Morphological Study of GeV Emission from the Nearby Supernova Remnant G332.5-5.6 (Postprint)

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Date: 2024-05-10T00:00:00+00:00

Abstract

Spatial templates are of great importance for studying nearby supernova remnants (SNRs). For SNR G332.5-5.6, we report a Gaussian disk with a radius of approximately 106 as a potentially good spatial model in the gamma-ray band. Using this new Gaussian disk, the GeV light curve shows significant variability of about 7σ. The gamma-ray observations of this SNR can be well explained by either a leptonic model or a hadronic model, both of which require the ejected electrons/protons to have a flat energy spectrum.

Full Text

Preamble

Research in Astronomy and Astrophysics, 24:045012 (7pp), 2024 April

https://doi.org/10.1088/1674-4527/ad3287

Morphology Study for GeV Emission of Nearby Supernova Remnant G332.5-5.6

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Received 2023 October 23; revised 2024 March 5; accepted 2024 March 8; published 2024 April 9

Abstract

A spatial template is important for studying nearby supernova remnants (SNRs). For SNR G332.5-5.6, we report that a Gaussian disk with a radius of approximately 1°.06 serves as a potentially good spatial model in the γ-ray band. Employing this new Gaussian disk, its GeV lightcurve shows significant variability at about seven sigma. The γ-ray observations of this SNR can be well explained by either a leptonic model or a hadronic model, both of which require a flat spectrum for the ejected electrons/protons.

Key words: ISM: supernova remnants -gamma-rays: ISM

1. Introduction

The energy released by supernova events is of great importance for our understanding of the interstellar medium (ISM). Depending on the environment, supernova remnants (SNRs) can display a vast range of shapes (Whiteoak & Green 1996). The released energy is transferred to electrons and protons, which interact with interstellar radiation or protons, and finally emit observable electromagnetic signals up to high-energy bands (>100 MeV) (Acero et al. 2016).

In the Anglo Australian Observatory (AAO)/United Kingdom Schmidt Telescope (UKST) Hα survey, a new Galactic SNR was uncovered (Parker et al. 2005). This source, with an unusual morphology dubbed the "paperclip," was discovered from the original Hα survey films and was further confirmed as SNR G332.5-5.6 (Stupar et al. 2007). SNR G332.5-5.6 shows three patches of filamentary emission with a total size of about 30 at radio bands (Reynoso & Green 2007). It has an extended X-ray morphology in the central region, which shows good correlation with radio emission detected at different frequencies (Suárez et al. 2015). SNR G332.5-5.6 is found to be at a distance of about 3.4 kpc with an age of 7–9 kyr (Zhu et al. 2015). For its γ-ray observations, such as in the Fermi High-Latitude Extended Sources (FHES) catalog, SNR G332.5-5.6 is the potential association of FHES J1642.1-5428, which has a uniform disk with a radius of about 0°.57 (Ackermann et al. 2018). In an incremental version of the fourth full catalog of Fermi-LAT sources (4FGL-DR3), SNR G332.5-5.6 associates with an extended source 4FGL J1642.1-5428e, which shares a disk radius of about 0°.70 (Abdollahi et al. 2022).

Morphology in the γ-ray band is very different from that in low-energy bands, such as radio or X-ray bands. Since the FHES catalog employed only 8 yr of observations by the Fermi Large Area Telescope (Fermi/LAT), the spatial model of SNR G332.5-5.6 could be studied in greater depth employing more γ-ray observations. We thus performed a morphology study in high-energy gamma-ray bands using 14.3 yr of Fermi-LAT observations. The paper is organized as follows. In Section 2, data analysis is presented. In Section 3, the physical origin of GeV emission from SNR G332.5-5.6 is explored. A summary and conclusions are presented in Section 4.

2.1 Data Selection

The FermiPy version 1.2 package is used to analyze the Fermi/LAT data, which is a python package that facilitates analysis of the Fermi-LAT data with the latest Fermi Science Tools version 2.2.0 (Wood et al. 2017). Pass 8 events are selected in the region of interest (ROI) of 15° around the position of SNR G332.5-5.6, that is R.A., decl. = 250°.538, −54°.477 (Ajello et al. 2017). We selected photons in the energy range between 100 MeV and 1 TeV within the period from 2008 August to 2022 December.

The events were selected with event class of 128 and event type of 3. Events with zenith angles larger than 90° are excluded to avoid contamination from the Earth' s limb. We use the standard data quality selection criteria (DATA_{QUAL} > 0) && (LAT_{CONFIG} == 1). We adopted a pixel size of 0°.02 spatially and eight logarithmic energy bins per decade when performing the energy selection. The P8R3_{{{SOURCE}}_{{V3}}} instrument response function is used in our data analysis.

