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Gamma Ray Astronomy with LHAASO

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Abstract.

The aim of LHAASO is the development of an air shower experiment able to monitor with unprecedented sensitivity the gamma ray sky at energies from ~ 200 GeV to 1 PeV, and at the same time be an instrument able to measure the cosmic ray spectrum, composition and anisotropy in a wide energy range (~ 1 TeV to 1 EeV). LHAASO, thanks to the large area and the high capability of background rejection, can reach sensitivities to gamma ray fluxes above 30 TeV that are about 100 times higher than that of current instruments, offering the possibility to monitor for the first time the gamma ray sky up to PeV energies and to discover the long sought “Pevatrons”.

1. LHAASO and Gamma Ray Astronomy

The Large High Altitude Air Shower Observatory (LHAASO) is a project of a multi-component air shower detector, to be built at the Daochen site (Sichuan province, P.R.China) at an altitude of 4410 m. a.s.l., devoted to gamma ray astronomy in the energy range $\sim 2 \times 10^{11}$ - 10^{15} eV and cosmic ray studies at energies $\sim 10^{12}$ - 10^{18} eV.

The LHAASO layout for gamma ray astronomy is shown in Fig.1. It consists of an array of detectors distributed over a circular area of ~ 1 km² (KM2A), around a large Water Cherenkov Detector Array (WCDA) located in the center. KM2A is designed to measure the electromagnetic and muonic components of the shower, and consists of a grid of 5242 plastic scintillators (15 m spacing) of area 1 m² (each covered by a 5 mm-thick lead plate), superimposed to a grid of ~ 1146 water Cherenkov tanks (30 m spacing), each of area 36 m² and water depth 1.2 m, located under a mound of dirt 2.5 m thick, and provided by a 8 inch photomultiplier at the top of the tank.

WCDA consists of three water ponds with a total surface of 78,000 m² and water depth 4.4 m, in which the charged secondary particles of the shower produce Cherenkov light. The ponds are divided in 5×5 m² cells by black plastic curtains to prevent the penetration of the light in the adjacent cells. At the bottom of each cell there is a 8-9 inch photomultiplier, collecting the light from upwards. For more details on the detector layout and performance, see [1].

Thanks to the employment of different detection techniques, LHAASO can study gamma ray sources over almost 4 decades of energy. Fig.2 shows the LHAASO differential sensitivity in one year of measurement, obtained by simulating the response of the detector to a gamma ray flux from a Crab-like source, compared to that of other experiments. The double structure of the curve is due to the combination of the sensitivities of WCDA, mainly operating at ~ 0.2 - 10 TeV, and KM2A, mainly efficient above 10 TeV [2]. As can be seen in the figure, LHAASO is



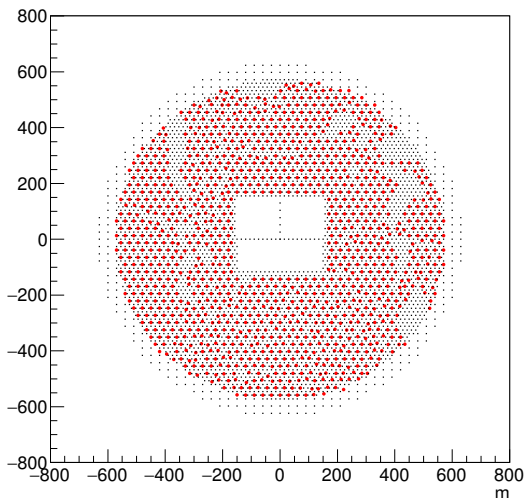


Figure 1. Layout of LHAASO. Black points: position of scintillators. Red circles: position of muon detectors. At the center, the three WCDA ponds.

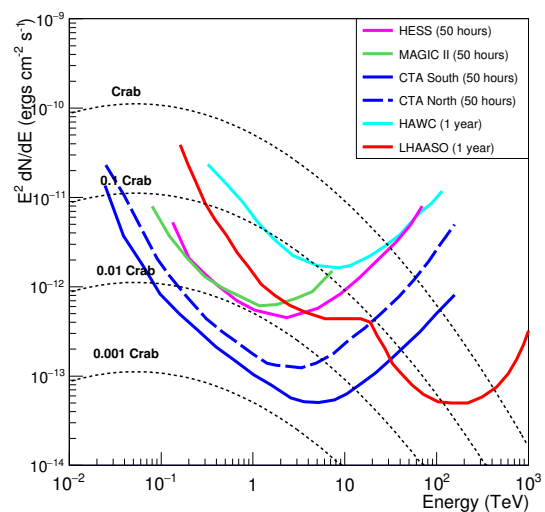


Figure 2. LHAASO differential sensitivity to a Crab-like point gamma ray source compared to that of other experiments. The Crab nebula flux is shown as a reference.

particularly competitive in the gamma ray energy range above a few tens of TeVs, an energy region almost completely unexplored.

