Detection of gamma-ray emission in the region of the supernova remnants G296.5+10.0 and G166.0+4.3

Miguel Araya*

Space Research Centre (CINESPA), Universidad de Costa Rica, San José 2060, Costa Rica

Accepted 2013 June 23. Received 2013 June 18; in original form 2013 March 13

ABSTRACT

52 months of accumulated observations by the Large Area Telescope onboard the Fermi Gamma-ray Space Telescope in the region of the supernova remnants G296.5+10.0 (PKS 1209-51/52) and G166.0+4.3 (VRO 42.05.01) are analysed. GeV emission is detected coincident with the position of the sources at the $\sim 5\sigma$ and $11\sigma$ levels above the background, respectively, for the best-fitting spectral and spatial scenarios. The gamma-ray spectrum of the sources can be described with a power law in energy. G166.0+4.3 shows a soft GeV spectrum while that of G296.5+10.0 is flat (in the $vF_v$ representation). The origin of the gamma-ray emission from the sources is explored. Both leptonic and hadronic mechanisms can account for the high-energy emission from G296.5+10.0, while a leptonic scenario is preferred for G166.0+4.3.

Key words: acceleration of particles – radiation mechanisms: non-thermal – ISM: supernova remnants.

1 INTRODUCTION

Supernova remnants (SNRs) are known to be high-energy sources exhibiting non-thermal photon spectra from radio to gamma-rays. High-energy photon emission may result from interactions of high-energy protons with ambient nuclei resulting in the production of neutral pions that decay to gamma-rays. This is generally referred to as the hadronic scenario. Leptonic mechanisms for the production of gamma-rays in SNRs include inverse Compton up-scattering (IC) of low-energy photons by high-energy electrons and non-thermal bremsstrahlung emission (e.g. Gaisser, Protheroe & Stanev 1998) from high-energy electrons interacting with ambient particles.

Certainly, high-energy electrons are known to be accelerated in SNRs from their radio and X-ray synchrotron emission; the latter is usually associated with the forward shock of young remnants (e.g. Gotthelf et al. 2001; Berezhko, Ksenofontov & Völk 2002; Hwang et al. 2002; Rho et al. 2002; Long et al. 2003; Vink & Laming 2003; Berezhko & Völk 2004). Particles are thought to gain energy through first-order Fermi acceleration (Bell 1978; Blandford & Eichler 1987), also known as diffusive shock acceleration (DSA) after crossing the shock front of the supernova explosion, which occurs many times as the particles move in the presence of magnetic fields that result either from shock compression of the interstellar field or from amplification by cosmic ray instabilities (see Schure et al. 2012 for a recent review).

It is thought that a considerable (1–10 per cent) fraction of the SNR energy can be transferred to particles via DSA, which is one of the reasons why they are considered the main source of Galactic cosmic rays. However, identifying and separating the emission from leptonic and hadronic components is a challenging task. Some SNRs interacting with molecular clouds, such as W28, W49B, W51C and G8.7–0.1, show gamma-ray emission that seems to favour a hadronic origin (Abdo et al. 2009b, 2010b, 2010c; Ajello et al. 2012). Other studies show that some young SNRs with a relatively hard GeV photon spectrum are probably leptonic dominated, such as RX J1713.7–3946 (Abdo et al. 2011) and RX J0852.0–4622 (Tanaka et al. 2011). The softer spectrum of other young sources such as Cas A (Abdo et al. 2010a; Araya & Cui 2010) and Tycho SNR (Giordano et al. 2012) might also favour a hadronic origin. Recent observations of the SNRs IC 443 and W44 seem to have confirmed the presence of cosmic ray protons (more generally, ions) through their characteristic photon spectral features around $\sim 100$ MeV (Ackermann et al. 2013).

Observations from the recently launched Fermi satellite (Atwood et al. 2009) have contributed to form a more consistent picture of gamma-ray emission from SNRs and particle acceleration in SNR shocks (e.g. Caprioli 2012). Despite the advances in the understanding of SNR properties, important limitations are still common for gamma-ray studies. For example, the broad point spread function (PSF) of the Large Area Telescope (LAT) onboard Fermi and the high Galactic radiation background often present challenges for data analysis. In this paper, a study of Fermi LAT observations is carried out for two remnants located outside the Galactic plane, where the expected Galactic diffuse level is lower.

