detector.

Fig. 2. Angular resolution for cosmic ray showers measured by ARGO-YBJ using the Moon shadow as a function of the particle multiplicity, compared with Monte Carlo expectations.

Fig. 3. Upper panel: displacement of the Moon shadow in the North–South direction (black squares) as a function of the primary rigidity, compared to the Monte Carlo expectations (red circles). Lower panel: displacement of the Moon shadow in the East–West direction, as a function of the particle multiplicity. The rigidity scale represents the median rigidity associated to a given multiplicity bin. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
In order to extract the excess of $\gamma$ rays, the cosmic ray background is estimated using the time swapping method [13] and it is used to build the “background maps”. The maps are then smoothed using the PSF corresponding to the given $N_{\text{pad}}$ intervals, and subsequently the smoothed background maps are subtracted to the relative smoothed event maps, obtaining the “signal maps”, where for each bin the statistical significance of the excess is calculated.

An excess at the source position is observed in every map, giving a global significance of 13.5 standard deviations.

The number of excess events is then corrected for the loss of signal due to the time swapping method, that overestimates the background by a factor depending on the PSF. This correction is larger for small $N_{\text{pad}}$, where the PSF is wider, and ranges from 4% for $N_{\text{pad}} > 1000$ to 16% for $N_{\text{pad}} = 20–40$.

The source spectrum is evaluated by means of a simulation, by comparing the number of excess events for each $N_{\text{pad}}$ interval, with the corresponding values expected assuming a set of test spectra. Assuming a power law spectrum, the obtained best fit in the energy range $\sim 0.5–10 \text{TeV}$ is: $dN/dE = 3.0 \pm 0.30 \times 10^{-11} \text{photons cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$, with a $\chi^2$ of 8.4 for 5 degrees of freedom.

The quoted errors are purely statistical. According to our estimates the systematic error on the flux is less than 30%, mainly due to the background evaluation and to the uncertainty on the absolute energy scale.

Fig. 4 shows the obtained spectrum, in agreement with previous measurements by other detectors in the same energy range [14,15]. The energy of each flux point represents the gamma ray median energy in the corresponding $N_{\text{pad}}$ interval.

The strong signal of the Crab Nebula is also used to test possible methods to improve the detector sensitivity. The effects of a selection of showers according to some reconstruction parameters are currently under study. A preliminary result shows that selecting the showers that are spatially more compact and with a smaller dispersion of the arrival time of the particles around the shower front, the cosmic ray background is reduced with respect to gamma rays, giving an increase of the sensitivity by a factor 1.2–1.5, in particular for events with a large number of fired pads. As an example, using this selection for the Crab Nebula events, the significance of the signal increases from 3.7 to 5.1 s.d. for events with 500–999 $N_{\text{pad}}$.

3.1. Search for flares

Thanks to its high flux and stability the Crab Nebula has been considered for many years a “standard candle” for VHE gamma-ray astronomy. This scenario changed on 2010 September 19 when the AGILE satellite detected a strong and unexpected gamma-ray flare from the Crab Nebula at energies above 100 MeV [16,17]. The flare reached its maximum during 2 days, with a flux 3 times larger than usual. The event was subsequently confirmed by the Fermi-LAT instrument working in the same energy range [18,19], and different groups obtained multifrequency data in the following days.

Moreover, the analysis of the whole Crab dataset by AGILE and Fermi showed the presence of a significant gamma ray flux variability during the last years. In particular two strong flares were observed by AGILE in October–November 2007 [17] and by Fermi in February 2009 [19], both lasting 15–20 days. A very intense flare has been detected by Fermi and AGILE on April 2011, with a flux increase of a factor larger than 10 [20,21].

So far, the origin of this surprising activity is not clear. In this new scenario, the observations at TeV energies are extremely important to understand and constrain the mechanisms that produced these unusual events.

First, the long-term stability of the TeV emission is studied by dividing the ARGO-YBJ data in 200 days intervals, and comparing the average rate detected from the Crab Nebula in every interval with the rate averaged over the whole observation period. According to our data the emission is compatible with a uniform flux [22].

A search for possible variations of the flux on shorter time scales is performed using the dataset containing the ARGO-YBJ daily event rates observed from the Crab Nebula. We consider all the time intervals of duration $\Delta t = n$ days (with $n$ ranging from 1 to 20) and starting at 00:00 UT each day. For every interval the rate expected from the steady flux is subtracted to the observed rate, obtaining the “flare rates”. In order to search for flares in different energy ranges, this procedure has been done for 4 $N_{\text{pad}}$ thresholds: 40, 100, 500 and 1000.

