**Fermi** LAT detection of the supernova remnant

**SN 1006 revisited: the south-west limb**

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**Abstract**

The data from the Large Area Telescope (LAT) onboard the Fermi Gamma-ray Space Telescope have recently been updated. We thus re-analyze the LAT data for the supernova remnant (SNR) SN 1006. Two parts of γ-ray emission from the region is clearly resolved, which correspond to the north-east (NE) and south-west (SW) limbs of the SNR. The former was detected in the previous LAT data (Xing et al. 2016), but the latter is newly detected in this work. The detection of the two limbs are at a ∼ 4σ significance level, and the spectral results for the NE limb is consistent with those obtained in previous detection analyses. We construct the broadband spectral energy distribution (SED) for the SW limb. Different scenarios are considered for the SED in γ-ray energies. We conclude very similar to that of the NE limb, the high-energy and very high-energy emission from the SW limb is likely dominated by the leptonic process, in which high-energy electrons accelerated from the shell region of the SNR inverse-Compton scatter background photons to γ-rays.

**Key words:** acceleration of particles — gamma rays: ISM — ISM: individual objects (SN 1006) — ISM: supernova remnants
1 Introduction

As the remnant of the supernova AD 1006, one of a few supernovae historically recorded (Stephenson & Green 2002), SN 1006 appears like a disk with a diameter of 30′. The Galactic latitude of the source is ~14°5, far away from the Galactic plane. A source distance of 2.2 kpc was derived for SN 1006 based on the measurements of the proper motion of the shock front and the expanding velocity obtained with optical observations (Winkler et al. 2003). It was the first supernova remnant (SNR) with a non-thermal X-ray emission component detected (Koyama et al. 1995), as the radio and hard X-ray emission from the front shell regions is dominated by synchrotron emission (Reynolds & Gilmore 1986; Rothenflug et al. 2004; Winkler et al. 2014), while the interior region was found to have a thermal spectrum with line features (Uchida et al. 2013). The X-rays emitted by SN 1006 indicate that the electrons can be accelerated to 100 TeV energies in the shock front (Koyama et al. 1995). Therefore it is considered as an efficient site of cosmic rays acceleration in the Milky Way, although in a relatively low ambient-density environment.

As part of the shell of the SNR, two identifiable limbs are at northeast (NE) and southwest (SW) regions (cf., Figure 1). In the very high-energy (VHE; >100 GeV) ranges, two sources were detected with the High Energy Stereoscopic System (HESS) as HESS J1504−418 and HESS J1502−421, which correspond to the NE and SW limbs, respectively (Acero et al. 2010). In the high-energy range of 0.1–300 GeV, the detection of the NE limb was reported by Xing et al. (2016) at a ~4σ significance level from analysis of the data obtained with the Large Area Telescope (LAT) onboard the Fermi Gamma-ray Space Telescope (Fermi). Although the GeV counterpart was not well resolved due to the large point-spread function of the LAT and the low detection significance, the detection was confirmed by Condon et al. (2017) at a ~6σ significance level. In any case, the broadband spectral energy distribution (SED) of the NE limb was found to be well described with a leptonic scenario, in which the high-energy and VHE photons are produced from the inverse Compton (IC) process of high-energy electrons (Xing et al. 2016). The synchrotron emission of the limb is from the same population of the electrons.

While the GeV γ-ray emission from the SW limb has not been detected in the previous studies, Miceli et al. (2014) reported evidence for the interaction with a HI cloud in the region, making it a promising region for γ-ray hadronic emission in SN 1006. In the HESS VHE observation, the brightness of the NE limb is ~50% higher than that of the SW limb. Given these, it was predicted by Xing et al. (2016) that the SW limb would likely be detected with the
accumulation of the *Fermi* LAT data. With the release of the updated *Fermi* LAT Pass 8 data (P8R3) and the accumulation of >10 years of data (comparing to 7 years and 8 years in Xing et al. 2016 and Condon et al. 2017, respectively), re-analysis of the LAT data for SN 1006 is warranted. In this paper, we report the results from our analysis of the data. Now GeV γ-ray emission from both the NE and SW limbs are detected. We describe the *Fermi* LAT data and source model for analysis in Section 2, and present the data analysis and results in Section 3. Different models are discussed in Section 4 to explain the SED of the SW limb.