The capability to identify and reject the cosmic rays background is one of the main factors that determines the sensitivity of an instrument. The hadron discrimination in WCDA is based on the different topology of gamma ray and hadronic showers, employing the same technique developed by the Milagro detector and now used by HAWC. The KM2A array instead employs the detection of muons to recognize cosmic rays showers, that above 10 TeV have a muon content ~ 10 -20 times larger than that of gamma ray showers, for the same electronic size. According to simulations, the fraction of cosmic rays that survives the discrimination cuts is less than 0.001% at energies above ~ 100 TeV. This means that in this energy range the study of the gamma emission can be considered as background free, because after applying the rejection procedure the expected background is less than one event per year. In these conditions the sensitivity increases linearly with time instead of the square root of time, as in presence of background.

The LHAASO field of view (FOV) in principle includes all the sky above the horizon, but actually is limited by the decrease of sensitivity at large zenith angles. Considering only the region of the sky visible at zenith angles smaller than 40° , every day LHAASO (located at latitude 29° North) can survey the declination band from -11° to $+69^\circ$ (about 56% of the whole sky) that includes the galactic plane in the longitude interval from $+20^\circ$ to $+225^\circ$.

2. Galactic gamma ray astronomy

Presently there is a general consensus that cosmic rays with energy up to the “knee” of the spectrum (2-4 PeV) are accelerated inside our Galaxy, and Supernova remnants (SNR) are the most likely sources, even if this idea still lacks a clear experimental evidence. TeV gamma rays have been observed from a number of SNRs, demonstrating that in SNRs some kind of acceleration occurs, however the question whether TeV gamma rays are produced by the decay of π^0 from hadronic interactions, or by relativistic electrons via Inverse Compton scattering or bremsstrahlung, still needs a conclusive answer. A key observation would be the detection of

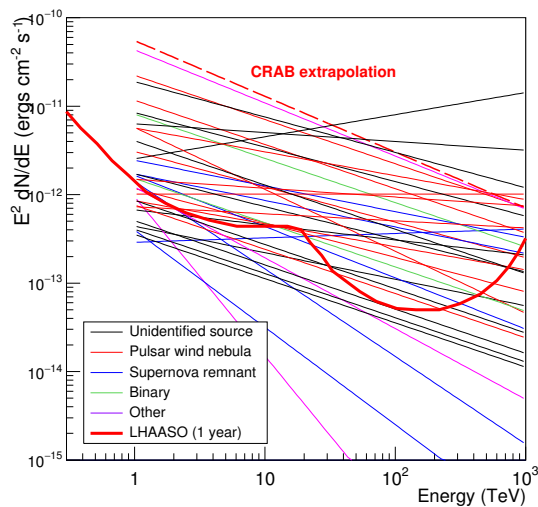


Figure 3. Spectra of 35 TeV gamma ray sources of different type visible by LHAASO, extrapolated to 1 PeV, compared to the LHAASO sensitivity.

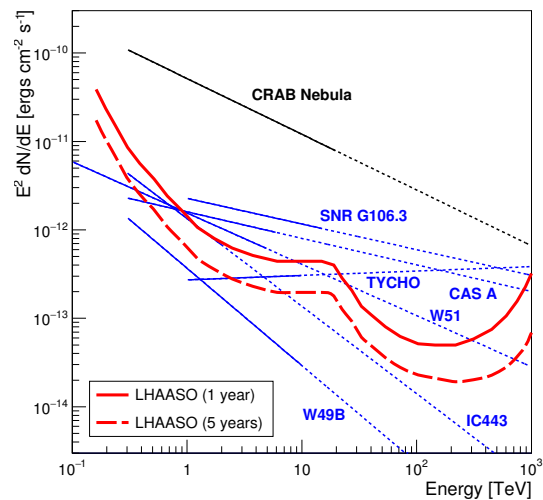


Figure 4. Spectra of six TeV SNRs visible by LHAASO (solid blue lines), extrapolated to 1 PeV (dotted blue lines), compared to the LHAASO sensitivity.

gamma rays of energy a factor 10-30 times less than the maximum energy of galactic cosmic rays. The measurement of a gamma ray power law spectrum with no break up to 100 TeV would be a sufficient condition to proof the hadronic nature of the interaction, since the Inverse Compton scattering at these energies is strongly suppressed by the Klein-Nishina effect.