The distribution of the significances of the flare rates (for the 4 $N_{\text{pad}}$ thresholds together) is given in Fig. 5. The number of entries in the distribution is $4 \times 18,083$. Note that the excesses are not independent, because the time intervals overlap, and the $N_{\text{pad}}$ intervals also overlap. The distribution can be fitted with a Gaussian function, with a mean value $m = -0.021 \pm 0.004$, r.m.s. $= 0.983 \pm 0.003$, and $\chi^2 = 27$ for 16 d.o.f. The “bump” visible in the distribution for significances larger than 4 standard deviations is due to an excess of 4.6 s.d. with a duration of 15 days, starting on MJD 55 030. The excess is observed for events with $N_{\text{pad}} > 40$, while for higher $N_{\text{pad}}$ thresholds the significance is less than 2 standard deviations. Given the number of trials, the excess chance probability can be estimated of the order of 15%.

A more detailed analysis for the time periods where the satellite detectors have observed a flare has been carried out. According to the AGILE and Fermi data [17,19,21] three major flaring episodes at energies $E > 100 \text{MeV}$ occurred during the ARGO-YBJ data acquisition.

**Flare 1.** Starting time MJD 54 857, duration $\Delta t \sim 16$ days, maximum flux $F_{\text{max}} \sim 5$ times larger than the steady flux [19]. During this flare no excess is present in our data, for any $N_{\text{pad}}$ threshold.

**Flare 2.** Starting time MJD 55 457, duration $\Delta t \sim 4$ days, maximum flux $F_{\text{max}} \sim 5$ times larger than the steady flux [17,19].

![Fig. 4](image-url) The Crab Nebula spectrum obtained by ARGO-YBJ, compared with other measurements [14,15]. The reported errors are only statistical.
4. MGRO J1908+06

The extended gamma ray source MGRO J1908+06 has been discovered in 2007 by the Milagro air shower detector in a survey of the Galactic plane at a median energy of \( \sim 20 \) TeV [27]. The source was later observed by H.E.S.S. [28] and VERITAS [29]. In particular, H.E.S.S. measured a power law energy spectrum with a photon index of \( 2.10 \pm 0.07_{\text{stat}} \pm 0.2_{\text{sys}} \) in the energy range 0.3–20 TeV, corresponding to an integral flux of 0.17 Crab units above 1 TeV. Assuming a Gaussian shape for the source, H.E.S.S. evaluated an extension of \( \sigma_{\text{ext}} = 0.34^{+0.04}_{-0.03} \).

The proximity of MGRO J1908+06 to the Fermi LAT pulsar J1907+0602, lying at a distance \( \sim 14' \) from the centroid of the H.E.S.S. source, suggested to identify it with the Wind Nebula of the pulsar [30,31]. Performing an off-pulse measurement, Fermi set an upper limit to the nebula flux in the energy region 0.1–25 GeV, showing that the spectrum has a low-energy turnover between 20 GeV and 300 GeV. With radio and X-ray data, a lower limit to the pulsar distance was set to \( \sim 3.2 \) kpc, deriving for the nebula a physical size \( \geq 40 \) pc.

Finally Milagro evaluated the energy spectrum in the 2–100 TeV energy region, reporting a very hard power law spectrum with an exponential cutoff [32]. The best fit obtained is \( \text{d}N/\text{d}E = 0.62 \times 10^{-11} \ E^{-1.59} \exp(-E/14.1) \ \text{photons TeV}^{-1} \ \text{cm}^{-2} \ \text{s}^{-1} \), with \( E \) in TeV. This flux is in disagreement with that given by H.E.S.S. by \( \sim 2 \) standard deviations, being about a factor 3 higher at 10 TeV. The authors suggest that the discrepancy can be simply due to a statistical fluctuation, or to the fact that Milagro, given its relatively poor angular resolution, integrates the signal over a larger solid angle compared to H.E.S.S., and likely detects more of the diffuse lateral tails of the extended source.

In this work we report on the observation of MGRO J1908+06 with the ARGO-YBJ detector performed during \( \sim 3 \) years, with an evaluation of the extension and the energy spectrum.

At the ARGO-YBJ site, MGRO J1908+06 culminates at the zenith angle of 24°, and is visible for 5.4 h per day with a zenith angle less than 45°.

The dataset used in this analysis refers to the period from November 2007 to February 2011, containing all the showers with zenith angle less than 45° and \( N_{\text{pad}} \geq 40 \). The total on-source time is 5358 h.

