GeV Gamma-Ray Emission and Molecular Clouds toward Supernova Remnant G35.6–0.4 and the TeV Source HESS J1858+020

Xiao Zhang1,2, Yang Chen1,2, Fa-xiang Zheng1, Qian-Cheng Liu1, Ping Zhou1,2, and Bing Liu2,3,4

1 School of Astronomy & Space Science, Nanjing University, 163 Xianlin Avenue, Nanjing 210023, People’s Republic of China; xiaozhang@nju.edu.cn
2 Key Laboratory of Modern Astronomy and Astrophysics, Nanjing University, Ministry of Education, Nanjing 210023, People’s Republic of China
3 Department of Astronomy, School of Physical Sciences, University of Science and Technology of China, Hefei, Anhui 230026, People’s Republic of China
4 CAS Key Laboratory for Research in Galaxies and Cosmology, University of Science and Technology of China, Hefei, Anhui 230026, People’s Republic of China

Abstract

It is difficult to distinguish the hadronic process from the leptonic one in γ-ray observation, which is however crucial in revealing the origin of cosmic rays. As an endeavor in this regard, we focus in this work on the complex γ-ray emitting region, which partially overlaps with the unidentified TeV source HESS J1858+020 and includes supernova remnant (SNR) G35.6–0.4 and H II region G35.6–0.5. We reanalyze CO line, H I, and Fermi-LAT GeV γ-ray emission data of this region. The analysis of the molecular and H I data suggests that SNR G35.6–0.4 and H II region G35.6–0.5 are located at different distances. The analysis of the GeV γ-rays shows that GeV emission arises from two point sources: one (SrcA) coincident with the SNR, and the other (SrcB) coincident with both HESS J1858+020 and H II region G35.6–0.5. The GeV emission of SrcA can be explained by the hadronic process in the SNR–molecular cloud association scenario. The GeV-band spectrum of SrcB and the TeV-band spectrum of HESS J1858+020 can be smoothly connected by a power-law function, with an index of ∼2.2. The connected spectrum is well explained with a hadronic emission, with the cutoff energy of protons above 1 PeV. It thus indicates that there is a potential PeVatron in the H II region and should be further verified with ultra-high-energy observations with, e.g., LHAASO.

Unified Astronomy Thesaurus concepts: Supernova remnants (1667); Gamma-rays (637); Gamma-ray sources (633); Molecular clouds (1072)

1. Introduction

In γ-ray astrophysics, multiband observations play an important role in identifying the source types and understanding the origin of the γ-ray emissions. Thanks to the observations facilitated in the wide electromagnetic wave window, about 2/3 of the TeV-γ-ray sources have counterparts at other wavelengths. Because of this, it was known that there are a number of types of Galactic γ-ray emitters, such as supernova remnants (SNRs), pulsars (PSRs), and their wind nebulae (PWNe), H II regions (HIIRs; or star-forming regions), superbubbles, etc. These Galactic γ-ray sources may be the accelerators of cosmic rays (CRs) below the “knee” energy around $3 \times 10^{15}$ eV if they have the hadronic origin and have the maximum energy of γ-rays above ~100 TeV. For example, based on the observations of the typical HIIRs in the Milky Way, e.g., the Cygnus Region (Aliu et al. 2014; Bartoli et al. 2014; Abeysekara et al. 2021; Amenomori et al. 2021), it is suggested that HIIRs are efficient particle accelerators and may be a type of contributors of Galactic CRs. Due to the TeV spectrum without an obvious cutoff, the unidentified TeV source HESS J1858+020 (Aharonian et al. 2008; H.E.S.S. Collaboration et al. 2018), likely associated with an SNR-HIIR complex5 G35.6–0.4, may be a good candidate CR source and provide a unique opportunity to distinguish the contribution of high-energy γ-rays from the two components.

The extended radio source G35.6–0.4 was discovered in the early radio surveys (Beard & Kerr 1969; Altenhoff et al. 1970) and had a longtime debate on its class: an HIIR, an SNR, or an SNR-HIIR complex (see Green 2009). According to the nonthermal spectral index $\alpha_{\nu} = 0.47 \pm 0.07 (S \propto \nu^{-\alpha_{\nu}}$, where $S$ is the radio flux and $\nu$ the frequency) and the faint infrared (IR) emission, it was reidentified as an SNR although radio recombination lines were detected from it (Green 2009). Its radio morphology revealed by the VGPS 1.4 GHz data (Stil et al. 2006; Green 2009) shows a partially limb-brightened structure elongated in the Galactic latitude with a size of $15' \times 11'$. With deep observations performed by the Giant Metrewave Radio Telescope (GMRT), however, it was resolved at 610 MHz into two nearly circular sources which appear connected with each other (Paredes et al. 2014). This high-resolution GMRT image suggests that the radio source G35.6–0.4 defined in the previous works consists of an SNR (G35.6–0.4) represented by the big circular structure, and an HIIR (G35.6–0.5), containing the radio recombination lines (RRLs, Lockman 1989), represented by the ring-shaped structure with a smaller size (see the left panel of Figure 1). Moreover, there is a semicircular structure in the Wide-field Infrared Survey Explorer (WISE) 12 μm image (Wright et al. 2010) which well delineates the small radio semiring (see the right panel of Figure 1).

