ABSTRACT

We present the analysis of Fermi Large Area Telescope γ-ray observations of HB 21 (G89.0+4.7). We detect significant γ-ray emission associated with the remnant: the flux >100 MeV is 9.4 ± 0.8 (stat) ± 1.6 (syst) × 10^{-11} erg cm^{-2} s^{-1}. HB 21 is well modeled by a uniform disk centered at l = 88:75 ± 0:04, b = +4:65 ± 0:06 with a radius of 1:19 ± 0:06. The γ-ray spectrum shows clear evidence of curvature, suggesting a cutoff or break in the underlying particle population at an energy of a few GeV. We complement γ-ray observations with the analysis of the WMAP 7 yr data from 23 to 93 GHz, achieving the first detection of HB 21 at these frequencies. In combination with archival radio data, the radio spectrum shows a spectral break, which helps to constrain the relativistic electron spectrum and, in turn, parameters of simple non-thermal radiation models. In one-zone models multwavelength data favor the origin of γ rays from nucleon-nucleon collisions. A single population of electrons cannot produce both γ rays through bremsstrahlung and radio emission through synchrotron radiation. A predominantly inverse-Compton origin of the γ-ray emission is disfavored because it requires lower interstellar densities than are inferred for HB 21. In the hadronic-dominated scenarios, accelerated nuclei contribute a total energy of ∼3 × 10^{49} erg, while, in a two-zone bremsstrahlung-dominated scenario, the total energy in accelerated particles is ∼1 × 10^{49} erg.

Key words: acceleration of particles – cosmic rays – ISM: individual objects (HB 21) – radiation mechanisms: non-thermal

Online-only material: color figures

1. INTRODUCTION

It is strongly believed that diffusive shock acceleration in supernova remnants (SNRs) is the mechanism responsible for the acceleration of Galactic cosmic rays (CRs; e.g., Drury 2012). High-energy emission from SNRs is a powerful probe of this process (Reynolds 2008). In particular, high-energy γ-ray emission can pinpoint the presence of energetic leptons or ions, constraining the acceleration efficiency and the maximum energy of accelerated particles (e.g., Aharonian et al. 2007; Abdo et al. 2011; Acctari et al. 2011; Giordano et al. 2012).

SNRs interacting with dense molecular clouds are expected to be bright γ-ray sources (e.g., Hewitt et al. 2009). Archetypal remnants of this class are IC 443 and W44, for which GeV- and, for the former, TeV-energy γ-ray emission are observed and interpreted as the signature of collisions between accelerated nuclei and interstellar matter (Abdo et al. 2010b, 2010c; Albert et al. 2007), as recently confirmed by the detection of the characteristic spectral feature of γ-rays produced from the decay of neutral pions (Giuliani et al. 2011; Ackermann et al. 2013a).

Both sources belong to a class of objects known as mixed-morphology (MM) SNRs, where an outer shell revealed by non-thermal radio emission surrounds a central region filled by thermal gas emitting in X-rays (Rho & Petre 1998). There is a strong association between MM SNRs and evidence for interactions between shock fronts and dense clouds revealed by OH masers (Yusef-Zadeh et al. 2003). Therefore, MM SNRs are good candidates to be bright γ-ray sources. In addition to W44 and IC 443, other members of this class are known to be GeV γ-ray emitters: W28 (Abdo et al. 2010a), W49B (Abdo et al. 2010b), W51C (Abdo et al. 2009b), and 3C 391 (Castro & Slane 2010).

HB 21 (also known as G89.0+4.7, Green 2009) is an MM SNR interacting with molecular clouds. Evidence for interaction comes from several different wavelengths. X-ray observations with Einstein provide evidence that the SN explosion took place in a low-density cavity, therefore suggesting a massive stellar progenitor (Knoedlseder et al. 1996). HB 21 has a radio shape with bright filaments and indentations suggesting interactions with the nearby clouds (Byun et al. 2006). Looking at the CO distribution, it is possible to distinguish two different structures based on the velocity of the molecular clouds. Koo & Heiles (1991) report the presence of broad CO lines emitted from shocked clumps of molecular gas with high column densities. Infrared line observations (Shinn et al. 2009) reveal an infrared spectrum from H2 gas with a mixture of temperatures, indicating shocks propagating in a multi-phase medium, typical of molecular clouds.

The distance to HB 21 was first estimated to be 0.8 kpc, on the basis of an association with the Cygnus OB7 complex and
ROSAT observations of X-ray absorption (Leahy & Aschenbach 1996). Considering the preshock velocities, the X-ray absorbing column density, the H I and CO distribution along the line of sight, and the highly polarized emission, the distance was later determined to be ∼1.7 kpc (Byun et al. 2006). In this work, we adopt the later, revised distance.

The age of the SNR is also uncertain. Lazendic & Slane (2006) determine an age of ∼5600 yr by fitting evolutionary models to the thermal X-ray spectrum of the SNR. However, this results from assuming that the SNR is located at 0.8 kpc, and still in the adiabatic phase. Kinematics of the H I shell velocity of 124 km s$^{-1}$ indicates a much older age for the remnant of 4.5 × 10$^4$ yr (Koo & Heiles 1991). This gives evidence, we argue that HB 21 is a middle-aged SNR, at an age of a few tens of thousands of years, similar to other SNRs interacting with molecular clouds detected by Fermi Large Area Telescope (LAT).

High-energy γ-ray sources coincident with HB 21 were reported in the 2 yr Catalog of the LAT on board the Fermi Gamma-ray Space Telescope (Nolan et al. 2012). Three sources are associated with the remnant (2FGL J2043.3+5105, J2046.0+4954, and J2041.5+5003) and an additional source is present on the edge of the SNR (2FGL J2051.8+5054): we will investigate if it is part of the emission of the remnant or it is a source itself. Reichardt et al. (2012) recently reported an analysis of 3.5 yr of Fermi LAT data toward HB 21, finding evidence for extended emission and a softer spectrum in the direction of a shocked cloud in the northwestern region of the remnant.

Because of the large apparent size (∼2′), this object is well suited for a detailed morphological study using Fermi LAT data. Therefore, it is ideal to further assess the correlation between cloud-interacting shocks and γ-ray emission as a tracer of particle acceleration in MM SNRs, as well as to investigate the possible spectral variations that could shed light on the poorly known processes of particle escape from the shocks (e.g., Gabici et al. 2009).

In this paper, we present the analysis of ∼4 yr of LAT observations of HB 21 and discuss the γ-ray emission mechanism through examining new analysis of WMAP 7 yr data and using archival radio data. In Section 2, we describe the γ-ray observations and the morphological and spectral characterization of the γ-ray emission from HB 21. In Section 3, we present the analysis of the Wilkinson Microwave Anisotropy Probe (WMAP) and archival radio data, which reveal a break in the high-frequency radio spectrum. In Section 4, the interpretation of these results is discussed.

