Experimental Gamma-Ray Astronomy

David Paneque
Max-Planck-Institut für Physik, Munich, Germany
E-mail: dpaneque@mppmu.mpg.de

Abstract. Our knowledge of the γ-ray sky has dramatically changed due to the advent of the new ground-based Imaging Atmospheric Cherenkov Telescopes (H.E.S.S., MAGIC and VERITAS) and the satellite-borne instruments (AGILE and Fermi). These facilities boosted the number of γ-ray sources by one order of magnitude in the last 6 years, providing us with about 2000 sources detected above 100 MeV (from space) and about 100 sources detected above 100 GeV (from the ground). The combination of this large leap in experimental capabilities together with the fact that the Universe is still quite unexplored at these extreme energies is evidence of a large scientific discovery potential that will surely make the decade 2010–2020 a golden age for γ-ray astronomy. In this manuscript I provide a subjective review of some of the most exciting observations from this rapidly evolving field during the last two years.

1. Introduction
The field of γ-ray astronomy is a very novel discipline which started to mature during the last 1–2 decades. The sensitivity, angular resolution and the number of γ-ray instruments is still quite limited when compared with astronomical observations performed at other more conventional portions of the electromagnetic spectrum, like radio, optical or X-ray energies. But the current instrumental limitation is precisely what makes γ-ray astronomy a very exciting and challenging field of research. From the instrumental perspective, there is a lot of room for improvement at a rather moderate cost (in comparison with the large radio/optical/X-ray facilities); and from the scientific perspective there is an enormous discovery potential because the Universe is still quite unexplored at these energies.

At energies of a few tens of MeV, the γ-rays can be directly (and effectively!) detected with instruments operating from space. The detection is based on the conversion of the γ-ray into a $e^+e^-$ pair in a foil of a dense metal, together with the tracking and the energy measurement of the converted $e^+e^-$ pair using standard particle physics techniques (tracker+calorimeter). In these detectors, the rejection of the much more abundant cosmic-ray background is achieved by means of a charge particle anticoincidence shield covering the instrument. Because of the steeply falling γ-ray fluxes from even the brightest sources, at energies above 50–100 GeV, the sensitivity of space-based instruments is severely limited by the low number of photons collected in the ∼1m² size detectors. At energies above 100 GeV the most efficient way of detecting the γ-rays is through ground-based instruments that use the Earth’s atmosphere as a calorimeter and can...
achieve collection areas that are \( \sim 5 \) orders of magnitude larger than those achievable from space. There are basically two types of successful ground-based instruments for \( \gamma \)-ray astronomy: 
a) the Imaging Atmospheric Cherenkov telescopes (IACT), that detect the astronomical \( \gamma \)-rays through the Cherenkov light emitted by the \( e^+ / e^- \) from the \( \gamma \)-ray-induced electromagnetic showers in the atmosphere; and 
b) the particle detector arrays, that detect the astronomical \( \gamma \)-rays through direct measurement of the air-shower particles. The particle detector arrays provide a larger duty cycle (potentially by about one order of magnitude) and larger fields of view (by about two–three orders of magnitude) than the IACTs, but their performance is hampered by an inefficient rejection of the (much more abundant) cosmic-ray background, as well as by the reconstruction of the energy and direction of the incoming \( \gamma \)-ray using the exponentially decreasing number of shower particles far below the shower maximum. Therefore, even though current (or past) particle detector arrays like MILAGRO, Tibet AS and ARGO-YBJ have done some interesting \( \gamma \)-ray observations, this technique will probably not be competitive until the arrival of the next generation of instruments like HAWC or LHAASO.

The experimental observations that will be reported in this manuscript relate to results published or presented in conferences that use data from the current generation of ground-based IACTs, namely H.E.S.S., MAGIC and VERITAS, which have been in scientific operation since \( \sim 2004 \); and the space-based instruments AGILE and specially the Fermi Large Area Telescope (LAT), which have been in scientific operation since 2007 and 2008, respectively. These instruments represent a substantial technological improvement with respect to previous instruments operating at this portion of the electromagnetic spectrum, and hence have boosted our capability to perform \( \gamma \)-ray astronomy.

2. A subjective list of recent \( \gamma \)-ray observations

As mentioned above, the arrival of the new \( \gamma \)-ray instruments provides us with a wealth of possibilities that did not exist before, and that translates into a large number of relevant scientific results. I would need hundreds of pages in order to produce a fair summary of the most relevant \( \gamma \)-ray observations. Therefore, in this manuscript I can only attempt to report in a brief and incomplete manner (but hopefully comprehensible) about few of these results, which were selected according to the following criteria: 
a) the results were published or presented in conferences in the last 1–2 years, and mostly during the few months prior to the Taup 2011 conference; 
b) I tried to select experimental observations from different scientific topics in order to cover a large range of areas; 
c) I gave special attention to those results reporting the “unexpected”; 
d) I focussed mostly on results that were not presented at the Taup 2011 conference by other speakers. For instance, experimental results related to indirect searches of dark matter particles were extensively reported on Pasquale Serpico’s invited talk [85] and hence will not be covered in this manuscript.

One of the subjects that I reported in my oral presentation but unfortunately I had to skip in this document is the large number of results related to the detection and characterization of pulsars with Fermi-LAT: the large fraction (about 1/3) of radio-quiet pulsars indicating that the \( \gamma \)-ray beam is broader than the radio beam [84]; the large number (\( \sim 30 \)) of detected millisecond pulsars among the unidentified LAT sources [80, 65, 51, 66]; the surprisingly similar behaviour of the (old) millisecond pulsars in comparison to the (young) regular pulsars [4]; or the application of gravitational wave detection techniques together with large computing resources such as the Einstein@Home (http://einstein.phys.uwm.edu) to successfully find new pulsars in the Fermi-LAT data [79].

