Gamma-Ray Astronomy from the Ground

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Abstract. The observation of cosmic gamma-rays from the ground is based upon the detection of gamma-ray initiated air showers. At energies between approximately \(10^{11}\) eV and \(10^{13}\) eV, the imaging air Cherenkov technique is a particularly successful approach to observe gamma-ray sources with energy fluxes as low as \(\approx 10^{-13}\) \(\text{erg cm}^{-2}\text{s}^{-1}\). The observations of gamma-rays in this energy band probe particle acceleration in astrophysical plasma conditions and are sensitive to high energy phenomena beyond the standard model of particle physics (e.g., self-annihilating or decaying dark matter, violation of Lorentz invariance, mixing of photons with light pseudoscalars). The current standing of the field and its major instruments are summarized briefly by presenting selected highlights. A new generation of ground based gamma-ray instruments is currently under development. The perspectives and opportunities of these future facilities will be discussed.

1. Introduction

The field of ground based gamma-ray observations has been driven by the pioneering efforts to detect air Cherenkov light from extended air showers. The vivid history leading up to the discovery of the first cosmic gamma-ray source, the Crab nebula, with the Whipple telescope and the subsequent evolution of mainly imaging air Cherenkov telescopes has been told by one of the pioneers himself in [1]. Currently, the ground based detection of gamma-rays is dominated by the imaging air Cherenkov technique which combines a collection area of \(\approx 10^5\) \(\text{m}^2\) and a field of view of \(\approx 5\) msrad with an event-by-event relative energy resolution better than 20 % and an angular resolution better than 0.1°. Alternative approaches are explored to increase the size of the field of view (e.g., the water-Cherenkov detector HAWC) or increase the collection area to improve the sensitivity for ultra-high energy gamma-rays (> 100 TeV) (see also section 4). With the very successful operation of the Fermi-LAT (in orbit since August 2008, see also the review article in this volume), it has become feasible for the first time to study the energy spectra of gamma-ray sources with continuous coverage from 100 MeV up to 100 TeV. In the following section, we summarize the status of the operating instruments and present selected highlights of the past two years (for prior results see reviews of previous TAUP conferences [2, 3]).

2. Status of currently operating major instruments

2.1. High Altitude Water Cherenkov Observatory (HAWC)

The HAWC is designed to detect air showers via Cherenkov light generated by through-going charged particles in water tanks. An array of 300 water tanks has been installed over the past three years (see Fig. 1 for a picture of the installation) at an altitude of 4 100 m a.s.l. in Mexico. At this high altitude, air showers can be detected that were initiated by gamma-rays with an
energy above 100 GeV. The main array has been completed in 2015 [4]. HAWC combines a low energy threshold, large collection area, $\approx 100$ % duty cycle, and a large field of view of 5 sr. The sensitivity of the instrument after one year of operation is sufficient to detect any gamma-ray source above 2 TeV with an energy flux of $\approx 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in the northern sky. This matches quite well the sensitivity of the air Cherenkov telescopes after a few ten hours of pointed observation time. The survey of the northern sky has already started with data taking during the commissioning phase [4, 5], demonstrating the opportunities of a large field of view instrument, i.e., an unbiased survey and the sensitivity to detect extended emission difficult to achieve with narrow field of view instruments. Another important ingredient of the scientific shopping list are transient events in the gamma-ray sky, e.g., gamma-ray bursts which should be detectable with HAWC.

2.2. High Energy Stereoscopic System (H.E.S.S.): Phase II
The H.E.S.S. array in its current configuration (Phase II), consists of four telescopes (100 m$^2$ mirror surface area) located at the corners of a square with 120 m side length and a considerably larger telescope of $\approx 600$ m$^2$ surface area in the center (see Fig. 2 for a picture of the installation). The large telescope (CT 5) was inaugurated in 2012 and has considerably lowered the detection threshold below 100 GeV and has improved the reconstruction accuracy of so-called hybrid events. These events are triggered by the large telescope in conjunction with at least one smaller telescope. The small telescopes are currently undergoing an extensive update of the camera readout to improve the performance at low energies [6].