2 *Fermi* LAT Data and Source Model

LAT is one of the two main instruments onboard *Fermi*, conducting all-sky survey in the energy range from 100 MeV to 500 GeV (Atwood et al. 2009). For this analysis, we selected the 0.1–500 GeV LAT events from the recently updated *Fermi* P8R3 database. The region considered is 20° × 20°, with the central position at the radio center of SN 1006 (R.A.=15h02m50, Decl.=−41°56′00, equinox J2000.0). The time period of the data selected was from 2008-08-04 15:43:36 (UTC) to 2018-12-02 08:29:55 (UTC), more than 10 years. As suggested by the LAT team\(^1\), events with zenith angles greater than 90 degrees and with quality flags of ‘bad’ were excluded, which are for the purpose of preventing the Earth’s limb contamination and the spacecraft events affection, respectively.

We included sources within 20 degrees centered at the position of SN 1006 to make the source model. The preliminary LAT 8-year point source list\(^2\) (FL8Y) was released in early 2018, but it is not suggested to be used directly since the Galactic diffuse emission model has not been updated. Given these, we included the FL8Y sources within 5 degrees from SN 1006. For sources 5–20 degrees away, we used those given in the *Fermi* LAT 4-year catalog (3FGL; Acero et al. 2015b). The spectral forms of these sources are provided in the two catalogs. The background Galactic and extragalactic diffuse emission models used were gll\_iem\_v06.fits and the file iso\_P8R3\_SOURCE\_V2.txt, respectively.

3 Data Analysis and Results

3.1 Maximum Likelihood Analysis

We performed the standard binned likelihood analysis to the LAT data in the >0.5 GeV band using *Fermitools* 1.0.0. The low-energy data in the <0.5 GeV band were not used, which

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1 http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/
2 https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/
Fig. 1. TS maps of the $2^\circ \times 2^\circ$ region centered at SN 1006 in the 0.5–500 GeV band. The image scale of the maps is 0\degree.04 pixel$^{-1}$. All catalog sources except the counterpart to the NE limb were considered and removed. The blue plus marks the position of the NE limb given in the FL8Y catalog, and the blue circle is the 2$\sigma$ error circle of the best-fit position obtained for the SW limb. The green contours indicate the 0.75–1.3 keV X-ray intensity measurements of SN 1006. The dark (or white) circle marks the 2$\sigma$ error circle of the best-fit position obtained for a nearby source, which is revealed and removed in the left and right panel, respectively.

helps to reduce the effects of the Galactic background and to avoid the relatively large uncertainties of the instrument response function of the LAT in the low energy range. The spectral parameters of the sources within 5 degrees from SN 1006 and the normalizations of the diffuse components were set as free parameters, and the other parameters of the sources were fixed at their catalog values. The NE limb has already been included in the source model as a point source FL8Y J1503.5–4146, with power-law emission. From the analysis, we found photon index $\Gamma = 1.9 \pm 0.2$ and 0.5–500 GeV flux $F_{0.5–500} = 2.4 \pm 1.1 \times 10^{-10}$ photons s$^{-1}$ cm$^{-2}$ for the NE part. The photon index value is consistent with those previously reported (Xing et al. 2016; Condon et al. 2017).

Using the fitted source model, we constructed a 0.5–500 GeV Test Statistic (TS) map of a $2^\circ \times 2^\circ$ region centered at the radio position of SN 1006. All of the known sources given in the LAT catalogs were removed from the TS map, except the $\gamma$-ray counterpart of the NE limb. The obtained TS map is shown in the left panel of Figure 1. The SN 1006 region is resolved as two parts in the TS map. Besides the NE limb (TS$\sim$24), which previously appeared slightly extended (but could not be determined from likelihood analysis; Xing et al. 2016; Condon et al. 2017) covering most of the SNR’s disk, now there is isolated excess emission at the SW limb with TS$\sim$22.
However in the bottom of Figure 1, there is an extra source with TS $\sim 24$. In order to check whether it might affect our detection, we ran `gtfindsrc` in `Fermitools` to determine its position: R.A.=226°00, Decl.=−42°80, (equinox J2000.0), with 1σ nominal uncertainty of 0°08. Considering it as a point source with power-law emission in the source model, we re-performed the likelihood analysis. The resulting TS map with this source removed is shown in the right panel of Figure 1. The two parts of excess emission at the NE and SW limbs can still be clearly revealed, with slightly lower TS values of $\sim 21$ and $\sim 19$, respectively. We ran `gtfindsrc` to determine the position of the SW part and obtained R.A.=225°54, Decl.=−42°06, (equinox J2000.0), with 1σ nominal uncertainty of 0°03.