The distance to the SNR was first assumed to be the same as that, ~10.5 kpc, to the nearby HIIR G35.5–0.0, which seems consistent with the $\Sigma-D$ relation (Green 2009). It was also put at a small distance of $3.6 \pm 0.4$ kpc based on the H I absorption

5 The term “complex” here does not necessarily mean that the SNR and the HIIR are physically related.
feature abstracted from the radio continuum brightness peak region (Zhu et al. 2013) and the association with a CO cloud at the local standard of rest (LSR) velocity $V_{\text{LSR}} \sim +55$ km s$^{-1}$ as suggested by Paron & Giacani (2010). The small distance was also supported by the latest H I study (Ranasinghe & Leahy 2018). As will be shown below, however, SNR G35.6–0.4 and HIIR G35.6–0.5 are located at different distances and are not in physical association with one another.

At a very high-energy band, a TeV source HESS J1858+020 was found to partially overlap with the southern (in the Galactic coordinate system) part of SNR G35.6–0.4 (Aharonian et al. 2008). Assuming a purely hadronic origin, a lower limit on the proton cutoff energy is derived as $\sim 30$ TeV at a 90% confidence level (Spengler 2020). Based on the CO observation, in the overlapped region there is a molecular cloud (MC) that was suggested to be likely associated with the SNR, and the TeV $\gamma$-ray emission detected in HESS J1858+020 was ascribed to SNR-MC hadronic interaction (Paron & Giacani 2010; Paron et al. 2011). At the GeV band, no emission was found from the 2 yr Fermi-LAT data (Torres et al. 2011). Recently, Cui et al. (2021) performed a Fermi-LAT $\gamma$-ray analysis with 10.7 yr data and found that there are two GeV point sources toward the G35.6–0.4 region from the spatial study in the energy range 5–500 GeV. One hard source (SrcX2) is spatially coincident with HESS J1858+020 and a molecular clump. It was suggested that the GeV–TeV $\gamma$-ray emission is from the MC bombarded by the protons that escaped from the SNR (Cui et al. 2021). The other (SrcX1) with a soft GeV spectrum is located at the northern boundary of the SNR, with the origin of the $\gamma$-rays remaining unclear.

In this work, we revisit the Fermi-LAT observational data of the $\gamma$-ray emitting sources toward the SNR-HIIR complex G35.6–0.4 and perform a study of the molecular environment of the complex. Data used in this work and the corresponding results are given in Sections 2 and 3, respectively. In Section 4, the revised distances of the two emitting sources and the origin of the $\gamma$-ray emissions are discussed. Finally, we summarize our results in Section 5.

2. Observations and Data

2.1. Fermi-LAT Observational Data

In this study, we analyze more than 12 yr (from 2008 August 04 15:43:36 (UTC) to 2020 November 30 05:38:25 (UTC)) of Fermi-LAT Pass 8 SOURCE class (evclass = 128, evtype = 3) data in the energy range 0.2–500 GeV using the python package Fermipy (v1.0.1)6 (Wood et al. 2017). The corresponding instrument respond functions (IRFs) are “P8R3_SOURCE_V3_v1.” The region of interest (ROI) is a $15^\circ \times 15^\circ$ square centered at the position of SNR G35.6–0.4 (R.A. = 284°479, decl. = 2°217). We only select the events within a maximum zenith angle of 90° to filter out the background $\gamma$-rays from the Earth’s limb and apply the recommended filter string “(DATA_QUAL > 0)&(LAT_CONFIG==1)” to choose the good time intervals. The Galactic diffuse emission (gll_iem_v07.fits) and isotropic emission (iso_P8R3_SOURCE_V3_v1.txt), as well as all the sources listed in the LAT 10 yr Source Catalog (4FGL-DR2, Abdollahi et al. 2020) within a radius of 25° from the ROI center, are included for background modeling, namely the baseline model.

2.2. CO Observations and Archival Data

The observations of $^{12}$CO $J = 1 - 0$ (at 115.271 GHz) and $^{13}$CO $J = 1 - 0$ (at 110.201 GHz) were made during 2013 April–May with the 13.7 m millimeter-wavelength telescope of the Purple Mountain Observatory at Delingha (PMOD), China.
The total bandwidth of the fast Fourier transform spectrometer of PMOD is 1 GHz and the half-power beamwidth is about 50\,\arcsec for the two lines. The typical rms noise level is about 0.5 K for $^{12}\text{CO}$ ($J = 1 - 0$) at the velocity resolution of 0.16 km s$^{-1}$ and 0.3 K for $^{13}\text{CO}$ ($J = 1 - 0$) at 0.17 km s$^{-1}$.

We also use the archival $^{12}\text{CO}$ data of the FOREST Unbiased Galactic plane Imaging survey with the Nobeyama 45 m telescope (FUGIN; Umemoto et al. 2017) observation. The data have an angular resolution of 25\,\arcsec and an average rms of 1.5 K at a velocity resolution of 0.65 km s$^{-1}$.

2.3. Other Data

We also retrieve the Very Large Array (VLA) radio continuum image at 1.4 GHz and H$1$ data from the HI/OH/Recombination line survey (THOR) project (Beuther et al. 2016; Wang et al. 2020). The data have a spatial resolution of 25\,\arcsec and a velocity resolution of 1.5 km s$^{-1}$.