2. GAMMA-RAY ANALYSIS

2.1. Observations

The Fermi LAT is a pair-conversion γ-ray telescope detecting photons from 20 MeV to >300 GeV (Atwood et al. 2009). Its on-orbit calibration is described in Abdo et al. (2009a) and Ackermann et al. (2012a) along with the event classification and instrument performance.

For this analysis, data are accumulated from the beginning of scientific operations on 2008 August 4 to 2012 June 14, selecting the low-background P7SOURCE event class. The data analysis was performed using the LAT Science Tools package (v9r27p1), available from the Fermi Science Support Center. For the morphological characterization, we use only events with energy >1 GeV to profit from the narrower point-spread function (PSF) to separate the γ-ray emission associated with HB 21 from neighboring sources and interstellar emission. We then use events down to 100 MeV to determine the spectral energy distribution (SED) of the remnant. Below this energy, the PSF becomes much broader than the SNR and the uncertainties related to the instrument response are larger. In both the morphological and spectral characterization, we consider photons with measured energies up to 300 GeV, but only find a significant detection of the source up to energies of several GeV as a result of the limited number of events at high energies.

We perform the analysis in a 10° × 10° region of interest (RoI) centered at the radio position of HB 21 (l = 89°0, b = +4°7). The RoI approximately corresponds to the 68% event containment region for the P7SOURCE events at 100 MeV and exceeds the 95% event containment region for energies ≳700 MeV. We adopted this narrower than usual RoI to limit the lowest energies the large uncertainties due to the modeling of the bright interstellar emission from the nearby Cygnus region (Ackermann et al. 2011, 2012b). We also exclude few time intervals when the LAT boresight was rocked with respect to the local zenith by more than 52° (mostly for calibration purposes or to point at specific sources) and events with a reconstructed angle with respect to the local zenith >100° to limit the contribution from the Earth’s atmospheric γ-ray emission. To take into account the latter selection criterion in the calculation of the exposure, we exclude time intervals when any part of the RoI was observed at zenith angles >100°.

2.2. Background Model and Analysis Method

The background is composed of diffuse emission and individual nearby γ-ray sources. Diffuse emission is taken into account using the standard models provided by the Fermi LAT collaboration for the P7SOURCE selection (see Nolan et al. 2012). They include a model that accounts for the Galactic interstellar emission from CR interactions with interstellar gas and low-energy radiation fields, and an isotropic background spectrum that accounts for diffuse γ-ray emission of extragalactic origin and residual background events due to charged particle interactions in the LAT misclassified as γ-rays. We leave the normalization of the Galactic interstellar model as a free parameter, yet fix the isotropic background spectrum because it is difficult to separate it from the other components in such a small RoI and it is more reliably determined over larger regions of the sky.

We include, in the background model, all the point sources present in the 2FGL catalog (Nolan et al. 2012) with distances less than 15° from the RoI center and that are not associated with the SNR. We discuss, in Section 2.4, the case of the source 2FGL J2051.8+5054, which is located at the edge of the SNR. The spectral models used for background sources are those reported in the 2FGL catalog. Fluxes and spectral indices are left as free parameters in the fit if the source is within the RoI. Otherwise they are fixed to the catalog values.

12 http://fermi.gsfc.nasa.gov/ssc
13 http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html
The background model and the various models for HB 21 are fitted to the LAT data using a binned maximum-likelihood method based on Poisson statistics (e.g., Mattox et al. 1996), as implemented in the \textit{gtlike} tool. For this purpose, data were binned on an angular grid with 0:1 spacing, and different binning in energy as detailed below. The analysis uses the post-launch instrument response functions (IRFs) \texttt{P7SOURCE\_V6} (Ackermann et al. 2012a).

Finally, the radio pulsar J2047+5029 is 0:5 away from the remnant’s radio center (Janssen et al. 2009). While pulsars represent the largest Galactic $\gamma$-ray source class, this particular pulsar likely contributes no detectable flux to the RoI. The spin-down power is $E \sim 2 \times 10^{33}$ erg s$^{-1}$, lower than that of any known $\gamma$-ray pulsar, and three times lower than for any young, radio-loud $\gamma$-ray pulsar (Abdo et al. 2013). That is, the pulsar is probably below the “deathline” expected from the outer magnetospheric emission models that best describe the LAT pulsars (Wang & Hirotani 2011). Further, the pulsar’s dispersion measure indicates a distance $D = 4.4$ kpc. The ratio $\sqrt{\sigma^2/D^2} = 2.3 \times 10^{-5}$ erg$^{1/2}$ kpc$^{-5}$ (a proxy of the expected $\gamma$-ray luminosity) is five times lower than for any known $\gamma$-ray pulsar (see Figure 15 in Abdo et al. 2013). The 2 yr LAT catalog shows no point source at the pulsar position (Nolan et al. 2012), nor does the 4 yr catalog currently in preparation. Nevertheless, we searched PSR J2047+5029 for $\gamma$-ray pulsations. It is not part of \textit{Fermi}’s pulsar timing campaign (Smith et al. 2008), so we obtained a timing solution based on Westerbork Synthesis Radio Telescope and Jodrell Bank radio data taken concurrently with the \textit{Fermi} data.\textsuperscript{14} The ephemeres will be presented in future work (G. H. Janssen et al., in preparation). We used the timing solution to phase-fold the LAT data, over a grid of minimum energy cuts (100–1000 MeV, in 50 MeV steps) and maximum radius cuts to phase-fold the LAT data, over a grid of minimum energy cuts (100–1000 MeV, in 50 MeV steps) and maximum radius cuts (from 0:4 to 2:0 from the pulsar position, in 0:1 steps). For pulsars with unknown $\gamma$-ray spectral shapes and unknown pulse profile shapes, such grids amount to a search for the maximum pulsar signal-to-background ratio. At each grid location, we calculated the H-test, which never exceeded 3$\sigma$ statistical significance (see Section 5 in Abdo et al. 2013). The pulsar’s energy flux above 100 MeV is, therefore, lower than for any known $\gamma$-ray pulsar, that is, below $2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. We conclude that the pulsar can be neglected when characterizing $\gamma$-ray emission from HB 21.

2.3. Systematic Uncertainties

Two major sources of systematic errors on the results are the uncertainties in the LAT effective area and the modeling of interstellar emission. The uncertainties in the effective area for the IRFs we use are evaluated as 10% at 100 MeV, 5% at 516 MeV, and 10% above 10 GeV, linearly varying with the logarithm of energy between those values (Ackermann et al. 2012a). We estimate the error in the characterization of the $\gamma$-ray fluxes of HB 21 by repeating the analysis with two sets of modified IRFs, where the effective area was upscaled or downscaled by its uncertainty. This approach neglects errors introduced by possibly more complicated variations of the effective area and, therefore, does not capture uncertainties in the spectral shape of the source. However, this is sufficient for our purpose since, as discussed in Section 2.5, for HB 21 systematic uncertainties are dominated by the modeling of interstellar emission.

