Ultrahigh-energy γ-Rays from Past Explosions in Our Galaxy

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Abstract

The discovery of the sources of ultrahigh-energy photons in our Galaxy by the High-Altitude Water Cherenkov Gamma-ray Observatory and the Large High Altitude Air Shower Observatory (LHAASO) has revolutionized the field of gamma-ray astronomy in the last few years. These emissions are sometimes found in the vicinity of powerful pulsars or supernova remnants (SNRs) associated with giant molecular clouds (GMCs). Inverse Compton emission by shock-accelerated electrons emitted by pulsars and proton–proton interactions of shock-accelerated protons emitted by SNRs with cold protons in molecular clouds are often identified as the causes of these emissions. In this paper we have selected two ultrahigh-energy photon sources, LHAASO J2108+5157 and LHAASO J0341+5258, which are associated with GMCs, but no powerful pulsar or SNR has been detected in their vicinity. We have proposed a scenario where shock-accelerated electrons and protons are injected in the local environment of these sources from past explosions, which happened thousands of years ago. We show that the observed ultrahigh-energy photon flux can be explained with the secondary gamma rays produced by the time-evolved relativistic electron and proton spectra.

Unified Astronomy Thesaurus concepts: Gamma-ray astronomy (628); Gamma-ray sources (633); High energy astrophysics (739)

1. Introduction

The field of gamma-ray astronomy has been rapidly progressing in the past ten years due to the successful operation of many ground-based detectors such as H.E.S.S.1 (High Energy Stereoscopic System), MAGIC2 (Major Atmospheric Gamma Imaging Cherenkov) telescope, Tibet,3 HAWC4 (High-Altitude Water Cherenkov) Gamma-ray Observatory, and LHAASO5 (Large High Altitude Air Shower Observatory), and the space-based detectors Fermi-LAT6 and AGILE.7 With the detection of gamma rays with energy from several hundreds of TeV to several PeV in our Galaxy, ultrahigh-energy (UHE) gamma-ray astronomy has emerged as an active area of research. These gamma rays are attenuated by the cosmic microwave background (CMB) and infrared background, and therefore it is challenging to detect UHE gamma-ray sources outside our Galaxy. Gamma rays are messengers of cosmic-ray acceleration sites. Thus by detecting the highest energy gamma rays it would be possible to reveal the highest energy cosmic-ray acceleration sites within our Galaxy.

The first catalog of gamma-ray sources above 56 and 100 TeV detected by HAWC (Abeysekara et al. 2020) shows nine sources above 56 TeV that have at least one pulsar within 0°.5 of the HAWC high-energy location. Their spatial extents are much larger than pulsar wind nebulae (PWNe) detected in X-rays, which indicates there could be TeV halos. The gamma rays could be produced in inverse Compton (IC) emission by relativistic electrons escaping from PWNe, which are powered by pulsars. This scenario has been used to explain even 100 TeV gamma-ray emission detected by HAWC (Breuhaus et al. 2021). In this case the IC emission happens in the Klein–Nishina regime and the gamma-ray spectrum is softer than that in the Thomson regime.

The three gamma-ray sources above 100 TeV listed in the first HAWC catalog may also result from proton–proton interactions, because cosmic-ray protons of PeV energy escaping from supernova remnants (SNRs) can efficiently produce gamma rays of 100 TeV energy by interacting with cold protons in giant molecular clouds (GMCs).

The quest to find the acceleration sites of cosmic rays and the highest energy of the Galactic cosmic rays has led to the discovery of a dozen UHE gamma-ray sources in our Galaxy (Cao et al. 2021c) by LHAASO. Many of these sources are associated with pulsars or SNRs. The curvature in the gamma-ray spectrum at the highest energy could be an indication of attenuation by background photons. This curvature may also result from an exponential cutoff in the parent proton or electron spectrum. Below we discuss two UHE gamma-ray sources detected by LHAASO. They were modeled earlier by the LHAASO Collaboration using leptonic and hadronic emission in a steady-state model. Since no PWN or SNR has been detected in their vicinity, it is hard to explain the origin of the constant supply of parent cosmic rays that produce the observed UHE gamma rays. We propose that shock-accelerated electrons and protons were injected from explosions more than several thousand years ago at the locations of the UHE gamma-ray sources. The highly relativistic electrons have been losing energy by synchrotron, bremsstrahlung, and IC emission and the protons have been losing energy in proton–proton interactions inside GMCs. The time-evolved secondary gamma-ray spectrum at the present day can explain the UHE gamma-ray data recorded by LHAASO.