The sources are G296.5+10.0 and G166.0+4.3, shell-type SNRs with radio extensions 90 arcmin $\times$ 65 arcmin and 55 arcmin $\times$ 35 arcmin, respectively. The distance adopted here for G296.5+10.0 and G166.0+4.3 is 10.0 and 11.0 kpc, respectively, for the best-fitting spectral and spatial scenarios. The gamma-ray spectrum of the sources can be described with a power law in energy. G166.0+4.3 shows a soft GeV spectrum while that of G296.5+10.0 is flat (in the $vF_v$ representation). The origin of the gamma-ray emission from the sources is explored. Both leptonic and hadronic mechanisms can account for the high-energy emission from G296.5+10.0, while a leptonic scenario is preferred for G166.0+4.3.

Key words: acceleration of particles – radiation mechanisms: non-thermal – ISM: supernova remnants.
is 2.1 kpc (Giacani et al. 2000). In the case of G166.0+4.3, a distance estimate of 4.5 ± 1.5 kpc (Landecker et al. 1989) is used.

G166.0+4.3 is composed of two parts as seen in radio images: a regular shell to the east and a region expanding into a low-density medium (the extended ‘wing’) to the west. The morphology of this remnant possibly results from the shock encountering a density discontinuity (Pineault et al. 1985) in the interstellar medium (ISM).

The X-ray emission is only present in the interior and peaks towards the west wing (Burrows & Guo 1994), where the shock has encountered denser material (Landecker et al. 1989). H{	extsc{i}} observations have shown ISM features interacting with the SNR (Landecker et al. 1989).

G296.5+10.0 is a barrel-shaped SNR. The detected X-ray emission is in good correspondence with the radio. The morphology of barrel-shaped SNRs might be the result of their interactions with the ISM material or the magnetic field in the ISM, or result from the intrinsic properties of the outburst and later interaction with the ISM (e.g. Kesteven & Caswell 1987). Located relatively far above the Galactic plane, G296.5+10.0 is possibly surrounded by low-density, uniform ISM. However, H{	extsc{i}} observations have revealed three clouds that are associated with the SNR (Giacani et al. 2000): a long, broad structure of size 1° × 25 arcmin to the north-east, a cloud along the south-western limb, near the Galactic coordinates (l, b) ~ (296:00, +9:50) (volume density ~13 cm^{-3}) and the H{	extsc{i}} cloud across the eastern limb close to the brightest filaments near (l, b) ~ (296:67, +9:67) (density ~13 cm^{-3}).

The structure of this paper is as follows. In Section 2, the gamma-ray data reduction is discussed, paying attention to the morphology and spectral properties of the emission detected in the direction of the SNRs. In Section 3, the non-thermal spectral energy distributions (SEDs) are modelled with different emission mechanisms. The discussion of results and final remarks are given in Section 4.

2 OBSERVATIONS

2.1 Radio data

The radio data points for G296.5+10.0 and G166.0+4.3 are obtained from the literature (Milne & Haynes 1994; Leahy & Tian 2005, 2006). The radio spectrum of the sources used here can be accounted for by optically thin synchrotron emission from cosmic ray electrons. The particle spectrum responsible for the radio emission is a power law in energy (\( \propto \epsilon^{-\gamma} \)) with \( \epsilon \) the particle energy. From standard results concerning the synchrotron emission by a power-law population of electrons, the radio data imply \( s \approx 2 \) and \( \approx 1.7 \) for G296.5+10.0 and G166.0+4.3, respectively.

2.2 Fermi LAT data

Fermi LAT data taken between 2008 August 04 and 2013 January 24 were analysed with the standard software SCIENCTOOLS version v9r27pl1 released on 2012 April 18. Several selection criteria are applied to events, including the selection of events with high probability of being gamma-rays (the so-called Pass 7 Source class) and with a reconstructed zenith angle less than 100° to avoid contamination from gamma-rays from Earth’s limb. Time intervals when the spacecraft is within the range of rocking angles used during nominal sky-survey observations (the rocking angle is less than 52°) are also selected. The spectral analysis is further restricted above 200 MeV to avoid uncertainties in the effective area and broad PSF at lower energies, and below 100 GeV due to limited statistics. The same data selection criteria were used for regions near SNRs G296.5+10.0 and G166.0+4.3.