To gauge the systematic uncertainties as a result of the interstellar emission model, we compare the results obtained using the standard model in Section 2.2 with the results based on eight alternative interstellar emission models. The alternative emission models are based on a subsample of those examined by Ackermann et al. (2012c). We varied some of the most important parameters of the interstellar emission models, namely the uniform spin temperature used to estimate the column densities of interstellar atomic hydrogen (150 K and $10^5$ K, the latter being equivalent to the small optical depth approximation), the vertical height of the CR propagation halo (4 kpc and 10 kpc), the CR source distribution in the Galaxy (the pulsar distribution by Lorimer et al. 2006, and the SNR distribution by Case & Bhattacharya 1998\textsuperscript{15}). In this way, we built a grid of eight alternative interstellar emission models. We refer the reader to Ackermann et al. (2012c) for further details about the modeling strategy and multimeter/multiwavelength constraints on these parameters.

Each of these models was fitted to the whole-sky \texttt{P7SOURCE} data in the energy range between 100 MeV and 300 GeV using the maximum likelihood method described in Ackermann et al. (2012c). We determine independent log-parabolic renormalization functions separately for the inverse-Compton (IC) component and the components associated with atomic hydrogen and molecular hydrogen (traced by CO), split along the line of sight into four broad Galactocentric annuli between 0–4 kpc, 4–8 kpc, 8–10 kpc (the local annulus), and 10–30 kpc.

The eight resulting models were used to repeat the source analysis described in Section 2.4, for the determination of the disk dimension, and Section 2.5 for the spectral analysis of the source. In each of the iterations, we replaced the standard isotropic background and Galactic interstellar emission models with the alternative isotropic background spectra and Galactic interstellar emission templates, independently for the sub-components described above (for the line of sight of HB 21, only the two outermost Galactocentric annuli are relevant). For the same reasons as for the standard model, we fix the isotropic background spectrum. We leave free the normalization parameters of the interstellar model components in the third and fourth ring, and of the IC component. Through this procedure, we explored the impact of adopting a different model-construction strategy, of varying the model parameters and of allowing more freedom in the fit. We stress that we explored only some of the uncertainties related to the modeling of interstellar emission, but we are nevertheless able to obtain an indication about some important systematic effects. A more thorough discussion on this method for exploring the systematic uncertainties due to the modeling of diffuse emission is available in de Palma et al. (2013).

2.4. Morphological Analysis

In Figure 1(a), we show a count map of the RoI for energies $>1$ GeV, to visually illustrate the morphology of the $\gamma$-ray emission in the region. We consider different spatial models for the emission from HB 21, summarized in Table 1. For each model we evaluate the test statistic

$$TS = 2(\ln \mathcal{L}_1 - \ln \mathcal{L}_0),$$

(1)

where $\mathcal{L}_1$ is the maximum-likelihood value for the model including the remnant and $\mathcal{L}_0$ is the maximum-likelihood value

\textsuperscript{15} The validity of the Case & Bhattacharya (1998) $\sigma$–$D$ relation has been criticized: it is used in Ackermann et al. (2012c) as an alternative to probe the effect of changing the CR distribution.
We determine the position and extension of the $\gamma$-ray emission associated to HB 21, considering separately 2FGL J2051.8+5054 in the model or removed. In the first case, we obtain the best-fit parameters: $l = 88^\circ.62 \pm 0.05, b = 4^\circ.79 \pm 0.06$, and $r = 1^\circ.14 \pm 0.07$. In the second, we have $l = 88^\circ.75 \pm 0.04, b = 4^\circ.65 \pm 0.06$, and $r = 1^\circ.19 \pm 0.06$. Errors reflect statistical uncertainties only. The TS for the case, including separately 2FGL J2051.8+5054 in the model, is larger by 14 than the case with the disk only (Table 1). The significance of the separate source hypothesis is below the threshold usually required to claim a detection for LAT sources (TS > 25). Deeper observations are needed to determine if 2FGL J2051.8+5054 can be distinguished as a source independent from the remnant. In the rest of the paper, we do not consider 2FGL J2051.8+5054 as a separate source and, therefore, we remove it from the model. The results concerning the morphology of HB 21 are robust regardless of whether 2FGL J2051.8+5054 is included as a separate source in the model or not. Using the best-fit disk, the significance of the detection of HB 21 is $\sim 29\sigma$. We also check whether the source size changes with energy by separately fitting a disk to the LAT data from 1 to 10 GeV with color scale in counts pixel$^{-1}$.

(A color version of this figure is available in the online journal.)

Table 1

| Sources                  | TS  | dof |
|--------------------------|-----|-----|
| Null hypothesis          | 0   | 0   |
| Four-point sources       | 256 | 10  |
| Disk                     | 302 | 5   |
| disk + 2FGL J2051.8+5054 | 316 | 7   |
| X-ray image              | 212 | 2   |
| X-ray image+ 2FGL J2051.8+5054 | 234 | 4   |
| Radio image              | 298 | 2   |
| Radio image+ 2FGL J2051.8+5054 | 312 | 4   |

for the model not including it (null hypothesis). If the null hypothesis is verified (no $\gamma$-ray emission associated to HB 21), TS is expected to be distributed as a $\chi^2$ with a number of degrees of freedom given by the additional number of free parameters in the model including the source, with the caveats discussed in Protassov et al. (2002). We model the source as a disk with a power-law spectrum and we determine the position of its center ($l, b$) and radius $r$, along with flux and spectral index from LAT data, using an energy binning of eight bins per decade. We considered both the cases where 2FGL J2051.8+5054 is included as a separate point source in the model or removed. In the first case, we obtain the best-fit parameters: $l = 88^\circ.62 \pm 0.05, b = 4^\circ.79 \pm 0.06$, and $r = 1^\circ.14 \pm 0.07$. In the second, we have $l = 88^\circ.75 \pm 0.04, b = 4^\circ.65 \pm 0.06$, and $r = 1^\circ.19 \pm 0.06$. Errors reflect statistical uncertainties only. The TS for the case, including separately 2FGL J2051.8+5054 in the model, is larger by 14 than the case with the disk only (Table 1). The significance of the separate source hypothesis is below the threshold usually required to claim a detection for LAT sources (TS > 25). Deeper observations are needed to determine if 2FGL J2051.8+5054 can be distinguished as a source independent from the remnant. In the rest of the paper, we do not consider 2FGL J2051.8+5054 as a separate source and, therefore, we remove it from the model. The results concerning the morphology of HB 21 are robust regardless of whether 2FGL J2051.8+5054 is included as a separate source in the model or not. Using the best-fit disk, the significance of the detection of HB 21 is $\sim 29\sigma$. We also check whether the source size changes with energy by separately fitting a disk to the LAT data from 1 to 10 GeV with color scale in counts pixel$^{-1}$.

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3 GeV and from 3 to 10 GeV. We obtain $r = 1\,^\circ\,19 \pm 0\,^\circ\,09$ in the lower-energy range and $r = 1\,^\circ\,24 \pm 0\,^\circ\,09$ in the higher-energy range. No significant change in size with energy is detected.

