The status of gamma-ray astronomy

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Abstract: Gamma-ray studies are an essential tool in our search for the origin of cosmic rays. Instruments like the Fermi-LAT, H.E.S.S., MAGIC and VERITAS have revolutionized our understanding of the high energy Universe. This paper describes the status of the very rich field of gamma-ray astrophysics that contains a wealth of data on Galactic and extragalactic particle accelerators. It is the write-up of a rapporteur talk given at the 32nd ICRC in Beijing, China in which new results were presented with an emphasis on the cosmic-ray related studies of the Universe.

Key words:

1 Introduction and General statements

This paper is intended to give a summary of the results reported from the sessions OG 2.1-2.5 of the 32nd ICRC that took place in August of 2011 in Beijing, China. The basis of this write-up is the Rapporteur talk on these sessions (available at http://indico.ihep.ac.cn/getFile.py/access?contribId=1388&sessionId=16&resId=0&materialId=slides&confId=1628) The aim of this paper is to give an overview over the vibrant field of gamma-ray astronomy at the time of writing (focusing on results presented at the ICRC but mentioning where necessary the bigger picture). Where appropriate I will use updated plots if journal publications have become available since the ICRC. The sessions in OG 2 cover topics related to the origin of cosmic rays (CRs) as probed by both X-ray and gamma-ray measurements. In particular, gamma-ray studies that address fundamental physics questions, such as the particle nature of dark matter are not part of OG2 (they are presented in HE3) and will thus not be part of this summary. Traditionally, only very few X-ray results are presented at the ICRC and in the following I will solely focus on the gamma-ray results. A total of 101 talks and 105 posters were presented. These were split into the different sessions as follows:

- OG 2.1: Diffuse X-ray and gamma-ray emission: 11
- OG 2.2: Galactic sources: 60
- OG 2.3: Extragalactic sources: 46
- OG 2.4: Gamma-ray bursts: 11
- OG 2.5: Instrumentation: 65

Taking a step back and looking at the overall situation of the field since the last ICRC two years ago, the field has clearly seen several important milestones.

- The Fermi-LAT team has released their first (1FGL) [1] and second (2FGL) [2] catalogs of the GeV sky. The 2FGL catalog contains 1873 sources and has important implications for the origin of cosmic rays in its own right but is also extremely important for the ground-based instruments that measure at higher energies to guide them towards interesting objects. The
The identification of the GeV sources is a very active field of study. In 2FGL 127 out of the 1873 2FGL sources are firmly identified (based on criteria such as correlated periodicity, correlated variability, or matching spatial morphology). Among those 127, 83 are pulsars, 28 are Active Galactic Nuclei (AGN), 6 are supernova remnants (SNRs), 4 are High-mass Binaries (HMB), 3 are Pulsar Wind Nebulae (PWNe), 2 are normal galaxies, and one is a nova. A larger number of 2FGL sources have positional associations (though no firm identifications) but 572 of the 2FGL sources are not even positionally associated with any object in the catalogs that have been searched. Given the very large number of unidentified sources interesting (and unexpected) physics might be waiting to be discovered.

- **MAGIC-II** has started operation by commissioning the second 17-m telescope and has reported first results at this ICRC [3, 4]. The energy threshold of the stereo system is 50 GeV for a Crab-like spectrum [4]. In addition, the two other large ground-based arrays VERITAS and *H.E.S.S.* continue to produce first-class science [5, 6] and are in the process of upgrading their systems which will improve sensitivity and lower the energy threshold in both cases.

- **HAWC**, a large water Cherenkov array in the Sierra Negra in Mexico [7], has started operation as a prototype array called VAMOS (with 7 out of the 300 tanks). A first skymap collected in 24 hours of lifetime with 4 of the VAMOS tanks was shown, including 16.6 million events with a threshold of 15 hit PMTs [8]. By the spring of 2012 the HAWC collaboration expects to have deployed 30 tanks which would give a sensitivity comparable to *MILAGRO*.

- The field is vibrant and lots of projects are ongoing (see Figure 1, showing the “ground-based gamma-ray world”). There seems to be a solidification of the techniques that are used in gamma-ray astronomy - we have learned how to build the best instruments. The main future projects use imaging atmospheric Cherenkov telescopes (as in the case of CTA) or a large array of water tanks (as in the case of HAWC) or a combination of them with added particle detector arrays (as in the case of LHAASO). These two main techniques are very complimentary to each other in terms of energy range, sky coverage and angular resolution and promise to provide exciting science well into the next decade. It should also be mentioned that two of the pioneering observatories of the field have stopped operation since the last ICRC: the **CANGAROO-III** array and the **Whipple 10m** telescope, the grand-father of all modern imaging Cherenkov telescopes∗).

*W. Benbow quoted T. Weekes during the ICRC on the Whipple 10m telescope as saying “Thank god for Mkn421!”

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Fig. 1. The ground-based gamma-ray world as of spring 2012, showing currently operating gamma-ray instruments that presented results at the 32nd ICRC in Beijing.
The success of the field can be illustrated by the number of sources detected at GeV and at TeV energies (see Figure 2). At the time of this writing 1873 GeV and 132 TeV sources are known and we have a good knowledge about the objects that dominate the GeV and the TeV sky. However, more importantly, the field is moving beyond quantity towards a qualitatively better understanding about the high-energy processes at work in these sources as will hopefully become apparent in this write-up. In the following, I will give my personal selection of highlights.

2 Diffuse emission Studies

The study of diffuse emission at the ICRC has focused mostly on the Galactic diffuse emission (as opposed to the isotropic extragalactic diffuse emission). The Galactic diffuse emission is produced by the interaction of CRs (protons, nuclei and electrons) with interstellar gas and radiation fields [9]. While diffuse emission is the dominant source of astrophysical photons at GeV energies (∼80% of all LAT photons are Galactic diffuse emission), at TeV energies this emission is sub-dominant, due to the rapidly falling spectrum compared to most galactic gamma-ray sources. Eleven contributions have been submitted to OG 2.1 Diffuse emission studies (Fermi-LAT: 3, TIBET: 2, ARGO-YBJ: 1, INTEGRAL: 1, MILAGRO: 1, Interpretation: 3).

