Crab Nebula: five-year observation with ARGO-YBJ postprint

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Abstract

The ARGO-YBJ air shower detector monitored the Crab Nebula gamma ray emission from 2007 November to 2013 February. The integrated signal, consisting of 3.3 × 105 events,reached the statistical significance of 21.1 standard deviations. The obtained energy spectrum in the energy range 0.3-20 TeV can be described by a power law function dN/dE = I0 (E / 2 TeV)− , with a flux normalization I0 = (5.2 ± 0.2) × 10−12 photons cm−2 s−1 TeV−1and = 2.63 ± 0.05, corresponding to an integrated flux above 1 TeV of 1.97 × 10−11 photons cm−2 s−1. The systematic error is estimated to be less than 30% for the flux normalization and 0.06 for the spectral index. Assuming a power law spectrum with an exponential cutoff dN/dE = I0 (E / 2 TeV)− exp (-E / Ecut), the lower limit of the cutoff energy Ecut is 12 TeV, at 90% confidence level. Our extended dataset allows the study of the TeV emission over long timescales. Over five years, the light curve of the Crab Nebula in 200-day bins is compatible with a steady emission with a probability of 7.3 × 10−2. A correlated analysis with Fermi-LAT data over 4.5 years using the light curves of the two experiments gives a Pearson correlation coefficient r = 0.56 ± 0.22. Concerning flux variations on timescales of days, a "blind" search for flares with a duration of 1-15 days gives no excess with a significance higher than four standard deviations. The average rate measured by ARGO-YBJ during the three most powerful flares detected by Fermi-LAT is 205 ± 91 photons day−1, consistent with the average value of 137 ± 10 day−1.

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CRAB NEBULA: FIVE-YEAR OBSERVATION WITH ARGO-YBJ

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Abstract

The ARGO-YBJ air shower detector monitored the Crab Nebula gamma-ray emission from 2007 November to 2013 February. The integrated signal, consisting of 10 events, reached a statistical significance of 21.1 standard deviations. The obtained energy spectrum in the range 0.3–20 TeV can be described by a power-law function dN/dE = I (E/2 TeV) , with flux normalization I = (5.2 ± 0.2) × 10 ^{11} photons cm ^{2} s ^{1} TeV ^{1} and spectral index   = 2.63 ± 0.05. The systematic error is estimated to be less than 30% for the flux normalization and 0.06 for the spectral index. Assuming a power-law spectrum with an exponential cutoff dN/dE = I (E/2 TeV)   exp(−E/E_cut), the lower limit of the cutoff energy E_cut is 12 TeV at 90% confidence level. Our extended dataset allows study of the TeV emission over long timescales. Over five years, the light curve of the Crab Nebula in 200-day bins is compatible with steady emission with a probability of 7.3 × 10 ^{2}. A correlated analysis with Fermi-LAT data over 4.5 years gives a Pearson correlation coefficient r = 0.56 ± 0.22. Concerning flux variations on timescales of days, a "blind" search for flares with duration of 1-15 days yields no excess with significance higher than four standard deviations. The average rate measured by ARGO-YBJ during the three most powerful flares detected by Fermi-LAT is 205 ± 91 photons day ^{1}, consistent with the average value of 137 ± 10 day ^{1}.

1. Introduction

The Crab Nebula is the remnant of a supernova that exploded in 1054 A.D. at a distance of 2 kpc. It contains a 33 ms pulsar that powers a wind of relativistic particles. The interactions of these particles with the remnant gas, photons, and magnetic field produce non-thermal radiation extending from radio waves to TeV gamma rays [?]. Most of the emission is generally attributed to synchrotron radiation of relativistic electrons and positrons. The spectral energy distribution (SED) peaks between optical and X-ray frequencies. A second component arises above 400 MeV, interpreted as inverse Compton (IC) scattering of the same electrons off synchrotron photons and CMB photons.

The Crab Nebula is one of the most luminous sources of very high energy (VHE) gamma rays in the sky, and the first source detected at TeV energies [?]. Thanks to its high flux and apparent stability, it is considered a reference source in gamma-ray astronomy. Detected by many experiments, both Cherenkov telescopes [?, ?] and air shower arrays [?], the Crab Nebula is often used to check detector performance, including sensitivity, pointing accuracy, and angular resolution.

In 2010 September, the AGILE satellite unexpectedly detected a strong flare from the direction of the Crab Nebula at energies above 100 MeV. It lasted two days, with a maximum flux three times higher than the average value [?], later confirmed by Fermi [?]. Since then, Fermi and AGILE have reported additional flares, characterized by rapid increase and decay of the flux, typically lasting a few days. The most impressive occurred in 2011 April, when the observed flux was 10 times higher than usual [?]. The measured SED shows a new spectral component emerging during flares, peaking at high energies (up to hundreds of MeV in the 2011 April flare), attributed to synchrotron emission from a population of electrons accelerated up to energies of 10^{1} eV. The Fermi-LAT data also show that these sharp emission peaks are superimposed on long-lasting smoother modulations with timescales of weeks or months [?]. The observed flux variations are attributed to the nebula, since the pulsar emission was found to be stable within 20% [?]. However, the origin of this activity remains unclear.