Events within a square region of 14’ × 14’ of the catalogued positions of the SNRs G296.5+10.0 and G166.0+4.3, RA (J2000) = 12° 09′ 40′′, Dec. (J2000) = −52° 25′ 00″ and RA (J2000) = 05° 26′ 30″, Dec. (J2000) = 42° 56′ 00″, respectively, are included in the analysis. This is necessary to account for the large PSF of the LAT. The emission model that is used in the analysis includes the positions and spectral parameter values of the sources within this region that are found in the LAT 2 yr Source Catalog (Nolan et al. 2012). In the case of the region containing G296.5+10.0, nearby extended sources (known as Cen A and MSH 15-52) are modelled with spatial templates provided within the SCIENCTOOLS. The data are binned in sky coordinates with the tool gtbin in square bins of size 0.1 to construct count maps for visualization.

The spectral and spatial properties of Fermi LAT data are explored by means of a maximum likelihood analysis\(^2\) using the tool glike. The likelihood is defined as the probability of obtaining the data given an input spatial and spectral model for the sources. The starting point for the fitting procedure is obtained from the LAT 2 yr Source Catalog, as mentioned above. The currently released instrument response functions (P7SOURCE_V6) are used throughout the analysis, as well as the latest galactic and extragalactic diffuse background components (as specified in the files gal_2yearp7v6_v0.fits and iso_p7v6source.txt, respectively). The spectral parameters of the catalogued sources beyond 7° from the position of G296.5+10.0 and G166.0+4.3 are kept fixed to the values reported in the catalogue. The fit is performed with the optimizer NEWMINUIT until convergence is achieved.

In the case of the SNR G166.0+4.3, the previously detected point source 2FGL J0526.6+4308 is removed from the model. This source is found at the position RA (J2000) = 05° 26′ 39′′ 7, Dec. (J2000) = 43° 08′ 48′′ 8 within the remnant’s shell. Therefore, no source at the positions of the SNRs is originally included in this part of the analysis. The resulting model is referred to as the null hypothesis and it is thus a model of the background.

The significance of a source is estimated by means of a test statistic (TS) defined as \( -2 \log(L_0/L) \), where \( L_0 \) and \( L \) are the maximum likelihood values for the null hypothesis and for a model including the additional source, respectively. In the limit of a large number of counts, despite some caveats (Protassov et al. 2002), the detection significance of the source is roughly given by \( \sqrt{TS} \) (Mattox et al. 1996), and therefore TS = 25 is usually considered the threshold value for detection (corresponding to a significance of 5\( \sigma \) for one degree of freedom).

The best-fitting models that result from the maximization procedures are used to generate maps of the background emission which are smoothed with a boxcar of length 0.5. When subtracted from the corresponding smoothed count maps, the resulting residuals maps can be used to visualize the disagreement between the observed counts and the model. These background-subtracted maps are obtained for different energy bands and then divided by the square root of the background, resulting in the signal-to-noise maps that are shown in Figs 1 and 2 for the two sources.

Representative radio contours of G296.5+10.0 and G166.0+4.3 obtained from observations of the Green Bank catalogue of radio

\(^1\) See http://fermi.gsfc.nasa.gov/ssc

\(^2\) See http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/binned_likelihood_tutorial.html.
Figure 1. Signal-to-noise maps in the region of the SNR G296.5+10.0 smoothed with a boxcar of length 0.5 in two energy bands: (a) 2–7 GeV and (b) 7–100 GeV (see the text), and green contours of a GB6 4860 MHz observation of the SNR. The position of the CRATES sources is represented by (yellow) crosses and Galactic coordinates are shown in degrees. The insets in the bottom-left corner show the smoothed PSF.

Figure 2. Signal-to-noise maps in the region of the SNR G166.0+4.3 smoothed with a boxcar of length 0.5 in two energy bands: (a) 0.5–2 GeV and (b) 2–100 GeV. Overlaid are green contours of the radio WENSS observation (325 MHz) of the SNR. The magenta cross indicates the position of the source 2FGL J0526.6+4308. Galactic coordinates are shown in degrees and the PSF is only shown for the higher energy map.

sources (GB6, 4860 MHz; Gregory et al. 1996) and the Westerbork Northern Sky Survey (WENSS, 325 MHz; Rengelink et al. 1997), respectively, are overlaid on to the signal-to-noise maps. Residual emission coincident with the positions of the sources is apparent. Maximum likelihood analyses are next performed in order to quantify the significance and test the spatial morphology and spectral parameters of the emission.