In Figure 1(b), we show the background model map obtained from the fit with the disk, and in Figure 1(c) the background-subtracted count map where the emission associated with HB 21 is visible. If we compare the TS with the model in which HB 21 is modeled by the four point sources in the 2FGL Catalog (Table 1), we find that the extended source provides a higher likelihood for a lower number of free parameters in the fit. Therefore, we conclude that the hypothesis of extended emission is preferred over four individual point sources.

We then calculate the systematic uncertainties related to interstellar emission using the alternative models as described in Section 2.3. When the alternative interstellar emission models are used, the $\gamma$-ray disk is systematically shifted toward the northwest part, with respect to the radio shell (with shifts in longitude between $0\,^\circ\,19$ and $0\,^\circ\,24$, and in latitude between $0\,^\circ\,06$ and $0\,^\circ\,09$), and the disk radius is systematically smaller by $0\,^\circ\,18$–$0\,^\circ\,24$, but the significance of the detection of HB 21 does not change sizably. This effect is mainly the result of the different approaches used to deal with the dark gas, neutral interstellar gas, which is not well traced by the linear combination of column densities inferred from the $21\,cm$ H$^1$ line and the $2.6\,mm$ CO line, but which is traced by correlated residuals in dust emission/absorption and interstellar $\gamma$-ray emission (Grenier et al. 2005). Dust residuals are used as a dark-gas template fitted to the $\gamma$-ray data in the standard interstellar model, whereas they are used to correct the H$^1$ column densities in the alternative models, assuming a dust-to-gas ratio independent from $\gamma$-ray observations. This leads to different estimates of the gas column densities and, therefore, to different structures in the interstellar emission models. Additionally, the standard model accounts for enhanced interstellar emission toward the nearby Cygnus X complex (see Ackermann et al. 2011, 2012b), whereas the alternative models do not. These differences are found to have a significant impact on the determination of the SNR morphology. For all the alternative models, the disk extends beyond the rim of the remnant in coincidence with the western molecular cloud, but leave the faint southeast edge of the radio shell off.

In Figure 2, we compare the $\gamma$-ray emission associated with HB 21 with emission from the remnant at other wavelengths. Figure 2(a) compares the $\gamma$-ray image with radio emission at $6\,cm$ tracing non-thermal electrons (see later Section 3). Figure 2(b) compares the $\gamma$-ray morphology with X-ray emission from the thermal plasma filling the center of the remnant, measured by ROSAT (Voges et al. 1999). The ROSAT image was cleaned using the standard background maps. Finally, Figure 2(c) compares the $\gamma$-ray emitting region with the distribution of molecular material. Molecular column densities in the Local-arm region are traced by the CO line intensities at $2.6\,mm$ (Dame et al. 2001; Dame & Thaddeus 2011) integrated over velocities with respect to the local standard of rest within $\pm20\,km\,s^{-1}$. We also show the positions of shocked CO clumps and of two large CO clouds distributed along the boundary of the radio shell (Koo & Heiles 1991). The $\gamma$-ray emission associated with HB 21 is broader than the central region filled by thermal X-ray emitting plasma. It compares well with the radio shell, but appears to extend beyond the radio shell in regions where molecular clouds are present. The brightest $\gamma$-ray regions coincide with the southern shocked CO clumps identified by Koo & Heiles (1991). This correlation with CO suggests that at least part of the $\gamma$-ray emission from HB 21 may be produced by accelerated particles colliding with dense interstellar matter.

To quantitatively assess the correlation between $\gamma$-ray, X-ray, and radio emission from HB 21, we use the X-ray and radio images as templates in the $\gamma$-ray analysis. For both templates we compare the cases when 2FGL J2051.8+5054 is included in the fit as a background source or not. All the spatial templates are fitted with a power-law spectrum. From the results reported in Table 1, we confirm that the morphology of the remnant in $\gamma$-rays significantly differs, as expected, from the emission in X-rays. Both the radio template and the $\gamma$-ray disk provide a good fit to the data, though the first has less degrees of freedom, as shown in Table 1. Since the two models are not nested, it is not possible to conclude which is the best one. Given that the disk model provides the largest TS of all single source models, and is derived from the $\gamma$-ray data, we use this model to compute the spectrum of the remnant.

2.5. Spectral Analysis

The SED of HB 21 is determined over the full energy range between 100 MeV and 300 GeV (using 35 logarithmic energy bins for the likelihood analysis) by modeling the remnant with the best-fit disk. We compare the hypotheses of a power law

$$\frac{dN}{dE} = N_0 \left( \frac{E}{100\,MeV} \right)^{-\Gamma}$$

with three different curved spectral models to quantify deviations from the former. The three functional forms are as follows.

1. Log-parabola.

$$\frac{dN}{dE} = N_0 \left( \frac{E}{100\,MeV} \right)^{-\alpha \beta \ln(E/1000\,MeV)}$$

2. smooth broken power law

$$\frac{dN}{dE} = N_0 \left( \frac{E}{100} \right)^{-\Gamma_1} \left( 1 + \left( \frac{E}{E_b} \right)^{(\Gamma_2 - \Gamma_1)/0.2} \right)^{-0.2}$$

3. power law with exponential cutoff

$$\frac{dN}{dE} = N_0 \left( \frac{E}{200\,MeV} \right)^{-\Gamma} \exp\left( -\frac{E}{E_c} \right)$$

where $E_c$ is the cutoff energy.

In Table 2 we report the TS values and the additional degrees of freedom for the curved spectral models compared with the power law. All the curved models have a higher TS than the power-law distribution. For the following discussion we adopt the log-parabola because it yields the largest improvement with respect to the simple power law, with a $\Delta$TS = 92, corresponding to an improvement at a $\sim9\sigma$ significance level in the energy range from 100 MeV to 300 GeV. The total $\gamma$-ray energy flux from HB 21 results to be $9.4 \pm 0.8$ (stat) $\pm 1.6$ (syst) $\times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ and the photon flux 1.48 $\pm 0.2$ (stat)$\pm0.4$ (syst) $\times 10^{-7}$ ph cm$^{-2}$ s$^{-1}$. The systematic errors shown in this section are calculated as described in Section 2.3.
Figure 2. Emission associated with HB 21 (Figure 1(c)) overlaid with contours from emission at other wavelengths (see text for details): (a) radio emission intensity at 6 cm with a beam size of 0.16, smoothed with a Gaussian kernel with $\sigma = 0.2$. The seven contour levels are linearly spaced from 0 to 2.0 Jy beam$^{-1}$. (b) Background-subtracted X-ray emission (ROSAT) smoothed with a Gaussian kernel of $\sigma = 0.25$. The three contour levels are linearly spaced from $0.36 \times 10^{-3}$ to $2.13 \times 10^{-3}$ counts s$^{-1}$ arcmin$^{-2}$. (c) Intensities of the 2.6 mm CO line in the Local-arm region. The six contour levels are linearly spaced from 1.5 K km s$^{-1}$ to 28 K km s$^{-1}$. We also show the positions of the shocked CO clumps (diamonds) and clouds A and B (squares) given in Koo & Heiles (1991).

(A color version of this figure is available in the online journal.)