2.2 Basic Model

A basic model is built by adding the background gamma-ray sources. 4FGL-DR3 is employed, in which we include all sources within 25° of the SNR G332.5-5.6 center, as well as the diffuse galactic interstellar emission (gll_{{{iem}}*{{v07}}}.fits) and the isotropic emission (iso*{{{P8R3}}*{{SOURCE}}}*{{{V3}}_{{V1}}}.txt). The spectral parameters of the diffuse galactic interstellar emission, the isotropic emission, and all sources within 3° of the SNR G332.5-5.6 center are allowed to be free. We found there are 11 point sources, as shown in Figure 1 [Figure 1: see original paper], whose spectral parameters are allowed to be free. Lastly, we removed the catalog source 4FGL J1642.1-5428e at the ROI center and then built a basic model (hereafter the model with the spatial template of NONE).

2.3 Spatial Analysis

We evaluate the significance of all test spatial models, which is quantified through the likelihood ratio test with two statistical methods. One is the test statistic (TS) to compute the significance for a test model over the NONE spatial model, which is defined as TS = -2(ln L_{NONE} - ln L_{test}), where L_{test} and L_{NONE} are the maximum likelihood values of the test model and of the basic NONE model, respectively (Mattox et al. 1996). The likelihood value depends on the model and the observations. For the Fermi-LAT observations, the photon numbers in the ROI are 9,065,267 in the energy band of 0.1-1 GeV, 1,691,719 in 1-10 GeV, 56,799 in 10-100 GeV, and 2,052 in 100-1000 GeV, respectively. The other method is the Akaike information criterion (AIC) test to find a better model between two nested or non-nested models (Akaike 1974; Tibaldo et al. 2018; Tang et al. 2021; Guo & Xin 2024), which is defined as AIC = 2k - 2ln(L), where k is the number of degrees of freedom (d.o.f) and L is the maximum likelihood value of a model. Usually, a model with a smaller AIC is the better one among several models. In this case, we employed the difference in AIC (ΔAIC) between two models to claim the preferred model, which could be calculated by ΔAIC = AIC_1 - AIC_2.

Four spatial templates are tested with a single power-law (PL) spectral model, as shown in Table 1 . TS maps excluding SNR G332.5-5.6 in each model are plotted in Figure 2 [Figure 2: see original paper].

The **PS model** shares the spatial template of a point source, which has four additional free parameters (two for the free position and two PL spectral parameters). The resultant maximum TS is 35.16 and the best-fit position is about R.A., decl. = 250°.925, −54°.388.

The **GLEAM model** is derived from radio observations of the Galactic and Extragalactic Allsky MWA Survey between 170 and 231 MHz (Wayth et al. 2015), see Figure A1, which has two additional free parameters (two PL spectral parameters). The resultant maximum TS is 71.36.

The **DISK model** is a uniform disk, which has five additional free parameters (one for free radius, two for the free centered position, and two PL spectral parameters). We scanned the disk radius from 0°.01 to 1°.20 using the tool of source finding. We found a best-fit radius of 0°.536 with the maximum TS of 223.34. The best-fit centered position is about R.A., decl. = 250°.564, −54°.245.

The **GAUSS model** is a two-dimensional Gaussian disk, which also has five additional free parameters. The scanning method is the same as that in the DISK model. The best-fit 68% radius is found at about 1°.061 with the maximum TS of 249.94. The best-fit centered position is about R.A., decl. = 250°.173, −54°.401.

Results of the AIC test are shown in Table 1. As seen, the GAUSS model is confirmed to be the best representation of the data, with a minimum ΔAIC of −239.94 with respect to the NONE model. Considering that GAUSS also has the largest TS value among the four test spatial models, the GAUSS model is the preferred model in our spatial analysis. In the latest Fermi-LAT catalog (4FGL-DR4), there are three SNRs with a spatial template of GAUSS, such as SNR G51.3+0.1, SNR G150.3+4.5, and SNR G292.2-0.5. Therefore, the GAUSS spatial template is selected for SNR G332.5-5.6 to produce its lightcurve (LC) and spectral energy distribution (SED) in the following analyses.

2.5 Spectral Analysis

Gamma-ray emission of the analyzed source is represented by a PL spectral model in the 4FGL-DR3 catalog. To fully investigate the γ-ray properties of this source, we considered other types of spectral models, such as broken PL (BPL), log-parabola (LP), and PLSuperExpCutoff (PLEC), which however do not result in any significant likelihood of improvement. We thus employed a PL spectral model to fit the GeV emission of SNR G332.5-5.6, e.g., dN/dE   E^(-Γ). The resultant photon index (Γ_{ph}) is 2.14 $\pm$ 0.04. The spectral energy distribution is plotted in Figure 4 [Figure 4: see original paper].

3. Physical Model

We explore the physical origins utilizing Fermi/LAT observations of SNR G332.5-5.6. The Naima package is employed to find the best-fit parameters in two physical models: a leptonic model and a hadronic model (Zabalza 2015).