2.2.1 Morphology

As shown in Figs 1 and 2, only events above 0.5 GeV are used for morphology studies, to take advantage of the narrower PSF at higher energies. Several hypotheses for the morphology of the residual gamma-ray emission are tested.

G296.5+10.0. Fig. 1 shows the signal-to-noise maps obtained for the region around this SNR with the corresponding radio contours of the bipolar shell for two energy bands: 2–7 and 7–100 GeV. In the energy range above 2 GeV, the emission seems to come in part from a region towards the interior of the remnant, and it becomes more prominent towards the western limb of the SNR at the highest energies. This excess seems to follow the western radio emission.

In order to evaluate the significance of the emission, a ‘TS map’ is calculated above 500 MeV for the region near the SNR. The map is obtained by evaluating the TS value of a point source that is moved in a predefined grid. Based on this result, the gamma-ray morphology is assessed by fitting different spatial models for G296.5+10.0: (a) a spatial template obtained from the radio GB6 observation, (b) a uniform disc template and (c) a point source located at the position of maximum value in the TS map. A simple power-law model is assumed for the energy spectrum. For the disc, the TS values with respect to the null hypothesis are evaluated for different locations and sizes. The radius of the disc template is systematically increased in steps of 0.1 and the position of its centroid is changed within the interior of the remnant shell.

The TS values obtained for the radio template, uniform disc and point-source hypotheses are 28, 36 and 25, respectively, as shown
in Table 1. The best-fitting disc radius and centroid position are $0.6 \pm 0.1$ and RA (J2000) = $12^\text{h} 09^\text{m}$, Dec. (J2000) = $-52^\circ 27'$. The error of the centroid is 0.2 at the 95 per cent confidence level. Although the fit with the disc template has a higher TS with respect to the fit with the radio template (the difference being $\Delta$TS = 8), the corresponding model has three additional parameters and therefore both can be considered statistically similar descriptions of the source morphology. The disc hypothesis is an improvement with respect to the point source ($\Delta$TS = 11, see Table 1); the analysis thus indicates that the source extension is detected at the 3$\sigma$ level (Lande et al. 2012). The disc hypothesis will then be adopted for spectral analysis here and as explained later on the systematic uncertainties of changing the hypothesis for the source morphology will be considered.

As an additional test to evaluate the amount of background emission that may have not been accounted for in the model, new fits are performed by moving the disc template in different azimuthal positions outside and around the radio contours. No significant emission is detected outside/around the shell of the SNR.

**Table 1.** TS for different spatial models compared to the null hypothesis (0.5–100 GeV).

| Model                        | TS  | Additional degrees of freedom |
|------------------------------|-----|-------------------------------|
| G296.5+10.0                  |     |                               |
| Null hypothesis (background only) | 0   | 0                             |
| Uniform disc                 | 36  | 5                             |
| Point source                 | 25  | 4                             |
| 4860 MHz radio continuum     | 28  | 2                             |
| G166.0+4.3                   | 91  | 2                             |

*a* Best-fitting radius and centroid position $0.6 \pm 0.1$, RA (J2000) = $12^\text{h} 09^\text{m}$, Dec. (J2000) = $-52^\circ 27'$ (at the 95 per cent confidence level).

2.2.2 Spectral analysis

A binned likelihood analysis is performed in the energy band 0.2–100 GeV for both sources using the best-fitting spatial templates found in Section 2.2.1. Using 10 energy bins per decade in the exposure map calculation and assuming power-law spectra, the resulting TS values for the sources G166.0+4.3 and G296.5+10.0 in this energy band are 136 and 36, corresponding to significances of roughly 11$\sigma$ and 5$\sigma$ over the background for two and five degrees of freedom, respectively.

In order to probe for curvature in the spectra, a log-parabola spectral shape, $dN/dE = N_0(E/E_0)^{-\alpha+e\log(E/E_0)}$, is tested in the fit for both sources, but no significance of a deviation from a power-law spectral distribution can be claimed for either. The best-fitting spectral parameters are summarized in Table 2.

The spectral indices are very different for both sources, G166.0+4.3 having a much steeper spectrum. No significant emission for this source is detected above 10 GeV. On the other hand, G296.5+10.0 would be among the dimmest gamma-ray emitting SNRs detected so far, with a luminosity of $(3.3 \pm 0.9) \times 10^{33}$ erg s$^{-1}$ (1–100 GeV), about three times that of the Cygnus Loop (Katagiri et al. 2011).