In this scenario, observations at higher energies could provide precious information to understand the mechanisms responsible for this behavior. A preliminary analysis of data recorded by the air shower detector ARGO-YBJ during the flares showed an increase of the Crab flux at TeV energies with moderate statistical significance in 3 out of 4 flares [?]. These results have not been confirmed by Imaging Atmospheric Cherenkov Telescopes (IACTs) because Moonlight hampered observations. However, sporadic and short measurements carried out during the first part of the 2010 September flare by MAGIC and VERITAS show no evidence for flux variability [?]. Observations by VERITAS and HESS during a flare in 2013 March (when ARGO-YBJ was already switched off) report a counting rate consistent with the steady flux [?].

In this paper we present a detailed analysis of the ARGO-YBJ data, carried out with improved reconstruction of the shower arrival direction obtained by applying quality cuts on the events. The study concerns not only the flaring episodes but the whole Crab Nebula dataset, consisting of more than five years of observation. The ARGO-YBJ layout and operation mode are presented in Section 2, with particular attention to performance in gamma-ray astronomy. In Section 3 the analysis technique to extract the gamma-ray signal is outlined, followed by results obtained with Crab Nebula data. Section 4 reports the energy spectrum evaluation and discusses systematic errors. In Section 5 the analysis of the temporal behavior of the Crab Nebula signal is presented, with a search for possible flares and rate variations on different timescales. A time correlation analysis with Fermi-LAT data at E > 100 MeV during 4.5 years is also reported. Finally, Section 6 contains a summary of the results and concluding remarks.

2. The ARGO-YBJ Experiment

The ARGO-YBJ is a "full coverage" air shower detector located at the Yangbajing Cosmic Ray Laboratory (Tibet, P.R. China, longitude 90.5° East, latitude 30.1° North) at an altitude of 4300 m above sea level, devoted to gamma-ray astronomy at energies above 300 GeV and cosmic ray studies at energies above 1 TeV.

During its lifetime, from 2007 November to 2013 February, ARGO-YBJ monitored the gamma-ray sky with an integrated sensitivity ranging from 0.24 to 1 Crab Units [?] and studied in detail the emission of the most luminous gamma-ray sources at energies above 300 GeV, namely the Crab Nebula, MGRO J1908+06 [?], HESS J1841-055 [?], the Cygnus Region [?, ?], and the blazars Mrk421 [?] and Mrk501 [?].

The detector consists of a 78 m^2 carpet made of a single layer of Resistive Plate Chambers (RPCs) with 7.6 m^2 active area, surrounded by a partially instrumented area up to 110 m^2. The apparatus has a modular structure, with the basic data acquisition element being a cluster (5.7 × 7.6 m^2), made of 12 RPCs (2.85 × 1.23 m^2). Each RPC is read by 80 strips of 6.75 × 61.8 cm^2 (the spatial pixels), logically organized in 10 independent pads of 55.6 × 61.8 cm^2 which are individually acquired and represent the time pixels of the detector [?]. To extend the dynamical range up to PeV energies, each RPC is equipped with two large pads (139 × 123 cm^2) to collect the total charge developed by particles hitting the detector [?]. The full experiment comprises 153 clusters (18360 pads), for a total active surface of 6600 m^2.

ARGO-YBJ operated in two independent acquisition modes: the shower mode and the scaler mode [?]. In this analysis we refer to data recorded from the digital read-out in shower mode. In this mode, electronic logic was implemented to build an inclusive trigger based on time correlation between pad signals, depending on their relative distance. In this way, all showers with a number of fired pads N_pad N_trig in the central carpet in a time window of 420 ns generated the trigger. This trigger worked with high efficiency down to N_trig = 20, keeping the rate of random coincidences negligible [?].

The time of each fired pad in a window of 2 µsec around the trigger time and its location were recorded. To calibrate the 18360 pads in time, a software procedure was developed based on the Characteristic Plane method [?] that uses secondary particles from large vertical showers as calibration beams, iteratively reducing differences between time measurements and the time fit of the shower front [?].

The full detector was in stable data taking with the trigger condition N_trig = 20 and an average duty cycle of 86%. The trigger rate was 3.5 kHz with a dead time of 4%.

The detector performance and capabilities in gamma-ray astronomy have been studied and improved through Monte Carlo simulations describing shower development in the atmosphere using the CORSIKA code [?] and detector response with a code based on the GEANT package [?].

2.1. Field of View

One distinctive feature of air shower arrays is the large field of view (FOV), in principle including the entire overhead sky. Gamma-ray sources cross the FOV with different paths according to their declinations. The sensitivity is not uniform across the field of view. Given a photon flux, atmospheric absorption reduces the shower rate for increasing zenith angles. The cosmic-ray background also decreases but more slowly, and the combination of the two rates determines the trend of sensitivity as a function of zenith angle.