3. Data Analysis and Results

3.1. Fermi-LAT Data Analysis

3.1.1. Spatial Analysis

We note that there are two 4FGL-DR2 catalog sources 4FGL J1857.6+0212 and 4FGL J1858.3+0209 toward the SNR-HIIR complex G35.6−0.4 region. They are first treated as backgrounds to check the residual emission around our target. We use the fit method to refit the spectral parameters of the sources within 3\,\arcmin from the ROI center with a significance above 4\,$\sigma$ and the normalization parameters of the two diffuse background components. Then, we fix all parameters except for the normalization of the Galactic diffuse emission to their best-fit values and generate the residual test-statistic (TS) map which is shown in the left panel of Figure 2. Here, the TS value is defined as $\text{TS} = 2\log(L_{0}/L_{i})$, in which $L_{0}$ is the maximum likelihood of the null hypothesis and $L_{i}$ is the maximum likelihood with a putative source located in this pixel. As can be seen in Figure 2(a), there is still strong residual emission to the west of the SNR-HIIR complex. We thus add three point sources with simple power-law spectra located at the peak pixels with TS > 20, the positions of which are listed in Table 1, to model the residuals and repeat the above procedures. After this, we find that there is still some excess to the south of the complex. We then try adding this access as the fourth point source with the power-law spectrum. Compared to the three-point-source model, the likelihood of the four-point-source model can be increased by about 15, resulting in TS$_{\text{model}} = 2\log(L_{4ps}/L_{3ps}) \approx 30$. So we use the four point sources to model the residual emission. Finally, the background-subtracted TS map is displayed in Figure 2(b).

Next, we study the $\gamma$-ray morphology toward SNR-HIIR complex G35.6−0.4 in detail. After excluding the 4FGL-DR2 catalog sources 4FGL J1857.6+0212 and 4FGL J1858.3+0209 from the source model, the TS maps in 0.2−500 GeV and 8−500 GeV are shown in Figures 3(a) and (b), respectively. As can be seen, there is little emission above 8 GeV in the SNR region (represented by the bigger radio contours), while the emission at such energies concentrates on the H II region (represented by the smaller radio contours), suggesting that there are likely two sources. Meanwhile, we use the likelihood ratio to test three spatial models: one point source, one uniform disk, and two point sources. The model with the largest likelihood value will be preferred. To do so, we first use one point source with a LogParabola (LogP) spectrum, and then explore its best-fit position and extension to obtain the likelihood values of $L_{\text{4ps}}$ for the one-point-source model and $L_{\text{disk}}$ for the uniform disk model. For the two-point-source model, we use the templates of 4FGL J1857.6+0212 and 4FGL J1858.3+0209 and refit their best-fit positions, resulting in SrcA (R.A. = 284\,\degree, decl. = 2\,\degree, 1\,$\sigma$ error = 0\,\arcmin).

![Figure 2. TS maps of a 1.5\,\arcmin × 1.5\,\arcmin region centered at SNR G35.6−0.4 in the energy range of 0.2−500 GeV. The image is smoothed by the pixel size of 0\,\arcsec 05. The pink and cyan contours represent the SNR-HIIR complex G35.6−0.4 in 1.4 GHz (Stil et al. 2006) and 610 MHz (Paredes et al. 2014), respectively. Left: baseline model. Right: four point sources p1−p4 with positions listed in Table 1 are included in the source model.](image)

| Name | R.A.(J2000) | Decl. (J2000) | TS  |
|------|-------------|---------------|-----|
| p1   | 283.850     | 2.345         | 41.5|
| p2   | 283.800     | 2.650         | 39.1|
| p3   | 283.900     | 1.695         | 23.5|
| p4   | 284.653     | 1.549         | 16.5|

Table 1

Locations and TS Values of the Peak Pixels for p1−p4
SrcB (R.A. = 284°582, decl. = 2°142, 1σ error = 0°042) for 4FGL J1857.6+0212 and 4FGL J1858.3+0209, respectively.

The extension of the two sources is also explored, giving TS_{ext} = 2.4 and 4.0 for SrcA and SrcB, respectively. Finally, according to the likelihood values for the three spatial models, we obtain TS_{disk} = 2\log(L_{disk}/L_{ps}) = 13 and TS_{2ps} = 30 for the uniform disk and two-point-source models, respectively. Considering the TS distribution in the different energy ranges and the likelihood ratio test for the three spatial models, the two-point-source model for the SNR-HIIR complex G35.6−0.4 is preferred and used in the following analysis. The TS values of SrcA and SrcB in the two-point-source model are fitted to be 761.2 and 55.3, corresponding to the significance of 27.1σ and 6.7σ, respectively.

In Figure 3, the TS maps for SrcA and SrcB are also presented in the second-row panels. Our best-fit positions with 1σ uncertainty are displayed with the red pluses and circles, respectively. For comparison, the 4FGL-DR2 positions and the best-fit ones in Cui et al. (2021) are shown with green pluses and green diamonds, respectively. As can be seen, the new best-fit positions for both sources are very close to their original ones listed in the catalog, but are different from those in Cui et al. (2021), in particular for SrcA. To check this difference, we fit the positions by just using 5–500 GeV data and obtain similar results to those of our above treatment in 0.2–500 GeV, ruling out the effect of different energy ranges used in the two studies. Further, we repeat the analysis in Cui et al. (2021) by replacing the IRFs “P8R3_SOURCE_V3_v1” with “P8R3_SOURCE_V2_v1” and using 8 yr catalog for the background, and reproduce the results in Cui et al. (2021). Thus, the discrepancy in the best-fit position for SrcA is verified to be caused by using different IRFs and catalogs.

