EXPECTATION ON OBSERVATION OF SUPERNova REMNANTS WITH THE LHAASO PROJECT

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ABSTRACT

Supernova remnants (SNRs) are believed to be the most important acceleration sites for cosmic rays (CRs) below \( \sim 10^{16} \) eV in the Galaxy. High-energy photons, either directly from the shocks of the SNRs or indirectly from the interaction between SNRs and the nearby clouds, are crucial probes for the CR acceleration. Big progresses on observations of SNRs have been achieved by space- and ground-based \( \gamma \)-ray facilities. However, whether \( \gamma \)-rays come from accelerated hadrons or not, as well as their connection with the CRs observed at Earth, remains in debate. Large High Altitude Air Shower Observatory (LHAASO), a next-generation experiment, is designed to survey the northern part of the very high energy \( \gamma \)-ray sky from \( \sim 0.3 \) TeV to PeV with the sensitivity of \( \sim 1 \% \) of the Crab Nebula flux. In this paper, we indicate that LHAASO will be dedicated to enlarging the \( \gamma \)-ray SNR samples and improving the spectral and morphological measurements. These measurements, especially at energies above 30 TeV, will be important for us to finally understand the CR acceleration in SNRs.

Key words: acceleration of particles – cosmic rays – gamma rays: general

1. INTRODUCTION

Cosmic rays (CRs), discovered more than a century ago, represent the most energetic and, to some degree, fundamental aspect of the universe. Nuclei constitute dominantly (\( \sim 99\% \)) CRs, and electrons contribute the remaining \( \sim 1\% \). The energy spectrum of CRs observed at Earth is well described by a single power law up to energies of a few PeV, above which the spectrum steepsen to form the so-called “knee” (Horandel 2003; Blumer et al. 2009). It is generally believed that CRs below the “knee” originate from the Galaxy, due to a simple argument that the Galactic magnetic field would effectively confine such particles. However, their acceleration sites and the acceleration mechanism remain open questions.

The deflection of charged CRs in the Galactic magnetic field makes it very difficult to identify the sources of CRs. High-energy \( \gamma \)-rays, produced by either the collision between CR hadrons and the ambient medium or the interaction between CR leptons and the interstellar radiation field and/or the medium, are thus more powerful to probe the sources of CRs. With quick development of the detection technology, great progresses have been achieved in high-energy \( \gamma \)-ray astronomy during the past 2 decades. The satellite-borne instrument Fermi Large Area Telescope (Fermi-LAT), launched in 2008, discovered over 3000 sources in GeV energies (Ackermann et al. 2015a). In TeV energies, more than 160 \( \gamma \)-ray sources\(^5\) have been firmly detected by the ground-based detectors, including Imaging Atmospheric Cerenkov Telescopes (IACTs) such as H.E.S.S., MAGIC, and VERITAS, and extensive air shower (EAS) arrays such as Tibet-AS\( \gamma \), Milagro, and ARGO-YBJ. Most of these \( \gamma \)-ray sources are likely to be leptonic, including pulsars, pulsar wind nebulae (PWNs), binary systems, and so on (e.g., Aharonian et al. 2006; Chen 2013; Bartoli et al. 2015). Clear evidence of the sources of hadronic CRs is observationally rare.

It is widely believed that supernova remnants (SNRs) could efficiently accelerate particles at the shock front where the expanding supernova ejecta encounter the surrounding medium (Bell 1978a, 1978b; Drury et al. 1994). The well-established diffusive shock acceleration theory (Drury 1983; Blandford & Eichler 1987) predicts a power-law spectrum of the accelerated particles with an index of \( \sim 2 \) (Holder 2012; Schure et al. 2012), well consistent with the radio observations of SNRs,\(^7\) as well as the locally observed CR spectrum accounting for the propagation effect. Moreover, the importance of magnetic field amplification by the accelerated particles themselves has been increasingly recognized, which is expected to play a particularly important role in explaining the CRs around the knee region (\( \sim \)PeV; Bell 2004).

