Frascati Physics Series Vol. 58 (2014)
Frontier Objects in Astrophysics and Particle Physics
May 18-24, 2014

LHAASO: Science and Status

Zhen Cao
(for LHAASO Collaboration)
Institute of high energy physics, 19B Yunquan St. Beijing, 100049, China

Abstract

A major instrument for very high energy gamma ray astronomy and researches on cosmic rays around knees will be built at 4400 m above sea level in Sichuan province, China. With a sensitivity of 10 mili-Crab, LHAASO will survey the entire northern sky for gamma ray sources with a 100% duty cycle. The spectra of all the sources will be measured simultaneously over a wide energy range from 300 GeV to 1 PeV. This will offer a great opportunity for identifying cosmic ray origins among the sources. With its wide field of view, LHAASO is particularly sensitive to the spatially extended sources and temporally transient phenomena. Equipped also with Cherenkov/fluorescence telescopes and in-filled burst detector array, LHAASO will serve as the most effective detector for energy spectra of different mass groups of cosmic rays. Features of cosmic rays associated with the transition from the galactic to extra galactic originated will be the main topics of the LHAASO cosmic ray researches, including the accelerating mechanisms and the maximum energy of galactic cosmic rays, components of nearby celestial objects and so forth. The LHAASO site is

decided at Mt. Haizi in Daocheng county. The construction will be started next year.

1 Introduction

The Large High Altitude Air Shower Observatory (LHAASO) project is planned to be built a complex array of particle detectors in an area of 1 km^2 at 4410 m above sea level in Sichuan province, China. A water Cherenkov detector with an area of 90,000 m^2 will be built at the center of the array to detect gamma ray showers above 300 GeV from all directions. It works as a survey telescope for all gamma ray sources in the northern sky. A larger detector array is necessary for the much smaller gamma ray fluxes at higher energies. It is an array of 5600 scintillator detectors of 1 m^2 in a triangle grid with a spacing of 15 m. It covers an area of 1 km^2 which is sufficient to observe the gamma rays above 10 TeV up to 1 PeV for many sources. In order to suppress the cosmic ray back ground, muons in the showers must be detected. They can be recognized in the water Cherenkov telescope because they generate huge signals in the pool particularly at large distances from shower cores. About 1200 muon detectors of 36 m^2 each are built evenly in the array of 1 km^2, also using the water Cherenkov technique. Among the total active area of 40,000 m^2, the muon-less criterion guarantees a background-free detection of gamma ray fluxes above 50 TeV. The features of the combination of the arrays enable measurements of energy spectra of most galactic sources over a very wide energy range from 300 GeV to 1 PeV. It will be the most powerful tool in search for cosmic ray pevatrons in our galaxy. The all sky survey using the combination will reach to a depth of 10 mili-Crab. The detailed comparison of the sensitivity of the instrument with other experiments and future projects is displayed in Figure 1.

90,000 m^2 full coverage of the water Cherenkov detector with the cell size of 5×5 m^2, is also a very good detector for cosmic rays at energies below 10 PeV where the knees are. Shower geometry and muon content can be measured very well. On top of those, 24 wide field of view (FoV) imaging Cherenkov telescopes and about 200 m^2 "burst" detectors will be deployed close by. The combination of all the techniques offers great opportunity of multi-parameter analysis for shower composition before knowing the shower energy. For identified primary nuclei, the shower energy can be measured by using the total numbers of Cherenkov photons in the images. The telescopes will be re-configured to make the other combination with the scintillator array and muon detector array in 1 km^2 for detection of showers at higher energies up to 100 PeV. The telescopes can be further modified as fluorescence detectors to cover higher energies up to 1 EeV for detecting the "second knee" of the cosmic ray spectrum.

It is clear that the LHAASO instrument offers great opportunities for both gamma ray astronomy and cosmic ray physics. In following sections, the science cases in both fields are discussed. The status of the project is reported as well in the last section of this paper.