Another topic that was reported in the oral presentation, but I sadly had to skip in the proceedings, are the results related to the acceleration, propagation and interaction of cosmic rays through the observation of \( \gamma \)-rays in supernova remnants, which are believed to be one of the main sources of the charged cosmic rays we detect on Earth. The origin of these cosmic rays is a
mystery which even today (100 years after its first discovery) is not resolved, despite being one of the main motivations that led the foundation of the field of \(\gamma\)-ray astronomy. A case of special interest is that of RX J1713.7-3946, which is one of the brightest high-energy emitting supernova remnant, and the one where the shell glowing in \(\gamma\)-rays could be imaged for the first time [29].

As recently reported in [21], when combining the spectra from \textit{Fermi}-LAT and H.E.S.S one sees that the leptonic models are favored over the hadronic models, which somewhat contradicts the classical picture of supernova remnants being the cosmic-ray accelerators. On the other hand, hadronic models seem to be very successful in describing the combined \textit{Fermi}-LAT and IACT (H.E.S.S., MAGIC, VERITAS) spectra for many other supernova remnants [42, 17, 62]. In this proceedings I will also have to skip reporting on objects from our solar system like the quiet [12] and the flaring Sun [25, 88] or the terrestrial \(\gamma\)-ray flashes, which are very short (\(\sim 0.2–3\) ms) bursts of X-ray and \(\gamma\)-rays associated with powerful discharges during thunderstorms in the Earth atmosphere [90, 55].

2.1. The \(\gamma\)-ray sky

The advent of the new generation of \(\gamma\)-ray instruments improved dramatically our view of the Universe at these extreme energies. An easy way (but not the only one) of quantifying this improvement is by bringing into focus the increase in the number and the diversity of known \(\gamma\)-ray sources during the last decade.

In the energy range from 100 MeV to 100 GeV, customarily denoted by GeV energies, the number of sources known 10 years ago were essentially the ones listed in the 3rd EGRET catalog [63], which are shown in the left panel of Figure 1. The number of detected \(\gamma\)-ray sources was 271, containing 4 radio-loud pulsars and 1 radio-quiet pulsar, one solar flare, the Large Magellanic Cloud, and sources associated with the radio galaxy Centaurus A and with 93 blazars. The other 170 sources (63%) remained unassociated.

By summer 2011, the 2nd \textit{Fermi}-LAT catalog was made available to the scientific community [74]. This catalog is based on the average flux over the first two years of scientific operation of \textit{Fermi} (from August 2008 to August 2010), and reported the detection of 1873 \(\gamma\)-ray sources, which are shown in the right panel of Figure 1. The number of \(\gamma\)-ray sources that could be identified and associated amount to 127 and 1171 respectively; hence one order of magnitude larger than the ones known a decade ago (with EGRET). But not only the number of sources
Figure 2. Increase in the number of $\gamma$-ray sources detected at “TeV energies” in the last decade. Both sky images were retrieved from the online TeV catalog (http://tevcat.uchicago.edu/), and display the various $\gamma$-ray sources detected from ground $\gamma$-ray instruments. Most of the detections were performed by IACTs, which typically operate above 100 GeV. Left) $\gamma$-ray sources reported up to September 2001; Right) $\gamma$-ray sources reported up to September 2011.

increased, also the diversity in the classes of sources. Besides the type of objects reported in the 3rd EGRET catalog, the second Fermi-LAT catalog includes pulsar wind nebulae, supernova remnants, X-ray binaries and microquasars, globular clusters, regular galaxies as well as starburst and Seyfert galaxies, and even the detection of a Nova. Therefore, Fermi-LAT showed that the $\gamma$-ray sky is extremely rich and diverse. But even with the higher sensitivity and better point-spread function of Fermi-LAT (in comparison with EGRET), the number of $\gamma$-ray sources that could not be associated with known objects is relatively high: 575 (31%). It is believed that many of these objects will be identified with known classes of objects like blazars, radio-faint pulsars and supernova remnants. But there is also a large potential of discovering new classes of objects, which include the possibility of identifying objects where $\gamma$-rays are produced by the decay or annihilation of dark matter particles.

In the energy range above 100 GeV, typically denoted by TeV energies or Very-High-Energy (VHE), the improvement in our knowledge of the $\gamma$-ray sky during the last decade is similar to that at the GeV energies. The left plot in Figure 2 reports the ten TeV-emitting sources known by 2001, which had been detected with the so-called first generation of IACTs (Whipple, HEGRA, CANGAROO, Utah Seven Telescope Array, Mark 6 and GT-48). At the time, only 7 blazars, 2 supernova remnants and 1 pulsar-wind nebula were known.

