FERMI LARGE AREA TELESCOPE DETECTION OF SUPERNOVA REMNANT RCW 86

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ABSTRACT

Using 5.4 yr Fermi Large Area Telescope data, we report the detection of GeV γ-ray emission from the shell-type supernova remnant RCW 86 (G315.4-2.3) with a significance of ~5.1σ. The data slightly favors an extended emission of this supernova remnant. The spectral index of RCW 86 is found to be very hard, Γ ~ 1.4, in the 0.4–300 GeV range. A one-zone leptonic model can well fit the multi-wavelength data from radio to very high energy γ-rays. The very hard GeV γ-ray spectrum and the inferred low gas density seem to disfavor a hadronic origin for the γ-rays. The γ-ray behavior of RCW 86 is very similar to several other TeV shell-type supernova remnants, e.g., RX J1713.7-3946, RX J0852.0-4622, SN 1006, and HESS J1731-347.

Key words: cosmic rays – gamma rays: ISM – ISM: supernova remnants – radiation mechanisms: non-thermal

1. INTRODUCTION

Supernova remnants (SNRs) are believed to be the most probable candidates for Galactic cosmic ray (CR) acceleration sources. However, direct observational evidence is not available until there are γ-ray detections of SNRs (e.g., Tavani et al. 2010; Ackermann et al. 2013). Nearly 20 SNRs have been discovered in the TeV γ-ray band to this day, among which 7 are firmly identified as shell-type SNRs (Rieger et al. 2013) and about half are interacting with molecular clouds. In the 2 yr catalog of Fermi-LAT (2FGL), there are six firmly identified SNRs based on their spatial extension and four associated point-like SNRs (Nolan et al. 2012). Additionally there are 59 2FGL sources which might be associated with SNRs based on the spatial match between the error circles of the 2FGL sources and the SNR extensions (Nolan et al. 2012). With the accumulation of Fermi Large Area Telescope (LAT) data, more and more SNRs have been detected (Castro & Slane 2010; Tanaka et al. 2011; Abdo et al. 2011; Wu et al. 2011; Giordano et al. 2012; Ajello et al. 2012; Katsuta et al. 2012; Hewitt et al. 2012; Castro et al. 2013; Araya 2013; Pavato et al. 2013; Xing et al. 2014; Auchettl et al. 2014). Although the γ-ray emission mechanism of individual SNRs is subject to debate, it is possible to approach the nature of γ-ray emission of SNRs through a population study with a large sample of γ-ray SNRs (Yuan et al. 2012; Dermer & Powale 2013). Increasing the sample of γ-ray SNRs can be essential for understanding their non-thermal characteristics.

The shell-type SNR G315.4-2.3, also known as RCW 86, is a young remnant probably associated with supernova SN 185 (Stephenson & Green 2002; Zhao et al. 2006). The angular diameter of this SNR is about ~42', with a clear shell in radio (Kesteven & Caswell 1987; Whiteoak & Green 1996; Dickel et al. 2001), infrared (Williams et al. 2011), optical (van den Bergh et al. 1973; Smith 1997), and X-ray bands (Vink et al. 1997; Bocchino et al. 2000; Bamba et al. 2000; Borkowski et al. 2001; Rho et al. 2002). The distance of RCW 86 is estimated to be 2.3–2.8 kpc from optical spectroscopy observations (Rosado et al. 1996; Sollerman et al. 2003). In the very high energy (VHE) γ-ray band, a well extended source with morphology consistent with the X-ray image has been revealed by HESS (Aharonian et al. 2009). The spectral index of VHE γ-rays is about 2.5 and the flux is about 10% that of the Crab Nebula (Aharonian et al. 2009). Lemoine-Goumard et al. (2012) analyzed ~3 yr Fermi-LAT data and found no significant excess from this SNR. Upper limits of the γ-ray flux in the GeV band were derived by Lemoine-Goumard et al. (2012). With multi-wavelength observations, the high energy radiation mechanism and particle acceleration can be studied (Aharonian et al. 2009; Lemoine-Goumard et al. 2012).

Here we report the detection of GeV γ-ray emission from RCW 86, with 5.4 yr Fermi-LAT data. The data analysis, including the morphology and the spectrum, is presented in Section 2. Based on the γ-ray spectrum and the multi-wavelength spectral energy distribution (SED) of RCW 86, we discuss its non-thermal emission mechanism in Section 3. Finally, we conclude in Section 4.