2 Gamma Astronomy

In last two decodes, gamma ray astronomic observations over a wide energy range from 1 GeV to tens of TeV have had great progresses. FERMI has finished the full sky survey and found more than 1800 gamma ray sources [1] below tens of GeV. Mainly Cherenkov telescopes have found nearly 150 gamma ray sources [2] in the energy range above 100 GeV. Many sources have been identified by combining all observational data in bands of radio, optical, X-ray and gamma ray together. The spectral energy distribution (SED) of the sources over the very wide range greatly enhanced one's knowledge about the high energy non-thermal radiation mechanism of those sources. There are still many phenomena that are totally beyond our understanding. The radiation mechanism of shell-type supernova remnants (SNRs, e.g. RXJ-1713.7-3946 [3]), electron or hadron originated, is the most important issue among others, such as the fast transient active galactic nuclei (AGN, e.g. PKS 2155-304 [4]), very clear SED evolution during flares (e.g. a flare on Mrk501 in Figure 1), the very remote quasars (e.g. 3C279 [5] with z=0.5362), the very hard SED of very extended sources (e.g. MGRO J2019+37 [6]) and the very big gamma ray super-bubble FERMI-Cocoon [7], also referred to ARGO J3031+4157 [9]. The main topics are clear for the further experiments, 1) surveying for more sources, such as those in the FERMI catalog, and 2) deep investigations on the interesting sources in both spectroscopy and morphology. Before getting in more details about the all sky surveying, it is interesting to note that only 2/3 of the TeV sources are found in the FERMI catalog. This is not expected. One thought that there would be a boost of the discovery of the TeV gamma ray sources because the telescopes know where to point with the FERMI catalog.

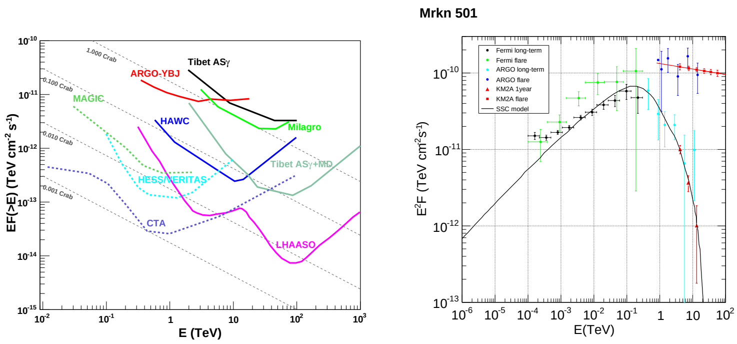

Figure 1: *The left panel is the sensitivities of current VHE gamma ray astronomic instruments and projects in near future. The solid curve in purple represents LHAASO. It is clearly divided in two parts. The one below 10 TeV is due to the water Cherenkov array of 90000 m^2, and the other in high energy range is due to the array of the scintillator and muon detectors covering 1 km^2. In the right panel, the SED of a flare of Mrk501 and its steady gamma ray emission measured by ARGO-YBJ and FERMI* [12]*. The expectations of the observation of the similar flare and the steady emission by LHAASO are also plotted here. The detailed evolution of the SED from the steady state to the flare state and return back to the steady state will be able to be observed in details*

LHAASO is designed to carry out a full sky survey to the depth of 10 mili-Crab in the northern sky. The energy coverage will be extended to 1 PeV. This feature is very useful in search for very extended sources with very hard SED that were expected to be likely hadronic accelerators, or Pevatrons in other name. In Cygnus region, MGRO J2019+37 is a mystery source not being seen by any detector for long time except the high threshold MILAGRO [6] above 20 TeV, even not by the ARGO-YBJ experiment [6], until recent deep-scanning of this region by VERITAS [8] at a depth of 10 mili-Crab at energies above 1 TeV. The reason for such hard SED from such a spatially extended region is totally unknown. The discovery of many this type of sources and detailed multi-wavelength spectroscopic investigations in particular seems to be an efficient way to clarify the radiation mechanism of them. In the same region, FERMI found an even larger object called Cygnus Cocoon which may be associated with a super-bubble. Recent observation of ARGO-YBJ on this source identified it as the counterpart of the Cocoon at TeV range [9]. In Figure 2, the coincidence of the spatial location and extension between FERMI, ARGO-YBJ and MILAGRO is displayed, together with the consistent connection of SED by FERMI and ARGO-YBJ. Combining the MILAGRO measurement at higher energies, one may recognize an interesting cut-off feature. LHAASO will well cover the range in which the spectrum may be cut off depending on the acceleration model in the cocoon. As shown in the figure, one year operation of LHAASO will be sufficient to make a clear choice between the cut-off models. This might be useful in identification whether or not it is a hadronic cosmic ray source. In the TeV catalog, there are many SNRs and pulsar-wind-nebulae. Recent observation of the interaction between the shock front and molecule clouds [10] opens a window for searches for the cosmic ray origins. In [11], authors detailed the multi-wavelength investigation on NSRs with future instruments such as LHAASO. LHAASO is suitable not only to measure their SEDs over a wide range but also carry out morphologic investigations on those sources at high energies. The angular resolution of $0.2°$ of LHAASO above 10 TeV enables the study and may locate spatial regions where the gamma rays are emitted.