3.1.2. Spectral Analysis

In the 4FGL-DR2 catalog, the spectral types of SrcA and SrcB are LogP and PowerLaw (PL), respectively. To study the
spectral properties of both sources in the whole energy range of 0.2–500 GeV, other spectral types including ExpCutoffPower-Law (ECPL) and BrokenPowerLaw (BPL) will also be explored. We first change the spectral type of SrcA to PL, ECPL, and BPL, respectively, to find the best spectral type. At the same time, the spectral type of SrcB remains to be PL. After this, we keep the best choice for SrcA and change the spectral type of SrcB to LogP, ECPL, and BPL, respectively, to find the best spectral formula for SrcB. The formulae of these spectra are listed in Table 2. The spectral type is favored if it has the largest TS value defined as $T_{S\text{model}} = -2\log(L_{\text{PL}}/L_{\text{model}})$. As shown in Table 3, a LogP spectrum is preferred for SrcA. But for SrcB, there is no obvious difference between the four spectral types and the simplest PL form is adopted. Finally, we keep the best choice for SrcA and change the spectral type of SrcB to LogP, ECPL, and BPL, respectively, to find the best spectral formula for SrcB.

Table 2

| Name  | Formula                                                                 | Free Parameters |
|-------|--------------------------------------------------------------------------|-----------------|
| PL    | $dN/dE = N_0(E/E_0)^{\Gamma}$                                            | $N_0$, $\Gamma$ |
| ECPL  | $dN/dE = N_0(E/E_0)^{-\Gamma} \exp(-E/E_{\text{cut}})$                   | $N_0$, $\Gamma$, $E_{\text{cut}}$ |
| LogP  | $dN/dE = N_0(E/E_0)^{-\Gamma} \cdot \log(E/E_0)$                         | $N_0$, $\Gamma$, $\beta$ |
| BPL   | $dN/dE = N_0 \left\{ \frac{(E/E_0)^{\Gamma}}{(E/E_1)^{\Gamma}}, E \leq E_b \right\} \cdot \left\{ \frac{(E/E_1)^{\Gamma}}{(E/E_b)^{\Gamma}}, E > E_b \right\}$ | $N_0$, $E_b$, $\Gamma_1$, $\Gamma_2$ |

The spectral energy distributions (SEDs) within 0.2–500 GeV of SrcA and SrcB are generated by using the maximum likelihood analysis in seven logarithmically spaced energy bins. During the fitting process, the free parameters only include the normalization parameters of the sources with the significance $4\sigma$ within $5''$ from the ROI center as well as the Galactic and isotropic diffuse background components, while all the other parameters are fixed to their best-fit values from the above analysis in the whole energy (0.2–500 GeV) range. In the energy bins where the TS value of SrcA or SrcB is smaller than 4, we calculate the 95%-confidence level upper limit of its flux. The results are displayed in Figure 9.

3.2. Molecular Environments

The $^{12}$CO spectra toward SNR G35.6–0.4 show multiple line components from +6 to +100 km s$^{-1}$. At $V_{\text{LSR}}$ lower than $\sim$+40 km s$^{-1}$ or higher than $\sim$+70 km s$^{-1}$, little spatial correspondence between the MCs and the SNR can be found from the CO emission. Figure 4 shows the spatial distribution of the Nobeyama $^{12}$CO emission in velocity range $\sim$+47 to +58 km s$^{-1}$, with velocity intervals of 0.65 km s$^{-1}$. The molecular gas in this velocity range seems to generally have a spatial correspondence with the western edge of SNR G35.6–0.4. In particular, a bright, clear-cut molecular filament nicely follows the western shell of SNR G35.6–0.4 at $V_{\text{LSR}}$ $\sim$ +50 km s$^{-1}$. Notably, the peak $^{12}$CO main-beam temperature of the filament is about 20 K, which is noticeably higher than the typical temperature of $\sim$10 K in interstellar MCs.

To investigate whether the molecular gas at the western edge of SNR G35.6–0.4 in the velocity range is perturbed by the shock of the SNR shock, we inspect the CO line grid toward this region. As shown in a grid of both $^{12}$CO $(J = 1 - 0)$ and $^{13}$CO $(J = 1 - 0)$ spectra covering the western edge of the SNR at $V_{\text{LSR}} \sim$ +50 to +70 km s$^{-1}$ (see Figure 5), the red wings of the $^{12}$CO lines, which peak at around +57 km s$^{-1}$, seem to be asymmetrically broadened from about +59 to +64 km s$^{-1}$, and these features are only presented within the boundary of the SNR. Figure 6 shows the averaged CO line profiles of a few pixels at the western edge of the SNR (regions A and B, as marked in Figure 5). In these regions, at $V_{\text{LSR}}$ $\sim$ +59 to +64 km s$^{-1}$ there are non-negligible $^{12}$CO intensities while there is little $^{13}$CO emission. Because the $^{13}$CO is usually optically thin and yielded in quiescent, intrinsically high-column-density molecular material, an asymmetrical $^{12}$CO line profile without a similar $^{13}$CO counterpart could be a kinematic signature of shock perturbation of the molecular gas. Therefore, the broadened $^{12}$CO red wings indicate that the MCs in this velocity range are probably perturbed by SNR G35.6–0.4.