Table 2

| Spectrum Shape          | $\Delta$TS | Additional dof | Fit Parameters                  |
|------------------------|------------|----------------|---------------------------------|
| Power law              | 0          | 0              | $\gamma = 2.33 \pm 0.03$        |
| log-parabola           | 92         | 1              | $\alpha = 2.54 \pm 0.05$, $\beta = 0.39 \pm 0.04$ |
| Smooth broken power law| 41         | 2              | $\gamma_1 = 1.67 \pm 0.02$, $\gamma_2 = 3.54 \pm 0.05$, $E_b = 789 \pm 65$ MeV |
| Power law with exponential cutoff | 82 | 1 | $\gamma_1 = 1.42 \pm 0.03$, $E_c = 958 \pm 41$ MeV |

Note. For each model, we report the values of the best-fit parameters.

and by extracting the root mean square of the variations with respect to the values from the standard model.

We also computed the SED in a model-independent way by splitting the energy range between 0.1 MeV and 60 GeV in 12 logarithmically spaced bins. The model is the same as described above, but, in each narrow energy bin, we leave free only the overall fluxes; other spectral parameters are fixed to the 2FGL values for background sources and to a power-law index of 2 for HB 21 (the results are insensitive to this particular choice). When $\Delta$TS for an individual bin is < 9, we calculate an upper limit at the 95% confidence level determined through the likelihood profile method.

We show the resulting SED in Figure 3 also with systematic errors indicated. Systematic errors as a result of using the interstellar emission model are then summed in quadrature with the error due to the LAT effective area uncertainties (Section 2.3) for display. The SED points are reported in Table 3. The contributions due to the modeling of interstellar emission and the LAT effective area are presented separately. In the energy range considered, the systematic errors are driven by the interstellar emission model.

2.6. Search for Spectral Variations across the Remnant

HB 21 is an extended source, located in an area rich in interstellar matter. The interaction with nearby molecular clouds (Byun et al. 2006) might cause spectral variation across the SNR,
Table 3
Table 3. SED of γ-ray Emission from HB 21

| Energy Bin Center (MeV) | $E^2dN/dE$ (eV cm$^{-2}$ s$^{-1}$) | Statistical (eV cm$^{-2}$ s$^{-1}$) | IEM (eV cm$^{-2}$ s$^{-1}$) | EA (eV cm$^{-2}$ s$^{-1}$) | Total Syst. (eV cm$^{-2}$ s$^{-1}$) |
|-------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 135                     | 12.8            | ±1.1            | ±4.1            | ±1.2            | ±4.3            |
| 250                     | 21.3            | ±0.8            | ±4.3            | ±1.8            | ±4.7            |
| 393                     | 37.5            | ±1.9            | ±3.8            | ±1.6            | ±4.1            |
| 670                     | 22.5            | ±4.6            | ±1.1            | ±4.8            |
| 1143                    | 18.3            | ±2.7            | ±0.9            | ±2.9            |
| 1950                    | 13.1            | ±1.4            | ±0.7            | ±1.6            |
| 3327                    | 7.9             | ±1.5            | ±0.5            | ±1.6            |

Notes. For each SED point we report the systematic uncertainties separately for those related to interstellar emission modeling (IEM) and LAT effective area (EA), as well as the overall uncertainty obtained by summing them in quadrature.

Table 4
Table 4. Likelihood Values and Spectral Indices for the Models Described in Section 2.6, Splitting the Single Best-fit Disk in Different Subregions

| Region Splitting | ΔTS | Δ dof | Index 1 | Index 2 | Index 3 |
|------------------|-----|-------|---------|---------|---------|
| Single disk      | 0   | 0     | 3.09 ± 0.12 |
| a                | 2.8 | 2     | 2.98 ± 0.12 | 3.35 ± 0.10 |
| b                | 4.2 | 2     | 2.88 ± 0.31 | 3.14 ± 0.15 |
| c                | 2.2 | 2     | 2.86 ± 0.4  | 3.29 ± 0.1  |
| d                | 1.6 | 4     | 2.92 ± 0.22 | 3.29 ± 0.21 | 2.95 ± 0.17 |

Notes. For each case we report the number of additional degrees of freedom (dof) and the spectral indices. Analysis performed above 1 GeV.

Table 5
Table 5. Likelihood Values and Spectral Indices for the Models Described in Section 2.6, Splitting the Single Best-fit Disk in Different Subregions

| Region Splitting | ΔTS | Δ dof | α | β |
|------------------|-----|-------|---|---|
| Single disk      | 0   | 0     | 2.54 ± 0.05 | 0.39 ± 0.04 |
| a                | 13  | 3     | $\alpha_{\text{other}} = 2.41 ± 0.09$ | $\beta_{\text{other}} = 0.40 ± 0.06$ |
| b                | 13.4 | 3    | $\alpha_{\text{other}} = 2.27 ± 0.06$ | $\beta_{\text{other}} = 0.38 ± 0.04$ |
| c                | 8   | 3     | $\alpha_1 = 2.47 ± 0.06$ | $\beta_1 = 0.36 ± 0.03$ |
| d                | 3   | 6     | $\alpha_1 = 2.35 ± 0.12$ | $\beta_1 = 0.38 ± 0.10$ |

Notes. For each case we report the number of additional degrees of freedom (dof) and the spectral indices. The analysis is performed above 100 MeV.

Figure 3. Spectral energy distribution of HB 21. The line shows the best-fit log-parabola model, the light-red filled area shows the statistical error band and the dashed gray area shows the systematic uncertainties. The bar markers correspond to statistical errors only, while lines show the larger systematic errors. For energy bins where the TS of the source is <9, 95% confidence level upper limits are given.

(A color version of this figure is available in the online journal.)

As suggested in the analysis by Reichardt et al. (2012), to further investigate the possibility, we repeat the analysis described in Section 2.4 after splitting the best-fit disk in different ways (Figure 4):

1. radio-emitting area (modeled with a uniform disk centered at $l = 89^\circ 0^\prime 0 = +4^\circ 7$ with radius $1^\circ$) and the remainder of the best-fit disk (Figure 4(a));
2. southern shocked-CO region (modeled as a uniform disk centered at $l = 88^\circ 38 b = 4^\circ 50$ and radius $0^\circ 35$) and the remainder of the best-fit disk (Figure 4(b));
3. disk split into two halves to separate the southern shocked CO area from the rest (Figure 4(c)); and
4. finally, we test the division proposed by Reichardt et al. (2012) splitting the uniform disk into three subregions covering $120^\circ$ each (Figure 4(d)).

We first perform the analysis above 1 GeV to profit from the narrower PSF. For this configuration we modeled the source spectrum as a simple power law. The results are reported in Table 4. There are no significant improvements in the likelihood from splitting the disk in subregions ($<2\sigma$). This means that there is no evidence of spectral variations across the γ-ray emitting region. The spectral indices of the subregions are all compatible within statistical uncertainties.