Figure 1 [Figure 1: see original paper] shows the event rate in ARGO-YBJ expected from a Crab-like source as a function of zenith angle , normalized to the rate at = 0°, compared to the background rate. The figure also shows the dependence of detector sensitivity on . According to simulations, the sensitivity at = 30° (45°) is reduced by a factor of 2 (10) with respect to sensitivity at = 0°.

The capability to detect a given source depends on its path in the field of view (determined by source declination), particularly the amount of time the source lies at different zenith angles. The maximum significance occurs for declination __max = , where = 30.1° is the detector latitude. For a Crab-like source, sensitivity decreases by less than 10% for declinations | - __max| < 10°, while it is reduced by a factor of 2 for declinations | - __max| = 30°. The declination dependence is slightly stronger (weaker) for sources with softer (harder) spectra relative to the Crab Nebula [**?**].

At the ARGO-YBJ site, the Crab Nebula (declination = 22.01°) culminates at zenith angle = 8.1° and lies at zenith angles < 45° for 6.6 hours per sidereal day. In general, following a source for longer time per day increases signal significance due to improved statistics, but since the signal-to-background ratio decreases at large zenith angles, there is a maximum zenith angle beyond which significance begins to reduce. According to simulations, the maximum zenith angle for the Crab Nebula is 45°.

2.2. Angular Resolution

The sensitivity needed to observe a gamma-ray source is related to the angular resolution, which determines the amount of cosmic-ray background. We evaluate the shower arrival direction by fitting the shower front with a conical shape centered on the shower core position to account for the time delay of secondary particles relative to a flat front, a delay that increases with distance from the core. We set this delay to 0.1 ns m^{1} [**?**].

The high granularity of the detector allows detailed study of the shower profile and accurate determination of the core position by fitting the lateral density distribution with a Nishimura-Kamata-Greisen-like function. According to simulations, the core position error depends on the number of hit pads N__pad and the core distance from the detector center. For gamma-ray induced showers with core distance less than 50 m, the average core position error is less than 8 m (2 m) for N__pad < 100 (N__pad > 1000).

The point spread function (PSF) also depends on N__pad, and for a given N__pad value, it worsens as the shower core distance from the detector center increases. The angular resolution for showers induced by cosmic rays has been verified by studying the Moon shadow, observed by ARGO-YBJ with a statistical significance of 9 standard deviations per month. The shape of the shadow cast by the Moon on the cosmic-ray flux provides a measurement of the detector PSF. This measurement has been found to be in excellent agreement with expectations, confirming the reliability of the simulation procedure [**?**].

The PSF for gamma-ray showers is narrower than the cosmic-ray PSF by 30-40%, due to the better-defined time profile of the showers. To improve angular resolution for gamma-ray astronomy studies, quality cuts have been implemented by rejecting events with core distance larger than a given value D_cut (depending on N_pad) and with average time spread of particles relative to the fitted shower front exceeding 9 ns [**?**]. The D_cut values are given in Table 1 . The fraction of gamma rays passing the selection cuts depends on N_pad, whereas the fraction of surviving background events is 50% for N_pad $<$ 100 and 30% for N_pad $>$ 100. The selection also acts as mild gamma/hadron discrimination for events with N_pad $>$ 100 (the sensitivity increases by a factor of 1.1).

The arrival directions of selected showers are also corrected for systematic error due to partial sampling of the shower front when the core is near the detector edge [**?**]. This systematic error is related to the angle between the vector "shower core-detector center" and the shower arrival direction. For events with N_pad $>$ 100, for which the core position is determined with greater accuracy, the error can be considerably reduced.

These selections and corrections shrink the PSF by a factor ranging from 1.1 for events with N_pad = 20–39 to 1.5 for N_pad $>$ 1000. The PSFs obtained by simulating the Crab Nebula along its daily path up to = 45° are shown in Figure 2 [Figure 2: see original paper] for different N_pad intervals.

To describe the PSFs analytically (they cannot be simply fitted by a two-dimensional Gaussian function for small N_pad values), the simulated distributions have been fitted with a linear combination of two Gaussians. In general, when the PSF is described by a single Gaussian (F(r) = 1/(2 ^{2}) exp(−r^2/ ^{2}), where r is the angular distance from the source position), the root mean square is commonly defined as the "angular resolution." In this case the fraction of events within 1 is 39%. For our PSFs, the value of the 39% containment radius R ranges from 0.19° for N_pad $>$ 2000 to 1.9° for N_pad = 20–39. Table 1 reports the R values for different N_pad intervals, together with the core position error after quality cuts, as obtained by simulating the source during its daily path in the ARGO-YBJ field of view.

2.3. Energy Measurement

The number of hit pads N_pad is the observable related to primary energy that is used to infer the source spectrum. In general, the number of particles at ground level is not a very accurate estimator of the primary energy of a single event due to large fluctuations in shower development in the atmosphere. Moreover, for a given shower, the number of particles detected in a finite-area detector like ARGO-YBJ depends on the position of the shower core relative to the detector center; for small showers this is especially poorly determined.