The study of the diffuse emission has benefited tremendously from the launch of the Fermi-LAT representing a significantly improved instrument compared to previous ones in this energy range. The main result since the last ICRC (at which a thorough discussion on the absence of the EGRET excess was presented) came through the detection of the so-called Fermi bubbles [10] (see Figure 3). These residual (after removing the Galactic diffuse, and the bright sources) large-scale structures (scale height ∼10kpc if at the distance of the Galactic Center) are located towards the Galactic center and extend to large scale heights. Their main characteristics are not yet firmly established (a publication by the LAT team is still pending), but they seem to show rather hard energy spectra (compared to the Galactic diffuse). Whether they have sharp edges and whether they are symmetric with respect to the plane is more difficult to establish and seems to depend on the choice of the Galactic diffuse model that is removed [13]. If they are symmetric about the Galactic center, they are likely related to some past activity of the super-massive black hole in the center of our Galaxy.

![Fermi-LAT all-sky residual image after subtracting a diffuse model using photons in the range between 1 GeV and 10 GeV. Reproduced from nasa.gov, contributions by [10–12]. Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.](image-url)
decay of accelerated protons has been published elsewhere [14]. The general problem these models have to face are: a) the cooling time scales if assuming that the bubbles are generated by Inverse-Compton scattering accelerated electrons, b) the fact that there is no apparent limb-brightening in the emission but rather a flat-top profile and c) the total power in the emission at a distance of 10 kpc from the supermassive black hole. [11] explain the bubbles as generated by accelerated electrons through first-order Fermi-acceleration. The shocks are generated by the tidal disruption of stars by the central black hole which generated a system of hundreds of concentric shock fronts that accelerate electrons in the bubbles. These shocks are then thought to be constricted in the Galactic disk to generate the apparent pinched bubble shape. [12] suggest that the bubbles are generated by accelerated electrons through second-order Fermi-acceleration in plasma wave turbulence in the interior of the bubbles. Whether these explanation or the alternative hadronic scenario is correct is (at least) partially testable with Fermi-LAT data and it should be expected that by the time of the next ICRC we will have improved our understanding of these fascinating structures.

The Galactic diffuse emission is by itself a useful tool in studying Cosmic rays in our Galaxy. [15] presented an analysis of the Fermi-LAT observations of diffuse emission towards the outer Galaxy. This region has the advantage of not being susceptible to the distance ambiguity in the velocity separation of the gas and is suitable to study CRs associated with both arms and inter-arm regions. Two important conclusions were drawn from these studies: a) the shape of the emissivity spectra does not change significantly with Galactocentric distance but agree well with the model for the locally measured CRs. b) the Cosmic ray density (i.e. the emissivity normalization) is larger than expected in the outer regions of the Galaxy, pointing to a rather large CR halo (larger than 10 kpc) or a flatter CR source distribution than the canonical pulsars or supernova remnants. [16] summarized the results of the studies of the diffuse emission at TeV energies with ARGO-YBJ (a resistive place chamber array that has an energy threshold of ∼300 GeV). ARGO-YBJ detected diffuse TeV gamma-ray emission from two regions along the galactic plane described by a power-law with spectral index Γ = 2.9±0.3. The normalization is significantly larger than the expectation from the extrapolation of the Fermi-LAT diffuse emission, so unresolved sources might contribute to this emission in a significant way.

The Cygnus region also received considerable attention. It is the brightest region in gamma rays in the northern sky from GeV to multi-TeV energies and updates were presented by the Fermi-LAT, MILAGRO and VERITAS collaborations. [17] showed that the TeV emission seen by MILAGRO is dominated by two sources both of which seem to coincide with Fermi-LAT sources and which exhibit energy spectra up to ∼ 100 TeV. The higher-angular-resolution VERITAS array has performed a survey of the Cygnus region in 2007-2009 [18]. The observations resolve one of the two MILAGRO sources (MGRO J2019+37) into a very complex region consisting of at least one point-source coincident with the SNR CTB 87A, and an additional large-scale structure that coincides with the brightest part of the MILAGRO emission. At energies above 10 GeV, the Fermi-LAT also resolves a very complex structure in the Cygnus region consisting of diffuse emission and individual point sources [19]. One of the sources that can be detected when removing the galactic diffuse emission is the SNR γ-Cygni. When also removing this bright point-source at energies >10 GeV, a residual diffuse emission of size ∼ 10° can be detected coinciding with a region bounded by ionized gas (so-called Cocoon) that shows a rather hard energy spectrum. The interpretation put forward is that this feature shows freshly accelerated particles (combination of electrons and protons) that leave the γ-Cygni SNR and stream into a low-density cavity (see also [20]).

In summary, all these studies show that there is a large amount of information on Galactic cosmic rays that can be drawn from the study of the Galactic diffuse emission. The Fermi bubbles are residual structures that are clearly seen beyond a reasonable range of Galactic diffuse models. Their explanation is not straightforward but different models should be testable with LAT data in the future.