To study the gamma ray emission from this source, first we build a sky map with a method similar to the one previously described for the Crab Nebula. Fig. 6 shows the ARGO-YBJ sky map for events with \( N_{\text{pad}} > 40 \). An area of excesses with statistical significance larger than 4–5 s.d. is evident around the location of the H.E.S.S. source.

Since MGRO J1908+06 is an extended source, the procedure for the spectrum evaluation is slightly different from the Crab Nebula case.

For a point source, given a \( N_{\text{pad}} \) interval, the value of \( \psi_{\text{max}} \), i.e. the window the maximize the signal to noise ratio, is related to the PSF, that depends both on the detector characteristics and on the source spectrum. In case of an extended source the value of \( \psi_{\text{max}} \) also depends on the intrinsic angular extension and on the shape of the source.

From the experimental point of view, if the extension is unknown, one should first determine it in order to evaluate the correct windows to extract the signal for the spectrum. On the other hand, to evaluate the extension one has to study the angular distribution of the events around the source, that also depends on the PSF, that in turn depends on the spectrum. In conclusion, the spectrum and the extension cannot be independently determined. To solve this “circular” problem an iterative procedure has been adopted, described in detail in [33].
While the obtained energy spectrum is $\sigma_{\text{ext}} = 0.50 \pm 0.35$, consistent with the H.E.S.S. measurement, while the obtained energy spectrum is $dN/dE = 2.2 \pm 0.4 \times 10^{-13}$ (E/7 TeV) $- 2.3 \pm 0.3$ photons cm$^{-2}$ s$^{-1}$ TeV$^{-1}$, with a $\chi^2$ value of 0.17 for 2 degrees of freedom (the errors on the fit parameters are statistical).

Beside the statistical errors, this measurement could be affected by a systematic uncertainty less than 30%.

The spectrum (Fig. 7) is in agreement with Milagro, but only marginally consistent with H.E.S.S., being the ARGO-YBJ flux a factor $\sim 3$ larger. The origin of such a disagreement could be a statistical fluctuation and/or the effect of systematic uncertainties (H.E.S.S. reports a systematic error of $\sim 20\%$ on the flux). However, since a higher flux has been observed also by Milagro, it is worthwhile to suggest different possibilities.

A possibility is that the larger flux measured by the ARGO and Milagro detectors is the result of the contamination of other extended sources lying near the object observed by H.E.S.S., since the former detectors have a worse angular resolution and integrate the signal over a larger area. Fig. 6 shows the positions of all the gamma ray sources detected by Fermi in the same region (all of them unidentified except PSR J1907$+0602$), according to the Fermi First Catalogue [34]. A few of them, if associated with extended TeV nebulae, could in principle contribute to the observed signal, lying at a distance less than $\sim 2\,\text{--3'}$ from MGRO J1908$+06$. Their contribution however should be small, since the ARGO-YBJ excess is consistent with the position of PSR J1907$+0602$.

A larger contribution is expected from the diffuse gamma ray flux produced by cosmic rays interacting with matter and radiation in the Galaxy. According to the prediction of the “optimized” GALPROP model [35,36], confirmed by a MILAGRO measurement at 15 TeV [37], the amount of this contribution to the measured flux from MGRO J1908$+06$ at a few TeV can be of the order of $15\%$--$20\%$, and cannot account for the entire observed disagreement.

A complex morphology of the source could also affect the flux measurement. Both ARGO-YBJ and H.E.S.S. use an one-parameter Gaussian to model the shape of the emission region, that could be insufficient for a description of the source, producing some biases.

Finally, one cannot exclude the possibility of a flux variation as the origin of the observed disagreement among the detectors. In fact Milagro, H.E.S.S. and ARGO-YBJ data have been recorded in different periods. Milagro integrates over 7 years (July 2000–November 2007) while the total H.E.S.S. dataset only amounts to 27 h of observation during 2005–2007, before the ARGO-YBJ data. However, a temporal analysis of the ARGO-YBJ data has shown that the signal, in the limit of the detector sensitivity, is consistent with a stable flux, on time scales ranging from a few days to months. Moreover, it should be noted that the MGRO J1908$+06$ emission, differently from that of the Crab Nebula, originates from a region large $\gtrsim 40$ pc, implying that the variation time scale cannot be less than $\sim 130$ years, unless relativistic beaming effects are present.

So far, the problem remains open. The collection of higher statistics by continuously monitoring MGRO J1908$+06$ should lead to the solution of this question.