Finally we included both of the NE and SW parts in the source model as point sources at the catalog position and the obtained best-fit position, respectively, and re-performed the likelihood analysis. The source, $\sim 0°8$ away from SN 1006 in the south (the bottom of Figure 1), was also included in the source model. We obtained $\Gamma = 1.7 \pm 0.2$ and $F_{0.5-500} = 1.3 \pm 0.7 \times 10^{-10}$ photons s$^{-1}$ cm$^{-2}$, for the NE part, and $\Gamma = 2.0 \pm 0.2$ and $F_{0.5-500} = 2.0 \pm 1.0 \times 10^{-10}$ photons s$^{-1}$ cm$^{-2}$ for the SW part. Based on the face values, the $\gamma$-ray emission from the NE limb seems to be harder than that from the SW limb, but the uncertainties are large and no conclusion can be made. The TS values for the NE and SW parts are 18 and 17, respectively, both corresponding to $\sim 4\sigma$ detection significance.

### 3.2 Spatial Distribution Analysis

Since the $\gamma$-ray emission from both of the NE and SW limbs of SN 1006 are detected by `Fermi`, we performed the likelihood analysis with the total excess emission in the SNR region considered to be one extended source. From this analysis, we examined whether the excess emission would be better described as one extended source or two separate point sources. A template was created with the `XMM-Newton` image (0.75–1.3 keV)$^3$, shown as the green contours in Figure 1. A power-law emission model was assumed for the extended source. We obtained $\Gamma = 1.8 \pm 0.2$ and $F_{0.5-500} = 3.4 \pm 1.0 \times 10^{-10}$ photons s$^{-1}$ cm$^{-2}$, with a TS value of 31. The TS value indicates a $>5\sigma$ detection significance. However, the likelihood value for the extended source model ($L_e$) is approximately equal to that for the two point sources model ($L_{2ps}$) in our analysis, indicating that the former is not preferred based on the current data. Considering that the two limbs may have different emission origins, in the following sections we treated the excess $\gamma$-ray emission as two separate point sources.

$^3$https://heasarc.gsfc.nasa.gov/docs/xmm/gallery/esas-gallery/xmm_gal_science_snr1006.html
3.3 Spectral Analysis

We extracted the γ-ray spectra of the NE and SW parts by including them as point sources with power-law emission and performing maximum likelihood analysis to the LAT data in 5 evenly divided energy bands in logarithm from 0.1–500 GeV. In the extraction, the spectral normalizations of the sources within 5 degrees from the central position of SN 1006 were set as free parameters, while all the other parameters of the sources were fixed at the values obtained from the above maximum likelihood analysis. We kept only spectral flux points with the flux values >2 times larger than the uncertainties, or derived 95% flux upper limits otherwise. The obtained spectra are shown in Figure 2, with the fluxes and uncertainties provided in Table 1.

3.4 Variability Analysis

In order to fully study the γ-ray emission properties of SN 1006, we also searched for any long-term variability of it. We calculated the variability index $TS_{\text{var}}$ for the NE and SW parts with 126 time bins (each bin was constructed from 30-day data) in the energy ranges of 0.5–500 GeV, following the procedure introduced in Nolan et al. (2012). If the flux is constant, $TS_{\text{var}}$ would be distributed as $\chi^2$ with 125 degrees of freedom. Variable sources would be identified with $TS_{\text{var}}$ larger than 164.7 (at a 99% confidence level). The computed $TS_{\text{var}}$ for the NE and
SW parts are 94.7 and 83.4, respectively, indicating that there were no significant long-term variability in them.