3 Galactic Sources (OG 2.2)

One of the main motivations for the study of Galactic gamma-ray sources has direct relevance for one of the main topics of this conference: the search for the origin of cosmic rays. However, as we have learned by now, the process is far from straightforward, given that competing processes emit gamma rays in the relevant energy range and one of the main challenges is to distinguish gamma rays emitted through hadronic processes (π0-decay) from those originating in leptonic processes (inverse Compton scattering and bremsstrahlung). Multi-wavelength
observations are one crucial ingredient in the quest
for separating the two and therefore the identifica-
tion of Galactic gamma-ray emitters with astrophys-
ical objects known at other wave bands is an impor-
tant prerequisite in the study of the origin of cos-
mic rays. Sixty contributions have been submitted to
*OG 2.2 Galactic Sources* (H.E.S.S.: 16, MAGIC: 7, Fer-

The last decade has shown that gamma-ray emis-
sion is prevalent and occurs in many different kinds of
sources. By now, several classes of objects are known
to emit gamma rays in the GeV and TeV band in
our Galaxy: supernova remnants (SNRs), and Pulsar
Wind Nebulae (PWNe) are by far the most abun-
dant ones as can be seen from Table 1, which lists the
firmly identified TeV objects. In addition, pulsars are
prevalent at GeV energies in the Fermi-LAT sky and
the most energetic Galactic one - the Crab - is now
also seen at higher energies (>100 GeV) with VERI-
TAS [21] and MAGIC [22, 23]. In addition, a handful
of gamma-ray binaries are now detected, mostly both
at GeV and TeV energies and in addition, one nova
has been observed by the Fermi-LAT team at GeV en-
ergies [24]. Also at GeV energies, globular clusters are
clearly detected, emitting gamma rays most probably
through the combined emission of their population of
milisecond pulsars (MSPs). This ICRC has seen a
report of a possible detection of the globular cluster
Terzan 5 with H.E.S.S. at higher energies [25]. The
slight offset of the gamma-ray emission from the cen-
ter of globular cluster and the rather large extension
of the emission is challenging for the Globular cluster
interpretation. The chance coincidence is however
quoted at the level of $10^{-4}$.

The H.E.S.S. Galactic plane survey, for a long
time a source of new discoveries has been expanded
since the last ICRC and now comprises 2300 hours of
data [26]. By now, over 60 sources of VHE gamma
rays have been found within its current range of
$l = 250^\circ$ to $60^\circ$ in longitude and $|b| \leq 3.5^\circ$ in lati-
tude and the sensitivity of the survey is below 2% of
the Crab flux everywhere within the survey region.
Interestingly, nearly a third of the sources detected
in this region remain unidentified or confused.

### 3.1 The Crab

At the time of the last ICRC there was no reason
to believe that we had not firmly understood the Crab
Pulsar and Nebula. The Crab Pulsar is the most en-
ergic pulsar in our Galaxy. The pulsed emission was
thought to be generated by curvature radiation in the
outer magnetosphere, following the detailed measure-
ments of the Crab pulsar with the Fermi-LAT. The
Crab nebula, the brightest steady TeV gamma-ray
source, was often used by ground-based instruments
as a test-source which was observed during the com-
missioning of a new instrument due to its flux stabili-
ty. The emission of the Crab nebula is comprised

<table>
<thead>
<tr>
<th>Object</th>
<th>Discovered</th>
<th>Year</th>
<th>Type</th>
<th>Method</th>
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<td>SNR</td>
<td>Morphology</td>
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<td>HEGRA</td>
<td>2001</td>
<td>SNR</td>
<td>Position</td>
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<td>2005</td>
<td>SNR</td>
<td>Morphology</td>
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<td>PWN</td>
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<td>$\gamma$-ray binary</td>
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<td>2006</td>
<td>$\gamma$-ray binary</td>
<td>Periodicity</td>
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<td>2006</td>
<td>PWN</td>
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<td>VERITAS</td>
<td>2010</td>
<td>SNR</td>
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of synchrotron and inverse Compton emission from relativistic electrons that were thought to be accelerated somewhere in the vicinity of the termination shock. The fact that the synchrotron emission extends to $\sim 100$ MeV was taken as a sign that the Crab Nebula could in fact accelerate particles to energies close to 1 PeV assuming that the acceleration happened in a region in which the magnetic field was close to the average field of $\sim 300 \mu$G for the nebula.

However, around the time of the ICRC several exciting new observations demonstrated that some of the old assumptions about the Crab pulsar and nebula were wrong: *The Crab Nebula Flares detected by AGILE and Fermi-LAT* [27, 28] and the detection of pulsed emission from the Crab Pulsar up to beyond 100 GeV [21, 23].

The overall spectral energy distribution (SED) of the Crab Nebula is well sampled from radio all the way to TeV gamma rays. The Fermi-LAT is observing in an interesting energy range, covering the band where the synchrotron emission drops sharply and the inverse Compton emission starts to rise (which happens at $\sim 100$ MeV). The TeV instruments have traditionally observed beyond the peak of the inverse Compton emission. MAGIC [4] reported their first stereo data, taken with MAGIC-II for which the first flux point is at 58 GeV, clearly the lowest energy threshold of all the operating IACTs. A joint MAGIC and Fermi-LAT data fit, constraining the peak of the Inverse Compton emission to $59 \pm 6_{\text{stat}}$ GeV, demonstrates that the combination of ground-based and space-based instruments have the capability to severely constrain the properties of the Crab Nebula. It should be noted that this ICRC also saw the first detection of the Crab Nebula with a compton telescope. [29] reported on a possible 4$\sigma$-detection with the NCT (Nuclear Compton Telescope) in the range between 0.2 and 2 MeV.

The first clear indication that something was not well understood came from simultaneous Fermi-LAT and AGILE detections of flaring episodes from the Crab Nebula in the highest-energy part of the synchrotron emission at energies around 100 MeV. In particular the Fermi-LAT observed a “superflare” in April 2011, where the flux in the synchrotron component increased by a factor of $\sim 30$ over the average emission. The doubling time was $\sim 8$ hours. Light-crossing time arguments point to an extremely compact region for the emission of the flares [28].