The second generation of IACTs, namely H.E.S.S., MAGIC and VERITAS, started scientific operation in ~2004 and in only a few years they brought data that transformed our view of the high-energy $\gamma$-ray sky. The 127 TeV-emitting sources known by September 2011 are shown in the right plot in Figure 2. Apart from four sources that were first detected with the shower array instrument MILAGRO (MGRO J2019+37, MGRO J1908+06, Boomerang and Geminga), the other VHE-sources were first detected (and later on characterized) by IACTs. Besides the increase in the number of sources, we also learnt about new classes of VHE-emitting sources: pulsars, binary systems, globular clusters, star-forming regions, and starburst galaxies. Therefore, as occurred in the GeV range, the number of known TeV sources increased by one order of magnitude in the last decade, and new types of objects could be detected at these energies. The number of unassociated VHE-sources is 27 (21%) which is also a relatively large fraction of the known TeV-emitting objects. Unlike at the GeV energies, at the TeV energies the unidentified objects lie essentially on the Galactic plane only. But this could be an observational bias: while at GeV energies, the wide field of view (2.4 sr) and the survey mode operation of Fermi-LAT allows for a roughly (within a factor two) uniform exposure of the entire sky, at TeV energies the IACTs (the most sensitive instruments) have very narrow effective fields of
view (less than 4 deg) and the Galactic plane is the only large fraction of the sky that has been scanned with some level of detail, due to the dedicated survey of 2300 hours of pointed observations performed by H.E.S.S., which is the IACT with the largest field of view and the only one in the Southern hemisphere with good observation conditions for the Galactic plane [60].

In addition to performing studies on individual γ-ray sources, it is also very revealing to characterize and try to understand the diffuse γ-ray backgrounds. This type of studies benefits from a large field of view, like the one from the satellite pair conversion instruments (e.g. AGILE and Fermi-LAT) or the ground-based shower array instruments (e.g. MILAGRO, Tibet AS, ARGO-YBJ). As mentioned above, the current shower array instruments have moderate sensitivities (due to a relatively poor gamma/hadron separation), which precludes a precise measurement of these diffuse backgrounds at the TeV energies (see e.g. [46, 47, 2, 34]); and hence we may have to wait for the next generation of shower array instruments like HAWC and LHAASO. On the other hand, at the GeV energies the satellite-based instruments are able to detect and characterize very well these diffuse backgrounds, as I will show below.

One of the most interesting diffuse backgrounds is that of the extragalactic γ-ray background (EGB), which is the γ-ray component of the extragalactic background light (EBL) and brings information about the non-thermal activity throughout the history of the Universe. The EGB consists of the emission of unresolved γ-ray sources (e.g. blazars, γ-ray bursts, regular galaxies ...) and truly diffuse processes like ultra-high-energy cosmic-ray interactions with the EBL, or perhaps the decay or annihilation of dark matter particles in the Galactic halo or from cosmological sources. During 2011 many efforts were made to estimate the contribution to the EGB from the unresolved sources, using the knowledge acquired from Fermi-LAT data on the individual populations of resolved γ-ray sources. A brief overview of these results is shown in the left panel of Figure 3 (see [6, 23] for further information). The overall contribution from unresolved radio galaxies, flat spectrum radio quasars, blazars and star-forming galaxies can only account for 50-80% of the EGB. With the caveat that the measurement of the EGB is affected by a ~25% systematic due to uncertainties in the γ-ray foreground modeling, these studies suggest that there is room for additional components. A possibility may be the contribution from a new class of γ-ray sources, like the clusters of galaxies where γ-rays are expected to be emitted by the high-energy particles produced in the intergalactic shocks. Yet an even more stimulating discovery would be the association of the missing contribution (to the EGB) with a potential signature of the decay or annihilation of the long-sought dark matter particles.

One of the most unexpected and exciting recent experimental results related to large-scale diffuse structures is the evidence for an extended region with a high-energy γ-ray excess above and below the Galactic plane [87, 58]. These structures were called the Fermi Bubbles and are shown in the right panel of Figure 3. They extend about 50 deg from the Galactic plane, which implies a size of about 10 kiloparsec. The bubbles show up more clearly at the highest γ-ray energies because their spectrum \(dN/dE \sim E^{-2.5}\) is harder than that of the Galactic diffuse emission \(dN/dE \sim E^{-2.4}\) which is dominated by the inverse Compton scattering of electrons on the interstellar radiation field and γ-rays from the \(\pi^0\) decays from proton-interstellar medium collisions. It is worth mentioning that the brightness of the Fermi bubbles is comparable to that of the EGB, but their extension is about 15-20 times smaller. Consequently, even though they were not taken into account when computing the EGB spectrum shown in the left panel of Figure 3, their impact would be of only few percent (~5%), which is well below the quoted systematics (~20-30%) for this analysis (see [6, 23]).

The Fermi bubbles seem to be spatially correlated with the microwave excess known as the WMAP haze, and the edges of the bubbles also seem to line up with features in the ROSAT X-ray maps at 1.52 keV [87]. Since their discovery, there have been many theoretical interpretations of this observation. The conventional scenarios invoke quasar-like or Galactic-wind activity around...
Figure 3. Left) Extragalactic $\gamma$-ray background (EGB) as measured by Fermi-LAT above 200 MeV when using events with Galactic latitude $|b| > 10^\circ$ (black data points) and various bands reporting the estimated contribution from various unresolved point sources: star forming galaxies (grey band), BL Lacs (blue band), FSRQ (red band) and radio galaxies (hatched band). The width of the band reports the systematic error from the estimation. The yellow band reports the sum of all the previous components, where the errors from the single components are treated as independent. The lower panel shows the ratio between the sum of all the component and the EGB, which is the fraction of the EGB that can be explained with unresolved point $\gamma$-ray sources. Figure extracted from [23]. Right) Residual map (after subtracting all point sources) in the energy range 1-10 GeV showing the existence of $\gamma$-ray structures (so-called Fermi bubbles) emerging from the Galactic center and extending about 50 degrees to the North and South of the Galactic plane. Credit: NASA/DOE/Fermi-LAT /D. Finkbeiner et al.