According to the online TeV source catalogue TeVCat [3] at the time of writing the number of known sources is ~ 170 . Among them, 60% belong to our Galaxy and 40% are extragalactic. About 1/3 of galactic sources are still unidentified, 1/3 are pulsar wind nebulae (PWN), and the remaining ones are supernova remnants, compact binary systems and massive star clusters.

The spectrum of the galactic sources has been generally measured from a few hundreds GeV up to 10-20 TeV, and for most of sources it is consistent with a power-law behaviour. The precise measurement at higher energies would be of extreme interest to understand the emission mechanisms of gamma rays, that for most of the sources is not yet understood, and will surely help in the source identification. So far, only six sources have data above 30 TeV. They are all galactic and are among the most luminous objects of the TeV sky: the supernova remnant RX J1713.7-3946, the pulsar wind nebulae Crab and Vela-X, and the three extended sources MGROJ2031+41, MGROJ2019+37 (actually resolved in two different sources by VERITAS), and MGROJ1908+06, all of them probably pulsar wind nebulae too. Their spectrum above 30 TeV is however known with large uncertainties. Even the spectrum of the Crab Nebula, the most luminous among the steady TeV sources, is known with a good accuracy up to 10-20 TeV. Above this energy some disagreement exists in the measurements by different experiments.

Out of 84 sources crossing the LHAASO field of view with a zenith angle less than 40° , 23 are associated with known galactic objects, and 13, even if not yet identified, lay on the galactic plane and can be reasonably considered galactic too. For 35 out of these 36 galactic sources the flux has been measured and reported in [3]. Fig. 3 shows the spectra of the 35 objects extrapolated to 1 PeV, compared to the LHAASO one-year sensitivity. These extrapolations are clearly unrealistic, since the real spectra likely would show steepenings or cutoffs at some energy, but the purpose of the figure is to show that the flux of almost all the considered sources

is above the LHAASO sensitivity. LHAASO can study in detail the behaviour of the higher energy emission of most of the known sources, down to fluxes of $\sim 3 \times 10^{-18}$ photons $\text{s}^{-1} \text{cm}^{-2} \text{TeV}^{-1}$, at 100 TeV in one year of measurement. These high energy data are likely to play a crucial role for the understanding of the properties of the sources.

Among galactic sources, shell SNRs are probably the most interesting to be studied at high energy because the detection of an emission above 100 TeV could be the footprint of hadronic acceleration. In the LHAASO field of view there are six shell SNRs emitting TeV gamma rays (Thyco [4], CAS A [5], W51 [6], IC443 [7], W49B [8] and SNR G106.3+2.7 [9]). The measured spectra show a power law behaviour without any cutoff up to the maximum energy reached by the current instruments, that ranges from ~ 2 to 15 TeV for the sources considered. Fig.4 shows their spectra extrapolated to 1 PeV. Four of them have fluxes higher than the LHAASO one-year sensitivity.

Besides the observation of known sources, given the LHAASO capabilities in sky survey, new galactic sources will likely be discovered at high energy, since objects with fluxes at 1 TeV below the current instruments sensitivity but with hard spectra (i.e. spectral index < 2) would be easily detectable by LHAASO above ~ 10 TeV.

A problem to face when working at high energy, is the absorption of gamma rays due to pair production in the interstellar and intergalactic space. High energy gamma rays interact with the infrared/optical photons and with the Cosmic Microwave Background radiation (CMB), causing a flux attenuation usually expressed as $I = I_0 \exp^{-\tau}$, where the value of the optical depth τ depends on the gamma ray energy, the source distance and the density and energy of the target photons. The absorption increases with the gamma ray energy and the source distance, being particularly effective for extragalactic sources, but at sufficiently high energy can affect also the flux of galactic objects. The precise evaluation of the absorption depends on the exact knowledge of the low energy radiation intensity. The CMB is precisely measured, while the intensity of optical and infrared photons has large uncertainties. For this reason the evaluation of the opacity parameter is mostly indirect, based on assumptions and models, especially in the extragalactic case.