Studying the spectral evolution of the synchrotron component during the flares suggests that the flares are caused by relativistic beaming of a small-scale region within or close to the termination shock of the PWN. An alternative explanation was presented by [30] which employs a phenomenological model in which the gamma-ray flares are produced in large “knots” that are known from X-ray observations. Simultaneous high-angular resolution X-ray Chandra observations did not reveal any regions of significant variation in the nebula during the gamma-ray flares. At the ICRC, *ARGO-YBJ* reported a $\sim 3\sigma$ enhancement of the Crab flux during the LAT flare at a median energy of 1 TeV [31]. While not expected in the current models, it would be extremely interesting if those synchrotron flares could also be seen in the Inverse Compton component (it is expected at significantly higher energies than 1 TeV). However, such a flux enhancement of the IC component was not confirmed by the much more sensitive MAGIC [4] or VERITAS array [5], although their observations were not strictly simultaneous with the LAT flares. Also, non-detection of the 2007 AGILE-detected flare was reported with MILAGRO [32].

In addition to the exciting new observations on the Crab Nebula, the Crab Pulsar also received a lot of attention (see Figure 4 through the fact that both VERITAS [34] and MAGIC [35] report pulsed emission up to $\sim 400$ GeV. HAGAR [36] reported upper limits at energies $>250$GeV, albeit not at the sensitivity level of VERITAS and MAGIC. The spectrum of the Crab pulsar can be well fitted with a broken power law (as opposed to an exponential power law), clearly indicating that curvature radiation is not a likely mechanism at least for the high-energy emission (and possibly even for the whole emission from the Crab, given the smooth transition between the GeV and TeV spectrum). One possible radiation mechanism for the highest energy pulses is Inverse Compton scattering (e.g. from secondary pairs). Another interesting property is that the pulses seem significantly narrower than those measured by the Fermi-LAT, and that in addition the ratio of the amplitude of the two pulses changes with increasing energies. One possible explanation of this observed narrowing is that the region where acceleration occurs shrinks towards the neutron star with increasing energy. [37] presented an interesting possibility of doing Lorentz Invariance tests with pulsars, based on an idea by [38], by searching for a shift in the peak position of the Crab pulsar between the Fermi-LAT and VERITAS. While these limits currently are not competitive with the AGN and GRB observations done by the Fermi-LAT and IACTs, they do have the advantage of being able to more easily distinguish between source-intrinsic and
propagation effects and might be exploited competitively with a future instrument such as CTA.

### 3.2 Other PWNe

PWNe are still the dominant Galactic population of identified objects at TeV energies. The efficiency of converting spin-down power into gamma rays is typically in the range of 1-10% and a wide range of pulsar ages is seen. Interesting news in this area is that there is a growing number of objects where the pulsar has been detected with Fermi-LAT (often through a blind search procedure, e.g. [39]) and the PWN has then subsequently been detected with ground-based TeV instruments. Examples of this are the PWN in CTA 1, detected by both Fermi-LAT and VERITAS [18], and the gamma-ray emission in the complicated field of SNR G284.3-1.8 that was detected with H.E.S.S. and might comprise a PWN and a point-like source coinciding with the new Fermi-LAT detected γ-ray binary 1FGLJ1018.6−5856 [40].

![Fig. 4. Compilation of emission spectra from the Crab Pulsar (P1+P2) as measured by the Fermi-LAT [33], VERITAS [21] and MAGIC [23]. Reproduced from [23].](image)

### 3.3 Shell-type supernova remnants

The observations of shell-type supernova remnants is directly related to the origin of cosmic rays, given that these are the prime candidate sources for the acceleration of Galactic cosmic rays to the energy of the knee. While still no smoking gun (unambiguous) proof has been found to relate shell-type SNRs with the origin of cosmic rays, considerable progress has been made since the last ICRC, mainly through the release of the 1FGL and 2FGL catalogs. 2FGL lists 58 Fermi-LAT gamma-ray sources spatially coincident with SNRs and PWNe including such important objects as Cassiopeia A, Tycho’s SNR, the Cygnus Loop, W51C, W44 and IC443, and the TeV-bright SNRs RXJ1713.7−3946 and RXJ0852.0−4622 (Vela Junior). Before discussing individual objects in more detail, it is worth noting that combining measurements from Fermi-LAT and TeV instruments yields energy spectra over 5-6 orders of magnitude in energy.

Possibly the most prominent of these cases is the young (∼2000 years) SNR RXJ1713.7−3946 which was discussed by Aharonian in his summary talk [41] (see also Figure 5). This object has long been the best candidate for TeV gamma-ray emission stemming from hadronic interactions, although this claim has been extremely controversial. The Fermi-LAT measurements for this object resemble more what had been expected before those measurements in the case of a leptonic scenario [42] (making the case that protons might still be accelerated in the remnant but might not have enough ambient target density to interact and produce a flux of gamma rays that is larger than the leptonic “guaranteed” channel). However, Aharonian reminded that “life might be more complicated” and that the proton spectrum in a close-by molecular cloud might be extremely hard (Γ = 1.5) and the resulting gamma-ray spectrum could therefore fit the Fermi-LAT and H.E.S.S. data well. [44] presented the combined Fermi-LAT and VERITAS data for the young Tycho SNR in which again through SED modelling the leptonic model seems strongly disfavored. No cutoff is found in the VERITAS data and by equating the acceleration time to the SNR age, the maximum proton energy obtained is >300 TeV suggesting acceleration to close to the knee (see also [45]). However, Tycho’s SNR is a very weak source both in the Fermi-LAT data and for VERITAS and one should be careful in drawing strong conclusions from these faint sources. While the verdict on these cases might still be open, this should serve as a reminder that fitting the spectral energy distribution alone will render it extremely difficult to distinguish between hadronic and leptonic scenarios. A more robust smoking gun feature might be needed to settle this question in the future. One class of objects where this might ultimately be possible in the future are the GeV-bright mid-aged SNRs interacting with molecular clouds such as W51C or W44. The Fermi-LAT might ultimately be able to detect the pion-cutoff feature below 100 MeV. However, it should be stressed that such analyses will be very complicated due to
the combination of the bright Galactic diffuse emission and the rapidly changing effective area at these energies. [46] presented a study of W51C at TeV energies with the MAGIC telescope (see Figure 6). The bulk of the TeV gamma-ray emission coincides with shocked molecular material and suggests an extrapolation of the Fermi-LAT spectrum. Interesting in this regard is that MILAGRO detected a faint source at a median energy of 35 TeV coinciding with W51C. If this is correct, then a second spectral component might be emerging, something that will be tested with HAWC and CTA in the future.