1. https://www.mpi-hd.mpg.de/hfm/HESS/
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1.1. LHAASO J2108+5157

LHAASO J2108+5157 is a UHE gamma-ray source, discovered by Cao et al. (2021a) after analyzing the data from LHAASO-KM2A over 308.33 live days. This point-like source is located at R.A. = 312.17 ± 0.07\(_{\text{stat}}\), decl. = 51.95 ± 0.05\(_{\text{stat}}\). It is located near the center of a GMC [MML2017]4607 (Miville-Deschênes et al. 2017), which is within the upper limit of the extent of LHAASO J2108+5157. The average angular radius of the GMC [MML2017]4607 is 0\(_{\circ}\).236 and it has a mass of 8469 M\(_{\odot}\) at a distance of 3.28 kpc. The number density of particles in this GMC is estimated to be 30 cm\(^{-3}\). Due to this spatial correlation a hadronic origin of UHE gamma rays has been speculated, but a leptonic origin cannot be ruled out. The absence of any X-ray counterpart within 0\(_{\circ}\).26 or any very high-energy gamma-ray counterpart within a radius of 0\(_{\circ}\).5 of the source has been reported. Though there is a high-energy gamma-ray source 4FGL J2108.0+5155e spatially coincident with LHAASO J2108+5157, its flux is 10 times lower than that of the UHE gamma-ray source. Based on the catalog of SIMBAD2, Cao et al. (2021a) searched for possible cosmic accelerators within 0\(_{\circ}\).8 of the center of the LHAASO source. Though no SNR or PWN has been found, two young star clusters, Kronberger 82 (Kronberger et al. 2006) and Kronberger 80 (Kharchenko et al. 2016), have been located. These star clusters could be cosmic-ray acceleration sites.

1.2. LHAASO J0341+5258

LHAASO J0341+5258 is an extended γ-ray source discovered by Cao et al. (2021b) after analyzing the data recorded by LHAASO-KM2A over 308.33 days. It is located in the galactic plane, with best-fit position at R.A. = 55.34 ± 0.11 and decl. = 52.97 ± 0.07. The CO-line survey done by the Milky Way Imaging Scroll Painting project (Su et al. 2019) shows that molecular gas partially overlaps with LHAASO J0341+5258. The total mass of gas within 1° of the source is 10\(^7\) M\(_{\odot}\) if its distance is considered as 1 kpc. Assuming the average cloud thickness is 0\(_{\circ}\).5, the density of particles is estimated as 50 cm\(^{-3}\). The size of this GMC is 0\(_{\circ}\).33. The hadronic interaction model GEANT 4.10.0 has been used in our calculations.

2. Modeling of the Spectral Energy Distribution (SED) of Photons

We have assumed there were explosions thousands of years ago, which lasted for a year, at the locations of LHAASO J2108+5157 and LHAASO J0341+5258, which injected shock-accelerated electrons and protons. We have used a lepto-hadronic model that includes both leptonic and hadronic energy losses to calculate the SEDs of photons. The GAMERA code (Hahn 2016) has been used, which solves the transport equation to generate the time-evolved electron and proton spectra. It also calculates the resulting radiation spectrum. The transport equation for electrons or protons is given by

\[
\frac{\partial N}{\partial t} = \frac{\partial (bN)}{\partial E} - N(E, t) \cdot t_{\text{diff}}
\]

where \(Q(E, t)\) is the injection spectrum and \(b = b(E, t)\) represents the energy loss of injected particles. \(t_{\text{diff}}\) denotes the timescale on which the particles (electrons and protons) escape from the region of explosion by diffusion. \(N(E, t)\) is the resultant particle spectrum at any time \(t\).

We have assumed a power-law injection spectrum of electrons and protons. For leptonic modeling we have included synchrotron, bremsstrahlung, and IC scattering of photons from the CMB and radiation fields in the Galaxy in the transport equation given in Equation (1) by the term \(b(E, t)\). In the case of protons, the energy loss is accounted for by proton–proton interactions. GAMERA uses the full Klein–Nishina cross section for IC scattering from Blumenthal & Gould (1970) to calculate the IC photon flux radiated by the relativistic electrons. Electrons also produce bremsstrahlung radiation after interacting with molecular clouds. The code calculates this radiation for both electron–electron and electron–ion interactions (Baring et al. 1999). For proton–proton interactions GAMERA uses the parameterization developed by Kafexhiu et al. (2014). The hadronic interaction model GEANT 4.10.0 has been used in our calculations.