Concerning galactic sources, the absorption mainly depends on the relative position of the source and the Sun inside the Galaxy. According to [10, 11], up to ~ 10 TeV the gamma ray attenuation should be less than a few percent for every source position, while at ~ 100 TeV the flux of a source close to the galactic center would be reduced by 20%. Above ~ 200 TeV the CMB becomes effective and the absorption depends on the distance rather than on the position in the Galaxy: at ~ 2 PeV, about 70% of the flux of a source at the distance of the galactic center (8.5 kpc) is absorbed, while at 20 kpc the absorbed flux is 95%. These calculations show that the absorption is not an obstacle for galactic gamma ray astronomy up to a few hundred TeV, while at higher energies it can seriously hamper the observations.

An other interesting topic that can be investigated by LHAASO is the diffuse gamma ray emission from the galactic plane, mainly produced by the interactions of cosmic rays with the interstellar gas. The diffuse emission in the TeV range has been measured by ARGO-YBJ at galactic longitudes 25° – 100° for latitudes between $\pm 5^\circ$, reporting a differential flux consistent with the extrapolation of the Fermi-DGE model for the same region [12]. The study of the diffuse flux at 30-100 TeV energies would be of extreme importance to understand the propagation and the confinement of the parent cosmic rays in the Galaxy and their source distribution.

A rough evaluation of the LHAASO sensitivity to the galactic diffuse flux can be obtained by multiplying the point source sensitivity by the correction factor $f = (\Omega_{PSF} \Omega_{GP})^{-1/2}$, where Ω_{PSF} is the observation angular window, related to the detector point spread function (PSF) and Ω_{GP} in the solid angle of the galactic plane region to be studied. According to this simple calculation the 5 sigma minimum flux detectable by LHAASO in one year in the longitude interval 25° – 100° would be $F_{min} \sim 7 \times 10^{-16}$ photons $\text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1} \text{sr}^{-1}$ at 100 TeV, i.e. a

factor ~ 6 lower than the extrapolation of the Fermi-DGE model at the same energy, showing that LHAASO will likely be able to study the properties of gamma rays produced by the interaction of cosmic rays with energy up to the “knee” of the spectrum.

3. Extragalactic astronomy

In the LHAASO FOV (i.e. declination between -11° and $+69^\circ$) there are 47 extragalactic objects known as TeV emitters. Most of them are active galactic nuclei (AGNs) of the blazar class, whose redshift, measured for 39 of them, ranges between 0.0044 and 0.94. A wide FOV experiment with a large duty cycle like LHAASO is suitable for the observation and monitoring of flaring sources as AGNs and for the discovery of new variable objects.

As for galactic sources, the measurements of the AGNs high energy spectra would be of extreme importance for the understanding of the emission mechanisms, but in this case the observations are seriously hampered by the absorption of gamma rays during their travel to Earth. Gamma rays from ~ 1 TeV to ~ 200 TeV are mostly attenuated by the Extragalactic Background Light (that includes the light from stars/AGNs and dust emission, and whose intensity is related to the whole Universe history, star formation and galaxy evolution), while the absorption above 200 TeV is mostly due to CMB. The evaluation of the optical depth τ requires the modelling of the EBL spectrum at different redshifts. According to the model by Franceschini *et al.* [13], gamma rays above ~ 30 TeV from a source at $z=0.01$ are 90% absorbed. At $z=0.03$ (the redshift of Mrk421 and Mrk501) the flux above ~ 20 TeV is 95% absorbed. Increasing the energy or the redshift, the absorption becomes stronger and can seriously limit the study of most extragalactic sources. The possibility to observe a signal above a few tens of TeV from an extragalactic source appears limited to the very close objects.

Presently there are only three sources closer than Mrk421 in the LHAASO field of view: the radio galaxy M87 ($z=0.0044$), the radio galaxy NGC1275 ($z=0.018$), and the (probably) blazar IC310 ($z=0.019$). M87 and IC310 have hard spectra and their possible detection at high energy depends on the flux during active states. NGC1275 have a very soft spectrum and the detection seems unlikely. At the edge of the FOV, the starburst galaxy M82 at $z=0.0007$, the closest extragalactic source, culminates at a zenith angle of almost 41° . M82 is a steady source with a TeV flux $\sim 1\%$ of the Crab nebula. Starbursts are galaxies with a high star formation rate, hosting a large amount of gas where massive stars are formed causing a high rate of supernova explosions. If SNR are the sites where cosmic rays are accelerated, one expects a large flux of cosmic rays inside these galaxies and a consequent high flux of gamma rays produced by the interactions of cosmic rays with the ambient gas. The measurement of the spectrum at high energy would be of great value to understand the origin of gamma rays. The observation of a deabsorbed spectrum that extends up to 100 TeV as a power law would be a strong support of the hadronic origin of gamma rays and of the idea that SNR accelerate cosmic rays.

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