The relation between N_pad and primary gamma-ray energy for showers surviving the selection cuts is illustrated in Figure 3 [Figure 3: see original paper], which shows the corresponding primary energy distributions for different N_pad intervals, obtained by simulating a Crab-like source with a power-law spectrum with index −2.63. The distributions are broad, with extended overlapping regions spanning more than one order of magnitude for small N_pad values. The median energies for different N_pad intervals are given in Table 1 , ranging from 340 GeV for events with N_pad = 20–39 to 18 TeV for N_pad > 2000.

Since the variable N_pad does not allow accurate measurement of the primary energy of individual events, the energy spectrum is evaluated by studying the global distribution of N_pad. The observed distribution is compared to a set of simulated distributions obtained with different test spectra to determine the spectrum that best reproduces the data.

3. The Crab Nebula Signal

The dataset used for this analysis contains all events recorded from 2007 November to 2013 February with N_pad 20. The total on-source time is 1.12 × 10 hours. For each source transit, the events are used to fill a set of nine 12° × 12° sky maps centered on the Crab Nebula position, with a bin size of 0.1° in right ascension and declination ("event maps"). Each map corresponds to a defined N_pad interval: 20–39, 40–59, 60–99, 100–199, 200–299, 300–499, 500–999, 1000–1999, and N_pad 2000.

To extract the excess of gamma rays, the cosmic-ray background must be estimated and subtracted. Using the time swapping method [?], shower data recorded in a time interval Δt = 2–3 hours are used to evaluate "background maps," i.e., the expected number of cosmic-ray events at any location in the map for the given time interval. This method assumes that during Δt the shape of the distribution of arrival directions of cosmic rays in local coordinates does not change, while the overall rate may change due to atmospheric and detector effects.

The value of Δt is less than a few hours to minimize systematic effects from environmental parameter variations that could alter the distribution of arrival directions. The time swapping method is a sort of "simulation" based on real data: for each detected event, n_f "fake" events (with n_f = 10) are generated by replacing the original arrival time with new ones randomly selected from an event buffer spanning the Δt data-taking period. By changing the time, the fake events maintain the same declination as the original event but have different right ascension. With these events a new sky map (background map) is built, with statistics n_f times larger than the event map to reduce fluctuations.

To avoid inclusion of source events in the background evaluation, showers inside a circular region around the source (with radius related to the PSF and depending on N_pad) are excluded from the time swapping procedure. A correction on the number of swaps is applied to account for rejected events in the source region [**?**].

Event and background maps are then smoothed according to the PSF corresponding to each N_pad interval. Finally, the smoothed background maps are subtracted from the smoothed event maps, obtaining "excess maps" where for every bin the statistical significance of the excess is calculated as:

= (N_E − N_B) / √(N_E² + N_B²)

with N_E = Σ_i n_i w_i and N_B = Σ_i b_i w_i / n_f. In these expressions, n_i and b_i are the numbers of events in the ith bin of the event map and background map, respectively, w_i is a normalized weight proportional to the PSF value at the angular distance of the ith bin, and n_f is the number of swappings. The sum is over all bins inside a radius R_max chosen to contain the signal events and depending on the PSF. Since the number of events per bin is large, fluctuations follow Gaussian statistics, hence the errors on N_E and N_B are: N_E = √(Σ_i n_i w_i²) and N_B = √(Σ_i b_i w_i² / n_f²).

The number of gamma-ray events from the source is:

N_ = N_E − N_B = ^{R_max} [N_E(r) − N_B(r)] 2 r dr = ^{R_max} w(r)² 2 r dr

where w(r) is the weight used in the smoothing procedure calculated at angular distance r from the source position.

When adding all data, an excess consistent with the Crab Nebula position is observed in each of the nine maps, with total statistical significance of 21.1 standard deviations. The number of excess events is 1.05 × 10 , corresponding to 189 ± 16 day ¹, where a "day" means a source transit. Table 2 gives the signal significance for each map and the corresponding event rates measured from the source. For comparison, background rates measured inside an angular window of 1° radius around the source are provided. Figure 4 [Figure 4: see original paper] shows the total significance map.

Finally, the gamma-ray signal can be used to check the detector angular resolution since the Crab Nebula angular size is small compared to the detector PSF. Figure 5 [Figure 5: see original paper] shows the distribution of arrival directions of excess showers relative to the source position for N_pad 20, 100, and 500, compared to simulations. The agreement is excellent.

4. Energy Spectrum

The energy spectrum is evaluated by comparing the number of events detected from the Crab Nebula in the previously defined N_pad intervals to the expected number from simulation assuming a set of test spectra. We consider the power-law spectrum:

dN/dE = I (E/2 TeV)

where the flux normalization I and slope   are parameters to be estimated through the fitting procedure.

The fit is performed by minimizing the ^{2} value, evaluated for any parameter pair as:

^{2}(I ,) = Σ_{j=1,9} (N_ ^j − N_MC^j(I ,))^{2} / (N_ ^j)^{2}

where N_ ^j and N_MC^j are the numbers of detected and expected events, respectively, in the jth N_pad interval.