the Galactic center [87], where the Galactic-wind could be produced by a high density of star formation [53], supernovae explosions [54] or periodic star capture processes by the Galactic supermassive black hole Sgr A* [50]. But there are also alternative scenarios in which the $\gamma$-rays are produced by relativistic electrons undergoing stochastic 2nd-order Fermi acceleration by plasma wave turbulence through the entire volume of the bubbles [70], or where the $\gamma$-rays are the result of dark matter particles annihilation [59]. There is quite a vigorous debate on the characteristics and the origin of the Fermi bubbles; but the point on which everybody agrees is that this is currently one of the most exciting experimental and theoretical puzzles in high-energy astrophysics.

2.2. Extragalactic sources

Active Galactic Nuclei (AGN) are the most luminous (persistent) sources in the Universe. In the unified scheme proposed in [92], AGNs are systems consisting of a supermassive ($M \sim 10^6-9 M_\odot$) black hole surrounded by an accretion disk. The matter in the disk falls into the black hole, converting a large fraction of the gravitational potential into energy that, in some cases, is used to launch jets of particles that move outwards with relativistic bulk velocity up to $\beta=0.9998$. Despite having been studied for several decades, the existing experimental data do not allow one to unambiguously determine the structure and physical processes working in these objects. There are still many open questions regarding AGNs: (a) the content of their jets, (b) the location and structure of their dominant emission zones, (c) the origin of their variability, observed on timescales from years down to minutes, (d) the role of external photon fields (including the EBL) in shaping their observed $\gamma$-ray spectra, and (e) the energy distribution and the dominant acceleration mechanism for the underlying radiating particles. A major drawback to understand these “extreme particle accelerators” was the poor sensitivity of the previous generation of $\gamma$-ray instruments, which precluded detailed studies at the highest photon energies, where many of
those objects emit about half of their total power. Fortunately, the experimental capabilities of the new generation of ground-based and satellite-based instruments improved the situation substantially and, as I will explain below, this is already helping us to advance our understanding of AGNs.

One of the big achievements is the large increase in the number of AGNs that have been detected at \( \gamma \)-ray energies. A large number of AGNs is necessary in order to understand the physical properties of the various AGN types and move towards AGN unification schemes (see e.g. [71]). This is particularly the case in the GeV energy range, where the Fermi-LAT collaboration reported in summer 2011 that, in the two-year dataset, there are about 1000 AGN sources [22]. At TeV energies, the number of detected AGNs is approaching 50, and increasing rapidly due to the many discoveries from the major IACT facilities (H.E.S.S., MAGIC and VERITAS) in the last 2 years (see http://tevcat.uchicago.edu/).

The other important experimental achievement is the organization and scientific interpretation of a large number of multi-instrument observing programs which provide simultaneous observations from radio to \( \gamma \)-ray energies. Given the variability and the broadband nature of the jet emission, these coordinated efforts from the community are crucial for a detailed and unbiased study of AGNs. Naturally, a big advantage with respect to previous campaigns is the sensitive coverage in the MeV/GeV/TeV range. This energy coverage permitted the characterization (at least in some cases) of the entire high-energy bump in the spectral energy distribution (SED), hence strongly constraining models for the blazar emission. An example is shown in the left panel of Figure 4, which reports the most complete contemporaneous SED collected for the BL Lac AGN Mrk 421 to date. The combination of the spectral observations from the new \( \gamma \)-ray instruments Fermi-LAT and MAGIC permits characterizing, for the first time, the entire high-energy bump spanning 5 orders of magnitude of energy without gaps. Similar broadband studies were made for several other AGN sources [32, 10, 11, 15]. Another asset of several of the current multi-frequency campaigns is the large effort to monitor the parsec-scale jet with mm-wave VLBA images, as well as to monitor the polarization at radio and optical frequencies, which reveals information about the structure and the dynamics of the jet. The blazar emission zone is unresolved by all instruments (with perhaps the exception of VLBA observations for some sources), and hence measurements of variability are the only way of probing its structure. Several works during the last 1–2 years [8, 69, 64, 26, 27, 78] have shown a clear correlation of some \( \gamma \)-ray outbursts with optical polarization changes and/or with the passage of radio knots through the core structure in the mm-wave VLBA images, which, for those sources, is believed to be a standing shock situated several parsecs away from the central engine. Therefore, at least for some sources and detected outbursts, the blazar emission has been pinpointed to be far away (1–10 parsec) from the supermassive black hole. Moreover, the TeV-flare correlated with the MeV/GeV flare, which was recently reported from the \( z \sim 0.43 \) flat spectrum radio quasar PKS 1222 [39], also suggests that the \( \gamma \)-ray emission (at least during these outbursts) originates several parsecs (or tens of parsecs) away from the broad line region. The location of the \( \gamma \)-ray emission along the jets is one of the most challenging open questions related to AGNs, and thus this is a major experimental observation that could be achieved in the last 2 years thanks to the new \( \gamma \)-ray instrument capabilities and the various efforts coordinating multi-instrument observations. It is worth stressing that the high-variability seen in \( \gamma \)-rays, which in some cases show flux-doubling timescales as short as few minutes, hence constraining the size of the emitting region to be comparable to the Schwarzschild radius for reasonable assumptions on the Doppler factors (e.g. see [37, 30]), led to believe that the \( \gamma \)-rays were produced close to the central engine. The above-mentioned observations from the last 2 years show that, at least for several sources and flares, this is not occurring. However, AGNs are complicated animals and some sources show evidence for high-energy emission produced both, close to the central engine and far away from it, as reported in [16] and references therein for
Gamma-Ray Bursts (GRBs) are events associated with very energetic explosions occurring in distant galaxies and typically lasting from a fraction of a second to a few minutes (prompt emission measured at the Earth). They are the most powerful non-persistent sources in the Universe, which allow for their detection from very large distances. The most distant GRB is GRB 090423, with $z \sim 8.1$ [82], hence being produced only $\sim 600$ million years after the Big Bang. Consequently, understanding GRBs is important, not only because of the extreme conditions in the environments where these explosions were produced, but also because they bring information from very early stages of the Universe.