Then we perform the analysis over the full energy range above 100 MeV. We fit the spectrum of each subregion with a log-parabola function as for the uniform disk. The results are reported in Table 5. Even for this larger energy range, we find only marginal evidence ($<3\sigma$) of spectral variations across the remnant and the values for the spectral parameters are compatible within statistical errors.

In conclusion, we do not confirm the claim by Reichardt et al. (2012) of a softer spectrum toward the clouds NW and A. Spectral variations are not significant ($<3\sigma$), even when only considering statistical uncertainties. More data and a better handling of the current dominating uncertainties related to the modeling of interstellar emission (that were neglected in the study of Reichardt et al. 2012) are required to further probe for possible γ-ray spectral variations across HB 21.
3. WMAP OBSERVATIONS AND RADIO SPECTRUM

The radio morphology of HB 21 is that of a large oblate shell (see contours in Figure 4(a)). It has both a large angular diameter and high radio flux density, which have made it a favorable target for telescopes across the radio spectrum. High-resolution imaging reveals bright filaments and indentations along the periphery (Leahy & Roger 1998). We use the 7 yr all-sky data of the WMAP to extend the radio spectrum of HB 21 above 10 GHz. Five bands are analyzed with effective central frequencies ($\nu_{\text{eff}}$) of 23–93 GHz (Jarosik et al. 2011).

The WMAP data are fit within a 4° square region with a spatial template plus a sloping planar baseline (following Hewitt et al. 2012). For the spatial template, we use the map of HB 21 from the Sino-German 6 cm (4.8 GHz) survey (Gao et al. 2011, resolution of 9.5'). We include a separate, freely normalized point source to account for the bright nearby extragalactic point source 3C 418 (Hill 1974). The templates are smoothed to the WMAP beam at each band (Weiland et al. 2011) and fit to the data.

Figure 5 shows an example of the WMAP skymap, best-fit model, and residual map for the $Q$ band (61 GHz). Table 6 lists the beam sizes and fitted fluxes with errors estimated from the rms of the fit residuals. To ensure that fluxes we extracted from the WMAP data are properly calibrated, we also analyzed the bright radio sources 3C 58 and Cassiopeia A using the same procedure and find agreement with Weiland et al. (2011). The addition of a template for 3C 418 does not produce a significant change in the measured fluxes of HB 21.

The global radio spectrum of HB 21 from 38 MHz to 93 GHz is shown in Figure 6. We include our WMAP analysis along with published flux densities from the literature (Kothes et al. 2006 and references therein). It is evident that a spectral break is present in the spectrum at high frequencies. We first fit the radio spectrum with a single power law, $S(\nu) = S_0 \nu^{-\alpha}$, and find a flux normalization at 1 GHz of $S_0 = 201 \pm 3$ Jy and an index $\alpha = 0.50 \pm 0.02$. The fitted index is significantly steeper than $\alpha = 0.38$ determined from fitting only the data below 10 GHz because it does not account for the break at high frequencies.

We, therefore, include a spectral break of $\Delta \alpha = 0.5$ at a frequency $\nu_b$. This is appropriate for synchrotron losses in a homogeneous source of continuously injected electrons, as expected for middle-aged SNRs (Leahy & Roger 1998; Reynolds...
Figure 5. Example of the template fit to the WMAP data within a 4° square region of HB 21 in the Q band (61 GHz). The three panels present the 7 yr skymap image (left), the model resulting from a fit of the radio template plus a sloping planar baseline and a point source at the position of 3C 418 marked by a cross (center), and the fractional residuals (defined as the fit residual divided by the model). The upper and lower limits of the linear color bar are given beneath each image; data and model are on the same scale.

Figure 6. Integrated radio flux density of HB 21 as a function of frequency. Data points below 10 GHz, circles, are from the literature (see Kothes et al. 2006 and references therein). The new WMAP data points are shown as open diamonds and presented in Table 6. The upper limit is shown as a downward filled triangle. The dashed red line shows a power-law fit to the entire radio spectrum. The solid black line shows a fit to the data assuming a spectral break as described in the text. The dot-dashed black line shows the fit assuming an exponential cutoff.

(A color version of this figure is available in the online journal.)

2009, Section 2.1). With one additional free parameter, we can now produce a good fit to the radio spectrum. We find the spectral break to have a significance of 5.3σ by applying the F-test to compare the χ² fit with that of the simple power law. The best-fit parameters for the radio spectrum of HB 21 are α = 0.38 ± 0.02 and ν_b = 5.9 ± 1.2 GHz. Additionally, we tried to fit the spectrum using a power law with an exponential cutoff of the form, S(ν) = S_0 ν^{-α} exp(-ν/ν_c). This produces nearly as good a fit, with α = 0.34 ± 0.02, ν_c = 29 ± 4 GHz, and a significance of 5.2σ.

The radio index, α, is related to the particle index, Γ_p, by Γ_p = 2α+1. The observed radio index below the break α = 0.38 gives Γ_p ~ 1.8, which is similar to the spectral index obtained with the Fermi LAT data in Section 2.5. We explore physical mechanisms that could explain both the γ-ray and radio spectra in the discussion in Section 4.

The observed break in the high-frequency spectrum cannot be explained by spectral variations across HB 21. Leahy (2006) studied spectral variations using radio observations at 408 and 1420 MHz. Manual fits to 36 individual regions across the SNR show variations between 0.2–0.8, with a mean spectral index of 0.45 and a standard deviation of 0.16. The brightest regions tend to have an index that is flatter than average and than the canonical spectral index (0.5) from diffusive shock acceleration. Thus, fitting the radio spectral index of the flux from the entire remnant leads to an even flatter global index of 0.38.

4. DISCUSSION

4.1. Non-thermal Modeling

We have identified spatially extended γ-ray emission coincident with SNR HB 21, indicating the presence of relativistic particles. Determining the mechanism responsible for γ-ray emission is crucial to measure the underlying particle population accelerated by the SNR. To do so, we model emission from the remnant using ISIS, the Interactive Spectral Interpretation System (Houck & Denicola 2000). For arbitrary particle momentum distributions, a suite of interaction models available in the literature is used to calculate the non-thermal emission spectrum (Houck & Allen 2006 and references therein), which is then fit to radio and γ-ray data. We used an updated interaction cross section for hadronic interactions (Karlsson & Kamae 2008). The included prescriptions are in agreement with the results from Sturmer et al. (1997).

To constrain the emitting particle distribution, we simultaneously fit radio and γ-ray emission from non-thermal electrons and protons. Initially, we adopt the simplifying assumption that all emission originates from a region characterized by a constant matter density and magnetic field strength. This single-emitting zone is assumed to be equal to the size of the remnant derived from the best-fit γ-ray disk. Additionally, the population of accelerated nuclei and electrons is assumed to be described by the
same particle distribution, here assumed to follow a power law with an exponential cutoff of the form \( dN/dp \propto p^{-\Gamma} \times \exp(-p/p_{\text{max}}) \), where \( \eta_e/\eta_p \) gives the ratio of electrons to protons and \( p \) the momentum. The normalization and maximum energy cutoff are left as free parameters and are adjusted to fit the data. An exponential cutoff in the momentum spectra of electrons is expected when energy losses exceed the rate of energy gain from shock acceleration (Webb et al. 1984). In practice, we find that we do not have sufficient spectral coverage to strongly differentiate between an exponential cutoff or a broken power law.