LHAASO is also useful in monitoring flares of AGNs. The advantage is that there is no need for organizing any champaign of multi-wavelength observation of those flares by using the wide FoV instruments LHAASO, FERMI and X-ray telescopes in the sky. Any flare of any AGN in the common FoV will be observed continuously. Very importantly, the evolution of the flares will be recorded over a wide energy range by the full duty cycle detectors. In Figure 1, an evolution of the flare on Mrk501 for 35 days measured by SWIFT, FERMI and ARGO-YBJ [12] is demonstrated by its SED. It is clearly differ from the stable emission which is fitted well with the Synchrotron Self-Compton (SSC) model. Assuming the similar flare occurs again, the prediction for LHAASO's observation is also plotted in the figure taking into account the sensitivity of LHAASO. It is expected that many AGNs flares, not only Mrk421 and Mrk501, will be measured at different flux levels everywhere in the sky. LHAASO not only serves as a global alarm system for the high energy flares, but also opens a great opportunity to identify the emitting mechanism during the flares. The potential of LHAASO in these researches, including exploring on new physics

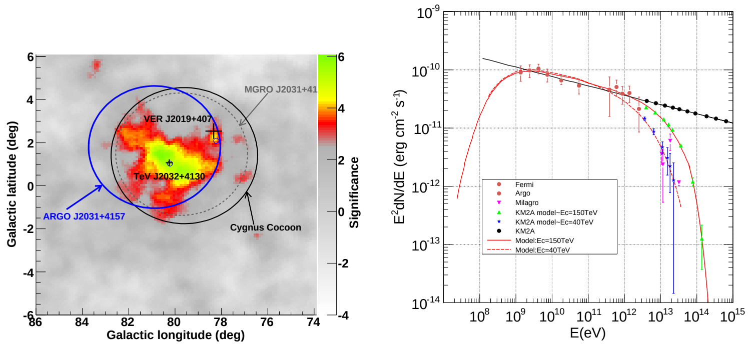

Figure 2: *In left panel, the sky map of the Cygnus Cocoon is plotted using ARGO-YBJ data. The location and the extension of the super bubble according to FERMI, MILAGRO and ARGO-YBJ are also plotted. In the right panel, the SED of the extended source measured by FERMI, ARGO-YBJ and MILAGRO shows a smooth power law with a possible cut-off which implies a hadronic origin. More details can be found elsewhere* [9]*. Here the expectation of LHAASO observation to the cocoon will extend at least by one order of magnitude in energy depending on the acceleration models. It shows that LHAASO will clearly make choice between the models with 1 year operation.*

such as intergalactic magnetic field detection and Lorentz invariance tests, has been discussed in depth elsewhere [13]. Statistic observation with many sources may help to improve our knowledge about the fascinating flaring phenomena, including the fast variation in the light curves.

AGNs are possibly sources of high energy cosmic rays above 10 PeV. Neutrinos observed by IceCube above 1 PeV reveal important clues of tracing back to the origins. The observation of the SED at high states demonstrates evidences of large deviation from the electron originated SSC model. A multi-messenger investigation combining X-rays, gamma rays, neutrinos and other observations focus on the flares of the AGNs may find useful clues. At distances of few hundred Mega-pc, radio relics and radio halos, such as CIZA J2242.8+5301, A667, A2163 and A2744, produced in the cluster merges, are pointed out by Brunetti et al. [14] in his paper in the same proceeding to be potentially the high energy cosmic ray acceleration regions. Only high sensitive detectors such as LHAASO and CTA may possibly detect the spectrum of those very remote giant cosmos accelerators at scales of 1 Mpc.