Based on the multilwavelength observations of SNRs, a class of SNRs have been suggested to be efficient electron accelerators, e.g., RX J1713.7-3946 (Ellison et al. 2010; Abdo et al. 2011; Li et al. 2011; Yuan et al. 2011), RX J0852+6262 (Tanaka et al. 2011), RCW 86 (Yuan et al. 2014), HESS J1731-347 (Yang et al. 2014; Acero et al. 2015b), and SN 1006 (Acero et al. 2010, 2015b; Araya & Frutos 2012). On the other hand, Fermi-LAT collaboration reported the detection of the characteristic pion-decay bump in the TeV \( \gamma \)-ray spectra of two ancient SNRs, IC 443 and W44, which are interacting with molecular clouds (Ackermann et al. 2013). An earlier detection of the hard sub-GeV spectrum of W44 by AGILE was also explained to be hadronic in origin (Giuliani et al. 2011). These observations might give direct evidence for hadronic CR acceleration in SNRs (Ackermann et al. 2013). However, the role of electron bremsstrahlung in this energy range is still

\(^{5}\) http://tevcat.uchicago.edu/

\(^{7}\) http://www.mrao.cam.ac.uk/surveys/snr/
unclear, due to the poorly constrained sub-GeV electron spectrum.

The observations of very high energy (e.g., >100 TeV) γ-ray emission from SNRs will provide a complimentary test of the leptonic/hadronic origin of the γ-rays. It is expected that it will be difficult to accelerate electrons sufficiently to high energies due to the strong synchrotron and/or inverse Compton cooling. A rough estimate of the synchrotron cooling gives the cooling energy, $E_c \sim 10(B/\mu G)^{-2} (T/10^3 \text{ yr})^{-1} \text{ PeV}$, above which electrons will cool down. For a typical magnetic field strength of tens of $\mu G$ and an age of $10^3$ yr, $E_c \lesssim 100 \text{ TeV}$. The acceleration of high-energy electrons will be even more difficult for old SNRs. Furthermore, the inverse Compton radiation efficiency of very high energy electrons will be suppressed due to the Klein–Nishina effect, making the contribution to very high energy γ-rays more difficult. It is thus expected that γ-ray emission above 100 TeV from SNRs (especially the old ones), either from shock-crushed dense clouds (e.g., Blandford & Cowie 1982; Uchiyama et al. 2010) or from the adjacent MCs illuminated by escaping protons (Li & Chen 2010, 2012), will strongly support the nuclei acceleration. Besides, the γ-ray observation above 100 TeV is also expected to give a constraint on the cutoff energy of shock-accelerated protons, which can help to make a distinction between the theoretical models (Zhang & Chen 2016). These become the major motivations for which we propose a next-generation, km$^2$-scale CR/γ-ray observatory: the Large High Altitude Air Shower Observatory (LHAASO; Cao 2010; He 2015). With a large effective area (∼km$^2$) and large field of view (∼2 sr), as well as a high CR rejection power (∼1%), LHAASO is dedicated to surveying the northern very high energy γ-ray sky with a sensitivity of ∼1% of the Crab Nebula flux. LHAASO is expected to not only discover many new sources but also improve the spectral and morphological measurements of known sources to the highest achievable energies (Cui et al. 2014; Zhao et al. 2016).

In this work we study the perspective of observing very high energy γ-ray emission from SNRs with LHAASO. We intend to understand the physical potential of LHAASO on the long-standing problem of the origin of hadronic CRs. The rest of this paper is organized as follows. We briefly introduce the design of LHAASO detectors and their performances on γ-ray detections in Section 2. The expected performance of SNR observations with LHAASO based on the current GeV and/or TeV γ-ray observations is presented in Section 3. We will pay special attention to the spectral measurements to >30 TeV energies. We conclude our work with some discussions in Section 4.

2. THE LHAASO PROJECT AND ITS PERFORMANCE

LHAASO (100°01E, 29°35N) is a recently approved, next-generation EAS experiment that will be built at 4410 m above sea level near the Daocheng village, in Sichuan province, China. LHAASO is a hybrid EAS array covering an area of 1 km$^2$ (KM2A), water Cerenkov detector array (WCDA), and wide field of view imaging Cerenkov telescope array (WFCTA). The major scientific goals of LHAASO are (1) precisely measuring the spectra of γ-ray sources at a high energy range for studying the acceleration and propagation of CRs, (2) deeply surveying the very high energy γ-ray sky (Decl. from $-10^\circ$ to $70^\circ$) for exploring the high-energy radiation mechanism, and (3) effectively searching for dark matter and the new physics (Cao 2010; He 2015). The setup of LHAASO (see Figure 1) and its performance are as follows:

1. KM2A, with an effective area of 1 km$^2$, is composed of 5195 scintillator electron detectors (EDs) with 1 m$^2$ each and a spacing of 15 m, and 1171 muon detectors (MDs) with 36 m$^2$ each and a spacing of 30 m. The detector performance is discussed in Cui et al. (2014) and He (2015). At 10 TeV, the effective area of KM2A can reach about 0.3 km$^2$, the angular resolution is about 0.6°, and the energy resolution for γ-rays is about 42%. The corresponding values are 0.8 km$^2$, 0.5°, and 33% at 30 TeV and 0.9 km$^2$, 0.3°, and 20% at 100 TeV. With the large area of the MD array, KM2A will reject the hadronic shower background at a level of 10$^{-5}$ at 50 TeV and even 10$^{-5}$ at higher energies, so that γ-ray samples can reach background-free above 100 TeV. The highest sensitivity of KM2A is ∼1% of the Crab Nebula flux in the energy range of 50–100 TeV for 1 yr of observation.

2. WCDA, with an effective area of 78,000 m$^2$ and 3000 units, will be built at the center of KM2A. The size of one unit is about 5 m × 5 m, and the effective water depth is about 4.4 m. Each unit is separated by plastic curtains vertically hung in water and contains a photomultiplier tube anchored at the center of the cell bottom. The detector performance is discussed in Yao et al. (2009, 2011). At 0.5 TeV, the effective area can reach 3000 m$^2$, the angular resolution is 0.6°, and the energy resolution for γ-rays is 95%. The corresponding values are 10,000 m$^2$, 0.4°, and 90% at 1 TeV and 50,000 m$^2$, 0.2°, and 60% at 10 TeV. The highest sensitivity is ∼1% of the Crab Nebula flux at an energy of around 3 TeV.

3. WFCTA, made up of 12 telescopes, will be built near WCDA. These detectors are to measure the energy spectra of different compositions of CRs up to the second knee, less relevant to the γ-ray detection as discussed in this work.

3. EXPECTATION ON OBSERVATION OF SNRs WITH LHAASO

3.1. Simulation of Observing a γ-ray Source

To estimate LHAASO observation for a γ-ray source, both γ-ray and CR background samples are produced by CORSIKA 6.600. The detector response of WCDA is simulated based on

![Figure 1. Schematic plot of LHAASO detectors.](image-url)
the GEAR4 program developed by the Milagro collaboration (Yao et al. 2009). For KM2A, a fast simulation presented in Cui et al. (2014) is adopted. The simulation events are sampled in the energy range from 100 GeV to 10 PeV, with the zenith angle less than 45°.

In order to obtain the signals (N_s) and background (N_bg) within a specific space angle center on the source, we have traced the source by means of a complete transit, i.e., 24 hr of observation. We only adopt the protons to simulate the CR background, while we adjusted the flux to the flux of all particles (Ivanenko 1988). We use Equation (17) of Li and Ma (Li & Ma 1983) to calculate the significance.

### 3.2. Detectability of SNRs and SNR Candidates

According to Dave Green’s Galactic SNR catalog (see footnote 7), 294 SNRs have been detected up to now. Most of these SNRs are detected in low-energy bands. In GeV energies, the Fermi-LAT collaboration reported their first SNR catalog based on 3 yr of survey data, in which 12 firm identifications and 11 possible associations with SNRs were found (Acero et al. 2015a). In TeV energies, there have been 23 SNRs or SNR candidates detected up to now, of which 10 of which are also GeV γ-ray emitters (see footnote 6). Furthermore, there are 34 unidentified TeV γ-ray sources that do not have clear counterparts in other wavelengths. Different from the Fermi unidentified sources, which are expected to be dominated by active galactic nuclei (Mao & Yu 2013), most of the unidentified TeV sources are located in the Galactic plane (see Figure 2) and could be potential SNRs. Figure 2 illustrates the locations of those sources (symbol) and their visibility by LHAASO (shaded region). In total, 92 out of 294 SNRs in the Green Catalog, 6 GeV SNRs or SNR candidates, 2 TeV SNRs, and 6 GeV–TeV SNRs are in the field of view of LHAASO. In addition, 17 unidentified TeV sources are located in the field of view of LHAASO.