2. DATA ANALYSIS

The newest reconstructed Pass 7 reprocessed version of the Fermi-LAT data3 are used in this analysis. We select the data recorded from 2008 August 4 to 2014 January 16, 284 weeks in total. The SOURCE (evclass = 2) event class is selected and the maximum zenith angle cut is 100°. The data are filtered with the recommended cuts (DATAQUAL == 1) & (LAT_CONFIG == 1) & (ROCK_ANGLE < 52). The energy range in the analysis is taken to be 400 MeV to 300 GeV, and the region of interest (ROI) is a 14° × 14° box around the position of RCW 86. Such a box size is reasonable compared with the ~1.5° resolution angle for photons above 400 MeV (Atwood et al. 2009). The analysis is based on the LAT Scientific tool version v9r32p5, and the instrument response function is P7REP_SOURCE_V15. The Galactic diffuse background gll_1em_v05.fits and isotropic diffuse background

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http://tevcat.uchicago.edu

http://fermi.gsfc.nasa.gov/ssc/data

http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
iso_source_v05.txt provided by the Fermi Science Support Center\textsuperscript{7} are adopted in the analysis.

We bin the data into 30 logarithmically distributed energy bins and \(140 \times 140\) spatial bins with size 0\'1, and perform the analysis following the standard binned likelihood analysis procedure. The 2FGL sources (Nolan et al. 2012) within a radius of 15\' around RCW 86 are included in the source model, which is generated by the user-contributed software make2FGLxml.py.\textsuperscript{8} In the likelihood fittings, the spectral parameters of all the sources located in the ROI together with the normalizations of the two diffuse backgrounds are left free.

We first fit the model with only the 2FGL sources. The Test Statistic (TS; defined as \(2(\ln L - \ln L_0)\) with \(L_0\) the likelihood of null hypothesis and \(L\) the likelihood with the source included) map for the 10\(^{-9}\) \times 10\(^{-9}\) region centered at RCW 86 after subtracting this baseline model is shown in the left panel of Figure 1. The TS map is smoothed with a \(\sigma = 0.3\) Gaussian function. From this TS map we find that there are some excesses that are not included in the 2FGL catalog. We will add five point sources close to the highest TS value locations, whose actual locations will be determined with the gtfindsrc tool, to approximate such excess emission (see the green circles in the TS map\textsuperscript{7}). At the location of RCW 86 (the center of the map) we see a relatively weak signal which may come from the emission from the SNR. We will also add RCW 86 in the new model. Power-law spectra are assumed for these newly added sources.

The radio and X-ray observations show clear morphology of RCW 86 (Whiteoak & Green 1996; Dickel et al. 2001; Vink et al. 1997; Bocchino et al. 2000; Bamba et al. 2000; Borkowski et al. 2001; Rho et al. 2002), and the angular radius is about 0.35. The HESS observation of TeV \(\gamma\)-rays reveals a spatial extension with radius of about 0.4 (Aharonian et al. 2009). Therefore RCW 86 should be treated as an extended source in the analysis. We will use a uniform disk with radius 0\'4; the radio image at 843 MHz from the Sydney University Molonglo Sky Survey (SUMSS: Mauch et al. 2003), and the HESS TeV \(\gamma\)-ray image as the spatial template for RCW 86. The central position of the disk template is adopted to be R.A. = 220.75, decl. = \(-62.43\), which can well match the HESS and SUMSS images of the SNR. The point source assumption will also be adopted for comparison. The three extended spatial templates are shown in Figure 2. In the left and middle panels the HESS excess contours of \(\gamma\)-rays are overlaid with green lines (Aharonian et al. 2009).

With these new sources in the model, the fitting improves significantly (the value of the log-likelihood increases by \(\sim 236\) compared with the fit without these new sources). The coordinates and TS values of the five new point sources are listed in Table 1. The TS map after subtracting the additional five new sources listed in Table 1 is shown in the right panel of Figure 1. It can be seen that this TS map became much smoother than the baseline model (the left panel). There are still some residual excesses, which might be due to the inaccuracy of the Galactic diffuse background or the existence of additional point sources. These residuals are not expected to affect the results of RCW 86 remarkably. Actually even when the five most significant new sources listed in Table 1 are not included in the model, the fitting results of RCW 86 do not change significantly.