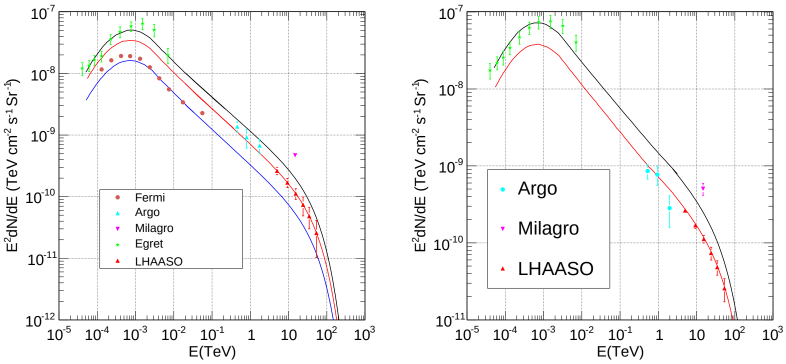

Figure 3: *The diffusive gamma ray on the galactic plane. The left is for the fluxes measured by FERMI, EGREAT and ARGO-YBJ, MILAGRO from the Cygnus region, i.e.* $65° < l < 85°$, *where* l *is the galactic latitude. The right is for the fluxes measured by ARGO-YBJ, MILAGRO and EGRET in the region* $25° < l < 100°$ *excluding the Cygnus region. A detailed analysis of this topic can be found elsewhere* [15]*. The expectations in both longitude windows of LHAASO are plotted with a cut-off of 50TeV. With 1 year operation, the observation will cover the cut-off which will strongly coupled with the knee of cosmic ray proton spectrum.*

3 Cosmic Ray Observation

The propagation through our galaxy of baryon cosmic rays can be traced by diffusive gamma rays from π^0 decay. This can be done only by the survey detectors such as FERMI at GeVs and ARGO-YBJ/HAWC at TeVs. LHAASO will extend the measurement to higher energies. The newest results by ARGO-YBJ experiment show good agreement with FERMI which measures fluxes at lower energies both from the Cygnus region and outside this region, as shown in Figure 3. It is going to be interesting to observe a cut-off at slightly higher energy of this spectrum. It can be done by a much more sensitive detector, e.g. LHAASO, as shown in Figure 3 at high energies. It would play a key role in understanding of the knee of the proton spectrum.

LHAASO is also equipped with wide FoV Cherenkov telescopes to measure shower images which is useful in shower energy measurements and identification of the primary cosmic ray species using the shape of the images. The telescopes will cover the sky up to 30° from the zenith. In the central part of the array, an infilled scintillator array with a spacing of about 4 m is deployed to catch the high energy gamma rays in showers. Each detector, referred to burst detector, is covered with a lead layer of 7 radiation length which is useful for those high energy gamma rays to initiate showers inside and develop the showers to their maxima before reach to the scintillator. The high energy gamma rays mainly from the decay of π^0s usually distributed near the shower cores. The effective area of the infilled array is about 5000 m^2 to guarantee sufficient exposure for cosmic rays up to 30 PeV for a coverage of the knees of the spectra of all species. Above 10 PeV, the shower detection is mainly rely on the 1 km^2 array with its measurements of the shower electrons and muons. The Cherenkov telescope array will be re-configured to optimize declined showers in the high energy range. For showers at even higher energies, above 100 PeV, the telescopes needs to be converted into fluorescence light detectors to make a hybrid measurement only with the muon detectors in the 1 km^2 array and the surface water Cherenkov detectors. The cosmic ray composition variation with energy and the second knee of the spectrum are the focus in this energy region. A transition from the galactic origin to the extra-galactic is the main topic. Both spectrum and composition could have many fine structures which may reveal important information about the transition. It is important to note that the whole interesting energy range is covered by the latest accelerator based experiments such as LHCf. The latest interaction models tuned with the LHC data is quite convergent at energies well below 100 PeV. Models are consistent with data in 20% for most of distributions of measurable parameters. See papers in the same proceedings [16) 17)] for more details. It enables us focusing the cosmic ray own topics, such as composition and energy spectrum, with minimized uncertainties associated with interaction models.