This ICRC also saw the convergence of three of the eminences in our field: Drury, Aharonian and Völk were present and thus is was an appropriate question when [49] asked whether these three (also known as DAV) were right in their seminal paper in 1994 [50] in which they predicted the gamma-ray flux from SNRs if these were the sources of hadronic cosmic rays. [49] used the H.E.S.S. Galactic plane survey in conjunction with Green’s catalog of 274 radio SNRs and determined upper limits to the gamma-ray emission from SNRs that are not detected. The results indicate that the upper limits are in the right ballpark (acceleration efficiency around 10%), although significantly lower than that in some cases. As Drury put it at the conference: “DAV survived a falsification test. That doesn’t prove it, but it makes it a little more plausible.”

Further results were reported on deeper observations of Vela Junior with H.E.S.S. which suggests a very good agreement between the TeV gamma rays and the non-thermal X-rays from this object [51]. [52] reported on the discovery of $^{26}$Al in Vela Junior with COMPTEL and [44] showed results that demonstrate the detection of parts of $\gamma$-Cygni with the VERITAS array. Finally, an object that was not detected is SN 1987A in the LMC. [53] presented the expected gamma-ray flux from SN1987A. Shortly afterwards [54] presented deep H.E.S.S. observations that put upper limits below these expectations. This by itself it turned out was not a contradiction, because
the H.E.S.S. data were accumulated constantly over the last 6 years during which time the predicted flux significantly increased. Thus the direct comparison between the average flux upper limits over the last 6 years with the prediction for the gamma-ray flux of SN 1987A as it is today is somewhat misleading. The results show, however, that we might be very close to detecting this object. It would be extremely exciting to see this object evolve in gamma rays!

3.4 Binary Systems

Binary systems are objects that contain a neutron star or a black hole and a companion star. While relatively few binaries have been discovered at GeV and TeV energies, these objects are important testbeds of our understanding of particle acceleration in astrophysical objects. The periodic occurrence of the same environmental conditions for the accelerator makes these objects one of the closest things a gamma-ray astronomer can get to a physical "experiment" and can help to distinguish between external properties and the properties of the accelerator itself. Before the ICRC four gamma-ray binaries had been established at TeV energies (LS 5039, LS 1+61 303, PSR B1259−63 and possibly Cyg X-1). The picture might be similar to what has been described before for the Crab Nebula: the more data we collect, the more detailed and rich the systems appear. One example is that the light curves of several of the binaries show very complex behavior with long-term variability overlaid on top of the periodicity as e.g. demonstrated in LS 1+61 303 [55].

In addition, two objects have recently been confirmed to be binary objects through the periodic behavior of the emission: HESS J0632+057 at TeV energies and 1FGL J1018.6−5856 at GeV energies. HESS J0632+057 was first detected in the H.E.S.S. Galactic plane survey [56] and was unusual in being one of the very few point-like sources detected in the original survey. The multi-frequency data led [57] to suggest that this is a binary system, in spite of the fact that no periodicity had been detected at any wave band. Long-term SWIFT monitoring in X-rays established the periodicity of 321 ± 5 days recently [58], strongly suggesting a binary nature of the underlying object and thus making it the first gamma-ray binary detected at gamma-ray energies first. The combination of VERITAS and H.E.S.S. data folded with the orbital period detected by SWIFT shows first hints of a periodicity in the TeV data as well [59] (see Figure 7). This source is not detected at GeV energies with Fermi-LAT yet. 1FGL J1018.6−5856 might be another object of this class. It was detected with Fermi-LAT and subsequently found to exhibit periodic emission at a period of 16.6 days. H.E.S.S. also detects TeV emission from this region but the picture is more complex at higher energies [40]. H.E.S.S. detects a point-like source coinciding with 1FGL J1018.6−5856 on top of an extended structure which might be unassociated with the binary object. Finally, when discussing these systems, the most massive binary star system in our Galaxy, Eta Carinae, should be mentioned. Particle acceleration has been predicted in systems like Eta Carinae through shocks in the wind-wind interaction zone. The Fermi-LAT clearly detected Eta Carinae during periastron. Also, there seems to be relatively clear evidence for two spectral components in the GeV emission, suggesting two populations of particles. The low-energy component (measured from 0.5-8 GeV) shows a cutoff and is stable over time, while the high-energy component (above 10 GeV) is clearly varying with time [60]. The source of these two components is controversial. It could be either electrons responsible for the low-energy component through Inverse Compton scattering and protons responsible for the high-energy component through pion-decay [60], or two populations of electrons generated by the double shock structure of the wind-wind interaction zone [61]. It should be added that the 50-hour sensitivity curves for H.E.S.S. touches the extrapolation of the Fermi-LAT high-energy component, so this is certainly an interesting target also for TeV instruments in the future.