Now we focus on the discussion about RCW 86. For a point source assumption of RCW 86, the best-fit position is R.A. = 220:96, decl. = \(-62:32\), and the TS value is 26.6. For four degrees of freedom (dof) such a TS value corresponds to a significance of \(\sim 4.2\sigma\). For comparison, in Lemoine-Goumard et al. (2012) the TS value of RCW 86 for a point source model

\begin{table}[h]
\centering
\caption{Coordinates and TS Values of the New Point Sources}
\begin{tabular}{llll}
\hline
\textbf{Name} & \textbf{R.A.} & \textbf{Decl.} & \textbf{TS} \\
& (deg) & (deg) & \\
\hline
NewPts1 & 225.91 & \(-64.46\) & 103.7 \\
NewPts2 & 212.62 & \(-61.00\) & 48.6 \\
NewPts3 & 221.49 & \(-59.36\) & 51.2 \\
NewPts4 & 213.08 & \(-66.55\) & 63.6 \\
NewPts5 & 216.22 & \(-68.15\) & 299.5 \\
\hline
\end{tabular}
\end{table}

\textsuperscript{7} http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html
\textsuperscript{8} http://fermi.gsfc.nasa.gov/ssc/data/analysis/user/
\textsuperscript{9} The initial postulated position of NewPts 5 is close to NewPts 4. However, the output location from the gtfindsrc tool is out of the 10\(^{-9}\) \times 10\(^{-9}\) region of the TS map.

Figure 1. TS maps above 400 MeV for a 10\(^{-9}\) \times 10\(^{-9}\) region centered at RCW 86. Left panel is for the model with the diffuse background and 2FGL sources subtracted, and the right panel is for the model with the additional sources listed in Table 1 subtracted. Green circles show the positions of the newly added sources and RCW 86.
is about 12. We then test the three spatial templates as shown in Figure 2. It is found that for the extended source assumption of RCW 86, the TS value is about 30. For two dof (normalization and spectral index) it corresponds to a 5.1σ significance. To better address the extension of the source, we compare the results for a disk with very small radius (0.1'). The results recover the point source assumption. If the central position of the small disk is the same as the above 0.4 disk (the best-fitting position of the point source assumption), the TS value is about 16.9 (28.1). It shows that the data do favor an extended emission of the source. The fitting TS values and spectral indices for different spatial templates are compiled in Table 2. No significant differences among the three spatial templates as shown in Figure 2 can be found from the Fermi-LAT data.

We test different central positions of the disk template by increasing or decreasing the right ascension (R.A.) or declination (decl.) by 0.1'. The resulting TS values of RCW 86 decreased by 0.7–4.1. We also test the disk templates with 0.3 and 0.5 radii, and obtain the TS values of 30.4 and 29.6, respectively, which are also slightly smaller than the value 32.1 given in Table 2. It is shown that the disk template shown in Figure 2 does fit the data well. The best-fitting spectral indices in these tests differ by about 0.04, which could be regarded as systematics due to the choice of position and extension of the disk.

The spectrum for RCW 86 is very hard. Such a hard spectrum will be difficult to explain with the hadronic scenario whose γ-ray spectrum just follows the proton spectrum. The inverse Compton scattering of background photons by high energy electrons, on the other hand, can easily account for the hard spectrum revealed by the Fermi-LAT data. Similar hard spectra of GeV photons are also shown in two other shell-type SNRs, RX J1713.7-3946 (Abdo et al. 2011) and RX J0852.0-4622 (Tanaka et al. 2011). For two other shell-type SNRs, SN 1006 (Araya & Frutos 2012) and HESS J1731-347 (Yang et al. 2014), although they have not yet been detected in Fermi-LAT data, the flux upper limits actually show similar behaviors for the GeV–TeV spectra, like RCW 86.