2.3. MAGIC$^2$: two 17 m-telescopes
The MAGIC collaboration has successfully constructed imaging air Cherenkov telescopes featuring a number of innovative technologies including a partial carbon fiber frame to reduce the weight and therefore increase the achievable re-pointing speed, new composite mirror technology, as well as hemispherical photomultiplier tubes to improve the optical detection efficiency. The most recent updates have been the addition of a second telescope (see Fig. 3) and the update of the cameras to achieve a more uniform performance for the stereoscopic observation of air
showers [7]. The improvement in performance of the telescope and its resulting sensitivity has been spectacular, pushing the initial flux sensitivity above 100 GeV down by as much as one order of magnitude. The recent upgrade of the camera and trigger system has improved the sensitivity by a factor of two at the energy threshold of 70 GeV (see Fig. 4) [8]. The MAGIC collaboration continues to pioneer new techniques to improve the performance of the telescopes. Recently, they demonstrated successfully that LIDAR backscattering results can be used to correct the air shower observations taken under conditions [9] which are usually rejected because of poor transparency of the atmosphere. This is an important step to both improve the energy reconstruction which suffer systematic uncertainties because of variations in the atmosphere and to recover observation time. The new technique is of relevance for observations taking place during unique flux states of variable sources or during multiwavelength campaigns where the weather conditions were not cooperative.

Figure 3. The two MAGIC telescopes located on the peak of the Roque de los Muchachos on La Palma (2200 m asl), picture courtesy of the MAGIC collaboration.

Figure 4. Evolution of the integrated flux sensitivity of the MAGIC telescopes following upgrades: the most recent update of the camera and trigger system has lead to the improvement from the curve with the black, filled triangles to the red, filled squares. Figure from [8].

2.4. VERITAS: four 12 m-telescopes
The VERITAS array has been operational since 2012 with new photomultiplier tubes with an increased detection efficiency [10]. The energy threshold for triggering on gamma-ray induced air showers has been reduced 30 %. At the same time, the sensitivity has been improved because of larger number of photo electrons that can be used to characterise the image and to separate cosmic-ray induced background. Recently, the VERITAS array started operation during (partial) moon light in order to increase the observation time available. Two different modes of observation have been successfully tested [11]: reducing the high voltage and adding UV bandpass filters in front of the PMTs. The resulting performance deteriorates only slightly with reduced high voltage while it permits for observations with a moon illumination up to 65 %. For observations with even more moonlight, UV filters can reduce the light load on the PMTs, however at the expense of an increased energy threshold and reduced sensitivity (roughly a factor of two with respect to nominal operation). These results are consistent with the previous studies carried out with the MAGIC telescope where routine moonlight observations are scheduled [12].
3. Scientific highlights since 2013