Gamma-ray SEDs for G166.0+4.3 and G296.5+10.0 are obtained with maximum likelihood fits for three logarithmically spaced energy intervals in the bands 0.2–8.3 and 0.2–100 GeV, respectively. If the significance of a detection within a bin is less than 3$\sigma$, an upper limit for the flux is derived. Several sources of systematic errors are considered for these bins: (a) the effect of changing the morphology of the emission as explained in Section 2.2.1; (b) the uncertainty of the Galactic diffuse emission, which is evaluated by artificially varying the best-fitting value of the normalization of the Galactic level by $\pm$6 per cent in each bin (as done by Abdo et al. 2009a); and (c) the systematic uncertainty in the effective area, which is energy dependent and given by 10 per cent at 100 MeV, 5 per cent at 560 MeV and 20 per cent at 10 GeV (Abdo et al. 2009a). Fig. 3 shows the broad-band SEDs and gamma-ray data.

**Table 2.** Best-fitting spectral parameters$^a$ (0.2–100 GeV).

| Source       | Spectral index | Integrated photon flux (cm$^{-2}$ s$^{-1}$) | TS  |
|--------------|----------------|--------------------------------------------|-----|
| G296.5+10.0  | 1.85 $\pm$ 0.13 | $(3.1 \pm 0.9) \times 10^{-9}$              | 36  |
| G166.0+4.3   | 2.7 $\pm$ 0.1   | $(1.84 \pm 0.18) \times 10^{-8}$           | 136 |

$^a$Assuming a power-law spectral shape. Only statistical errors are shown.
points with the resulting statistical and systematic errors added in quadrature.

3 EMISSION MODEL

The electron distributions used here are broken power laws of the form

$$N_e(\epsilon) = K \epsilon^{-s} \left(1 + \left(\frac{\epsilon}{\epsilon_{br}}\right)^2\right)^{-\delta}$$

extending up to a maximum energy $\epsilon_{max}$. The break ($\epsilon_{br}$) and maximum energy as well as the parameter $\delta$ are varied to fit the shape of the gamma-ray spectra. The proton distributions used to model the data are simple power laws, $N_p \propto \epsilon^{-s_p}$, based on the fact that the gamma-ray spectra of the sources are also power laws.

Instead of applying a model to follow the evolution of the SNRs and predict the break energies and magnetic field values, these parameters are derived under the assumption that the nature of the gamma-ray emission is either leptonic or hadronic; in other words, the necessary conditions that produce either outcome are explored. It is noted also that a full exploration of the parameters that reproduce the gamma-ray data is beyond the scope of this work and only a representative set of parameters is presented for each source.

The volume occupied by the particles is the volume of the SNR, and the supernova explosion energy is set to $E_{SNR} = 10^{51}$ erg. Gamma-ray emission mechanisms include IC of cosmic microwave background (CMB) photons, bremsstrahlung emission from electrons and neutral pion decay, which depend on the target material density, denoted as $n_{H}$ (cm$^{-3}$). For both SNRs, leptonic-dominated and hadronic-dominated scenarios are considered. The gamma-ray flux resulting from hadron interactions is calculated as in Kamae et al. (2006).

3.1 G296.5+10.0

As noted before, the spectral index of electrons is fixed from radio observations to $s = 2$. The remnant is approximated as a sphere of radius 0.7 (at a source distance of 2.1 kpc, this is equivalent to 26 pc).

3.1.1 Leptonic-dominated scenario

The gamma-ray emission can be accounted for by IC on the CMB, as shown in Fig. 3, with a ‘softening’ given by $\delta = 0.45$, an electron break energy $\epsilon_{br} \approx 100$ GeV, a magnetic field of 60 $\mu$G, a total electron energy of $5.5 \times 10^{48}$ erg and an ambient density of 0.05 cm$^{-3}$ or less. Although not shown, a bremsstrahlung-dominated scenario results with a magnetic field $B \approx 100$ $\mu$G, total electron energy $2.4 \times 10^{48}$ erg and ambient density 1 cm$^{-3}$. The maximum electron energy adopted is $\epsilon_{max} = 1.5$ TeV.