At the altitude of 4400 m a.s.l., a fully covered charged particle detector like water Cherenkov detector array in LHAASO can be triggered by 1 TeV showers that are well measured by space borne detectors such as AMS02 and CREAM for their charges and energies separately. They are also calibrated at test beams before launched. Therefore the overlap of the LHAASO detector with them is very important in both fixing the energy scale and obtaining the absolute fluxes for all species as references. Using the prototype of the LHAASO Cherenkov telescopes, we demonstrated that the hybrid measurement with the full coverage ARGO-YBJ detector array measured a spectrum of cosmic $H\&He$ nuclei without any knee structure up to 600 TeV. Our spectrum is quite consistent with ARGO-YBJ [18] and CREAM [19] up to an uncertainty in energy scale of $\pm3.5\%$. It is also discovered that the knee of the proton spectrum is around 630 TeV with an uncertainty of 78 TeV [20], see Figure 4. This just gives us a taste of the LHAASO experiment which, at its full scale, there will be 24 Cherenkov telescopes and 90,000 m^2 water Cherenkov detector which will measure the muon contents in showers as well. The huge statistics and multi-parameter analysis will enable separation between species and precise measurement of shower energies below 20 PeV. Above the energy, composition will be measured statistically, instead of event by event basis. The detector will be sufficiently sensitive to measure the change of composition with energy and energy spectrum. The transition of the origins of the cosmic rays is the topic, from galactic to extra-galactic.

4 Status of the LHAASO Project

In Feb. 2013, the Chinese government released the "mid- to long-term perspectives for the development of major national infrastructures in science and technology". 16 mega projects, including LHAASO, are suggested to be supported in the first five year cycle. Since 2009, the prototypes of LHAASO detector array at a scale of 1%, including a 9-unit water Cherenkov detector, 42-unit scintillator array, two water Cherenkov muon detectors, two wide FoV Cherenkov telescopes and 100-unit burst detector array, are developed and continuously deployed to the Tibet site that hosts AS_γ and ARGO-YBJ experiments. They are tested with the coincidence with the existing experiments. All of them are successfully operated over years and collected sufficient technical or even scientific data that are very essential in finalizing the detector designs. The collaboration is working on finalizing the technical design report. The first piece of important physics results has been reported and sent for publishing as described above.

Simultaneously, the LHAASO site selection has been carried out over the

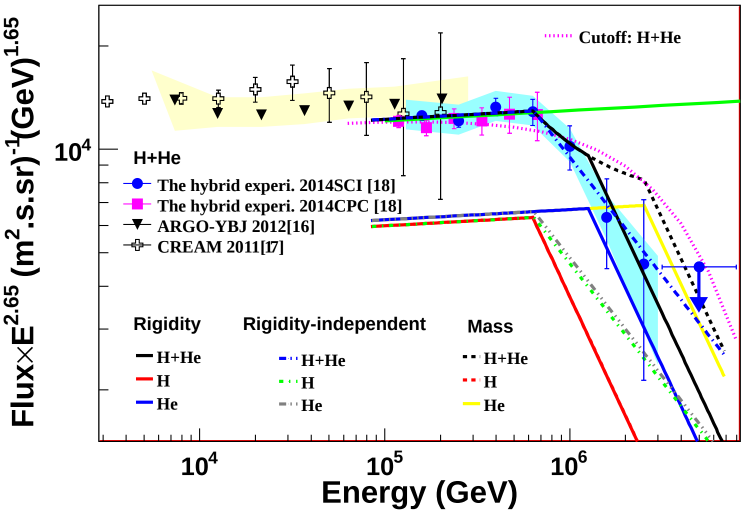

Figure 4: *The spectrum of proton and helium nuclei measured by the hybrid experiment with the LHAASO prototype Cherenkov telescopes and the ARGO-YBJ fully covered surface detector array. The bending at 630 TeV is due to the knee of the proton spectrum at the same place. LHAASO will measure even more parameters including muon content in showers and therefore will be able to separate pure samples out for several species. The knees and the spectra of the nuclei will be directly measured.*