In the last 2 years there has been substantial progress in the understanding of the high-energy $\gamma$-ray emission from GRBs thanks to the Fermi mission. The two instruments in the Fermi satellite, the LAT and the Gamma-Ray Burst Monitor (GBM), worked together to provide simultaneous coverage over the energy range extending from $\sim 10$keV to $\sim 100$GeV. During the first 3 years of operation (August 2008 to August 2011) there were 345-GBM-detected GRBs that were in the LAT field of view. The number of LAT-detected GRBs in this period is 32, which is substantially larger than the 5 GRBs detected by EGRET during its 9 years of operation. The progress is not only in the quantity of GRBs, but also in the quality with which these explosive objects could be studied. Besides the improved sensitivity, smaller dead time per measured $\gamma$-ray, and larger energy coverage of LAT (with respect to EGRET), during these last years, the GRB community also benefited from existing and very successful facilities like Swift (UVOT, XRT and BAT) and a large number of optical programs that provided essential information (like the determination of the redshift). The main characteristics of the 32-LAT-detected GRBs are summarized in the table shown in the right panel in Figure 4 [72]. The main experimental findings from the Fermi data are a) the onset of the $> 100$MeV (LAT) prompt emission is delayed with respect to the keV-MeV (GBM) prompt emission by less than a second in short GRBs and up to several seconds in long GRBs; b) the emission at $> 100$MeV (LAT) lasts minutes to hours longer than that at keV-MeV (GBM); c) some GRBs show an additional prompt hard power-law spectral component (e.g. see [19, 20]); and d) the high-energy ($> 10$ GeV) photons...
and the rapid variability allowed (through $\gamma \gamma$ opacity considerations) lower limits of about 1000 to the bulk Lorentz factors for some GRBs (e.g. see [3]) to be set. In addition to all this, the LAT-detected GRBs also could be used as tools to probe basic physics, like using the almost simultaneous MeV to GeV emission to set the most stringent constraints on Lorentz Invariance Violation [5], or using the highest-energy LAT photons to constrain the $\gamma$-ray opacity of the Universe and hence setting upper limits to the extragalactic background light (EBL) density [9].

GRBs have not yet been detected at VHE and hence only upper limits exist (e.g. see [1, 36, 83, 31, 38, 18, 43]). However, the delayed onsets, the temporally extended high-energy $\gamma$-ray emission (with respect to the keV-MeV emission) and the highest energy photons measured by Fermi-LAT (close to 100 GeV when correcting for the GRB redshift) implies that the VHE detection of a GRB with ground-based $\gamma$-ray facilities might still be possible.

2.3. Galactic sources
The two ground-breaking experimental results I report in this section come from the same location in the sky: the Crab nebula and pulsar.

The Crab nebula is the remnant of a supernova observed in 1054 AD, and it has been used for decades as a standard reference for calibrating $\gamma$-ray (and hard X-ray) instruments because it is the only source that is both steady and bright enough. However, during 2011 the AGILE and Fermi-LAT collaborations amazed the community by reporting that the Crab nebula had outbursts that changed its flux by factors of 3-6 during 2007, 2009 and 2010 [89, 14]. And subsequently it was reported that the $\gamma$-ray flux, as measured by Fermi-LAT, was actually variable on timescales of only half a day, and that the flux increased by a factor of $\sim$10 during these short time intervals [48]. $\gamma$-ray flux variations on timescales of about 1 year had been previously claimed in the energy range 0.75-30 MeV (a flux increase of $\sim$30%) with COMPTEL at a significance level of $4\sigma$ [73], and in the energy range 70-150 MeV (a flux decrease of $\sim$50%) with EGRET at a significance level of $3\sigma$ [56]. But the publications with AGILE and Fermi-LAT data in 2011 were the first ones reporting $\gamma$-ray variability with a confidence level above $5\sigma$. Moreover, the 2011 publications report variability on much shorter timescales (less than one day!) and with flux increases by a factor of up to 10. Later on, in April 2011 an even larger (by a factor of $\sim$3) flare from the Crab nebula was detected at $\gamma$-ray energies [86, 49]. The left panel in Figure 5 shows the light curve from Fermi-LAT during the first 3 years of scientific operation (until the Taup 2011 conference, September 2011). The three $\gamma$-ray flares detected by Fermi-LAT in 2009, 2010 and 2011 are clearly seen. During the large flare in April 2011, the photon statistics were high enough in the Fermi-LAT data to precisely characterize a new spectral component peaking at an energy of 375±26 MeV at the flare maximum. The variability with timescales of a fraction of day, the non-detection of correlated variability at neither keV energies [91] nor TeV energies (see below), the high frequency and brightness of the observed peak of the flaring $\gamma$-ray emission, and the spectral evolution during the flare seems to indicate that a) the flares were produced by synchrotron emission from PeV electrons, b) the emission region should have a size of less than $10^{-3}$pc and should be relativistically beamed towards the Earth with a Doppler factor of at least 2, and c) the variations in the Doppler factor are probably dominating the observed flux and spectral variability [49].