Based on the current GeV/TeV observations of SNRs and SNR candidates, we estimate their detectability by LHAASO. The γ-ray spectrum of each source is assumed to be an exponentially cutoff power-law form

\[
\frac{dN}{dE} = J_0(E/\text{TeV})^{-\alpha} \exp(-E/E_{\text{cut}}),
\]

where \(J_0\) is the flux at 1 TeV, \(\alpha\) is the source spectral index, and \(E_{\text{cut}}\) is the cutoff energy. We fit the observational data to find the spectral parameters for each source. For the GeV-only sources and some TeV sources, whose cutoff energies cannot be well determined, we assume \(E_{\text{cut}} = 30\) and 100 TeV, respectively.

We simulate the observation of each source and calculate its expected significance for a 5 yr sky survey of LHAASO. For GeV–TeV and TeV SNRs, the expected significance above 10 TeV under cutoff energies 30 and 100 TeV is presented in Table 1. Six SNRs can be detected by LHAASO with significance greater than 5σ if the cutoff energy is 100 TeV. The significance will decrease if the cutoff energy is lower, while there are still five SNRs that can be detected by LHAASO if the cutoff energy is 30 TeV. This is the key to confirming whether the SNR is hadronic in origin or not, showing that the observation level of LHAASO is sensitive to giving a judgment on the acceleration mechanism above 30 TeV.

Moreover, it has been found that some SNRs could emit TeV γ-rays, while in the GeV energy band there were no observation results, such as G106.3+2.7 and HESS J1912+101. G106.3+2.7 was first observed by DRAO at the radio energy range (Joncas & Higgs 1990). In 2000, Pineault & Joncas confirmed the object as an SNR, with an estimated age of 1.3 Myr and a distance of 12 kpc (Pineault & Joncas 2000). The pulsar PSR J2229+6114 is located at the northern edge of the remnant’s head, and it is associated with a boomerang-shaped radio- and X-ray-emitting wind nebula. At the GeV energy band, the EGRET source 3EG J2227+6122 is compatible with the pulsar position, as well as the main bulk of the radio remnant (Hartman et al. 1999). And at the TeV energy band, VERITAS reported that the total flux from the SNR G106.3+2.7 above 1 TeV is ~5% of the Crab Nebula in 2009 (Acciari et al. 2009b). HESS J1912+101 is plausibly associated with PSR J1913+1011, which is detected by the H.E.S.S. experiment. The integral flux between 1 and 10 TeV is 10% of the Crab Nebula, and the measured energy spectrum can be described by a power law with a photon index of ~2.7. From the current observation of these two TeV SNRs, we can conclude that LHAASO might discover a number of SNRs compared to conservative predictions based on the current SNR catalogs.

### 3.3. Case Studies

In this subsection we choose several GeV–TeV SNRs as examples to explore in more detail the spectral measurements of their very high energy γ-ray emissions by LHAASO, and we discuss the physical implications of these new measurements. Different from that in Section 3.2, whose purpose is a rough estimate of a big sample, we adopt a physically motivated model, either leptonic or hadronic, to characterize the γ-ray emission of these sources. In order to better fit the observed γ-ray data, we assume an exponentially cutoff broken power-law form.
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Table 1
Selection of Known GeV–TeV and TeV SNRs Shown with the Expected Significance above 10 TeV using 5 yr Monte Carlo Simulation Data of LHAASO, Assuming That the Sources Are Under the Specific Hypotheses for the Energy Spectrum

| Name            | Classification | R.A.            | Decl.          | $\alpha$ | $J_0$ (TeV$^{-1}$ cm$^{-2}$ s$^{-1}$) | $\sigma$ | $\sigma'$ | References |
|-----------------|----------------|-----------------|----------------|----------|------------------------------------|----------|----------|------------|
| Tycho(a)        | GeV–TeV        | 00$^\circ$25'18" | +64°09'        | 2.92 ± 0.46 | 2.2 × 10$^{-13}$                  | -        | -        | 1          |
| Tycho(b)        | GeV–TeV        | 00$^\circ$25'18" | +64°09'        | 1.95 ± 0.51 | 1.70 × 10$^{-13}$                  | 11.62    | 5.20     | 2          |
| IC 443          | GeV–TeV        | 06$^\circ$17'00" | +22°30'        | 2.99 ± 0.38 | 8.38 × 10$^{-13}$                  | 5.46     | -        | 3          |
| W49B            | GeV–TeV        | 19$^\circ$11'08" | +09°06'        | 3.1 ± 0.3   | 2.3 × 10$^{-13}$                  | -        | -        | 4          |
| HESS J1912-101  | TeV            | 19$^\circ$12'49" | +10°09'        | 2.7 ± 0.2   | 3.5 × 10$^{-12}$                  | 59.63    | 28.02    | 5          |
| W51C            | GeV–TeV        | 19$^\circ$23'50" | +14°06'        | 2.58 ± 0.07 | 9.7 × 10$^{-13}$                  | 31.44    | 14.87    | 6          |
| G106.3+2.7      | TeV            | 22$^\circ$27'59" | +60°52'        | 2.29 ± 0.33 | 1.42 × 10$^{-12}$                 | 57.43    | 21.10    | 7          |
| Cassiopeia A    | GeV–TeV        | 23$^h$23'26"    | +58°48'        | 2.3 ± 0.2   | 7.3 × 10$^{-13}$                  | 26.51    | 10.20    | 8          |