We derive the SED of RCW 86 using the same likelihood analysis, but performed in different energy bins. The spectral indices of all sources are fixed to be the best-fit values obtained in the previous global fitting; only the normalizations of the sources and the diffuse backgrounds are free during the fittings. The SED for the disk template is shown in the left panel of Figure 3. For the two other extended source templates, the results are essentially similar. In the first two energy bins the TS values for RCW 86 are very small, and the 99.9% upper limits are given. For comparison the upper limits obtained in Lemoine-Goumard et al. (2012) and the HESS data in the VHE band (Aharonian et al. 2009) are also shown. The GeV γ-ray SED derived in this work is consistent with the upper limits obtained in Lemoine-Goumard et al. (2012). It can be seen that connecting the GeV–TeV SED shows a peak at hundreds of GeV. Such a peak may indicate the leptonic feature of the γ-ray emission.

### Table 2

<table>
<thead>
<tr>
<th>Spatial Template</th>
<th>TS</th>
<th>Disk</th>
<th>SUMSS</th>
<th>HESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point</td>
<td>26.6</td>
<td>32.1</td>
<td>31.6</td>
<td>29.6</td>
</tr>
<tr>
<td>Disk</td>
<td>$1.21 \pm 0.32$</td>
<td>$1.38 \pm 0.18$</td>
<td>$1.36 \pm 0.18$</td>
<td>$1.33 \pm 0.19$</td>
</tr>
<tr>
<td>Flux$^a$</td>
<td>$2.16 \pm 1.55$</td>
<td>$6.12 \pm 2.95$</td>
<td>$5.66 \pm 2.67$</td>
<td>$5.37 \pm 2.78$</td>
</tr>
</tbody>
</table>

Note. $^a$ Flux between 0.4 and 300 GeV in $10^{-10}$ cm$^{-2}$ s$^{-1}$.

3. DISCUSSION

In the right panel of Figure 3 we compile the multi-wavelength observational data of RCW 86, from radio (Caswell et al. 1975), X-ray (Lemoine-Goumard et al. 2012), to VHE γ-rays (Aharonian et al. 2009). This wide-band SED shows a double-peak behavior, which might be reasonably described within the leptonic framework. The high energy electron spectrum is parameterized with an exponential cutoff power-law spectrum, $dN/dE \propto E^{-\Gamma} \exp(-E/E_c)$. The total energy of electrons above 1 GeV is normalized to $W_\gamma$, which could be a fraction of the total energy released by the supernova. We consider a simple one-zone model, where a single electron population radiates in a uniform magnetic field and matter field. For the background photons used to calculate the inverse Compton scattering emission, we adopt the interstellar radiation field as developed in Porter & Strong (2005), which is made up of optical emission from starlight, infrared from absorption, and re-emission from dust and the cosmic microwave background (CMB). To calculate the bremsstrahlung emission, we also adopt

(A color version of this figure is available in the online journal.)
a gas number density of 1 cm$^{-3}$. Adopting proper parameters, we reproduce the multi-wavelength emission of RCW 86 well, as shown in the right panel of Figure 3. The three bumps from left to right represent the synchrotron, bremsstrahlung, and inverse Compton scattering components generated by the same population of electrons. Although the radio and X-ray images show complex structures, the $\gamma$-ray observations are fully consistent with the one-zone model. The X-ray emission has contributions from a thermal component, and the synchrotron emission is also affected by the magnetic field structure. There is no compelling evidence for a two-zone emission model.

Assuming that the distance to RCW 86 is 2.5 kpc and the radius is 15 pc, we estimate the model parameters to reproduce the multi-wavelength SED, which are $\Gamma_\gamma \approx 2.3$, $E_\gamma \approx 22$ TeV, $W_e \approx 1.2 \times 10^{48}$ erg, and $B \approx 20 \mu$G. These parameters are consistent with\(^\text{10}\) that of the one-zone model in Lemoine-Goumard et al. (2012). The total energy going to high energy electrons is about $0.1\%$ of the typical released energy of a supernova, say $10^{53}$ erg. We also test the case with only the CMB as the target photon field producing the inverse Compton scattering emission. In this case, the total energy of electrons ($W_e$) needs to be $\sim 2$ times higher, the magnetic field needs to be about $\sqrt{2}$ times smaller, and the cutoff energy $E_c \approx 26$ TeV, which is slightly larger. The resulting photon spectrum for the CMB photon field case is very similar to the one shown in the right panel of Figure 3.