3.1.2 Hadronic-dominated scenario

Given the relatively low statistics of the observation and the high systematic errors at several hundreds of MeV, the gamma-ray index is not well constrained. If a standard power-law proton distribution is assumed with index $s_p = 2$, a total cosmic ray proton energy of $1.1 \times 10^{49} (n_{H}/1 \text{ cm}^{-3})^{-1}$ erg is needed to account for the high-energy SED. The proton energy spectrum shown in Fig. 4 extends from the pion production threshold to 250 GeV, although the Fermi LAT data are not inconsistent with higher proton energies, as there is no evidence for a spectral cutoff. The magnetic field is 240 $\mu$G in this case and the total electron energy is $6.6 \times 10^{47}$ erg, decreasing with increasing magnetic field.

3.2 G166.0+4.3

The spectral index of electrons, again from radio observations, is fixed at $s = 1.7$. The larger estimated distance and smaller angular extension of G166.0+4.3 compared to G296.5+10.0 yield, however, a similar intrinsic remnant size. The remnant is also approximated as a sphere of radius 26 pc.

3.2.1 Leptonic-dominated scenario

In the case that the emission is mainly from IC on the CMB, an electron spectral ‘softening’ given by the parameter $\delta = 0.5$, particle break energy and maximum energy of 50 and 500 GeV, respectively, are necessary. The magnetic field and total electron energy are $\approx 5$ $\mu$G and $8.7 \times 10^{49}$ erg, respectively. The value for the density
used for calculating the bremsstrahlung emission is $n_{\text{H}} = 0.1 \text{ cm}^{-3}$, although a value lower than this is probably more realistic, as X-ray observations show (Burrows & Guo 1994).

### 3.2.2 Hadronic-dominated scenario

The gamma-ray data require a steep cosmic ray proton spectrum (the photon spectral index is 2.7). Fig. 4 shows a scenario where the gamma-ray emission is accounted for by a power-law proton distribution with index $s_p = 2.7$. The magnetic field is $50 \mu$G and the total proton energy $(2.8^{+1.2}_{-1.5} \times 10^{46} (n_{\text{H}}/1 \text{ cm}^{-3})^{-1})$ erg, considering the uncertainty in the distance ($4.5 \pm 1.5$ kpc; Giacani et al. 2000). The maximum particle energy is not well constrained since the contribution from the highest energy particles is less important for such a steep distribution; the value used in Fig. 4 is $\approx 500 \text{ GeV}$.

Fig. 4 shows a scenario with $n_{\text{H}} = 1 \text{ cm}^{-3}$, a total proton energy of $\approx 30$ per cent of the available SNR energy, a total electron energy of $3.9 \times 10^{48} \text{ erg}$ and a bremsstrahlung flux calculated also with an ambient density $n_{\text{H}} = 1 \text{ cm}^{-3}$. Note that if instead a much lower ambient density is adopted as implied by X-ray observations ($n_{\text{H}} \sim 0.01 \text{ cm}^{-3}$; Burrows & Guo 1994), the gamma-ray observations require an unrealistically large total proton energy.

### 4 DISCUSSION AND CONCLUSIONS

Excess gamma-ray emission in the region of the SNRs G166.0+4.3 and G296.5+10.0 is revealed by an analysis of accumulated observations from the Fermi LAT. In the case of G166.0+4.3, a hypothesis for the emission from the radio shell and wing (325 MHz) is slightly preferred over the previously detected point source located in the shell. For SNR G296.5+10.0, extended gamma-ray morphology is also preferred over point source emission (see Table 1).

The gamma-ray spectra of the sources are very different. They can be described by simple power laws with no clear evidence of curvature. The spectrum of G166.0+4.3 is very steep (photonic index $2.7 \pm 0.1$, statistical errors only) while that of G296.5+10.0 (photonic index $1.85 \pm 0.13$, statistical errors only) is somewhat harder than that expected for a standard test-particle DSA spectrum with a power-law index of 2. The broad-band SEDs of both sources can be either of leptonic or hadronic origin.

The hadronic interpretation for the emission from G166.0+4.3 presents, however, some difficulties. The steep proton spectrum required to account for the gamma-ray SED is difficult to understand in the context of standard shock acceleration, and the ambient density required is much higher than that obtained from X-ray observations (Burrows & Guo 1994). The contradiction could be solved if the SNR interacts with irregular ISM with clumps of high-density material located in a low-density environment, as has been proposed for other SNRs (Castro & Slane 2010). It is believed, based on H I observations of the region, that the SNR has interacted with material in its environment (Landecker et al. 1989). However, it is unclear whether the density of the target material is enough to account for the flux and even if it was, it would still be difficult to explain the steep spectrum.