The obtained best-fit parameters are I = (5.2 ± 0.2) × 10 ^{11} photons cm ^{2} s ^{1} TeV ^{1} and   = 2.63 ± 0.05, with ^{2} = 5.8 for 7 degrees of freedom, corresponding to a p-value p = 0.56. The integral flux above 1 TeV is 1.97 × 10 ^{11} photons cm ^{2} s ^{1}. The flux at 1 TeV obtained in this work is 7% higher than that reported in a previous ARGO-YBJ paper [?]. The difference is due to correction of event rates applied in this work to reduce environmental and detector effects on the trigger rate, as described in Section 5.3.

Figure 6 [Figure 6: see original paper] shows the obtained spectrum compared with results from other experiments. The energy of each point is the gamma-ray median energy for the corresponding N_pad interval. Energy and differential flux values are given in Table 2 . The spectrum is consistent with a constant slope from 300 GeV to 20 TeV and agrees rather well with measurements by HEGRA and MAGIC, whereas the HESS and Milagro fluxes are about 20% higher in the 1-10 TeV energy range.

The data are less clear concerning a possible energy cutoff at higher energies. MAGIC [?] and HESS [?] show steepening below 20 TeV, while the HEGRA spectrum is harder and continues with slight softening up to 75 TeV [?]. A possible cutoff is also observed by Milagro at 30 TeV [?]. The limited statistics of our data at high energy do not allow conclusions about spectral properties above 20 TeV. Selecting events with N_pad > 3000 (median energy 26 TeV assuming a power-law spectrum with index   = 2.63) yields signal statistical significance of 0.75 .

When fitting the data with a power-law spectrum with exponential cutoff:

dN/dE = I (E/2 TeV)   exp(−E/E_cut)

the obtained p-value is always smaller than without a cutoff, for any E_cut value. For E_cut = 14.3 TeV (the best-fit value obtained by HESS) the p-value is 0.13. We find that the p-value exceeds 10% for any E_cut > 12 TeV, indicating that the presence of a cutoff above 10 TeV cannot be excluded, though our data seem more consistent with a pure power law.

4.1. Estimation of Systematic Errors

These results may be affected by systematic errors of different origins. Below we discuss possible sources of systematics, evaluating their effects on both flux normalization and spectral slope.

1. **Energy scale**: In our measurement the number of hit pads N__pad is used as an estimator of primary energy. The relation between primary energy and N__pad is given by Monte Carlo simulations. Possible uncertainties and simplifications in the simulation procedure (both in shower development and detector response) could produce incorrect N__pad values and consequently errors in the energy scale.

The energy scale reliability has been checked using the Moon shadow. Due to the geomagnetic field, cosmic rays are deflected according to their energy, and the shadow that the Moon casts on the cosmic-ray flux is shifted relative to the Moon position by an amount depending on energy. The westward shift of the shadow has been measured for different N__pad intervals and compared to simulations. From analysis of Moon data, we found that the total absolute energy scale error is less than 13% in the proton energy range 1–30 TeV [**?**]. This estimate includes uncertainties in cosmic-ray elemental composition and the hadronic interaction model. From this result, for a gamma-ray spectrum with index $= 2.63$, the corresponding systematic error in flux normalization would be less than 22%.

2. **Pointing error**: Fitting the angular distribution of gamma rays around the Crab Nebula position, we found the pointing error to be less than 0.1°. A pointing error affects the measured gamma-ray flux since the number of photons is obtained through a smoothing procedure weighting events with a PSF centered at the source nominal position. An incorrect position would produce signal loss. Since the PSF is narrower for events with large N__pad, the loss is greater at high multiplicities and generates spectrum steepening. According to our simulation, a pointing error of 0.1° would produce signal loss ranging from 0.1% for N__pad = 20–39 to 6.0% for N__pad > 2000. Consequently, the spectral index would increase by 0.01 and flux normalization would decrease by 2%.

3. **Background evaluation**: Our measurement is based on very precise background evaluation. As explained in Section 3, the number of gamma rays is given by the difference between events detected in the event map (containing source events plus cosmic-ray background) and background events estimated with the time swapping method. Since the ratio between gamma-ray and background events is very small (ranging from 10 for N__pad = 20–39 to 10^{2} for N__pad > 300), even a small systematic error in background evaluation could produce large errors in source flux.

Possible systematic sources include: (a) cosmic-ray excess regions due to medium-scale anisotropy near the source [**?**], (b) changes in atmospheric conditions modifying the background distribution in local coordinates on timescales shorter than 2–3 hours, and (c) detector malfunctioning. Such effects, when present, could generate extended regions in the signal map with evident excesses or deficits, in some cases involving the whole map. Instead, accurate background evaluation produces maps with all bin contents consistent with zero except at positions of real sources.