It should be noted that the cooling of electrons is not effective enough to alter the electron spectrum of RCW 86. From Figure 3 we see that most of the electron energy goes into synchrotron radiation. The synchrotron cooling time is estimated to be $\tau_{\text{sync}} \approx 1.25 \times 10^{10} (B/\mu\text{G})^{-2} (E/\text{GeV})^{-1}$ yr. The age of RCW 86 is about 1800 yr, thus the critical energy above which the electrons are cooled down is about $35 (17)$ TeV for a magnetic field of 14 (20) $\mu$G. Since our cutoff energy is about 20 TeV, the cooling does not affect the electron spectrum assumed in the modeling.

The hadronic scenario does not seem favorable for explaining the $\gamma$-ray spectrum since it requires too hard a spectrum of the accelerated CR protons, which cannot be easily understood in the shock acceleration theory. There might be another problem for the hadronic scenario: the low ambient medium density as revealed by the thermal X-ray emission. In the above calculation we arbitrarily adopt a gas density of 1 cm$^{-3}$. From the weak thermal X-ray emission, the post-shock density of this SNR was estimated to be $(0.26-0.68) f^{0.5} \text{cm}^{-3}$, where $f$ is the filling factor of the thermal component (Yamaguchi et al. 2008). A low density is also expected according to the high shock velocity of this SNR (Helder et al. 2009). Given a low density, the required energy for proton acceleration will be too high. For example, for the proton spectrum with index 1.7 and cutoff energy 50 TeV, the estimated total energy above 1 GeV is $1.3 \times 10^{50} (n_{\text{gas}}/1 \text{cm}^{-3})^{-1} (d/2.5 \text{kpc})^2$ erg. The energy fraction of CRs in the total energy released by the supernova may be too large if the density is lower than 1 cm$^{-3}$. In a recent study, Morlino et al. (2014) inferred the CR acceleration efficiency to be $\sim 20\%$ based on the Balmer line emission. Therefore the energy budget will be challenged in the hadronic scenario.

Similar circumstances also appear for SNRs RX J1713.7-3946 (Ellison et al. 2010; Yuan et al. 2011) and RX J0852.0-4622 (Tanaka et al. 2011); both have very hard GeV $\gamma$-ray spectra and no detection of thermal X-rays. Note that Fang et al. (2011) proposed the hadronic scenario based on nonlinear diffusive shock acceleration (Malkov & O’C Drury 2001; Blasi 2002) to explain the $\gamma$-ray emission of these three SNRs. The model prediction is generally higher and harder than the Fermi-LAT observations.

The GeV–TeV $\gamma$-ray emission of this SNR, together with the fact that the ambient medium density may be low, further supports the unified picture to describe the $\gamma$-ray SNRs (Yuan et al. 2012). In that model, the SNRs are classified into three classes according to the medium density. The sources located in a low-density medium tend to have an inverse Compton scattering origin for $\gamma$-rays, and the $\gamma$-ray spectrum will be very hard. There are probably five shell-type SNRs belonging to this class, i.e., RX J1713.7-0846, RX J0852.0-4622, RCW 86, SN 1006, and HESS J1731-347. A combined study of all

\(^{10}\) Except for $W_e$ which might be due to a different low threshold energy to calculate the total electron energy.
these sources and an evolutionary picture to describe them will be interesting.

4. CONCLUSION

In this work we report the detection of GeV $\gamma$-rays from a shell-type SNR, RCW 86, with Fermi-LAT. Analyzing 5.4 years of Fermi-LAT data, we find an extended source coincident with the radio or VHE $\gamma$-ray image of RCW 86 with a significance higher than 5$\sigma$. The point source assumption is less favored than the extended source assumption. The GeV $\gamma$-ray spectrum is found to be very hard, $\Gamma \approx 1.4 \pm 0.2$. The multi-wavelength SED from radio to VHE $\gamma$-rays can be well described with a simple one-zone leptonic model. The hadronic scenario may have difficulty producing the very hard GeV $\gamma$-ray spectrum and in the total energy budget, given that the environmental medium density is relatively low. The similarity of the non-thermal GeV–TeV spectrum and the lack of strong thermal X-ray emission of this SNR to several other shell-type SNRs makes them form a distinct class of $\gamma$-ray SNRs, which may point to the nature of particle acceleration and radiation in SNRs.

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