![Fig. 7. Folded gamma-ray light curve for HESS J0632+057, assuming a period of 321 days [58] as detected by SWIFT. Shown are H.E.S.S. (circular markers) and VERITAS (open square) measurements. The colors of the markers indicate the different periods of the observations. See [59] for details. Reproduced from [59].](image-url)
in deep observations of the LMC (90.4 hours) the H.E.S.S. collaboration [54] has detected a source coincident with the most energetic pulsar known (PSR J0537−6910) that is also known to have an X-ray pulsar wind nebula (detected with Chandra). The spectrum of the emission is rather soft ($\Gamma = 2.7 \pm 0.2$) but given the energetics, the amount of gamma-ray flux seems plausible ($\epsilon = 0.08$ where epsilon is the amount of spin-down power from the pulsar turned into gamma-ray emission). This source is therefore very likely a gamma-ray PWN and as such is the first of these objects detected outside our Galaxy. No detection of diffuse emission from this object at TeV energies has been reported.

4 Extragalactic Sources (OG 2.3)

The study of the extragalactic sky at gamma-ray energies has received a tremendous boost through the launch of the Fermi-LAT (see e.g. Figure 8). Beyond the wealth of information contained in the GeV data itself the Fermi-LAT catalogs coupled with the the all-sky monitoring of time-varying processes provides a very important guidance for the the scheduling of observations with the rather narrow-field-of-view ground-based TeV instruments. It should be stressed that while contemporaneous observations of the Fermi-LAT with HAWC and with CTA would be of great complementary value, the 10-year mission for the LAT is far from guaranteed. The ground-based community might benefit from pushing to support the Fermi-LAT mission extension that is currently under review. Forty-six contributions have been submitted to OG 2.3 Extragalactic Sources (MAGIC: 10, VERITAS: 9, H.E.S.S.: 5, ARGO-YBJ: 3, Shalon: 3, Fermi-LAT: 2, HAWC: 1, HAGAR: 1, CTA: 2, Interpretation: 10).

The extragalactic gamma-ray sky is completely dominated by active galactic nuclei (AGN). All major TeV facilities presented updates on their searches for extragalactic objects [62–65]. At TeV energies, 48 extragalactic objects have now been discovered. All are identified and all but two are AGN. These AGN are mostly (38) high-frequency BL LACs (i.e. sources with the jet pointing along the line-of-sight) although several Flat-spectrum radio quasars (FSRQs) have been discovered by now. 3 radio galaxies have been detected at TeV energies (Cen A, M 87 and NGC1275). At GeV energies the extragalactic sky ($|b| > 10^\circ$ has a significant number of unidentified sources. The only non-AGN sources detected at TeV energies are NGC 253 and M 82 [66], the most-massive close-by star forming Galaxies that are detected through their “galactic diffuse” gamma-ray emission. Both of these objects are also detected with the Fermi-LAT. In addition at GeV energies several local-group galaxies (LMC, SMC, M 31) as well as other star-forming galaxies have been discovered recently (NGC 4945, NGC 1068). These detections seem to confirm the relation between star-formation rate and gamma-ray luminosity, expected in the paradigm in which cosmic rays are accelerated by supernova remnants or other objects that are related to star-formation activity [67].

Various priors have been tested in the past two years to search for new extragalactic TeV sources. The most successful ones are a) based on Fermi-LAT data, using flaring sources at GeV energies to predict TeV variability [68] and also to look for hard-spectrum sources in the Fermi-LAT data b) optical monitoring campaigns to predict variability [62]. Based on these priors, the rate of detection of extragalactic objects has significantly increased over the past two years (see Figure 8).

![Fig. 8. Number of extragalactic TeV gamma-ray sources as a function of time. At the time of writing 48 sources are known, 43 blazar-like objects, 3 radio galaxies and 2 star-forming galaxies. Clearly an acceleration of the detection rate can be seen that coincides with the release of the first Fermi-LAT catalog (1FGL). Inset: Credit to Cosmovision, a group led by Dr. Wolfgang Steffen of the Instituto de Astronomia, UNAM, Ensenada, Mexico.](image)

In addition to increasing the number of detected objects on the extragalactic sky, several paradigm shifts have happened over the past three years. Instead of listing individual new results I would like to discuss in the following these changes in our study of the extragalactic sky that are apparent when comparing the results of this ICRC with earlier results.

- Strictly contemporaneous and broad-band sampling of spectral energy distributions (SEDs). As opposed to earlier times when SEDs were
assembled based on data that was not taken at the same times, an effort is now made to obtain data at the same time for different wavebands. This is particularly relevant for time-varying sources where changes in overall brightness are often accompanied by changes in the energy spectra. Given that the Fermi-LAT detects $\sim 90 - 95\%$ of all known extragalactic TeV-emitting objects, campaigns that involve the Fermi-LAT and several other instruments at higher and lower wavelengths have become feasible and are tried to be planned strictly contemporaneous.

- Related to the first item is that all the TeV instruments are involved in massive multi-wavelength campaigns (even cross-instrument collaborations at TeV energies). The most impressive of those is the multi-year campaign on M 87 [69] that involved VERITAS, MAGIC, H.E.S.S. (80 hours in total), the Fermi-LAT, Chandra, the HST and various other instruments all the way down to 1.7 GHz VLBA measurements (see Figure 9). 3-4 flaring episodes were detecting in these observations that provide a rich data set to study rise-and decay-times and spectral properties of flares in this close-by non-blazar AGN. Other examples of these large-scale multi-instrument efforts include the campaign on Mrk 421 and on Mrk 501 [71]. A further positive development in this regard is that members of the various TeV instruments are now conducting regular phone meetings and exchange observation schedules to coordinate the searches for extragalactic sources. This is particularly valuable as these large collaborations are starting to merge into one world-wide CTA community.