The loss of particles by diffusion has been included through the diffusion timescale \(t_{\text{diff}}\) in the third term of the transport equation. For cosmic-ray propagation in our Galaxy, \(t_{\text{diff}}\) can be expressed as

\[
t_{\text{diff}} = \frac{H^2}{D}.
\]

In the above equation \(H\) denotes the height of the Galaxy and \(D = D_0/E_0 (1 + \gamma_0)\) cm\(^2\) s\(^{-1}\) denotes the diffusion coefficient (Strong et al. 2004), with \(E_0 = 4\) GeV. We have replaced the size of the Galaxy by the size of the molecular clouds associated with the LHAASO sources to calculate the escape timescales during which the cosmic rays are trapped near the molecular clouds. The physical mechanism of trapping of very high-energy cosmic rays near their sources is an important topic of research; for a recent review on this see Marcowith et al. (2021). A lower value of the constant in the diffusion coefficient, \(D_0 = 10^{26}\) cm\(^2\) s\(^{-1}\) compared to the value \(D_0 = 10^{28}\) cm\(^2\) s\(^{-1}\) usually adopted to explain cosmic-ray propagation in our Galaxy, has been used to account for the trapping of the very high-energy cosmic rays in the vicinity of the LHAASO sources associated with molecular clouds. The masses and distances of the molecular clouds found in the vicinity of LHAASO J2108+5157 and J0341+5258 are 8469 M\(_{\odot}\), 3.28 kpc and 1000 M\(_{\odot}\), 1 kpc respectively. For LHAASO J2108+5157, the average angular radius of the associated GMC is 0\(_{\circ}\).236, therefore its size is about 4 \times 10^{19} cm. The size of the molecular cloud associated with LHAASO J0341+5258 is estimated to be 1.67 \times 10^{19} cm using the masses and densities of the clouds. We have calculated the diffusion timescales of cosmic rays from the molecular cloud regions associated with the LHAASO sources using the sizes of the
clouds in Equation (2):

\[ t_{\text{diff}} = 5.07292 \times 10^3 \left( \frac{E}{4 \text{ GeV}} \right)^{-0.33} \text{ yr} \quad (3) \]

for the region in the vicinity of LHAASO J2108+5157 and

\[ t_{\text{diff}} = 8.842 \times 10^4 \left( \frac{E}{4 \text{ GeV}} \right)^{-0.33} \text{ yr} \quad (4) \]

for the region in the vicinity of LHAASO J0341+5258. The diffusion and cooling timescales of electrons and protons are shown in Figures 1 and 2 for the regions in the vicinity of LHAASO J2108+5157 and LHAASO J0341+5258 respectively. The diffusion timescale for the cosmic rays producing gamma rays is shorter in the case of LHAASO J0341+5258 than in the case of LHAASO J2108+5157. The ages of the explosions are taken to be shorter than the diffusion and

Figure 1. Diffusion and cooling timescales of (a) electrons due to synchrotron, inverse Compton, and bremsstrahlung emission, where “sum” denotes the total cooling timescale after including all these processes, and (b) protons due to proton–proton interactions for LHAASO J2108+5157.

Figure 2. Diffusion and cooling timescales of (a) electrons due to synchrotron, inverse Compton, and bremsstrahlung emission, where “sum” denotes the total cooling timescale after including all these processes, and (b) protons due to proton–proton interactions for LHAASO J0341+5258.
cooling timescales of the cosmic-ray electrons and protons producing the gamma rays.

3. Results

LHAASO J2108+5157 (Cao et al. 2021a) and LHAASO J0341+5258 (Cao et al. 2021b) are not yet found to be associated with any powerful pulsar or SNR, which motivates us to consider alternative scenarios. We have assumed there were explosions that injected both shock-accelerated electrons and protons thousands of years ago. We have considered impulsive injections lasting for one year with luminosities $5.5 \times 10^{40}$ erg s$^{-1}$ and $5 \times 10^{38}$ erg s$^{-1}$ in protons and electrons respectively for LHAASO J2108+5157 and luminosities $4.5 \times 10^{38}$ erg s$^{-1}$ and $1.5 \times 10^{38}$ erg s$^{-1}$ in protons and electrons respectively for LHAASO J0341+5258. We have used the injected cosmic-ray spectrum as $(\text{electrons and protons}) \mu^2 Q \nu^2$. The GAMERA code has been used to calculate the time-evolved cosmic-ray spectrum and photon

Figure 3. Time evolution of gamma-ray emission in proton–proton interactions for (a) LHAASO J2108+5157 and (b) LHAASO J0341+5258.

Figure 4. Time evolution of leptonic emission including synchrotron, IC (CMB and ISRF), and bremsstrahlung radiations for (a) LHAASO J2108+5157 and (b) LHAASO J0341+5258.
spectrum at the present day after including radiative losses of electrons, hadronic interactions, and diffusion of cosmic rays.

Shock-accelerated protons interact with the molecular clouds present in the vicinity of the sources to emit gamma rays in proton–proton interactions. Figure 3 shows the time evolution of the γ-ray flux due to proton–proton interactions for the two sources. The time intervals labeled “age(yrs)” in the figures have been shown in equal intervals on a logarithmic scale.