Another possibility is that the emission from G166.0+4.3 is leptonic. As shown in Fig. 3, the IC on the CMB level is enough to account for the Fermi LAT points with reasonable SNR parameters, and it is compatible with the low ambient density implied by X-ray observations, which affects the bremsstrahlung level only. In this scenario, the observed steep gamma-ray spectrum is produced mainly by the highest energy synchrotron-emitting electrons in the tail of the distribution, above a particle break of $\approx 50 \text{ GeV}$ according to the model. The leptonic emission scenario is compatible with the observed correspondence between the radio contours of the source and the gamma-ray maps, as seen in Fig. 2.

From these considerations, the leptonic emission scenario for the SED of G166.0+4.3 is found to be a more natural explanation. Future observations might allow performing a more detailed analysis considering different electron populations, perhaps disentangling the properties of particles in the wing and shell, as well as studying spatial variations of spectral parameters.

In the case of G296.0+10.0, the hypothesis of a uniform disc, containing most of the radio shell, of radius $0.6 \pm 0.1$ and centroid location RA (J2000) = $12^{h}09^{m}$, Dec. (J2000) = $-52^{\circ}27^{\prime}$ Galactic coordinates $(l, b) \sim (296.4, +9.88)$ was adopted here. However, the residuals in Fig. 1 suggest that the gamma-ray morphology might be more complicated than the scenarios explored here would imply.

At the highest energies, the peak of the signal-to-noise maps (see Fig. 1) is located to the east of the western radio contours, where synchrotron emission is also present (Gregory et al. 1996). This is interesting since both the X-ray and radio fluxes are highest in

![Figure 4. Hadronic emission model: (a) G296.5+10.0 and (b) G166.0+4.3. The emission components are: synchrotron (solid line), IC-CMB (dotted line), non-thermal bremsstrahlung (dashed line, shown only above $\approx 2 \times 10^{22} \text{ Hz}$) and hadronic emission from $\pi^0$ decay, from proton–proton interactions (dash–dotted line). The dark solid line represents the total gamma-ray emission. Blue squares are obtained from the LAT observation presented in this paper.](https://academic.oup.com/mnras/article-abstract/434/3/2202/1034726)
the eastern hemisphere. It is possible, in the context of a hadronic scenario, that at least part of the gamma-ray emission is produced by high-energy particles that interact with the dense \( n_H = 13 \text{ cm}^{-3} \) south-western cloud seen (Giacani et al. 2000) in contact with the shell, although there is another dense cloud also interacting with the shell in the east. The SED parameters derived for leptonic and hadronic scenarios are both physically reasonable.

The required mean density for a bremsstrahlung-dominated scenario for G296.5+10.0 \( (n_H = 1 \text{ cm}^{-3}) \) might be in conflict with previous observations \((0.24 \text{ and } 0.08 \text{ cm}^{-3}); \) Kellett et al. 1987; Matsui, Long & Tuohy 1988, respectively). Roger et al. (1988) argue that this SNR is in the adiabatic (Sedov–Taylor) phase of evolution which is consistent with the remnant size, the observed low ambient density and thus an IC origin for the gamma-ray emission. Furthermore, the particle break and magnetic field required by the gamma-ray data \((\lesssim 100 \text{ GeV}) \) are consistent with a synchrotron cooling break (see, e.g., Tanaka et al. 2008) and a reasonable SNR age \((\sim 10^4 \text{ yr}); \) Vasisht et al. 1997). If the emission from this SNR is mainly leptonic, an IC origin seems then more plausible than a bremsstrahlung origin.

ACKNOWLEDGEMENTS

This research has made use of NASA’s Astrophysical Data System and of the SIMBAD data base, data from the WENSS team (Rengelink et al. 1997) and from the NRAO. Financial support from Universidad de Costa Rica is acknowledged. Valuable observations and of the SIMBAD data base, data from the WENSS team (Rengelink et al. 1997) and from the NRAO. Financial support from Universidad de Costa Rica is acknowledged. Valuable observations from the anonymous referee helped improve the quality of this work substantially.