- The TeV instruments are now at a level of about a factor $\sim 50$ more sensitive than the brightest sources by moving into the sub-1%-Crab regime. Two consequences of this enhanced sensitivity are that detailed studies of the historical (and thus bright) TeV-emitting blazars (like Mrk421 and Mrk501) can be taken down to study 5-minute variability (see e.g. [71]) and that TeV instruments are starting to see more than one object in extragalactic fields of view (typically $3' \times 3'$), see e.g. [5, 62, 72, 73]. In hand with this paradigm shift goes that TeV instruments are now shifting their observation strategies to move towards higher-quality data sets of individual sources rather than trying to simply increase the number of sources (VERITAS announced that their observation schedule now has 40% of the time devoted to “discoveries” and 60% devoted to “deep observations”).

In terms of modeling the gamma-ray emission [62, 74, 75], all high-frequency BL-LACs (HBLs) can be described by synchrotron-self compton (SSC) models, while for the intermediate-frequency ones (IBLs) SSC combined with external compton fields are needed to fit the data. For FSRQs the situation is rather complicated and probably lepto-hadronic models are necessary to fully explain the data.

Beyond the IACTs with limited fields-of-view continuous monitoring with non-IACTs is performed. Currently this is only possible for the brightest TeV sources (such as Mrk421 and Mrk501). ARGO-YBJ reported of an absence of lags between the X-ray (SWIFT and RXTE), Fermi-LAT and the TeV emission in flares in these objects [76]. The situation will clearly change once HAWC comes online. [77] presented sensitivity estimates which showed that the

![Fig. 9. Multi-frequency light curve of M87 from 2001 to 2011. The VHE gamma-ray fluxes are calculated above 350 GeV. Gray vertical bands show times of increased VHE activity in 2005, 2008 and 2010. For details, see [70]. Reproduced from [70].](image-url)
detection of a factor of 5 increase in flux of Mrk421 will be detected within 1 day at the 5σ-level.

Galaxy clusters are the most obvious class of objects where a detection might be imminent. They are the largest gravitationally bound structures in the Universe and a reservoir of Cosmic rays is expected to be present, possibly confined to the cluster over Hubble times. In addition the annihilation of dark matter might produce a detectable signal in these objects. So far, no unambiguous firm detection of a galaxy cluster has been reported above hard X-rays and limits were presented that put severe constraints on the CR content in Galaxy clusters. MAGIC spent 80 hours on the Perseus cluster [78] and gamma-ray flux limits are now clearly below predictions from detailed cosmological simulations [79]. The TeV instruments and the Fermi-LAT will continue to search for a signal. One would hope to one day combine the data sets for a given objects (e.g. Perseus) between different instruments to arrive at even tighter limits (or detections).

Additional highlights of OG 2.3 include:

- the possible detection of a gravitational lensing-induced light-echo from PKS1830–211 with the Fermi-LAT (but not by the LAT collaboration). [80] showed a study of the signal following a flaring episode. With a double-power-spectrum method, a significance of 4.2σ is reported for a light-echo flare at roughly the right delay time (28 days). However, employing an autocorrelation function the significance drops to 1.1σ. This system will surely be monitored in the future to follow up on this exciting possibility.

- [81] put severe constraints on the extragalactic background light (EBL) of infrared by using observations of very distant (and hard-spectrum) GeV and TeV AGN.

- [82] used the absence of GeV emission for hard TeV spectrum AGN (i.e. the absence of a cascading signal) to put constraints on the intergalactic B-field to be $>10^{-17}\text{G}$.

5 Gamma-ray Bursts (OG 2.4)

Also here the Fermi-LAT has had a significant impact on the progress in the field. It dramatically improved the data at high energies (compared with EGRET) and now makes more robust predictions for future instruments such as HAWC and CTA possible. Eleven contributions have been submitted to OG 2.4

**Gamma-ray bursts** (VERITAS: 1, HAWC: 1, ARGO-YBJ: 1, Interpretation: 5, New instruments: 3).

Roughly 682 Fermi-GBM (Gamma-ray Burst Monitor) GRBs have been detected since August 2008. About half (345) of these occurred within the field of view of the LAT (defined here at < 70°). Out of these 32 LAT GRBs have been detected (9 of which with a recently implemented new low-energy analysis technique - so-called LLE events). [83] summarized the lessons learned from the Fermi-LAT:

- Extended emission in time (up to 1000s after the initial burst) of a delayed high-energy component is detected in several cases (e.g. GRB 080916C). The fact that there is a high-energy component renders a future detection with ground-based detectors more likely. The fact that it is delayed with respect to the initial bursts further increases the chance for narrow-field IACTs to detect a GRB from the ground in the future.

- GRB spectra are often not simply described by a so-called “Band function”, but how additional high (and low-) energy components (e.g. GRB 090902B).

- Absorption of the GRB signal on the extragalactic background light (EBL) seems less severe than anticipated in some of the models that predicted a large amount of light, meaning that the detection of bursts with higher redshifts is possible for a given (high) energy.

- The LAT detects fewer bursts than expected pre-launch when predictions were based on a simple extrapolation from BAT-detected bursts (at keV energies) to the GeV band. This suggests breaks in the energy spectra between the keV and GeV bands is currently under study.

Still no ground-based detection (> 50GeV) has been reported rendering GRBs the other long-awaited source class (beyond galaxy clusters) that is not yet detected with TeV instruments. VERITAS reported no detection in observations of 49 GRBs [84]. It should however be stressed that the typical delay for the VERITAS observations is ~ 250s (the slewing is about 1°/s and there is a human in the loop). VERITAS is currently investigating whether the slew-speed could be increased (something MAGIC is already routinely doing, quoting < 20s for 180°). All major IACTs have the sensitivity to detect GRBs, they simply have to be lucky to catch a not-too-high-redshift
GRB within (or close to their) field of view. The Fermi-LAT team has implemented a GRB-detection algorithm based on LAT data alone. This will better localize the Fermi-LAT detected bursts compared to the GBM. Notices are expected to go to the community within 10s of the GRB.