4 Discussion

Having analyzed >10 years of Fermi LAT P8R3 data, the excess γ-ray emission at the SN 1006 region is clearly resolved, with two parts located at the NE and SW limbs. The obtained spectral parameters for the previously detected NE limb are consistent with those reported in Xing et al. (2016) and Condon et al. (2017). However the detection significance is ∼4σ, lower than that obtained with 8 years of data (6σ) in Condon et al. (2017). This issue is likely due to the use of FL8Y and the updated Pass 8 data. Within 5 degrees from SN 1006, there are 12 sources in FL8Y but only 5 sources in 3FGL, and the updated Pass 8 data has a residual background significantly lower than that of the previous data. Both these result in a cleaner background in the analysis. Likely due to the same reasons, we were able to detect the SW limb with a significance of ∼4σ, in addition to the longer time period of the data used. We also showed that if we considered the total excess emission as one extended source with the spatial distribution the same as that in the X-ray image, the γ-ray emission, following a $\Gamma = 1.8$ power law, could be detected with a $>5\sigma$ significance.

For the NE limb, we update its broadband SED in Figure 3, by including the spectral data points obtained in Section 3.3. Comparing to that in Xing et al. (2016), the radio (Allen et al. 2001), X-ray (Bamba et al. 2008), and HESS TeV (Acero et al. 2010) measurements remain unchanged. In addition, the X-ray flux measurements for the NE limb given in Kalemcı...
et al. (2006) are added. Since there are no significant changes in the data points, the leptonic model previously used in Xing et al. (2016) can provide a fit to the updated SED (the electron spectral index $\alpha_e = 2.2$, electron cutoff energy $E_{\text{cut},e} \approx 17$ TeV, and magnetic field strength of the SNR $B_{\text{SNR}} \approx 24$ $\mu$G; refer to Xing et al. 2016 for the detailed model and model parameters). In the model calculation, the synchrotron flux was multiplied by a factor of 2, as the radio and X-ray data were from the whole SNR and the two limbs were assumed to be symmetric for simplicity. The model fit is shown in Figure 3 (red and black curves), and the model parameters given in Xing et al. (2016) were adopted. We note that recently by fitting the radio and XMM-Newton and NuSTAR X-ray data for the NE and SW limbs, Li et al. (2018) obtained electron spectral indices of $\sim 1.9$ and electron cutoff energies of $\sim 7$ TeV. These values are different from what we used here. In their work, however, the magnetic field strength was fixed at 100 $\mu$G and a single-frequency radio flux measurement was used.

For the SW limb, we constructed its broadband SED and show it in Figure 4. The radio and X-ray data are the same as those used for the NE limb, and the HESS TeV measurement is from Acero et al. (2010). In addition, the X-ray flux measurements for the SW limb from Kalemci et al. (2006) are also included. We first considered the purely leptonic model used for the NE limb and found that it can well explain the SED of the SW limb. In deriving the model fit shown in the left panel of Figure 4 (red and black curves), the electron cutoff energy $E_{\text{cut},e} \approx 15$ TeV, the total electron energy of the SW limb $W_e(>1\text{GeV}) \approx 1.1 \times 10^{47}$ erg, and magnetic field strength $B_{\text{SNR}} \approx 30$ $\mu$G. The values are very similar to those used for the NE limb (see Xing et al. 2016).

It has been shown in Acero et al. (2010) that the HESS TeV emission cannot be attributed to a purely hadronic model, and when taking into account the Fermi LAT upper limits at the time, the hadronic origin was ruled out at a $>5\sigma$ confidence level in Acero et al. (2015a). It can be noted that the tenuous environment around SN 1006, with the density of the interstellar medium (ISM) estimated to be $n_{\text{ism}} \sim 0.035$ cm$^{-3}$ (Miceli et al. 2016), does not favor the proton-proton interactions. However, Miceli et al. (2014) reported the detection of a dense HI cloud interacting with the SW limb of SN 1006, which suggests a high ambient density for the hadronic process in this region. We thus also considered the hadronic origin for $\gamma$-ray emission of the SW limb.