To determine the total energy in relativistic particles from the normalization of the non-thermal emission, we must consider the physical conditions of the emitting region. HB 21 is known to lie in the vicinity of several large molecular clouds. The presence of optical [S II], but not oxygen line emission, indicates slow shocks \( < 100 \text{ km s}^{-1} \) into ambient densities of about 2.5 \( \text{cm}^{-3} \) (Mavromatakis et al. 2007). Shocked CO filaments are observed with densities of order \( \mathbf{10^3} \text{ cm}^{-3} \) (Mavromatakis et al. 2007). Shocked CO filaments are observed with densities of order \( \mathbf{10^5}–\mathbf{10^6} \text{ cm}^{-3} \) and small filling factors \( \mathbf{\lesssim 0.1} \) (Koo et al. 2001). For neutral gas, the mean ambient H\(_2\) density for the expanding shell is \( \mathbf{\sim 8} \text{ cm}^{-3} \) at a distance of 1.7 kpc (Koo & Heiles 1991). Reichardt et al. (2012) estimated the molecular mass within HB 21 by integrating all CO line emissions between the velocity range from \(+0\) to \(–20 \text{ km s}^{-1}\). This estimate likely includes molecular gas outside the SNR, but is a conservative upper limit. Adopting a distance of 1.7 kpc, the maximum molecular mass is \( 5.5 \times 10^4 \mathcal{M}_\odot \), the diameter of the SNR is 55 pc, and the maximum volume-averaged molecular-gas density is 25 \( \text{cm}^{-3} \). Therefore, we assume a gas density of 15 \( \text{cm}^{-3} \), which is uncertain by a factor of a few.

There are three primary emission mechanisms to produce \( \gamma\)-ray emission in SNRs. In the so-called hadronic scenario, the emission is dominated by \( \gamma\)-rays radiated through the decay of \( \pi^0 \) mesons produced in collisions between accelerated nuclei with the ambient gas. In the leptonic scenario, \( \gamma\)-ray emission results either from IC scattering of relativistic electrons on low-energy photon fields, such as the cosmic microwave background (CMB), or non-thermal bremsstrahlung. As the matter density is increased, the bremsstrahlung contribution will rise and dominate over the IC at densities \( \gtrsim 1 \text{ cm}^{-3} \), unless the photon field is greatly amplified above the CMB. HB 21 appears to have a high enough gas density that bremsstrahlung is expected to dominate over IC emission. In modeling the non-thermal spectrum of HB 21, we explored models in which the assumed physical conditions are modified such that each of these three emission mechanisms is dominant.

One-zone models for all three scenarios are presented as SED fits in Figure 7. Parameters are given in Table 7, including the total energy of accelerated particles integrated above 1 GeV for protons, and above 511 keV for electrons. We adjusted the ratio of electrons-to-protons to differentiate between bremsstrahlung- and hadronic-dominated models. A ratio \( \eta_e/\eta_p \sim 0.01 \) is seen in CRs at Earth around 10 GeV (Gaisser 1990), but an even lower ratio \( \sim 0.001 \) may be expected from diffusive shock acceleration models (Reynolds 2008). We cannot robustly constrain \( \eta_e/\eta_p \) through our fits, so we choose characteristic values for each scenario. While the chosen parameters are not unique in their ability to fit the broadband spectrum, they are representative.

Under our simple assumptions, in a single zone with a single particle distribution for both electrons and protons, we find that only hadronic models can reproduce both the observed radio and \( \gamma\)-ray spectra. For \( \eta_e/\eta_p = 0.001 \), we find a momentum cutoff of 10 GeV/c and a magnetic field of \( \sim 90 \mu\text{G} \). Decreasing \( \eta_e/\eta_p \) results in a higher magnetic field strength to simultaneously fit the synchrotron normalization and break in the radio. Bremsstrahlung dominates over neutral pion decay when \( \eta_e/\eta_p \geq 0.05 \), but there is no combination of magnetic field strength and momentum cutoff that can simultaneously produce the observed SED from one electron population, as can be seen in Figure 7. To produce a model in which IC emission dominates, we must adopt a density of \( \sim 0.1 \text{ cm}^{-3} \), which is well below gas density estimates. Therefore, an IC-dominated model is unlikely, and, further, cannot produce a good fit to the data. The energetics of our hadronic model indicate \( \sim 3 \times 10^{50} \text{ erg} \) in accelerated CR protons and nuclei, which is comparable with that estimated for other old SNRs in a dense environment detected by Fermi.

The failure of bremsstrahlung-dominated models is largely due to an inability to fit both the observed spectral breaks in the radio and \( \gamma\)-rays. To explain synchrotron emission at a peak frequency \( \nu \) from an electron in a magnetic field \( B \), requires the electron have an energy \( E = 14.7(\nu/\text{GeV}) B^2 \text{ GeV} \) (Reynolds 2008). For the observed radio break at \( \sim 6 \text{ GHz} \) and \( \gamma\)-ray break at \( \sim 1 \text{ GeV} \) to be explained by the same electron population requires a magnetic field of \( \gtrsim 1 \text{ mG} \), which is far in excess of the magnetic field expected for an SNR in such an evolved stage (unless the density is very high \( > 10^4 \text{ cm}^{-3} \)). However, molecular clouds have a well-known multiphase structure, so the density of HB 21 is unlikely to be uniform, and the one-zone approximation may be overly simplistic.

We, therefore, explored relaxing the single-zone assumption by modeling the radio and \( \gamma\)-ray emission as dominated by distinct regions. Allowing the normalization and spectrum of the radio emission to be separately fit from \( \gamma\)-rays is physically motivated. Radio emission is observed from dense filaments, but globally may be dominated by diffuse gas that fills a larger volume. For SNRs W44 and IC 443 the observed proton index from \( \pi^0\)-decay emission is softer than the electron index inferred from the radio spectrum (Ackermann et al. 2013b).