Concerning medium-scale anisotropy, we adopted a particular procedure to correct background systematics in sky regions coincident with or adjacent to cosmic-ray excesses [**?**]. This correction is not necessary in the Crab Nebula region. Concerning points (b) and (c), maps are built with 2–3 hour datasets and individually checked. When a map shows significant anomalies, the corresponding dataset is rejected, so only "good maps" are combined to build the "total maps."

To test background reliability of the total maps, we use regions not involved in Crab Nebula emission, i.e., bins with angular distance from the source larger than a minimum value depending on the PSF. From these "out-source" regions we expect no significant excess, since they do not include any other known gamma-ray source with flux above the ARGO-YBJ sensitivity. For each of the nine maps we evaluated the distribution of excesses in out-source region bins (before smoothing). All distributions are well described by Gaussian functions with mean values consistent with zero and r.m.s. consistent with unity.

Adding all nine maps together, the total number of events from out-source regions is 1.18×10 , differing from the corresponding estimated background by -9.3×10^3 events, corresponding to -0.3 standard deviations. Since there is no significant excess or deficit, we can calculate the upper limit of systematic error in the out-source region. The relative error in the background value is less than 3.7×10 at 90% confidence level.

We reasonably assume that similar systematic error affects the region containing the source signal, and that all nine maps have comparable systematic errors. Based on these assumptions, we evaluate the effects of such error on the signal, which are more relevant for maps with smaller signal-to-background ratio. The error in photon number is <13% for N_pad = 20–39, <1% for N_pad = 100–199, and <0.01% for N_pad > 1000. According to these values, the corresponding systematic error in spectrum flux normalization would be less than 2%, and the error in spectral index would be less than 0.05.

4. **Event rate variations**: Studying the cosmic-ray shower rate over five years, we observed variations on timescales from hours to months up to 10% relative to the mean value. These variations are mostly due to: (a) atmospheric pressure and temperature variations modifying shower propagation, (b) detector efficiency variations from local temperature and pressure changes, and (c) detector aging. Gamma rays are assumed subject to similar variations.

To study the stability of the Crab Nebula flux, we corrected the rate of events observed from the source using the cosmic-ray rate as a normalization factor (see

Section 5.3). However, absolute normalization cannot be performed. Monte Carlo simulations refer to fixed atmospheric conditions and given detection efficiency that cannot exactly reproduce the average effect over several years of varying conditions. Considering the magnitude of observed rate variations, a reasonable estimate indicates possible systematic flux error smaller than 4%.

Total systematic error: Adding all contributions linearly, we conservatively estimate the total systematic error to be less than 30% for flux normalization and 0.06 for the spectral index.

5. Crab Nebula Light Curve

To study the stability of Crab Nebula emission, we consider events with N__pad 40. Our total dataset consists of 1851 days with average observation time of 6.0 hours per day. The average rate of events with N__pad 40 is 137 ± 10 day ^{1}.

Figure 7 [Figure 7: see original paper] shows the observed rate for events with N__pad 40, 100, and 500 as a function of Julian date in 200-day bins. The median energies corresponding to these N__pad thresholds are 0.76, 1.8, and 5.1 TeV, respectively. The signal appears stable during five years for any threshold within statistical fluctuations. Assuming a constant rate, the obtained ^{2} values are 15.7, 3.27, and 5.17 (with 9 d.o.f.) for N__pad 40, 100, and 500. The corresponding p-values are 0.073, 0.95, and 0.82, respectively.

A six-year monitoring of the Crab Nebula was previously performed by the Tibet-III air shower array from 1999 to 2005 at energies >3 TeV, with sensitivity 3-4 times lower than ARGO-YBJ, reporting yearly flux consistent with steady emission [**?**].

5.1. Search for Flares

To perform a "blind" search for short-term rate variations, we consider all time intervals of duration Δt ranging from 1 to 15 days, starting from every observation day. This range was chosen based on flare durations observed in the GeV energy region. For each interval we compare the observed rate of Crab events with the average rate and evaluate the excess significance as:

_i = (R_i − R_m) / (R_i − R_m)

where R_i is the counting rate in the ith interval, R_m is the average counting rate, and (R_i − R_m) is the statistical error of the difference R_i − R_m. Note that _i values are not independent since time intervals overlap.

Figure 8 [Figure 8: see original paper] shows the _i distributions for Δt = 1 day and Δt = 2-15 days for N__pad 40. The total number of intervals is 1851 for Δt = 1 and 25911 for Δt = 2-15 days. The distributions can be fitted by Gaussian functions with mean value m = −0.04 ± 0.02 for Δt = 1 day and m = −0.06 ± 0.005 for Δt = 2-15 days. The root mean square values indicate rate variations slightly larger than expected from statistical fluctuations. However, no significant excess is observed for any considered time interval.

Given the ARGO-YBJ sensitivity, a flare would produce a 5 signal (pre-trial) if the flux exceeds the average value by a factor $f > 10 / \sqrt{\Delta t}$(days).

5.2. Correlation with Fermi-LAT Data

To reduce the number of trials in searching for possible flares, we can limit our analysis to days when a flare was observed by satellite instruments at lower energies. We consider the Fermi-LAT daily light curve at energy $E > 100$ MeV from 2008 August to 2013 February, obtained through analysis of scientific Fermi data publicly available at the Fermi Science Support Center[1].