There are two hadronic components, one is from the shocked cloud, and the other is from the shocked ISM. For simplicity, we assumed that their parent hadrons have the same energy distribution function of $dN_p/dE_p \propto E_p^{-\alpha_p}\exp(-E_p/E_{\text{cut},p})$. In a purely hadronic scenario, we obtained the proton spectral index $\alpha_p \approx 1.9$, the cutoff energy $E_{\text{cut},p} \approx 100$ TeV, and the total
proton energy $W_p(>1\text{GeV}) \approx 2.5 \times 10^{49}(n/0.2\text{ cm}^{-3})^{-1}\text{ erg}$, where $n$ is the average density of the gas in downstream. Considering $n_{\text{ISM}} = 0.035\text{ cm}^{-3}$, the average cloud density $n_{\text{cloud}} = 0.5\text{ cm}^{-3}$ (Miceli et al. 2016), and a proper geometric factor of $1/64$ (here we considered half of the remnant; Miceli et al. 2014), $n$ is approximately $0.2\text{ cm}^{-3}$. Although the model can fit the $\gamma$-ray SED (the blue curve in the left panel of Figure 4), $\alpha_p \approx 1.9$ is less than 2.2 derived from the radio data and the canonical value of 2.0 (predicted by the standard diffusive shock acceleration theory). Therefore $\gamma$-ray emission from the SW limb is not likely hadronic-dominated, which is consistent with that suggested in Acero et al. (2010) and Acero et al. (2015a).

A mixed scenario that includes leptonic and hadronic components may be considered. We fixed $\alpha_p = 2.2$, the same as that of the electrons. A model fit shown in the right panel of Figure 4 (the thick black curve) can be obtained. The leptonic component (the black curve) has the same model parameters as the purely leptonic model, but with a lower total energy of $W_e(>1\text{GeV})$ of $1.0 \times 10^{47}\text{ erg}$. The hadronic component (the blue curve) has $E_{\text{cut},p} = 100\text{ TeV}$ and $W_p(>1\text{GeV}) < 1 \times 10^{49}(n/0.2\text{ cm}^{-3})^{-1}\text{ erg}$. Assuming a canonical explosion energy of $10^{51}\text{ erg}$ and a symmetric geometry, the energy value implies that the fraction of explosion energy converted into hadrons for the full remnant is lower than the order of $\sim 2\%$ for the current stage. In this mixed scenario, the contribution of the leptonic component is only slightly lower ($< 10\%$) than that of the purely leptonic model. The $\gamma$-ray emission from the SW limb is still leptonic-dominated.

In summary, our analysis of the recently updated Fermi Pass 8 data for the SN 1006...
region results in the $\gamma$-ray detection of not only the NE part reported in Xing et al. (2016) and Condon et al. (2017), but also the SW part that has not been detected in previous studies. The $0.5$–$500$ GeV $\gamma$-ray luminosity of the NE and SW parts are $1 \times 10^{33}$ erg s$^{-1}$ and $6 \times 10^{32}$ erg s$^{-1}$, respectively. Similar to the emission process considered for the NE part, we find that the $\gamma$-ray emission of the SW part likely arises from the leptonic process with reasonable model parameters. The luminosity values support our modeling, as they are two orders of magnitude lower than those of the dynamically evolved SNRs (Xing et al. 2015, and references therein). $\gamma$-ray emission from the latter group originates from the hadronic process, due to the interaction between the SNRs and nearby molecular clouds. We suspect that the interacting area between the shock surface of SN 1006 and the HI cloud is much lower than that estimated in Miceli et al. (2014) or that the energy conversion efficiency of the SNR is lower than $\sim 2\%$ at the present age. Thus the high-energy and VHE $\gamma$-ray emission from the SW limb of SN 1006 is dominated by the leptonic process.

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Table 1. Fermi LAT flux measurements of the NE and SW limbs of SN 1006.*

| $E$ (GeV) | Band (GeV) | $F/10^{-13}$ (NE) (erg cm$^{-2}$ s$^{-1}$) | TS (NE) | $F/10^{-13}$ (SW) (erg cm$^{-2}$ s$^{-1}$) | TS (SW) |
|-----------|-----------|--------------------------------|
| 0.23      | 0.1–0.5   | <2.9                          | 0       | <5.5                                    | 0       |
| 1.29      | 0.5–3.0   | <3.5                          | 2       | <3.2                                    | 2       |
| 7.07      | 3.0–16.6  | 1.3±0.6                       | 6       | 1.4±0.7                                 | 6       |
| 38.84     | 16.6–91.0 | <5.0                          | 3       | 2±1                                     | 7       |
| 213.34    | 91.0–500.0| 10±5                          | 7       | <7.1                                    | 0       |

* $F$ is the energy flux ($E^2 dN/dE$). Fluxes without uncertainties are the 95% upper limits.

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