Table 3

| Likelihood Test Results ($T_{S\text{model}}$) from Spectral Analysis |
|---------------------|---------------------|---------------------|---------------------|
| SrcA                | $T_{S\text{PL}}$ | $T_{S\text{ECPL}}$ | $T_{S\text{LogP}}$ | $T_{S\text{BPL}}$ |
|                     | 0                  | 70.1               | 88.9               | 76.7               |
| SrcB                | 0                  | 0.1                | 1.7                | 2.3                |

4. Discussion

4.1. Distances to the HIIR and SNR

Based on the association with the +55 to +56 km s$^{-1}$ MCs suggested by Paron & Giacani (2010), the distance to SNR-HIIR complex G35.6–0.4 was constrained as 3.6 $\pm$ 0.4 kpc by the HI absorption feature (Zhu et al. 2013). The HI absorption spectra abstracted from the radio continuum brightness peak region (very close to the position of RRLs) show the maximum absorption velocity around $+61$ km s$^{-1}$, supporting the near distance. However, the radio image of SNR G35.6–0.4 presented in previous works (e.g., Green 2009) was later resolved into two circular structures by GMRT (Paredes et al. 2014). Although these two structures are projectively connected with each other, they may be at different distances. Thus the HI absorption spectra in Zhu et al. (2013) abstracted from...
the overlapped region of the two circles maybe only give constraint on the distance to one of them. To separately give constraints on the distances to the two structures, we examine HI absorption by selecting other regions marked in green boxes in Figure 1 and avoiding the overlapped region of the two circles.

The systemic velocity of the eastern HIIR has been well measured as $\sim +56$ km s$^{-1}$ according to the RRLs (Lockman 1989) and CO observations (Paron & Giacani 2010, and also this study). Assuming a flat Galactic rotation curve and adopting $R_0 = 8.34$ kpc and $V_0 = 240$ km s$^{-1}$ (Reid et al. 2014), this velocity corresponds to both a near distance 3.4 ± 0.4 kpc and a far distance 10.2 ± 0.5 kpc (Reid et al. 2014; Wenger et al. 2018), while the latter distance can be ruled out by HI absorption analysis. We follow the methods of Tian & Leahy (2008) and plot the HI absorption spectra, where the HI and continuum data are taken from the THOR VLA data. The HI absorption is calculated as $e^{-} = 1 - (T_{\text{on}}^{\text{HI}} - T_{\text{off}}^{\text{HI}})/(T_{\text{s}}^{\text{c}} - T_{\text{bg}}^{\text{c}})$, where $T_{\text{on}}^{\text{HI}}$ and $T_{\text{off}}^{\text{HI}}$ are HI temperatures at the source and background regions, and $T_{\text{s}}^{\text{c}}$ and $T_{\text{bg}}^{\text{c}}$ are the radio continuum brightness temperatures at the source and background regions, respectively. The selected source and background regions are displayed in Figure 1 with labels 1, 2, and 3. Figure 8 shows significant HI absorption in all of the three regions of the SNR at $V_{\text{LSR}} \sim +80$ km s$^{-1}$, which corresponds to a distance of $4.7 \pm 0.7$ kpc or $8.9 \pm 0.8$ kpc. Therefore, the SNR distance should be larger than $4.7 \pm 0.7$ kpc so as to explain the existence of the HI absorption at $\sim +80$ km s$^{-1}$. Therefore, the SNR is located at the far distance 10.5 ± 0.4 kpc, behind the tangent point toward the same line of sight (at $\sim 6.8$ kpc). Thus, SNR G35.6−0.4 and HIIR G35.6−0.5 are irrelevant to each other, given the different kinematic distances to them ($\sim 10.5$ kpc and 3.4 kpc, respectively).

By taking the two distances, the masses/densities of the MCs associated with SNR G35.6−0.4 and HIIR G35.6−0.5 are
4.2. Origin of Gamma-Rays

4.2.1. SNR G35.6–0.4

As shown in Figure 3(c), SrcA is located within the shell of SNR G35.6–0.4 and is projectively close to two pulsars, PSR J1857+0212 and PSR J1857+0210. We first discuss the possibility of the pulsar’s origin. According to the dispersion measures, PSR J1857+0212 and PSR J1857+0210 are at distances 7.98 kpc (Han et al. 2006) and 15.4 kpc (Morris et al. 2002), respectively. But the distances are revised to 6.0 and 7.3 kpc in the ATNF pulsar catalog (Manchester et al. 2005), respectively, based on the new electron-density model developed by Yao et al. (2017). Taking 6.0 kpc (the smaller one) for example, SrcA would have a luminosity of \( \sim 2 \times 10^{35} \, \text{erg s}^{-1} \) in the energy range 0.2–500 GeV, where \( d_{6\text{kpc}} \) is the distance in the unit of 6 kpc, which is significantly higher than the spin-down luminosity of \( 2.2 \times 10^{34} \, \text{erg s}^{-1} \) for PSR J1857+0212 (Manchester et al. 2005; Han et al. 2006) and \( 2.2 \times 10^{33} \, \text{erg s}^{-1} \) for PSR J1857+0212 (Morris et al. 2002; Manchester et al. 2005). Thus the pulsar’s origin for SrcA can be ruled out unless the true distance is smaller than 2 kpc for PSR J1857+0212 and 0.7 kpc for PSR J1857+0210.