For the future, the all-sky monitor HAWC promises to become an extremely sensitive follow-up to MILAGRO, with a factor of 15 improved sensitivity by 2014. [85] demonstrated that HAWC should detect bright Fermi-LAT GRBs if the cutoff is $>60\text{GeV}$ (the Fermi-LAT detects events up to $\sim 30\text{GeV}$ in e.g. GRB 090902B with no sign of a cutoff). Additionally, HAWC has received funding for a fourth PMT in each tank which should decrease the energy threshold further. While the energy resolution of HAWC at 100 GeV and below will not allow for a detailed determination of the energy spectrum, the combination of spectral index and cutoff energy will be constrained using scalars (see e.g. Figure 10). In the more distant future CTA promises to be a tool to detect GRBs (albeit again with the caveat that the slewing will take some time). [87] presented a phenomenological model based on Fermi-GBM and LAT measurements where depending on the way the extrapolation is done about 0.5–1 GRB should be detectable by CTA per year. If a GRB is detected with CTA there will be lots of photons detected and the determination of spectral properties such as energy cutoffs will be performed in exquisite detail.

One of the problems that was mentioned is that it is not completely sure that there will be burst alerts in the time HAWC and CTA operate. Some of the current missions might end soon or before the beginning of operation of CTA (e.g. SWIFT but possibly also the Fermi-GBM). SVOM is a Sino-French mission that is expected to be launched in 2013–2014 that will have capabilities similar to SWIFT. The typical GCN delay expected is 30s for 65% of the bursts. UFFO [88] is a revolutionary new concept for observing early optical photons from GRBs (within 1s) by rotating the mirrors (instead of rotating the spacecraft). A prototype system will be launched in 2012 and will provide some burst alerts.

Summarizing session OG 2.4, my prediction is that there will be a ground-based detection by the next ICRC, either by chance by an IACT or by HAWC.

6 Instrumentation (OG 2.5)

A large number of contributions were in session OG 2.5, demonstrating that the field is actively thinking about future upgrades to existing instruments and about new developments. Sixty-five contributions were presented in session OG 2.5 Instrumentation. CTA alone presented 26 contributions, HAWC and LHAASO-WCDA each 8, VERITAS 4, MAGIC and HAGAR 3 and UFFO 4. 9 were “other” contributions.

Lots of interesting studies were performed in the past two years. [89] and [90] reported on studies for LHAASO (the Large High Altitude Air Shower Observatory), a new planned detector in the Himalayas which will combine a charged particle array, a muon-detector array, a wide-field-of-view Cherenkov telescope array with a Water Cherenkov Array all on one (yet to be specified) site at high altitude above 5 km [91]. In the IACT community, there was a lot of excitement about the first Geiger-mode APD-based Cherenkov camera (FACT) which has been installed recently on a refurbished HEGRA telescope [92–94]. This will serve as an important test-bed for the application of these devices in a CTA camera. CTA has provided the largest number of contributions. It is the one project the whole IACT community (and beyond) is supporting and pushing for completion. Current plans call for a start of construction in 2014 [95].

In the meantime the currently operating IACTs are all updating their instruments and are all pushing their thresholds to lower energies to increase the overlap with the Fermi-LAT. MAGIC has installed a
second 17m telescope and is upgrading the camera on the first telescope to match the properties of the second camera (faster 2 GSamples/s sampling, increased pixelation from 577 to 1039 pixels and installation of a sum-trigger). VERITAS has already rearranged their telescopes to achieve a better geometry for viewing showers and is installing higher-sensitivity PMTs and a faster trigger for the camera. H.E.S.S. has possibly taken the most dramatic step by installing a huge 28 m dish in the center of the array. The steel construction is finished and first light for this telescope is expected in the summer of 2012.

The potentially most exciting new development is that HAWC is about to start operation [7, 32, 96–98]. [8] showed a first skymap using 16.6 million events from a prototype array with 7 tanks (VAMOS). Simultaneous all-sky monitoring between the GeV (Fermi-LAT) and the TeV (HAWC) band will be reported at the next ICRC.

7 Summary

The field of gamma-ray astronomy is a very vibrant field with a large number of talented young researchers demonstrating (and implementing) exciting new ideas. Significant progress in the understanding of particle acceleration in the Universe and in the study of the origin of cosmic rays has been achieved in the past years using instruments such as AGILE, Fermi-LAT, H.E.S.S, MAGIC and VERITAS. It is gratifying to see that the connection between different groups in the IACT community and also between the IACT and water Cherenkov community has been growing strongly in the past years. Joint MWL campaigns and an exchange of observing schedules are routinely done. Going a step further, shortly after the ICRC IACT collaborations are starting to exchange data on the Crab Nebula for cross-calibration and also for the development of common tools in the light of CTA. For all objects that might be on the verge of a discovery, joining dataset should be the way forward (e.g. for dwarf spheroidals, Galaxy clusters or for gamma-ray binaries). As has been learned in the case of dark matter limits on dwarf spheroidals from Fermi, stacking of dataset can really improve the significance substantially. My personal highlights were the presentations on the Fermi-bubbles, the detection of pulsed gamma rays up to 400 GeV from the Crab pulsar and the flares from the Crab Nebula.

The field still has lots of open questions that we would like to answer in the future (see Figure 11). Where are the Pevatrons? What is the cosmic ray content in supernova remnants or in Galaxy clusters? Up to what energies do GRBs accelerate particles? Can giant pair halos around AGNs be detected? What is the particle nature of dark matter, is the WIMP scenario valid and if yes, what is the mass and annihilation cross section of this particle? Clearly for many of these questions the scientific output from the community would be enhanced if the mission of the Fermi-LAT was extended beyond the currently approved 7 years (i.e. beyond 2015) and if there was an overlap with HAWC and with CTA to cover sources over as broad an energy range as possible.

Fig. 11. Current status of detection in the TeV gamma-ray regime. Adapted from [99].

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