REFERENCES

Abdo A. A. et al., 2009a, Phys. Rev. Lett., 103, 251101
Abdo A. A. et al., 2009b, ApJ, 706, L1
Abdo A. A. et al., 2010a, ApJ, 710, L92
Abdo A. A. et al., 2010b, ApJ, 718, 348
Abdo A. A. et al., 2010c, ApJ, 722, L1303
Abdo A. A. et al., 2011, ApJ, 734, 28
Ackermann M. et al., 2013, Sci, 339, 807
Ajello M. et al., 2012, ApJ, 744, 80
Araya M., Cui W., 2010, ApJ, 720, 20
Atwood W. B. et al. (Fermi LAT Collaboration), 2009, ApJ, 697, 1071
Bell A. R., 1978, MNRAS, 182, 147
Berezhko E. G., Völk H. J., 2004, A&A, 419, L27
Berezhko E. G., Ksenofontov L. T., Völk H. J., 2002, A&A, 395, 943
Blanford R. D., Eichler D., 1987, Phys. Rep., 154, 1
Burrows D. N., Guo Z., 1994, ApJ, 421, L19
Caprioli D., 2012, J. Cosmol. Astropart. Phys., 07, 038
Castro D., Slane P., 2010, ApJ, 717, 372
Gaisser T. K., Protheroe R. J., Stanev T., 1998, ApJ, 492, 219
Giacani E. B., Dubner G. M., Green A. J., Goss W. M., Gaensler B. M., 2000, ApJ, 119, 281
Giordano F. et al., 2012, ApJ, 744, L2
Gottlieb E. V., Koralessky B., Rudnick L., Jones T. W., Hwang U., Petre R., 2001, ApJ, 552, L39
Gregory P. C., Scott W. K., Douglas K., Condon J. J., 1996, ApJS, 103, 427
Healey S. E., Romani R. W., Taylor G. B., Sadler E. M., Ricci R., Murphy T., Ulvestad J. S., Winn J. N., 2007, ApJS, 171, 61
Hwang U., Decourchelle A., Holt S. S., Petre R., 2002, ApJ, 581, 1101
Kamae T., Karlsson N., Mizuno T., Abe T., Koi T., 2006, ApJ, 647, 692
Katagiri H. et al., 2011, ApJ, 741, 44
Kellett B. J., Bransard-Raymont G., Culhane J. L., Mason I. M., Mason K. O., Whitehouse D. R., 1987, MNRAS, 225, 199
Kesteven M. J., Caswell J. L., 1987, A&A, 183, 118
Landecker T. L., Pineault S., Routledge D., Vaneldik J. F., 1989, MNRAS, 237, 277
Lande J. et al., 2012, ApJ, 756, L5
Leahy D., Tian W., 2005, A&A, 440, 929
Leahy D., Tian W., 2006, A&A, 451, 991
Long K. S., Reynolds S. P., Raymond J. C., Winkler F. P., Dyer K. K., Petre R., 2003, ApJ, 586, 1162
Matsui Y., Long K. S., Tuohy I. R., 1988, in Roger R. S., Landecker T. L., eds, Proc. IAU Colloq. 101, Supernova Remnants and the Interstellar Medium. Cambridge Univ. Press, Cambridge, p. 157
Mattson J. R. et al., 1996, ApJ, 461, 396
Milne D. K., Haynes R. F., 1994, MNRAS, 270, 106
Nolan P. L. et al., 2012, ApJS, 199, 31
Pineault S., Pritchett C. J., Landecker T. L., Routledge D., Vaneldik J. F., 1985, A&A, 151, 52
Protassov R., van Dyk D. A., Connors A., Kashyap V. L., Siemiginowska A., 2002, ApJ, 571, 545
Rengelink R. B., Tang Y., de Bruyn A. G., Miley G. K., Bremer M. N., Roettgering H. J. A., Bremer M. A. R., 1997, A&A, 424, 259
Rho J., Dyer K. K., Borkowski K. J., Reynolds S. P., 2002, ApJ, 581, 1116
Roger R. S., Milne D. K., Kesteven M. J., Wellington K. J., Haynes R. F., 1988, ApJ, 332, 940
Schure K. M., Bell A. R., Drury L. O’C., Bykov A. M., 2012, Space Sci. Rev., 173, 491
Takahashi T. et al., 2008, ApJ, 685, 988
Tanaka T. et al., 2011, ApJ, 740, L51
Vasisht G., Kulkarni S. R., Anderson S. B., Hamilton T. T., 1997, ApJ, 476, L43
Vink J., Laming J. M., 2003, ApJ, 584, 758
Zavlin V. E., Pavlov G. G., Sanwal D., Trümper J., 2000, ApJ, 540, L25

This paper has been typeset from a \TeX file prepared by the author.