5. Mrk 421

The blazar Mrk 421 ($z = 0.031$) is one of the brightest TeV objects of the sky. The spectral energy distribution has a double-hump shape, generally interpreted as a synchrotron emission peak at X-ray energies followed by a peak at gamma ray energies, whose origin, leptonic or hadronic, is still under debate. Mrk 421 is a very active blazar with frequent outbursts composed by many flares that last as long as a few months. Multiwavelength observations during active periods are crucial to shed light on the mechanisms responsible for the high energy emission.

Different from Cherenkov Telescopes, whose duty cycle is limited by the Moon light and weather conditions, ARGO-YBJ
can continuously follow up the source and perform a long-term correlation with X-ray data [38].

Mrk 421 culminates at the ARGO-YBJ location at a zenith angle \( \theta_{\text{cmin}} = 8.1^\circ \) and it is observed for about ~6 h per day.

The data used in this analysis have been collected from November 2007 to February 2010. Integrating the whole dataset, we obtained a signal from the source with a statistical significance of more than 12 standard deviations.

In order to study the correlation between gamma rays and X-rays, the daily averaged light curves of BAT/Swift (15–50 keV) and ASM/RXTE (2–12 keV) are used.

Fig. 8 shows the accumulation rates of Mrk 421 events detected in ~3 years by ARGO-YBJ, Swift and RXTE. A clear correlation is visible among the three curves. The rapid increases of the rates during the first half of 2008 and 2010 are related to the strongest active periods, when the flux increased up to the level of several Crab units. A detailed analysis of the flares occurred in 2008 and 2010 has been reported by ARGO-YBJ in their dedicated works [39,40].

Concerning the long term behavior, in order to quantify the degree of correlation between gamma rays and X-rays, the Discrete Correlation Function (DCF) [41] has been used. The value of DCF as a function of the time lag between gamma ray and X-rays is close to 1 for a time lag equal to zero [38].

To study the SED for different flux levels the data are divided in four groups according to the X-ray rate measured by ASM/RXTE. Assuming a power low spectrum for both gamma rays and X-rays, the slope and the normalization parameter for the four flux levels are evaluated. Fig. 9 shows the obtained spectral indexes as a function of the flux for both ARGO-YBJ and ASM. A clear hardening of the spectra is visible for both experiments when the flux increases. This result is in agreement with a previous measurement by the Whipple Cherenkov Telescope [42].

Concerning the fluxes, the relation between the gamma ray and the X-ray fluxes is more compatible with a quadratic relation, instead of a linear one.

Finally, modelling the obtained SEDs, the X-ray and gamma ray data are consistent with a homogeneous one-zone SSC model [43].

6. Summary

ARGO-YBJ has observed for ~3 years the Crab Nebula, the blazar Mrk 421 and the extended galactic source MGRO J1908+06. Concerning the Crab Nebula, the spectrum obtained in the energy range 0.5–10 TeV is in good agreement with other experiments, showing the reliability of the ARGO-YBJ measurement, the stability of the detector and the accuracy of the analysis and simulation procedures.

A search for possible TeV flares on time scales ranging from 1 to 20 days during the whole observation period showed no statistical significant variation of the flux. A particular attention has been devoted to three periods in which a flaring emission has been observed at energies \( E > 100 \text{ MeV} \) by satellite experiments. In two out of three cases ARGO-YBJ detected an excess of events of ~2.5–3 standard deviations besides the steady flux, in coincidence with the lower energy emission. It is interesting to note that these two flares are the hardest ones detected by satellites.

For the extended source MGRO J1908+06, we estimate an extension consistent with a measurement by H.E.S.S. The energy spectrum in the range ~2–30 TeV is in agreement with the Milagro detector, but the flux is ~3 times larger than what has been obtained by H.E.S.S. The origin of this disagreement is not yet clear, but is probably related to the complex morphology of the source region.

The blazar Mrk 421 underwent several active periods during our observation time, showing a high gamma ray flux variability. A strong correlation between the gamma ray flux and the X-ray one has been observed over the whole observation period, with a hardening of both gamma and X-ray spectra during the flares. According to X-ray and gamma ray data, the spectral behavior during different flux states is consistent with the expectations of the one-zone synchrotron self-Compton model.

The shown results on gamma ray sources have been obtained without any gamma-hadron discrimination. Methods to recognize and reject cosmic ray showers based on the different space-time distributions of the particles of the shower front with respect to gamma ray showers are currently under study [44] in order to increase the sensitivity of the detector.
References