3.1. Surveying the Galactic plane

The population of charged cosmic rays arriving at Earth is commonly considered to be the result of localized acceleration processes – mainly at shock fronts formed by supernova shells, colliding winds etc. and in or near to magnetospheres of neutron stars. The Galactic plane is therefore an ideal target for a survey to take inventory of nearby and powerful cosmic-ray accelerators. The H.E.S.S. telescope array has been used to carry out an extensive survey of the inner part of the Galactic plane for a total of 3 000 hours [13]. The initial shallow survey carried out during the first years of operation resulted in the landmark discovery of a new population of gamma-ray sources [14] with many of the objects lacking obvious counterparts at other wavelengths. The current survey has improved both in coverage (longitude range: $l = -110^\circ \ldots + 70^\circ$ in comparison to $l = -30^\circ \ldots + 30^\circ$) and in depth, reaching a minimum detectable flux of $< 1\%$ in the inner Galaxy initially surveyed (previously 2\%). The first example of a gamma-ray emitting source which belongs to the most abundant type in the Galaxy type had already been discovered before the Galactic plane survey with H.E.S.S. started. During observations from 1999-2000, the first unidentified TeV gamma-ray source (TeV J2032+4130) had been discovered with the HEGRA Cherenkov telescopes [15]. The discovery was later confirmed with MAGIC [16] and VERITAS observations [17]. The majority of unidentified gamma-ray objects later discovered in the Galactic plane surveys share similar properties with the prototypical TeV J2032+4130: both, spatial extension as well as luminosity at gamma-rays are typically larger than potential counterpart candidates at X-rays. The common interpretation of these objects as evolved pulsar wind nebula systems assumes that the pulsar releases over its life time an expanding magnetized relativistic plasma. The decline of the magnetic field over time favors inverse Compton gamma-ray emission over synchrotron emission which explains the lack of obvious counterparts. This interpretation has been supported in individual cases by the discovery of pulsed emission with the Fermi LAT instrument as well as with the detection of faint X-ray nebula emission around known radio pulsars. In this scenario, the X-ray emitting nebula and the gamma-ray nebula do not necessarily have a similar morphology because of the different energy of the underlying electron population responsible for the emission in the respective energy band. A population study of the gamma-ray pulsar wind nebulae has been presented recently [18]. This sample of similar objects indicates that the efficiency (ratio of gamma-ray luminosity to spin-down power of the pulsar) increases with increasing age of the system: the gamma-ray luminosity is a proxy of the integrated spin-down power of the system while X-rays are emitted by the recently injected electrons. The analysis of Galactic plane data taken with HAWC during its commissioning phase [5] demonstrates the complementarity of a wide field instrument to narrow field imaging telescopes. The large field of view simplifies the
analysis of extended emission regions. Combining the data in overlapping energy ranges is an exciting opportunity to disentangle extended emission from more point-like contributions (see Fig. 5 for an overlay of HAWC significance isocontours with the H.E.S.S. data in an overlapping region in the first quadrant of the Galactic plane). Even though the detection of source emission extending beyond the field of view of Cherenkov telescopes is challenging, a recent result put forward by the H.E.S.S. collaboration claims the detection of diffuse emission along the Galactic plane [19]. After masking sources detected in the inner Galaxy (|l| < 70°), a diffuse emission centered on the Galactic equator with a full width half maximum of ≈ 0.75° is detected. The observed intensity is a factor 2-3 larger than expected in a simple model extrapolating Galactic emission models into the regime above 100 GeV. Future studies in conjunction with data taken with the Fermi-LAT and HAWC will help to clarify the origin of the diffuse emission.

3.2. Gamma-ray emission from the Galactic center

The Galactic center and the inner 100 pc are an exceptional region for the study of non-thermal emission and diagnostics of the relativistic plasma. A steady gamma-ray source consistent with the position of Sgr A* was discovered with ground-based observations [20, 21, 22]. Subsequent deeper observations with the H.E.S.S. telescopes revealed extended gamma-ray emission along the Galactic ridge, tracing the distribution of molecular gas [23]. The most recent results of even deeper observations resolve in more detail the distribution of cosmic-rays in the inner 200 pc [24]: The energy density of cosmic rays in the inner 200 pc is approximately an order of magnitude larger than the average local cosmic-ray energy density. This density falls off ∝ 1/r and the energy spectrum follows a power-law that extends without an indication for a cut-off well beyond 10 TeV. This in turn implies the acceleration and release of particles well beyond 100 TeV from the Galactic center. Deeper observations have also revealed the presence of structures in the morphology which follow the well-known radio feature known as the arc [25, 26]. Future studies and interpretational work will provide a better insight in the particle acceleration and cosmic ray release in the inner Galaxy.

3.3. Dark matter searches with gamma-rays

The indirect search for gamma-rays from self-annihilating Dark matter continues with a focus on observations of dwarf spheroidals and from the vicinity of the Galactic center. The sensitivity continues to improve with longer exposures, new instrumentation, and through combination of different observations. The combination of observational data from Fermi-LAT with MAGIC on dwarf galaxies has improved the energy coverage and sensitivity in comparison to the individual analysis [27](Fig. 6). Deeper observations of the Galactic center halo with H.E.S.S. have improved the sensitivity in comparison to previous observations. With upcoming data using the large central telescope, the sensitivity will mainly improve for the WIMP mass range below a few TeV [28] (see Fig. 7).