The first panel of Figure 9 [Figure 9: see original paper] shows the daily light curve representing the sum of nebula and pulsar fluxes. The average flux is $(2.66 \pm 0.01) \times 10$ photons cm^{2} s^{1}. Even excluding days with flares, the rate is variable with modulations on timescales of weeks and months.

First we consider the three largest Fermi flares, which occurred in 2009 February, 2010 September, and 2011 April [**?**]. To define the time boundaries and duration of these flares we select days where the Fermi flux exceeds 4×10 photons cm^{2} s^{1}. The dates and durations of the three flares are given in Table 3 . The counting rates from the Crab Nebula measured by ARGO-YBJ with events having N_pad   40 during the flares are compared with the average rate of 137 ± 10 day^{1}. In all cases the rates are slightly higher than average but consistent within statistical errors (see Table 3). Summing the three flares, the average rate is 205 ± 91 day^{1}. Table 3 also shows results for events with N_pad   100 and 500. No significant excess is present in these cases either.

Our preliminary analysis reported in [**?**] showed a 4 excess in the interval 2010 September 17–22 from a direction consistent with the Crab Nebula. However, removing the contribution of the steady flux and accounting for the number of trials, the post-trial significance was about two standard deviations. A further excess with similar post-trial significance was observed during the 2011 April flare [**?**]. In the present work, based on improved shower reconstruction and event selection described in Section 2.2, the significance of the Crab Nebula signal integrated over 5 years increases by about 15% relative to the old analysis, but the signal observed during the Fermi flares decreases. The flux measured during the flares appears slightly higher than expected from steady emission but consistent within one standard deviation. Both our previous and current analyses hint at possible flux enhancement during flares, but the reduced significance prevents a definitive conclusion.

To extend the flare search to the entire observation period rather than limiting to the largest flares, we selected Fermi data according to measured daily flux and checked the corresponding ARGO-YBJ event rate. Table 4 reports ARGO-YBJ rates for different Fermi flux levels and N_pad thresholds. The rates are consistent with the average rate for any Fermi flux level. In particular, the ARGO-YBJ rate (for N_pad 40) measured in the 62 days when the Fermi flux exceeds 4 × 10 ph cm ^{2} s ^{1} is 190 ± 55 day ^{1}, i.e., 1.4 ± 0.4 times higher than the average rate.

Finally, to study possible correlation on timescales of months or years, we compare the light curves of the two detectors over the common observing time (4.5 years), dividing data into 200-day bins. The bin width is chosen to yield significant signal in the ARGO-YBJ data (about 7). Since the flux measured by Fermi is the sum of nebula and pulsar contributions, and since the pulsar flux F_P averaged over the pulsation period is stable during flares (F_P = (2.04 ± 0.01) × 10 photons cm ^{2} s ^{1} for E > 100 MeV [?]), the pulsar flux has been subtracted. The resulting average nebula flux is (6.2 ± 0.1) × 10 photons cm ^{2} s ^{1}. The nebula flux shows variations up to 30% of the average flux, with ^{2} = 126 for 8 d.o.f. (see second panel of Figure 9). The large variations are not only due to flares. The dashed curve in the same figure shows the flux obtained excluding the 62 “flaring days.” In this case the average value is (5.6 ± 0.1) × 10 photons cm ^{2} s ^{1}, with ^{2} = 80.

The lower panel of Figure 9 shows the corresponding ARGO-YBJ data for N_pad 40. The average rate is 139.3 ± 10 events day ^{1} (^{2} = 14.2 for 8 d.o.f., p-value p = 0.077). Even if ARGO-YBJ rate variations are consistent with statistical fluctuations, the Fermi and ARGO-YBJ data seem to follow a similar trend. The ARGO-YBJ rate appears higher during “hot” Fermi periods. The dashed curve is obtained after excluding flaring days.

Figure 10 [Figure 10: see original paper] shows the ARGO-YBJ percentage rate variation relative to the mean value (ΔF_ARGO) as a function of the corresponding Fermi rate variation (ΔF_Fermi) for the nine bins of the light curve. The Pearson correlation coefficient between the two datasets is r = 0.56 ± 0.22. The quoted error for r is the root mean square of the distribution of correlation coefficients obtained by simulating fluctuations of the counting rates in each bin according to their statistical errors.

Fitting the nine points with the function ΔF_ARGO = a ΔF_Fermi + b, the best-fit parameters are a = 0.88 ± 0.37 and b = 0.018 ± 0.079, with ^{2} = 8.3 for 7 d.o.f. Discarding the 62 “flaring” days, the correlation coefficient becomes r = 0.45 ± 0.23 and the linear fit parameters are a = 0.96 ± 0.37 and b = 0.018 ± 0.082, with ^{2} = 10.4.