3.1 Leptonic Model

To test whether the GeV emission of SNR G332.5-5.6 is temporally variable, we construct its lightcurve using the GAUSS spatial model with a PL spectral model. We separate the Fermi-LAT observations into 14 time intervals in the energy range from 0.1 GeV to 1 TeV. Energy flux in each time interval is calculated and plotted in Figure 3 [Figure 3: see original paper]. The variability index (TS_{var}) is defined as TS_{var} = 2 Σ_i [ln L_i(F_i) - ln L_i(F_{const})], where L_i is the value of the likelihood corresponding to the i-th bin, F_i is the best-fit flux for bin i, and F_{const} is the best-fit flux for the full time assuming a constant flux (Nolan et al. 2012; Mo et al. 2023). The resultant TS_{var} is 83.40 with 6.9σ for the lightcurve of 14 time bins, which suggests that there is significant variability in the photon fluxes of SNR G332.5-5.6.

We considered a leptonic model to fit the observed GeV SED of SNR G332.5-5.6, e.g., the γ-ray emission is generated through inverse Compton (IC) scattering of soft photons by relativistic electrons (Kamae et al. 2006; Meyer et al. 2010; Tang 2018). The ejected electron distribution is assumed to follow an exponential-cutoff power-law function (PLEC): dN_e/dE = A (E/E_0)^(-*αe) exp(-E/E*{cutoff}), where A is the normalization, E_0 is the pivot energy fixed at 1 TeV, *αe is the electron injection spectral index, and E*{cutoff} stands for the cutoff energy. For IC, seed photons include (1) the cosmic microwave background (CMB), (2) the far-infrared dust emission (FIR) with a temperature of 30 K and energy density of 0.5 eV cm^(-3), and (3) the near-infrared stellar emission (NIR) with a temperature of 5000 K and energy density of 1.0 eV cm^(-3). The best-fit results are shown in Figure 5 [Figure 5: see original paper] and in Table 2 . An electron injection spectral index of α_e = 2.01 is required to produce the gamma-ray emission above 100 MeV. The total energy of the injected electrons is about 3.08 × 10^{48} erg.

3.2 Hadronic Model

We considered a one-zone hadronic model (Kamae et al. 2006; Tang et al. 2017; Mo et al. 2023), in which the main gamma-ray production mechanism is p–p interactions for relativistic protons followed by pion decay (PD). In addition to gamma-rays, secondary electrons and positrons are produced in the PD process, which results in inverse Compton emission (Secondary IC). Thus, the PD component plus a secondary IC component contributes to the Fermi-LAT observations. The distribution of the ejected protons is also assumed to follow a PLEC function: dN__p/dE = A (E/E__0)^(-*αp) exp(-E/E*{cutoff}), where A is the normalization, E__0 is the pivot energy fixed at 10 TeV, *αp is the spectral index of the injected protons, and E*{cutoff} represents the cutoff energy. The best-fit results are shown in Figure 6 [Figure 6: see original paper] and in Table 2. We performed the fit and derived the best-fit parameters: *αp = 2.03, E*{cutoff} = 29.82 TeV, and the gas density of n__{gas} = 1.00 cm^(-3). The total energy of the injected protons is about 1.32 × 10^{50} erg.

In summary, both a leptonic model and a hadronic model can fit the GeV SED of SNR G332.5-5.6 well, both sharing a flat spectrum for the ejected electrons or protons, i.e., spectral indices close to −2.00.

4. Summary and Conclusion

In this work, we present a GeV morphology analysis of SNR G332.5-5.6 employing Fermi/LAT observations from 2008 August to 2022 December. We found that a Gaussian-disk spatial template with a radius of 1°.06 is preferred over others, e.g., a point source, a uniform disk, and an extended template from radio observations. Employing this new Gaussian disk, the GeV lightcurve for SNR G332.5-5.6 shows significant variability. The gamma-ray observations can be well explained by either a leptonic model or a hadronic model, both of which require a flat spectrum for the ejected electrons or protons. Future observations in other bands could shed light on the nature of broadband emission from SNR G332.5-5.6.

Acknowledgments

We thank the anonymous referee for his/her comments and suggestions that significantly improved the manuscript. We also thank Ruo-Yu Liu for helpful discussions. This work is supported by the National Natural Science Foundation of China under grant 12065017, and the Jiangxi Provincial Natural Science Foundation of China under grant Nos. 20224ACB211001 and 20212BAB201029.

Appendix

Radio Observations and the GLEAM Spatial Template

The GLEAM spatial template is derived from radio observations of the Galactic and Extragalactic Allsky MWA Survey between 170 and 231 MHz (Wayth et al. 2015). Gaussian smoothing is performed with a bin size of 0°.01, as shown in Figure A1 [FIGURE:A1].

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Note: Figure translations are in progress. See original paper for figures.