In this two-zone scenario, we found that both bremsstrahlung- and hadronic-dominated models can fit the data. The cutoff in the accelerated particle spectrum responsible for \( \gamma\)-rays need not match that responsible for the radio emission, because of the different physical conditions. It is also possible that high-energy CR electrons may cool in the dense filaments formed by shock-interaction with molecular clumps, or that CR protons may have largely escaped from the SNR (Aharonian & Atiyon 1995; Malkov et al. 2011). In the latter case, we would expect

| Model | Index | \( p_{\text{max}} \) (GeV/c) | \( n_p \) (cm\(^{-3}\)) | \( B_{\text{tot}} \) (\( \mu\text{G} \)) | \( \eta_e/\eta_p \) | \( W_p \) (erg) | \( W_e \) (erg) |
|-------|-------|-----------------|------------------|------------------|----------------|----------------|----------------|
| IC    | 1.76  | 100             | 0.1              | 2                | 1              | \( 1.3 \times 10^{51} \) | \( 2.1 \times 10^{51} \) |
| Brems. | 1.76  | 19              | 15               | 24               | 0.1            | \( 6.4 \times 10^{48} \) | \( 3.0 \times 10^{48} \) |
| \( \pi^0\)-decay | 1.76  | 8.1             | 15               | 140              | 0.001          | \( 3.0 \times 10^{50} \) | \( 1.1 \times 10^{57} \) |
Figure 7. Single-zone models for which IC (top), bremsstrahlung (middle) and $\pi^0$-decay (bottom) are the dominant emission mechanism (see Table 7 for parameters). In each model, the radio data are fit with a synchrotron component, shown as a black curve. The individual contributions of $\pi^0$-decay (long dashed), bremsstrahlung (short dashed), and IC emission from CMB (dotted) are shown. The sum of the $\gamma$-ray emission is shown by the solid curve. The leptonic and hadronic components are colored blue and red, respectively.

that nearby clouds could be illuminated by the escaping CRs, but the geometry of the clouds in relation to HB 21 is not well known. While multi-zone models appear as feasible as single-zone models, they are not well constrained as a result of the poor spatial resolution of the data at $\gamma$-rays and high-frequency radio. The energy in CRs in bremsstrahlung-dominated two-zone models is several times $10^{48}$ erg, with a comparable energy in accelerated nuclei and leptons.

4.2. HB 21 and the Population of Detected $\gamma$-Ray SNRs

Here, we briefly discuss HB 21 in comparison with other $\gamma$-ray SNRs known to be interacting with molecular clouds. The total luminosity of HB 21 above 100 MeV, at a distance of 1.7 kpc, is $(3.3 \pm 0.6) \times 10^{34}$ erg s$^{-1}$. Other $\gamma$-ray-detected MM SNRs, such as W44 and IC 443, have luminosities of $\sim 10^{35}$ erg s$^{-1}$ and associated cloud masses of $> 10^4 M_\odot$. While the total CO line emission along the line of sight to HB 21 indicates a large cloud mass, this could be due to the Cygnus OB7 complex, which lies along the line of sight at a similar velocity to HB 21, but at a distance of only 0.8 kpc, between us and the SNR. It is, therefore, possible that the low luminosity of HB 21 is the result of the SNR currently encountering only a relatively small reservoir of material.

Flat radio indices, as for HB 21, are observed for other $\gamma$-ray detected SNRs known to be interacting with molecular clouds, such as IC 443 and W44. Leahy (2006) proposed two mechanisms to produce the observed flat spectrum: ionization losses due to emission from regions of high density, and low-frequency absorption by thermal electrons in the post-shock cooling regions. Alternatively, Uchiyama et al. (2010) proposed that re-acceleration takes place in the compressed cloud, resulting in a hardening of the spectrum of existing accelerated particles. Though it is likely interacting with a less-dense environment than HB 21, the latter model was shown to plausibly explain radio and $\gamma$-ray emission from SNR S147 (Katsuta et al. 2012).
HB 21 shows a cutoff or break in the γ-ray spectrum mirroring that of the underlying particle spectrum, which is typical of middle-aged SNRs detected by the LAT (e.g., the Cygnus Loop, Katagiri et al. 2011, and W28, Abdo et al. 2010a). This is in agreement with the circumstantial evidence for HB 21 to be a middle-aged or old remnant (see Section 1). Given the long timescales for radiative losses via proton-proton collision, bremsstrahlung or synchrotron losses for GeV particles, it is unlikely that such spectral curvature is produced by radiative losses. Several mechanisms have been proposed, including runaway CRs illuminating nearby clouds (Gabici et al. 2009), the aforementioned re-acceleration in highly compressed shocks at the interaction sites (Uchiyama et al. 2010), and magnetic damping of Alfvén waves in a partially ionized medium that leads to a break in the particle spectrum (Malkov et al. 2011). All these mechanisms appear viable for the case of HB 21, and could produce different particle distributions for electrons and protons remaining in the SNR. Given the many shared similarities with other MM SNRs, HB 21 appears to be an extension of this γ-ray class to lower luminosities.

5. SUMMARY

We analyzed Fermi LAT γ-ray data from the region around HB 21, a MM SNR. We detect significant γ-ray emission (∼29σ) associated with the remnant. The emission is best modeled by a disk centered at (l, b) = (88°75 ± 0°04, +4°65 ± 0°06), with a radius r = 1°19 ± 0°06, with a systematic uncertainty on the position of ∼0°25 and on the radius of ∼0°24, so it is well-resolved by the LAT for energies greater than 1 GeV. The γ-ray emission extends over the whole area of the non-thermal radio shell, larger than the X-ray emitting thermal core. The emission in γ-rays may extend beyond the radio shell in a region rich of interstellar matter in the north-western part of the SNR. Further, the brightest γ-ray emitting region coincides with known shocked molecular clumps. Both results suggest that collisions of shock-accelerated particles with interstellar matter are responsible for the observed γ-ray emission. No spectral variations across the γ-ray-emitting region that would further support this hypothesis were detected with the current observations.

The spectrum is best modeled by a curved function, indicative of a cutoff or break in the spectrum of the accelerated particles, typical of middle-aged and old SNRs in a dense interstellar environment. The total γ-ray luminosity of HB 21 above 100 MeV is estimated to be (3.3±0.6)×10^34 erg s^-1, fainter than other SNRs interacting with molecular clouds detected by the LAT. This can be explained by the lower mass of the molecular clouds supposed to be in interaction with the remnant.

Reichardt et al. (2012) recently reported a lower luminosity for HB 21. We assume a distance of 1.7 kpc, based on the arguments of Byun et al. (2006), while their work assumes a nearer distance of 0.8 kpc adopted in numerous earlier works. Taking this difference into account, our values of the 0.1–10 GeV flux and luminosity of SNR HB 21 are in agreement. Even considering statistical uncertainties only, we do not find any significant evidence for spectral variations across the SNR, as suggested for cloud NW and A in their work.

We complement the γ-ray analysis by exploiting the WMAP 7 yr observations from 23 to 93 GHz, obtaining the first detections of HB 21 at these energies. By combining WMAP with lower-energies radio observations, we find that the radio spectral index of HB 21 steepens significantly above 10 GHz. This spectral feature in the radio helps to constrain the relativistic electron spectrum and constrain possible physical parameters in simple non-thermal radiation models.

An IC origin of the γ-ray emission is disfavored because it would require unrealistically low interstellar densities to prevent bremsstrahlung from dominating. π^0 decay due to nuclei interactions can reproduce the data well. Bremsstrahlung and synchrotron emission from a single population of energetic electrons cannot reproduce both the γ-ray and radio SEDs. Based on the most likely values for the ISM densities over the volume of the remnant, in the hadronic-dominated scenario, accelerated nuclei contribute a total energy of ∼3 × 10^39 erg. This is reduced to several times 10^38 erg under a two-zone bremsstrahlung-dominated model, with a comparable energy in leptonic CRs.

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