The same analysis has been performed using different bin widths from 10 to 450 days. The corresponding correlation coefficient steadily increases from r = 0.10 ± 0.23 (10 days) to r = 0.59 ± 0.22 (450 days). However, when using small bin widths, the ARGO-YBJ signal is not significant enough to search for correlation unless flux variations are very large. In 10 days, for example, the average ARGO-YBJ signal is 137 ± 135 events day ^{1}. Statistical fluctuations would hide possible flux variations unless the flux becomes more than 4–5 times higher than average.

These results refer to events with N_pad 40. The correlation coefficient is lower when selecting more energetic events: using a 200-day bin width, for N_pad 100, r = 0.31; and for N_pad 500, r = 0.46.

5.3. Stability of the ARGO-YBJ Data

When studying the time evolution of a signal over several years, discussion of possible detector instabilities is mandatory to exclude systematic effects that could produce artificial rate variations. Since the measured number of source events N_S = N_E − N_B is the difference between events detected in the source map and background events estimated with the time swapping method, one must separately analyze the stability of the different contributions.

1. A loss of signal events N_S could be produced by variations in pointing accuracy. Studying the Moon shadow month by month, we verified that pointing is stable within 0.1° [**?**]. Given the moderate angular resolution for events with N_pad 40, such variation could produce signal fluctuations of less than 2%.
2. A worsening of detector angular resolution (due to increased time resolution of RPCs at particularly low temperatures) could produce loss of signal events N_S. A broadening of the PSF would also cause decreased Moon shadow signal, which is found to be stable within statistical fluctuations.
3. Atmospheric pressure and temperature variations can affect RPC detection efficiency, which can also be altered by malfunctioning RPCs or aging effects.
4. Pressure and temperature produce changes in shower rate of a few percent due to different atmospheric propagation conditions.

The latter two effects modify N_S, N_E, and N_B by approximately the same factor (neglecting different behavior of cosmic-ray and gamma-ray showers, which is a second-order effect in this context). This allows use of N_B to correct the Crab rate, multiplying the Crab rate observed in a given time interval by correction factor f_c = B_m/B, where B_m is the average background rate and B is the background rate in that interval. The light curve in Figure 7 has been corrected by this method, with f_c ranging from 0.91 to 1.07.

Further possible systematics could involve incorrect evaluation of background N_B. In Section 4 we evaluated background accuracy for the total source signal. To check background accuracy over the years, we use the same out-source regions previously defined. For events with N_pad 40, the out-source light curve in 200-day bins has mean value −7.9 ± 19.0 events day ^{1} and ^{2} = 10.2 for 9 d.o.f., corresponding to p-value p = 0.67. These results indicate the background is stable and should not introduce systematic effects on the Crab signal rate.

6. Summary and Conclusions

The ARGO-YBJ events recorded over five years have been analyzed to evaluate the Crab Nebula spectrum and study the temporal behavior of the gamma-ray emission. Using events with N_pad   20, the statistical significance of the gamma-ray signal exceeds 21 standard deviations, and the observed photon rate is 189 ± 16 day ^{1}. The event and angular distributions around the source are well described by PSFs obtained from simulations.

The source spectrum extends over nearly two decades in energy and five decades in flux. The spectral shape is consistent with power-law behavior in the range 0.3–20 TeV with spectral index 2.63 ± 0.05. An exponential cutoff would be consistent with our data only for cutoff energy higher than 12 TeV at 90% confidence level.

The Crab Nebula light curve has been studied to check flux stability over years and search for possible flares on daily timescales. All known sources of rate instabilities have been examined and their effects corrected.

Concerning flares, a blind search for flux increases of duration 1–15 days shows no significant excess. The average rate of events with N_pad   40 measured by ARGO-YBJ during the three most powerful flares detected by Fermi-LAT (in 2009 February, 2010 September, and 2011 April) is 205 ± 91 day ^{1}, consistent with the average value of 137 ± 10 day ^{1}.

The five-year ARGO-YBJ light curve with 200-day binning is consistent with constant flux with probability 0.07. A correlation analysis with corresponding Fermi-LAT data yields Pearson correlation coefficient $r = 0.56 \pm 0.22$. The small statistical significance of these results does not allow claiming flux variability correlated with observations at lower energies. If such correlation were due to a real astrophysical phenomenon, the found regression coefficient $a = 0.88 \pm 0.37$ would imply similar percentage variation in Fermi and ARGO-YBJ rates, suggesting similar behavior of gamma-ray emission at energies >1 TeV.

Thus far, no variation of the Crab Nebula flux at TeV energies has been reported by any detector. Assuming the flares observed by AGILE and Fermi are due to synchrotron radiation from electrons accelerated up to 10^{1} eV, the associated inverse Compton emission would occur in the Klein-Nishina regime and produce gamma rays of energy approximately equal to that of the electrons. Such flux would not be detectable by existing gamma-ray experiments. With these assumptions, a TeV excess could hardly be interpreted as IC emission associated with synchrotron radiation observed at lower energies and would require completely new interpretation.

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[1] http://fermi.gsfc.nasa.gov/ssc/data/access/

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