Note. "-" means that the significance is less than 5$\sigma$. Columns from left to right are as follows: source name, classification, R.A., decl., spectral index, flux normalization, cutoff energy, expected significance by LHAASO (for $E_{\text{cut}} = 100$ TeV, if the cutoff energy has not been measured), expected significance by LHAASO for $E_{\text{cut}} = 30$ TeV, and the references of the measurements.

References. (1) Park et al. 2015; (2) Acciari et al. 2011; (3) Acciari et al. 2009a; (4) Francois et al. 2011; (5) Aharonian et al. 2008b; (6) Aleksic et al. 2012; (7) Acciari et al. 2009b; (8) Albert et al. 2007b.

The energy spectrum from GeV to TeV can be described by a broad range of functions, which is not enough to explain the high-energy $\gamma$-ray emission.

Cassiopeia A (Cas A), which appeared in the sky in 1680, is the youngest of the historical Galactic SNRs (Abdo et al. 2010b; Acciari et al. 2010). It is one of the best-studied objects with both thermal and nonthermal broadband emission ranging from radio wavelengths to TeV $\gamma$-rays (Aharonian et al. 2001; Albert et al. 2007b; Acciari et al. 2010; Yuan et al. 2013). TeV $\gamma$-ray observations revealed a rather modest $\gamma$-ray flux, compared to the synchrotron radio through X-ray emission, which further strengthens the argument for a rather high magnetic field. In the GeV range, Fermi-LAT observation suggests that the leptonic model cannot fit the turnover well at low energy because the bremsstrahlung component that is dominant over IC below 1 GeV has a steep spectrum, and hadronic emission describing the $\gamma$-ray spectrum by a broken power-law is preferred. However, because the observed TeV $\gamma$-ray fluxes have large statistical uncertainties, it cannot be judged yet whether the TeV $\gamma$-rays are generated by interactions of accelerated protons and nuclei with the ambient gas or by electrons through bremsstrahlung and inverse Compton scattering. The maximum energy of the observed TeV $\gamma$-rays is only several TeV; the question whether Cas A accelerates particles to PeV energy is still open.

At the LHAASO site, the effective observation time is 6.2 hr per day for Tycho and 6.8 hr per day for Cas A with zenith angle less than 45°. Tycho culminates with a zenith angle of 34°, and Cas A culminates with a zenith angle of 29°. The expected spectrum of Cas A from 0.3 TeV to 1 PeV is shown in Figure 3, and the parameters for the leptonic and hadronic models are listed in Tables 2 and 3, respectively. According to the expectation results from Figure 3, we can see that from 300 GeV to 500 TeV, the statistic error of data obtained by LHAASO will be less than 10%. Due to the Klein–Nishina effect, the spectra dominated by electrons are much softer than the hadronic acceleration above 10 TeV, and the expected result of LHAASO with a low statistic error can give a reasonable explanation of the high-energy range. This estimation would be just sufficient to confirm whether the historical SNRs are PeVatrons or not and give the final judgment for the acceleration models.
3.3.2. SNRs Interacting with Molecular Clouds

The massive molecular clouds located in the vicinity of SNRs provide dense targets for hadronic interactions and thus dramatically increase the chances of tracing the runaway protons via the secondary $\gamma$-rays. The location of molecular clouds close to SNRs could be accidental, but in general there is a deep link between SNRs and molecular clouds (Jiang et al. 2010), especially in the star-forming regions (Aharonian & Atoyan 1996). SNRs interacting with molecular clouds are expected to strengthen $\pi^0$-decay emission and then could provide direct evidence of cosmic nuclei being accelerated at supernova shocks (Aharonian et al. 1994).