SNR G35.6–0.4 may be responsible for the \( \gamma \)-ray emission of SrcA, and we provide estimates for the emission in cases of hadronic and leptonic interaction separately. We simply assume that the particles accelerated in the SNR have a power-law form with a high-energy cutoff:

\[
\frac{dN_i}{dE} = A_i (E/E_0)^{-\alpha_i} \exp(-E/E_{i,c})
\]

where, \( i = e, p, \alpha, \) and \( E_{i,c} \) are the power-law index and high-energy cutoff, respectively. The normalization \( A_i \) is determined by the total energy (\( W_i \)) in particles with energy above 1 GeV. Since the SNR is very likely to be associated with the \( \sim +50 \, \text{km s}^{-1} \) MC at a distance of \( \sim 10.5 \, \text{kpc} \) as revealed
above, the γ-ray emission arising from the SNR-accelerated particles' hadronic interaction is first considered. In such a hadronic scenario, SrcA’s spectrum can be well fit (as shown in the left panel of Figure 7) and we obtain $\alpha_p \approx 3.0$ and $n_0 W_p \approx 8 \times 10^{51}$ erg cm$^{-3}$, where $n_0$ is the number density of the target gas for proton–proton hadronic interaction. The cutoff energy cannot be constrained by the current data and is fixed as 3 PeV in our calculation. With a mass of $9 \times 10^3 M_\odot$ and an average atomic hydrogen density $n_0 \sim 140$ cm$^{-3}$ for the $\sim+50$ km s$^{-1}$ filamentary molecular gas, the energy budget in protons $W_p$ is about $6 \times 10^{59}$ erg, which is acceptable and reasonable for the SNR scenario. The somewhat large index may be attributed to the strong ion-neutral collisions (Malkov et al. 2011) or the escaped process (e.g., Aharonian & Atoyan 1996; Li & Chen 2012). In addition, the luminosity of SrcA in 1–100 GeV is $2 \times 10^{36}$ erg s$^{-1}$, which is consistent with the known γ-ray–bright interacting SNRs (Liu et al. 2015; Acero et al. 2016). Thus the hadronic scenario in which the energetic protons are from SNR G35.6–0.4 is a plausible explanation for SrcA.

For the leptonic case in which γ-rays are produced via the inverse Compton (IC) process, due to the lack of constraint on the index by the GeV data, we fix $\alpha_e = 2.0$ based on the radio index $\alpha_r = 0.47$ (Green 2009). To explain the data (see the model curve in orange in the left panel of Figure 9), $E_{pe} \approx 80$ GeV and $W_e \approx 7 \times 10^{50}$ erg are obtained when the seed photons include the IR emission with a temperature of 35 K and an energy density of $0.6$ eV cm$^{-3}$ estimated from the interstellar radiation field (ISRF) model (Porter et al. 2006; Shibata et al. 2011) and the cosmic microwave background. Considering the large amount of energy in electrons, which is comparable to the canonical supernova explosion energy, the leptonic process seems not proper to explain the γ-ray emission of SrcA unless there is an unusually strong IR emission.

4.2.2. HII R G35.6–0.5 and HESS J1858+020

As shown in Figure 3(d), the GeV source SrcB is spatially coincident with the unidentified TeV source HESS J1858+020. Moreover, the GeV spectrum of SrcB can be well connected with the TeV spectrum of HESS J1858+020 by a simple power-law function with an index of $\sim 2.2$ (see the right panel in Figure 9). Thus, SrcB is very likely the GeV counterpart of TeV source HESS J1858+020. Meanwhile, both sources are spatially coincident with the MCs at a velocity around the $\sim+53$ to $+57$ km s$^{-1}$ which have a mass of $1.3 \times 10^3 M_\odot$ and an average atomic hydrogen number density of 600 cm$^{-3}$. As suggested in Paron & Giacani (2010) and this work (Section 3.2), this molecular arc is likely associated with HII R G35.6–0.5. Both the association with MCs and the soft GeV–TeV spectra (index >2) suggest the GeV–TeV γ-ray emissions likely have a hadronic origin. One possible scenario for SrcB and HESS J1858+020 is that the energetic protons accelerated in HII R G35.6–0.5 bombard the MC to produce the hadronic γ-ray emission. By adopting a distance of 3.4 kpc, $\alpha_p \approx 2.15$ and $W_p \approx 1.7 \times 10^{37}$ erg are obtained. To explain the TeV data, which seem not to have an obvious cutoff, the cutoff energy of protons $E_{p,c}$ should reach the PeV energy (see the right panel of Figure 9). This implies that there may be a potential PeV accelerator in HII R G35.6–0.5. This can be tested by the LHAASO experiment in the future. As one of the PeVatron candidates, the lower limit of the proton cutoff energy $\sim 30$ TeV for HESS J1858+020 is obtained by only using the TeV data (Spengler 2020). In fact, the index and the cutoff energy are strongly degenerated. We note that the index constrained in Spengler (2020) for this source is obviously smaller than 2.0. With the help of the GeV data, the index is fitted as $\sim 2.2$ in this study, resulting in a larger cutoff energy. HII R s vary from ~0.1 pc to a hundred pc in size, are generally related to the active star formations, and are considered to be particle accelerators. It has been proposed that particles can be accelerated by the colliding winds of binaries (e.g., Eichler & Usov 1993) and/or the young massive clusters (Aharonian et al. 2019), which are the ionizing sources of HIIs. This is supported by the TeV γ-ray observations toward η Car (H.E.S.S. Collaboration et al. 2020) for the colliding winds and the Cygnus region (Aliu et al. 2014; Bartoli et al. 2014; Abeysekara et al. 2021; Amenomori et al. 2021) for the massive star clusters. In HII R G35.6–0.5, although there are no massive stars detected as yet, Paron & Giacani (2010) found six young stellar object (YSO) candidates toward the molecular clump at $\sim+53$ km s$^{-1}$ (namely the southern clump in their paper) and concluded that there is an active star formation region. Further observations found at least one evolved YSO (i.e., IRS1) is embedded in the clump, although no signature of outflows was confirmed (Paron et al. 2011). By analyzing the Chandra data, Paredes et al. (2014) found seven X-ray sources, and suggested that sources X1–4, almost projectively distributed on the shell of the HII R (see the right panel of Figure 1), might be embedded protostars and that source X5, close to the “southern” (in the Galactic coordinate