Qing-Zang plateau of China. Among four candidates, the site at Mt. Haizi in Daocheng county, Sichuan province is finally selected. The site is in the middle of a plateau of thousands of square kilometers at about 4400 a.s.l. A brand new airport started to operate at the same altitude since last summer. It is 15 km from the site. The major highway from Chengdu, the capital city of Sichuan province, to Daocheng is just passing-by within 1 km. Nearby streams from the snow caps surrounding the plateau provide clear water to the site which is needed by the water Cherenkov detectors. It is very sunny on the plateau with a total 2700 hours of sunshine per year. The precipitation is about 700 mm and more than 80% of it is rains in three summer months. There is nearly no snow accumulation in winter. The site is 50 km from the town of Daocheng county at 3750 m a.s.l. The LHAASO base is going to be built in the town with the living base and monitoring facility. The field preparation will be done by Sichuan province after the evaluation on environment impact. The detector deployment will start next year. The construction of the whole array will last for four years since it starts. The scientific operation may start from the end of 2016 with the first quarter of the array.

5 Acknowledgements

This work is supported in China by NSFC (Contract No. 10975145 and No. 11075170), the Knowledge Innovation Fund (H85451D0U2) of IHEP, the Chinese Ministry of Science and Technology, the Chinese Academy of Science, and the Key Laboratory of Particle Astrophysics, CAS. We also acknowledge the essential support of W.Y. Chen, G. Yang, X.F. Yuan, in the installation, debugging, and maintenance of the detector.

References

1. on-line data center of FERMI LAT: http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/.
2. on-line catalog of the VHE gamma ray sources: http://tevcat.uchicago.edu/.
3. Aharonian, F.A. et al., Nature 432, p75-77 (2004).
4. Aharonian, F. et al., ApJ 664, pL71-L74 (2007).
5. MAGIC Collaboration, Albert, J. et al., Science 320, p1752 (2008).
6. Abdo, A.A. et al., ApJ 658, pL33-L36 (2007); B. Bartoli et al. (ARGO-YBJ Coll.), Astrophys.J. 745, pL22 (2012).
7. Ackermann, M., et al. (FERMI-LAT Coll.), Science, 334, p1103 (2011).
8. Ong, Rene A.; for the VERITAS Collaboration, arXiv1307.5003O (2013).
9. B. Bartoli et al. (ARGO-YBJ Coll.), Astrophys.J. 790, p152 (2014).
10. Ackermann, M., et al. (FERMI-LAT Coll.), Science, 339, p807 (2013).

11. W.Tian & J. Zhang, Science China, Physics, Mechanics & Astronomy, 56, p1443 (2012).

12. B. Bartoli et al. (ARGO-YBJ Coll.), Astrophys.J. 758, p2 (2012).

13. S. Chen, Science China, Physics, Mechanics & Astronomy, 56, p1455 (2012).

14. Brunetti et al., "Diffuse radio emission in galaxy clusters: crossroad between astrophysics and cosmology", This proceeding, p?? (2014).

15. B. Bartoli et al. (ARGO-YBJ Coll.), arXiv??, submitted to ApJ (2014).

16. R. Engel, T. Pierog, and R. Ulrich, "LHC Results and the Interpretation of Cosmic-Ray Data", This proceeding, p?? (2014).

17. A. Tricomi, "Astroparticle Physics with the LHCf Detector at LHC", This proceeding, p?? (2014).

18. B. Bartoli et al. (ARGO-YBJ Coll.), Phys.Rev. D85, p092005 (2012).

19. Y. S. Yoon et al. (CREAM Coll.), Astrophys. J. 728, p122 (2011).

20. B. Bartoli et al. (ARGO-YBJ Coll. and LHAASO Coll.), Chin.Phys. C38, p045001 (2014); B. Bartoli et al. (ARGO-YBJ Coll. and LHAASO Coll.), arXiv??, submitted to Science (2014).