SNR IC 443 possesses strong molecular line emission regions, which makes IC443 a case for an SNR interacting with molecular clouds. The X-ray emission of IC 443 is primarily thermal and peaked toward the interior of the northeast shell, indicating that IC 443 is an SNR with mixed morphology.

$\gamma$-rays from IC 443 were observed by Fermi (Abdo et al. 2010a) in the GeV region and VERITAS (Acciari et al. 2009a) and MAGIC (Albert et al. 2007a) in the TeV region up to 1 TeV detected the $\gamma$-ray spectrum of IC 443, but at a higher energy range, there is not yet observation, which is very important for the determination of the $\gamma$-ray emission mechanism.

W51C (G49.2-0.7) also interacts with the molecular clouds (Tian & Leahy 2013). The W51 region was widely studied as it is known to host several objects. It contains three main components: two star-forming regions W51A and W51B, surrounded by a very giant molecular cloud, and SNR W51C. W51C is a radio-bright SNR at a distance of 6 kpc from Earth with an estimated age of $\sim 3 \times 10^4$ yr (Koo et al. 1995). W51C is visible in X-rays showing both a shell type and center-filled morphology. Shocked atomic and molecular gases have been observed, providing direct evidence of the interaction of the W51C shock with a large molecular cloud (Reichardt et al. 2011; Aleksic et al. 2012). The GeV spectral result provided by Fermi indicates that it is difficult for the leptonic model to explain $\gamma$-ray production, and the most reasonable explanation is that hadronic interaction took place at the shocked shell of W51C, which emits GeV $\gamma$-rays (Abdo et al. 2009b). Moreover, MAGIC and H.E.S.S. also indicate that the $\gamma$-ray emission from W51C tends to be dominated by $\pi^0$-decay up to several TeV (Fiasson et al. 2009; Reichardt et al. 2011; Aleksic et al. 2012). But this still has uncertainties for the acceleration mechanism above 10 TeV.

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Table 2

| Name       | $d$ (kpc) | $n$ (cm$^{-3}$) | $\alpha_1$ | $\alpha_2$ | $E_{br}$ (GeV) | $W_e$ (erg) | References |
|------------|-----------|----------------|-------------|-------------|----------------|-------------|------------|
| Tycho      | 3.0       | 10             | 2.03        | 2.69        | 0.418          | 2.92 $\times 10^{48}$ | 1, 2       |
| Cassiopeia A | 3.4 | 10             | 1.03        | 2.81        | 6.38           | 6.18 $\times 10^{48}$ | 3         |
| IC 443     | 2.0       | 100            | 1.92        | 3.00        | 12.37          | 3.63 $\times 10^{48}$ | 4         |
| W51C       | 6.0       | 100            | 1.68        | 2.77        | 4.49           | 2.07 $\times 10^{49}$ | 5         |

Note. $W_e$ is the total energy of electrons.

References. (1) Giordano et al. 2012; (2) Zhang et al. 2013; (3) Abdo et al. 2010b; (4) Yuan et al. 2012; (5) Abdo et al. 2009b.

Table 3

| Name       | $d$ (kpc) | $n$ (cm$^{-3}$) | $\alpha_1$ | $\alpha_2$ | $E_{br}$ (GeV) | $W_p$ (erg) | References |
|------------|-----------|----------------|-------------|-------------|----------------|-------------|------------|
| Tycho      | 3.0       | 10             | 1.21        | 2.36        | 1.12           | 1.07 $\times 10^{50}$ |           |
| Cassiopeia A | 3.4 | 10             | 1.22        | 2.41        | 21.72          | 5.82 $\times 10^{50}$ |           |

Note. $W_p$ is the total energy of protons.
Besides the leptonic model described above, the accumulative diffusion model is also performed (in this paper, we call it the AD model for short; Li & Chen 2010, 2012; Zhang & Chen 2016). The AD model considers that the energetic protons colliding with the given molecular clouds are a collection of the diffusive protons escaping from the shock front as the SNR expands. A small distance between the SNR and molecular clouds is allowed. The distribution of escaping protons is assumed to be a power-law function, and the spectrum of the diffusive protons for any point near the SNR at any time is obtained. In the treatment of the dynamical evolution of an SNR, the Sedov–Taylor law is used for the adiabatic phase and the radiative phase. Besides, the finite volume of the cloud in the vicinity of SNRs is considered. The γ-rays emitted from the secondary leptons are negligible compared with the dominant contribution of the protons themselves (Gabici et al. 2007, 2009).