3.4. Gamma-rays from active galactic nuclei and gamma-ray propagation

The catalogue of gamma-ray emitting active galactic nuclei (AGN) continues to grow and to include different types of AGN. The majority of the sources belong however to the so-called high energy peaked BL Lac type, sources without strong line emission features in the optical spectra and a broad band spectral energy distribution with a maximum in the X-ray and one at gamma-ray energies. Recently a number of flat-spectrum radio quasars have been observed to emit gamma-rays and the red-shift of some these recently with MAGIC discovered gamma-ray emitting objects (PKS 1441+25 [29, 30, 31] and B0218+357 [32, 33]) is close to z ≈ 1. A striking property of the high energy emission from AGN is the dramatic variability observed at the highest energies. The short time-scales of variability impose severe constraints on the spatial extension...
Figure 6. Combined constraint (confidence level 95 %) on the cross section for self-annihilating dark matter from the dwarf spheroidal galaxy Segue 1 for a $b\bar{b}$ final state. The $H_0$ bands indicate containment of limits from simulated/blank field data for comparison. The combined limit using both Fermi-LAT and MAGIC data improves the sensitivity in the overlapping mass range (800 GeV-8 TeV) and improves the mass range covered, adapted from [27].

Figure 7. Expected constraint on the dark matter self-annihilation cross section from observations of the region close to the Galactic center with the H.E.S.S. phase II telescope (black solid and dashed line). For comparison, existing constraints from Galactic center observations (HESS I, blue line) and a new result (red line) based upon 254 hours of observation are shown [28].

of the emitting volume. The recent MAGIC observation of flares from the head-tail radio galaxy IC 310 with a variability time scale of approximately 4 minutes, is particularly puzzling as it requires an emission region more compact (by a factor of $\approx 5$) than the Schwarzschild radius of the super massive black hole [34]. Another independent inference of a potentially even more compact size of the emission region in Blazars is possible using the effect of gravitational micro lensing [35]. The observation of the time-delays and the ratios of the flux amplifications provides insights into the velocity of emitting volume as well as on its size. Recently, the observation of B0218+357 with MAGIC followed up on a flare detected with Fermi-LAT and lead to the discovery of the signal delayed by gravitational lensing [33]. The large red shift of gamma-ray sources and the observation of gamma-rays up to and beyond 20 TeV from AGN in general is surprising given that the gamma-ray flux from large distance sources is expected to be attenuated because of the effect of pair-production. Possible explanations for a reduced attenuation have been put forward and include the possibility of AGN to be powerful accelerators of ultra-high energy cosmic-rays with gamma-ray production through inter-galactic cascading as well as more exotic proposals like conversion of photons with low-mass axion-like particles [36], or violation of Lorentz invariance [37], for an overview of gamma-ray propagation see e.g., [38].

4. Towards the future
The future of ground based gamma-ray observations is starting with the planning and construction of the next generation of instruments. The Cherenkov telescope array (CTA) project [39] is close to finalizing the design of two future arrays of Cherenkov telescopes installed on the northern and southern hemisphere. While the site selection continues, the technical design
of the three telescope types (small: mirror area 12 m\(^2\), field of view 9\(^\circ\), medium: 110 m\(^2\), 7\(^\circ\) and large: 450 m\(^2\), 4.5\(^\circ\)) progresses quickly as it builds upon the experience with the current generation of telescopes. The aim of the project is a general improvement of the sensitivity by one order of magnitude and an extension of the energy reach, including both the low energies \((E < 100 \text{ GeV})\) and high energies \((E > 10 \text{ TeV})\). In order to achieve an even lower energy threshold, the MACE telescope (area of 340 m\(^2\), 4\(^\circ\)) is under construction at 4270 m altitude and is planned to start regular observations in 2017 with an energy threshold of 20 GeV [40].

At higher energies and going beyond 100 TeV, the current imaging concept is expensive to instrument sufficiently large areas to achieve sensitivity to detect the expected low fluxes. The LHAASO project will combine non-imaging and imaging techniques at a high altitude to achieve a broad energy coverage and reach high energies with a collection area of 1 km\(^2\) [41]. The TAIGA project is using non-imaging air Cherenkov detectors employed on a large surface (up to 10 km\(^2\)) in combination with imaging telescopes [42]. Both experiments are in the build-up phase and will start taking data with sufficient sensitivity to detect first sources in the next years.

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