The IACTs MAGIC and VERITAS have never detected a significant $\gamma$-ray flux variability from the Crab, not even during the GeV flares occurring in September 2010 and April 2011 [75, 68, 52]. These observations were performed during moonlight conditions, which increases the energy threshold (minimum achievable $\gamma$-ray energy) and deteriorates slightly the sensitivity of the observations. But still, both MAGIC and VERITAS could exclude flux variations larger than 20%, which needs to be compared to the large variability (factors of few and up to 30 !) observed by AGILE and Fermi. Given the fact that IACTs have a better photon flux sensitivity than AGILE and Fermi-LAT to detect variations from the Crab on day (or shorter) timescales,
Figure 5. *Left*) Daily light curve above 100 MeV from the Crab nebula as measured by *Fermi*-LAT from the beginning of scientific operation until September 2011 (Taup 2011 conference). The 3 flares from 2009, 2010 and 2011 are clearly seen and marked in the plot. The daily flux values reported in the plot were extracted from the public NASA *Fermi* Science Support Center (http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_1c/); *Right*) Spectral measurements of *Fermi*-LAT, MAGIC and VERITAS of the emission from the Crab pulsar and Crab nebula. Figure extracted from [41].

This observation suggests that the Crab nebula is stable in the VHE domain. Yet there is currently a bit of controversy on this subject because the shower array ARGO-YBJ reported a hint of VHE variability (at a significance level of 4σ) during the GeV flares measured by AGILE and *Fermi* in 2010 and 2011 [35, 57].

The other remarkable (Galactic) γ-ray observation reported in 2011 is the detection of pulsed emission from the Crab pulsar up to 400 GeV with the IACTs MAGIC and VERITAS. Because of the limited space in this manuscript, and because there were two dedicated talks (and hence proceedings) on this topic at the Taup 2011 conference, I will be more brief than what I would have liked regarding this very exciting subject.

The detection of pulsed emission from the Crab pulsar with an IACT was first announced by the MAGIC collaboration in 2008 [44], but the spectral measurements in the VHE domain were not reported until 2011 by both the MAGIC and VERITAS collaborations [81, 45, 40, 41]. Together with the *Fermi*-LAT spectral observations (below 30 GeV), the MAGIC and VERITAS spectral measurements provide, for the first time, the determination of the γ-ray emission from a pulsar from 0.1 GeV to 400 GeV (more than 3 orders of magnitude !) without any gap. This is shown in the right panel of Figure 5. This experimental observation sets strong constrains on the pulsar emission models (at least the ones used for the Crab pulsar). The 2008 publication already discarded the super-exponential cut-off in the γ-ray spectrum, hence suggesting that high-energy photons had to be produced from a region far away from the neutron star in order to avoid a strong attenuation due to pair-production. The 2011 publications go one step further by excluding also the simple exponential cut-off and hence suggesting that the high-energy photons cannot be produced by curvature radiation. A possible physical scenario is that the VHE-pulsed emission occurs close to the light cylinder as a consequence of the inverse Compton scattering of secondary and tertiary electron pairs off magnetospheric IR-UV photons (see e.g. [40, 61]). An alternative and more exciting scientific interpretation is that the VHE photons are produced by inverse Compton scattering of the pulsed photons by the un-shocked pulsar wind outside the light cylinder [28, 33] or in the striped pulsar wind [77]. In such a framework, the VHE observations from MAGIC and VERITAS would be the first detection of the elusive pulsar wind and hence a major experimental observation. The signatures of the pulsar wind scenario in
the pulsed $\gamma$-ray spectrum from the Crab would be: a) an upward-kink in the transition region between the curvature radiation and the inverse Compton (from the pulsar wind) component and b) a strong cut-off at the energy $E \sim \Gamma_w m_e c^2$, where $m_e$ is the mass of the electron and $\Gamma_w$ is the Lorentz factor of the wind. Given that $\Gamma_w$ is expected to be $\lesssim 10^6$, the cut-off energy is expected to be $\lesssim 500$ GeV. As one can note from the spectra shown in Figure 5, the current statistical uncertainties preclude the precise determination of either of the two above-mentioned signatures, and thus further IACT observations of the Crab pulsar will have to be made in order to distinguish among the various models. However, the proposed physical scenarios should also be consistent with the measured (by Fermi, MAGIC and VERITAS) evolution of the pulse profile with energy. In that respect, the pulsar wind scenario recently proposed in [33] produces $\gamma$-ray pulses above 100 GeV that seem to be wider than the ones from the pulse profiles reported by the MAGIC and VERITAS collaborations [45, 40, 41], and hence not consistent with the currently available experimental observations. Further information on this experimental result and its scientific interpretation can be found at the publications cited above, as well as in the two dedicated presentations given at this conference [67, 76].

3. Conclusions and Outlook

The current $\gamma$-ray instrumentation can be used to study the acceleration and radiation of high-energy particles in a large range of environments, from the Earth’s atmosphere and the Sun to Galactic and extragalactic objects (up to $z=4.3$ [3], so far), as well as to study fundamental physics, cosmology and perform indirect searches for new particles.