The parameters for the leptonic model are listed in Table 2, and the parameters for the AD model are given in the published paper (Li & Chen 2012). At the LHAASO site, the effective observation time is 6.53 hr per day for IC 443 and 6.0 hr per day for W51C, with zenith angle less than 45°. IC 443 culminates with a zenith angle of 8°, and W51C culminates with a zenith angle of 16°. The expectation of LHAASO is given in Figure 4, compared with the measurement of Fermi, MAGIC, and VERITAS. From 300 GeV to 500 TeV, the statistic error of data obtained by LHAASO will be less than 10%. The discrepancy between the expectations from the two models will reach more than 5σ above 20 TeV. This indicates that LHAASO will make a great contribution to the acceleration measurement in the TeV range, providing the final judgment on leptonic or hadronic acceleration.

### 3.4. Special Case Studies

Most of the unidentified TeV sources are extended γ-ray sources with SNRs, PWNs, or pulsars in their region. The estimation of their significance should include the source extension during the calculation of background events. To model the source extension, a symmetric two-dimensional Gaussian shape is used for all extended sources in this work. The source extensions σ_{ext} for each source are shown in Table 4.

We choose ARGO J2031+4157/Cygnus Cocoon as an example to explore in more detail the spectral measurements at a high energy range. The Cygnus region of the Galactic plane, discovered by Fermi-LAT at GeV energies in the Cygnus superbubble, is a famous region in the northern sky for the complex features observed in radio, infrared, X-rays, and γ-rays. It contains a high-density interstellar medium, rich in potential CR acceleration sites such as Wolf-Rayet stars, OB associations, and SNRs. This region is home to a number of GeV γ-ray sources detected by Fermi-LAT (Nolan et al. 2012) and several noteworthy TeV γ-ray sources detected by Milagro and ARGO-YBJ in the past decade. The Cygnus Cocoon, located in the star-forming region of Cygnus X, is interpreted as a cocoon of freshly accelerated CRs related to the Cygnus superbubble. The extended TeV γ-ray source ARGO J2031+4157 (or MGRO J2031+41) is positionally consistent with the Cygnus Cocoon, and another TeV source, MGRO J2019+37, is a mysterious source only being detected by Milagro (Abdo et al. 2007a) above 20 TeV and by VERITAS (Aliu et al. 2014) above 1 TeV. The reason for the hard spectral energy distribution from such a spatially extended region is totally unknown. The discovery of these kinds of sources and the more detailed multiwavelength spectroscopic investigations can be an efficient way to explain the radiation mechanism of them.

At the LHAASO site, Cygnus Cocoon culminates with a zenith angle of 12° and is observable for 7.2 hr per day. Figure 5 shows all the spectral measurements by Fermi-LAT (Ackermann et al. 2011), ARGO-YBJ (Bartoli et al. 2014), Milagro (Abdo et al. 2007a, 2007b, 2009a), and the expectation results with LHAASO. The hadronic emission model with energy cutoffs of 150 TeV is the maximum allowed by the ARGO-YBJ upper limit. Taking Milagro data into account, the cutoff energy would be around 40 TeV. One year of observation with LHAASO will be sufficient to give a
Table 4
Selection of Unidentified TeV $\gamma$-ray Sources and a Supperbubble (Cygnus Cocoon) Shown with the Expected Significance above 10 TeV using 5 yr Monte Carlo Simulation Data of LHAASO, Assuming That the Sources Are under the Specific Hypotheses for the Energy Spectrum