Figure 6. PMOD CO spectra in the $\pm 54$ to $+66$ km s$^{-1}$ interval for the two regions marked in Figure 5. The black and blue lines are for the $^{12}$CO ($J = 1 - 0$) and $^{13}$CO($J = 1 - 0$), respectively.
system) clump, might be coincident with the star formation region. Thus, it could not be excluded that there may be some nondetected massive stars embedded in the MC.

Alternatively, we also consider the lepto-hadronic hybrid case in which the GeV emissions are from the hadronic process and the TeV $\gamma$-rays are generated by the IC process. We assume the electrons and protons have the same power-law index and high-energy cutoff. For the seed photons in the IC process, the IR component of ISRF is also included and is estimated as 35 K and 0.6 eV cm$^{-3}$ by using the similar method for SrcA above. To explain the data (see the purple curve in the right panel of Figure 9), $\alpha_e = \alpha_p \approx 2.3$ and $E_{e,e} = E_{e,p} \approx 200$ TeV are obtained. Electrons will suffer the synchrotron radiation loss during the acceleration, giving a cooling-limited maximum energy $E_{\text{max,cool}} = 35u_3/\sqrt{\eta_g}B_1$ TeV (e.g., Zirakashvili & Aharonian 2007; Ohira et al. 2012), where $u_3$ is the shock velocity in unit of 1000 km s$^{-1}$, $\eta_g$ the gyrofactor, and $B_1$ the magnetic field strength in unit of 10 $\mu$G. For the wind velocity $u_3 = 1$ and the Bohm limit $\eta_g = 1$, it requires $B < 0.3 \mu$G to boost the energy of electrons up to 200 TeV. This magnetic strength is as weak as an order of magnitude lower than the mean value for Galactic ISM, which means that it is hard to accelerate electrons to the 100 TeV band for the standard interstellar magnetic field. Thus, the hybrid model seems rather unlikely according to the fitted results.

5. Summary

In this study, we focus on the SNR-HIIR complex including SNR G35.6$-$0.4 and HIIR G35.6$-$0.5, which partially overlaps with the unidentified TeV source HESS J1858+020 with a hard spectrum. We reanalyze CO line, H I, and Fermi-LAT GeV $\gamma$-ray emission data of this region. The main results are summarized as follows:

1. Based on the Nobeyama data, we found that a molecular arc at $\sim +56$ km s$^{-1}$ delineates the northern (in the equatorial coordinate system) shell of HIIR G35.6$-$0.5 and a molecular filament at $\sim +50$ km s$^{-1}$ nicely follows the western boundary of SNR G35.6$-$0.4. Such morphological agreements, together with the relatively high main-beam temperature and the asymmetric or broad CO line profiles, suggest that the two molecular structures are

Figure 7. Same as Figure 5 but for HIIR in the velocity range of +48 to +68 km s$^{-1}$.
likely to be associated with the HIIR and the SNR, respectively.

2. The H I absorption features suggest that the SNR is located behind the tangent point at a distance 10.5 kpc, and thus is not associated with the HIIR.

3. Performing the analysis of 12.3 yr Fermi-LAT data, we found that there are two point sources (SrcA and SrcB) with a significance of 27.1σ and 6.7σ in 0.2–500 GeV toward the SNR-HIIR complex, respectively. The two sources are spatially coincident with the SNR and the TeV source HESS J1858+020, respectively.

4. For SrcA, leptonic processes for the SNR scenario and the PSR scenario can be ruled out according to the energy budget. In the SNR-MC association scenario, the
hadronic process can explain the spectrum with reasonable physical parameters.

5. For SrcB, its GeV-band spectrum can be smoothly connected with the TeV-band spectrum of HESS J1858 +020 by a simple power-law function with an index of $\sim$2.2. In combination with the HIIR-MC association, it favors the hadronic origin. To explain the data, the cutoff energy of protons is the order of PeV. This indicates that there may be a potential PeV proton accelerator in HIIR G35.6$-$0.5, which needs to be tested with ultrahigh-energy observation, e.g., with LHAASO.

This publication makes use of data from FUGIN, FOREST Unbiased Galactic plane Imaging survey with the Nobeyama 45 m telescope, a legacy project in the Nobeyama 45 m radio telescope. X.Z. thanks Xin Zhou, Siming Liu, and Jian Li for helpful discussions. F.X.Z. thanks J. M. Paredes for proving the telescope. X.Z. thanks Xin Zhou, Siming Liu, and Jian Li for helpful discussions. F.X.Z. thanks J. M. Paredes for proving the GMRT data. We thank the support of the National Key R&D Program of China under Nos. U1931204, 11803011, 12173018, 12121003, 11773014, 11633007, 11851305, and 12103049.