The shock-accelerated electrons injected during explosions emit radiation through synchrotron, IC, and bremsstrahlung. Figure 4 represents the time evolution of the total leptonic contribution that is obtained by adding all the components (synchrotron, IC of background photons, bremsstrahlung) for both the sources. For IC we take into account both CMB and interstellar radiation fields (ISRF) in the solar vicinity (Popescu et al. 2017) as the target photon fields.

In Figure 4 we observe that, after a certain age, the peak of the secondary photon flux slightly shifts toward lower energy due to cooling of electrons. The radiation spectra of protons and electrons vary with the age of the explosion, and also with the total energy injected during the explosions. The values of these parameters are varied so that the total SEDs after adding the leptonic and hadronic contributions fit the observed spectra.

Table 1
Parameters Used for Modeling the Two Sources

| Parameters                                    | LHAASO J2108+5157 | LHAASO J0341+5258 |
|-----------------------------------------------|-------------------|-------------------|
| Energy injected in protons                    | $1.735 \times 10^{48}$ erg | $1.4193 \times 10^{46}$ erg |
| Energy injected in electrons                  | $1.577 \times 10^{46}$ erg | $4.731 \times 10^{45}$ erg |
| Maximum energy of electrons injected          | $10^2$ TeV         | $250$ TeV         |
| Minimum energy of electrons injected          | $10^{-3}$ TeV      | $10^{-3}$ TeV      |
| Maximum energy of protons injected            | $10^2$ TeV         | $300$ TeV         |
| Minimum energy of protons injected            | $10^{-2}$ TeV      | $10^{-2}$ TeV      |
| Spectral index of injected spectrum           | $-2$               | $-2$              |
| Magnetic field in emission region             | $3 \mu$G           | $3 \mu$G           |
| Number density of particles in molecular cloud| $30$ cm$^{-3}$     | $50$ cm$^{-3}$     |
| Distance of molecular cloud                   | $3.28$ kpc         | $1$ kpc           |
| Age of explosion                              | $4500$ yr          | $2000$ yr          |

Figure 5. (a) Multiwavelength SEDs of LHAASO J2108+5157. Multiwavelength data points and upper limits are shown from Cao et al. (2021a). The blue downward arrows are the upper limits of Fermi-LAT within the angular extent $\sigma = 0.26$ and gray points are the spectral points of Fermi-LAT within the angular extent $\sigma = 0.48$. The green triangles are the radio flux derived by Cao et al. (2021a) within $0.26$ of the source, obtained from the Canadian Galactic Plane Survey. (b) Multiwavelength SEDs of LHAASO J0341+5258. Multiwavelength data points and upper limits are shown from Cao et al. (2021b). The orange downward arrow is the upper limit from Chandra observation, the brown downward arrow is the HAWC upper limit. The lime green and gray points are the X-ray fluxes for 2SXPS 1712133 and 2SXPS 171354 respectively from the 2RXPS catalog (Evans et al. 2020). Green points and arrows are the Fermi-LAT spectral points and upper limits.
and $1.9 \times 10^{46}$ erg for LHAASO J2108+5157 and LHAASO J0341+5258, respectively.

4. Discussion and Conclusion

The UHE gamma-ray sources detected by HAWC and LHAASO in the last few years have received much attention from the gamma-ray community. Out of the dozen UHE gamma-ray sources detected by LHAASO we have selected two sources, LHAASO J2108+5157 and LHAASO J0341+5258, that are not found to be associated with any powerful pulsar or SNR. We consider a scenario where explosions in the past caused the injection of shock-accelerated electrons and protons in the locations of these two sources. We have studied the time evolution of shock-accelerated electrons and protons released during explosions and their energy losses. We have calculated the time-evolved SEDs of photons in a leptohadronic model including synchrotron, IC, bremsstrahlung, and proton–proton interactions in molecular clouds. The time-evolved SEDs of photons can explain the observed data at the present day. The weak supernova-like explosions are expected to have happened 4500 and 2000 yr ago. The cooling timescales of electrons and protons have been shown along with their diffusion timescale in Figures 1 and 2. The explosions released energies of the order of $10^{48}$ erg and $10^{46}$ erg respectively in accelerated particles (electrons and protons). In supernova explosions the energy emitted is typically of the order of $10^{51}$ erg, and only a few percent of it goes into nonthermal particle emission. Determining the exact nature of these explosions is beyond the scope of this paper. We conclude that supernova-like explosions in the past, whose remains are hard to identify at the present day, could also be the cause of UHE gamma-ray emission at the present day as shown in Figure 5.

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Software: GAMERA (http://libgamera.github.io/GAMERA/docs/documentation.html).

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