The instrumentation for performing $\gamma$-ray astronomy evolved very fast during the last decade, which rapidly resulted in precision measurements of previously known sources, as well as the discovery of many more (including new classes) of sources, which allows for detailed population studies. There were many “expected” results, but also many “unexpected” observations that challenge our current theoretical understanding of the non-thermal Universe. In this proceedings I tried to report in a brief (but hopefully comprehensible) manner about some of the most relevant results reported in the last two years.

The impending upgrades of the three major IACT facilities (H.E.S.S., MAGIC and VERITAS), and the beginning of operation of the next generation of ground-based instruments (like HAWC, LHAASO and CTA), ensure dynamism and excitement in this field during the next 5–10 years. The combination of this large leap in experimental capabilities together with the fact that the Universe is still quite unexplored at these extreme energies indicates a large scientific discovery potential that will surely make the following years a golden age for $\gamma$-ray astronomy.

My only concern is that, while the future ground-based facilities for $\gamma$-ray astronomy are quite modular and hence relatively easy to upgrade, there is no clear plan to build another instrument that improves or even matches the performance of Fermi-LAT. Therefore, after this decade is over, we might be able to study the $>30–50$ GeV sky with unprecedented detail, but the Universe might look darker at energies in the range 0.1-30 GeV.

Acknowledgments

First, I want to thank my three week old daughter Ayame Esther, who effectively kept me awake during many long nights so that I could work on this document. In addition, I would also like to express my gratitude to Markus Ackermann, Rudy Bock, Pierre Colin, Gulli Jóhannesson, Stefan Klepser, Pablo Saz Parkinson, Takayuki Saito and Burkhard Steinke for fruitful discussions and for providing constructive remarks, and I specially want to thank Seth Digel for carefully proofreading the entire document. And finally, I would also like to thank the anonymous referee for very well organized and constructive remarks that helped shaping the final version of this document.
References
[1] Abdo, A. A. et al. 2007, ApJ, 666, 361
[2] Abdo, A. A., Allen, B., Aune, T., et al. 2008, ApJ, 688, 1078
[3] Abdo, A. A. et al. 2009, Science, 323, 1688
[4] Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, Science, 325, 848
[5] Abdo, A. A. et al. Nature, 462, 331-334, 2009.
[6] Abdo, A. A. et al. 2010, Physical Review Letters, 104, 101101
[7] Abdo, A. A., et al. 2010, ApJ, 708, 1254
[8] Abdo, A. A. et al. 2010, Nature, 463, 919
[9] Abdo, A. et al. 2010, ApJ, 723, 1082
[10] Abdo, A. A. et al., 2011 ApJ, 726, 43
[11] Abdo, A. A. et al., 2011 ApJ, 727, 129
[12] Abdo, A. A., Ackermann, M., Ajello, M., et al. 2011, ApJ, 734, 116
[13] Abdo, A. A. et al., 2011, ApJ, 736, 131
[14] Abdo, A. A., et al. 2011, Science, 331, 739
[15] Abramowski, A. et al., Astronomy & Astrophysics, Volume 533, id.A110
[16] Abramowski, A., Acero, F., Aharonian, F., et al. 2012, ApJ, 746, 151
[17] Acciari, V. A., Aliu, E., Arlen, T., et al. 2011, ApJL, 730, L20
[18] Acciari, V. A., et al. 2011, ApJ, 743, 62
[19] Ackermann, M. et al. 2010., ApJ, 716, 1178,
[20] Ackermann, M. et al. 2010., ApJ, 729, 114,
[21] Abdo, A. A., Ackermann, M., Ajello, M., et al. 2011, ApJ, 734, 28
[22] Ackermann, M. et al. 2011, ApJ, 743, 171
[23] Ackermann M. (on behalf of the Fermi-LAT collaboration), 7th TeV Particle Astrophysics conference, AlbaNova University Center, Sweden, 2011
[24] Ackermann, M. et al. 2011, Science, 334, 1103
[25] Ackermann, M., Ajello, M., et al. 2012, ApJ, 745, 144
[26] Agudo, I., Jorstad, S. G., Marscher, A. P., et al. 2011, ApJL, 726, L13
[27] Agudo, I., Marscher, A. P., Jorstad, S. G., et al. 2011, ApJL, 735, L10
[28] Aharonian, F. A., & Bogovalov, S. V. 2003, New Astronomy, 8, 85
[29] Aharonian, F., et al. 2006, A&A, 449, 223
[30] Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2007, ApJL, 664, L71
[31] Aharonian, F. A., et al., 2009, ApJ, 690,1068
[32] Aharonian F., et al., 2009, ApJL, 649, L150
[33] Aharonian, F. A., Bogovalov, S. V., & Khangulyan, D. 2012, Nature, 482, 507
[34] Aiedi, G., et al., 2010, Nucl. Instr. and Meth. A
[35] Aiedi, G. et al. (ARGO-YBJ collab.), The Astronomers Telegram #2921
[36] Albert, J. et al. 2007, ApJ, 667, 358
[37] Albert, J., et al. 2007a, ApJ, 669, 862
[38] Aleksic, J., et al. 2010, A&A, 517, A5
[39] Aleksic, J., et al. 2011, ApJL, 730, L8
[40] Aleksic, J., et al. 2011., ApJ, 742, 43
[41] Aleksic, J., et al. 2011, Accepted for publication in A&A, doi: 10.1051/0004-6361/201118166 (ArXiv e-prints 1109.6124)
[42] Aleksic, J., et al., accepted for publication in A&A, (ArXiv e-prints 1201.4074)
[43] Aleksić, J., et al., 2012, in preparation
[44] Aliu, E. et al. 2008, Science, 322, 1221
[45] Aliu, E. et al. 2011, Science, 334, 69
[46] Amenomori, M. et al., 2005, ApJ, 633,1005
[47] Amenomori, M. et al., 2006, Advances in Space Research, 37, 1932
[48] Balbo, M., Walter, R., Ferrigno, C., & Bordas, P. 2011, A&A, 527, L4
[49] Buehler, R., Scargle, J. D., Blandford, R. D., et al. 2011, arXiv:1112.1979
[50] Cheng, K.-S., Chernyshov, D. O., Dogiel, V. A., Ko, C.-M., & Ip, W.-H. 2011, ApJL, 731, L17
[51] Cognard, I., Guillemon, L., Johnson, T. J., et al. 2011, ApJ, 732, 47
[52] Cortina, J., et al. (MAGIC collaboration) 32th ICRC, Beijing, 2011.
[53] Crocker, R. M., & Aharonian, F. 2011, Physical Review Letters, 106, 101102
[54] Crocker, R. M., Jones, D. I., Aharonian, F., et al. 2011, MNRAS, 413, 763
[55] Grove, E., et al al, 3rd Fermi Symposium, Rome, 2011
[56] de Jager, O. C., et al. 1996, ApJ, 457, 253