Software: APLpy (Robitaille & Bressert 2012; Robitaille 2019), Astropy (Astropy Collaboration et al. 2013, 2018), Fermipy (Wood et al. 2017), Naima (Zabalza 2015).

ORCID iDs
Xiao Zhang https://orcid.org/0000-0002-9392-547X
Yang Chen https://orcid.org/0000-0002-4753-2798
Qian-Cheng Liu https://orcid.org/0000-0002-5786-7268
Ping Zhou https://orcid.org/0000-0002-5683-822X
Bing Liu https://orcid.org/0000-0002-5965-5576

References
Abdollahi, S., Acero, F., Ackermann, M., et al. 2020, ApJS, 247, 33
Abeysekara, A. U., Albert, A., Alfaro, R., et al. 2021, NatAs, 5, 465
Acero, F., Ackermann, M., Ajello, M., et al. 2016, ApJS, 224, 8
Aharonian, F., Akperjanian, A. G., Barres de Almeida, U., et al. 2008, A&A, 477, 353
Aharonian, F., Yang, R., & de Oua Wilhelm, E. 2019, NatAs, 3, 561
Aharonian, F. A., & Atoyan, A. M. 1996, A&A, 309, 917
Aliu, E., Aune, T., Behera, B., et al. 2014, ApJ, 783, 16
Altenhoff, W. J., Downes, D., Goad, L., Maxwell, A., & Rinehart, R. 1970, A&AS, 1, 319
Amenomori, M., Bao, Y. W., Bi, X. J., et al. 2021, PhRvL, 127, 031102
Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, AJ, 156, 123
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Bartoli, B., Bernardini, P., Bi, X. J., et al. 2014, ApJ, 790, 152
Beard, M., & Kerr, F. J. 1969, ApJPh, 22, 121
Beuwer, H., Bihr, S., Rugel, M., et al. 2016, A&A, 595, A32
Cherenkov Telescope Array Consortium, Acharya, B. S., Agudo, I., et al. 2019, Science with the Cherenkov Telescope Array (Singapore: World Scientific)
Cui, Y., Xin, Y., Liu, S., et al. 2021, A&A, 646, A114
Di Sciascio, G. & LHAASO Collaboration 2016, NPPP, 279–281, 166
Eichler, D., & Usov, V. 1993, ApJ, 402, 271
Green, D. A. 2009, MNRAS, 399, 177
Han, J. L., Manchester, R. N., Lyne, A. G., Qiao, G. J., & van Straten, W. 2006, ApJ, 642, 668
H.E.S.S. Collaboration, Abdalla, H., Abramowski, A., et al. 2018, A&A, 612, A1
H.E.S.S. Collaboration, Abdalla, H., Adam, R., et al. 2020, A&A, 635, A167
Li, H., & Chen, Y. 2012, MNRAS, 421, 935
Liu, B., Chen, Y., Zhang, X., et al. 2015, ApJ, 809, 102
Lockman, F. J. 1989, ApJS, 71, 469
Malkov, M. A., Diamond, P. H., & Sagdeev, R. Z. 2011, NatCv, 2, 194
Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, AJ, 129, 1993
Morris, D. J., Hobbs, G., Lyne, A. G., et al. 2002, MNRAS, 335, 275
Ohira, Y., Yamazaki, R., Kawanaka, N., & Ioka, K. 2012, MNRAS, 427, 91
Paredes, J. M., Ishwara-Chandra, C. H., Bosch-Ramón, V., et al. 2014, A&A, 561, A56
Paron, S., & Giacani, E. 2010, A&A, 509, L4
Paron, S., Giacani, E., Rubio, M., & Dubner, G. 2011, A&A, 530, A25
Porter, T. A., Moskalenko, I. V., & Strong, A. W. 2006, ApJL, 648, L29
Ranasinghe, S., & Leahy, D. A. 2018, AJ, 155, 204
Reid, M. J., Menten, K. M., Brunthaler, A., et al. 2014, ApJ, 783, 130
Robitaille, T. 2019, APLpy v2.0: The Astronomical Plotting Library in Python, Zenodo, doi:10.5281/zenodo.2567476
Robitaille, T., & Bressert, E. 2012, APLpy: Astronomical Plotting Library in Python, Astrophysics Source Code Library, ascl:1208.017
Shibata, T., Ishikawa, T., & Sekiguchi, S. 2011, ApJ, 727, 38
Spengler, G. 2020, A&A, 633, A138
Stil, J. M., Taylor, A. R., Dickey, J. M., et al. 2006, AJ, 132, 1158
Tian, W. W., & Leahy, D. A. 2008, ApJ, 677, 292
Torres, D. F., Li, H., Chen, Y., et al. 2011, MNRAS, 417, 3072
Umemoto, T., Minamidani, T., Kuno, N., et al. 2017, PASJ, 69, 78
Wang, Y., Beuther, H., Rugel, M. R., et al. 2020, A&A, 643, A83
Wenger, T. V., Balser, D. S., Anderson, L. D., & Bania, T. M. 2018, ApJ, 856, 52
Wood, M., Caputo, R., Charles, E., et al. 2017, ICRC (Busan), 301, 824
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
Yao, J. M., Manchester, R. N., & Wang, N. 2017, ApJ, 835, 29
Zabalza, V. 2015, ICRC (The Hague), 34, 922
Zhu, H., Tian, W. W., Torres, D. F., Pedalenti, G., & Su, H. Q. 2013, ApJ, 775, 95
Zirakashvili, V. N., & Aharonian, F. 2007, A&A, 465, 695