| Name          | R.A.      | Decl.     | $\alpha$  | $I_0$ (TeV$^{-1}$ cm$^{-2}$ s$^{-1}$) | $\sigma_{\text{ext}}$ (°) | $\sigma$ (°) | $\sigma'$ (°) | References |
|---------------|-----------|-----------|-----------|-------------------------------------|---------------------------|-------------|--------------|------------|
| MAGIC J0223+403  | 02°23′11″2″ | +43°00′0″ | 3.1 ± 0.31 | 4.07 × 10$^{-13}$                  | 0                         | -           | -            | 1          |
| HESS J1832-093   | 18°32′50″0″ | -09°22′2″ | 2.6 ± 0.3  | 4.8 × 10$^{-13}$                   | 0                         | 15.27       | 5.15         | 2          |
| HESS J1834-087   | 18°34′45″16 | -08°45′0″ | 2.5 ± 0.2  | 3.7 × 10$^{-12}$                  | 0.1                       | 21.73       | 7.15         | 3          |
| HESS J1841-055   | 18°40′55″5″ | -05°33′0″ | 2.32 ± 0.23 | 3.76 × 10$^{-12}$                | 0.4                       | 690.27      | 234.89       | 4          |
| HESS J1857+026   | 18°57′11″1″ | +02°40′0″ | 2.16 ± 0.07 | 5.37 × 10$^{-12}$                | 0.17                      | 205.63      | 76.95        | 5          |
| HESS J1858+020   | 18°58′20″0″ | +02°05′0″ | 2.17 ± 0.12 | 6.0 × 10$^{-13}$                | 0.08                      | 20.10       | 7.45         | 6          |
| MGRO J1908+06    | 19°07′54″4″ | +06°16′0″ | 2.54 ± 0.36 | 2.06 × 10$^{-11}$                | 0.49                      | 220.80      | 97.17        | 7          |
| VER J2016+371    | 20°16′02″2″ | +37°11′2″ | 2.3 ± 0.3   | 3.1 × 10$^{-13}$                 | 0                         | 9.76        | 5.00         | 8          |
| VER J2019+368    | 20°19′25″25 | +36°48′2″ | 1.75 ± 0.08 | 1.35 × 10$^{-12}$                | 2.0                       | 58.36       | 22.40        | 9          |
| VER J2019+407    | 20°20′04″18 | +40°45′0″ | 2.37 ± 0.14 | 1.5 × 10$^{-12}$                | 0.23                      | 38.74       | 17.89        | 10         |
| ARGO J2031+4157  | 20°31′11″2″ | +42°30′0″ | 2.6 ± 0.3   | 3.05 × 10$^{-12}$                | 2.0                       | 10.86       | 5.3          | 11         |

Note. “−” means that the significance is less than 5σ. Columns from left to right are as follows: source name, R.A., decl., spectral index, flux normalization, cutoff energy, expected significance by LHAASO (for $E_{\text{cut}}$ = 100 TeV if the cutoff energy has not been measured), expected significance by LHAASO for $E_{\text{cut}}$ = 10 TeV, and the references of the measurements.

References. (1) Aliu et al. 2009; (2) Abramowski et al. 2015; (3) Albert et al. 2006; (4) Bartoli et al. 2013; (5) Aleksic et al. 2014; (6) Aharonian et al. 2008a; (7) Bartoli et al. 2012; (8) Aliu et al. 2014; (9) Aliu et al. 2014; (10) Aliu et al. 2013; (11) Bartoli et al. 2014.

![Cygnus Cocoon](image)

Figure 5. Expectation of the LHAASO project on Cygnus Cocoon by using 1 yr MC data, compared with the measurement of Fermi-LAT (Ackermann et al. 2011), ARGO-YBJ (Bartoli et al. 2014), and Milagro (Abdo et al. 2007a, 2007b, 2009a).

Judgment on the different cutoff energy models from 300 GeV to several hundred TeV. Besides, if the spectrum has no cutoff energy shown in Figure 5 (black dots), LHAASO will give an accurate measurement up to PeV. This will provide important information for investigating the particle acceleration within the superbubble.

4. CONCLUSIONS

With a sensitivity of 10 mcrab at 50 TeV, LHAASO will launch the most accurate detection of $\gamma$-ray spectra of SNRs in the energy region above 30 TeV. In the field of view of LHAASO, eight identified GeV–TeV or TeV SNRs observed by previous experiments will be detected by LHAASO with precise spectra unprecedentedly extended up to a few hundred TeV. Besides, LHAASO has the potential to discover more TeV SNRs, which have not yet been observed at GeV regions, and can also provide important information on unidentified TeV $\gamma$-ray sources with a high significance.

According to the detailed research on the spectrum, different theoretical models can obtain the effective tests by observation of LHAASO. Especially, with the high sensitivity of LHAASO above 30 TeV, it is expected that LHAASO will be more sensitive to different leptonic or hadronic models of SNR $\gamma$-ray emission. High statistics and accurate measurement provided by LHAASO will sufficiently offer a final judgment between different SNR theoretical models, to reveal the CR acceleration mechanism in the Galaxy.

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