12th International Conference on Topics in Astroparticle and Underground Physics (TAUP 2011) IOP Publishing
Journal of Physics: Conference Series 375 (2012) 052020
doi:10.1088/1742-6596/375/5/052020

References
57 de Mitri, I. (ARGO-YBJ collab.), *Highlights from the ARGO-YBJ Experiment*, this conference
58 Dobler, G., Finkbeiner, D. P., Cholis, I., Slatyer, T., & Weiner, N. 2010, ApJ, 717, 825
59 Dobler, G., Cholis, I., & Weiner, N. 2011, ApJ, 741, 25
60 Gast, H. et al., (on behalf of the H.E.S.S. collaboration) 32th ICRC, Beijing, 2011.
61 Lyutikov, M., Otte, N., & McClain, A. 2011, arXiv:1108.3824
62 Giordano, F., Naumann-Godo, M., Ballet, J., et al. 2012, ApJL, 744, L2
63 Hartman, R. C., Bertsch, D. L., Bloom, S. D., et al. 1999, ApJ Supplement Series, 123, 79
64 Jorstad, S. G., Marscher, A. P., Larionov, V. M., et al. 2010, ApJ, 715, 362
65 Keith, M. J., Johnston, S., Ray, P. S., et al. 2011, MNRAS, 414, 1292
66 Keith, M. J., Johnston, S., Bailes, M., et al. 2012, MNRAS, 419, 1752
67 Klepser, S. et al. (MAGIC collab.), *Phase-resolved Crab pulsar measurements from 25 to 400 GeV with the MAGIC telescopes*, this conference
68 Mariotti, M. (MAGIC collab.), The Astronomers Telegram #2967
69 Marscher, A. P., Jorstad, S. G., Larionov, V. M., et al. 2010, ApJL, 710, L126
70 Mertsch, P., & Sarkar, S. 2011, Physical Review Letters, 107, 091101
71 Meyer, E. T., Fossati, G., Georganopoulos, M., & Lister, M. L. 2011, ApJ, 740, 98
72 Michelson, P. (on behalf of Fermi-LAT collaboration) 32th ICRC, Beijing, 2011.
73 Much, R., et al. 1995, A&A, 299, 435
74 Nolan, P. L., et al., 2011, Accepted for publication in ApJ Supplement Series, arXiv:1108.1435
75 Ong, R. (VERITAS collab.), The Astronomers Telegram #2968
76 Otte, N. et al. (VERITAS collab.), *The Crab pulsar above 100 GeV*, this conference
77 Périé, J. 2011, MNRAS, 412, 1870
78 Pichel, A. & Paneque, D. (on behalf of VERITAS and Fermi collaborations) 32th ICRC, Beijing, 2011.
79 Pletsch, H. J., et al. 2012, ApJ, 744, 105
80 Ransom, S. M., Ray, P. S., Camilo, F., et al. 2011, ApJL, 727, L16
81 Saito, T. 2010, PhD thesis, Ludwig-Maximilians-Universität, München (ArXiv e-prints 1105.5400)
82 Salvaterra, R., Della Valle, M., Campana, S., et al. 2009, Nature, 461, 1258
83 Saz Parkinson, P. M. 2009, American Institute of Physics Conference Series, 1112, 181
84 Saz Parkinson, P. M., Dormody, M., Ziegler, M., et al. 2010, ApJ, 725, 571
85 Serpico, P., *Status of indirect detection*, this conference
86 Striani, E., et al. 2011, ApJL, 741, L5
87 Su, M., Slatyer, T. R., & Finkbeiner, D. P. 2010, ApJ, 724, 1044
88 Tanaka Y., et al, 3rd Fermi Symposium, Rome, 2011
89 Tavani, M., et al. 2011, Science, 331, 736
90 Tavani M., et al. 2011, Phys. Rev. Lett. 106, 018501
91 Tennant A. et al. 2011, The Astronomers Telegram #3283
92 Urry, C. M., & Padovani, P. 1995, PASP, 107, 803