**Fermi-LAT Detection of a Break in the Gamma-Ray Spectrum of the Supernova Remnant Cassiopeia A**

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## ABSTRACT

We report on observations of the supernova remnant Cassiopeia A in the energy range from 100 MeV to 100 GeV using 44 months of observations from the Large Area Telescope on board the *Fermi Gamma-ray Space Telescope*. We perform a detailed spectral analysis of this source and report on a low-energy break in the spectrum at $1.72^{+1.35}_{−0.89}$ GeV. By comparing the results with models for the γ-ray emission, we find that hadronic emission is preferred for the GeV energy range.

*Subject headings:* gamma-rays: general, ISM: supernova remnants, supernovae: individual (Cassiopeia A), Acceleration of particles, radiation mechanisms: non-thermal

## 1. Introduction

With an age of ~350 years, the supernova remnant (SNR) Cassiopeia A (Cas A) is one of the youngest objects of this class in our Galaxy. It is also one of the best studied objects with both thermal and non-thermal broad-band emission ranging from radio through X-ray all the way to GeV and TeV gamma rays. It is the brightest radio source in the sky outside...
of our solar system \cite{Baars1977} and is located at a distance of \(3.4^{+0.3}_{-0.1}\) kpc \cite{Reed1995}. Non-thermal emission tracing the acceleration of particles to relativistic energies has been detected in both the forward and reverse shocks (see e.g. \cite{Gotthelf2001, Hughes2000, Helder2008, Maeda2009}), in particular seen through high-angular resolution X-ray studies. Fast variability and small filaments seen in these X-ray observations also suggest rather large magnetic fields of 0.1–0.3 mG in the shock region of Cas A \cite{Patnaude2007, 2009, Uchiyama2008}. The observed brightness variations might, however, also be produced by local enhancements of the turbulent magnetic field \cite{Bykov2008}.

Gamma-ray observations further corroborate the existence of non-thermal particles in the shell of Cas A. The SNR was first detected at TeV energies with the HEGRA telescope system \cite{Aharonian2001}, later confirmed by MAGIC \cite{Albert2007} and VERITAS \cite{Acciari2010}, and subsequently detected at lower (GeV) energies with the Large Area Telescope (LAT) on board the Fermi Gamma-ray Space Telescope (Fermi) \cite{Abdo2010}. Those observations revealed a rather modest gamma-ray flux, compared to the synchrotron radio through X-ray emission, further strengthening the argument for a rather high magnetic field. The field can hardly be significantly less than \(100\,\mu\)G \cite{Abdo2010}, consistent with earlier studies (see e.g. \cite{Vink2003, Parizot2006}). It should be stressed that the magnetic field is likely to be non-uniform. This was originally proposed by \cite{Atoyan2000} who suggested greatly amplified magnetic fields of up to 1 mG in compact filaments. Because both the photon and matter densities in the shock regions are rather high, these gamma-ray studies also suggested that the non-thermal electron (and proton) densities are somewhat low, compared to estimates of the explosion energy (only a few percent). The centroids for the GeV to TeV emission seem to be shifted towards the western region of the remnant where nonthermal X-ray emission is also brightest \cite{Helder2008, Maeda2009, Abdo2010}.

However, given the gamma-ray data published so far it was not possible to unambiguously determine the particle population responsible for the bulk of the emission, in particular to distinguish between gamma rays produced through the bremsstrahlung and inverse Compton (IC) leptonic processes and the neutral pion decay hadronic process. Lower-energy gamma rays (below 1 GeV) hold the key to distinguishing between these scenarios, since a sharp low-energy roll-over in the spectrum of hadronically-produced gamma rays is expected \cite{Stecker1971}. Continuous observations of Cas A with the Fermi-LAT have provided us a better opportunity to investigate the gamma-ray emission in the \(\lesssim 1\) GeV range.

The LAT is a pair-conversion detector that operates between 20 MeV and \(> 300\) GeV.
The telescope has been in routine scientific operation since 2008 August 4. With its wide field of view of 2.4 sr, the LAT observes the whole sky every $\sim 3$ hours. More details about the LAT instrument and its operation can be found in Atwood et al. (2009). In addition, the data reduction process and instrument response functions recently have been improved based on two years of in-flight data (so-called Pass7v6, Ackermann et al. 2012b). According to the updated instrument performance, the point-spread function of the LAT gives a 68% containment angle of $< 6^\circ$ radius at 100 MeV and $< 0.3^\circ$ at $> 10$ GeV for normal incidence photons in P7SOURCE class. The sensitivity of the LAT for a point source with a power law photon spectrum of index 2 and a location similar to Cas A is $\sim 9 \times 10^{-9}$ ph cm$^{-2}$s$^{-1}$ for a 5$\sigma$ detection above 100 MeV after 44 months of sky survey. Our analysis takes advantage of both the increase in data quantity and quality.

In this letter, we describe our analysis method in §2, present the Fermi results in §3, and then discuss the gamma-ray emission mechanism of Cas A in §4.

### 2. Analysis Method

We analyzed Fermi-LAT observations of Cas A using data collected from 2008 August 4 to 2012 April 18 (Mission elapsed time 239557565.63 – 356436692.23, about 44 months of data). The analysis was performed in the energy range 100 MeV-100 GeV using the LAT Science Tools\textsuperscript{1} as well as an independent tool pointlike. In particular, we used the maximum-likelihood fitting packages pointlike to fit the position and test for significant spatial extension of Cas A, then with the updated localization result we used gtlike to fit the spectrum of the source. Our analysis procedure is very similar to that of the second LAT source catalog (2FGL, Nolan et al. 2012). When analyzing the data, we used the P7SOURCE class event selection and P7_V6 instrument response functions (IRFs, Ackermann et al. 2012b). In order to reduce contamination from gamma rays produced in the Earth’s limb, we excluded events with reconstructed zenith angle greater than 100$^\circ$, and selected times when the rocking angle was less than 52$^\circ$.

Emission produced by the interactions of cosmic rays with interstellar gas and radiation fields substantially contributes to the gamma-ray intensities measured by the LAT near the Galactic plane. We accounted for it using the standard diffuse model used in the 2FGL analysis. We also included the standard isotropic template accounting for the isotropic

\textsuperscript{1}The LAT Science Tools are distributed through the Fermi Science Support Center (FSSC, http://fermi.gsfc.nasa.gov).
gamma-ray background and residual cosmic-ray contamination. In addition, we modeled as background sources all nearby 2FGL sources: in pointlike we used a circular region of interest (ROI) with a radius of 15° centered on Cas A; in gtlike we used a square region of interest with a size of 20° × 20° aligned with Galactic coordinates, using a spatial binning of 0′:125 × 0′:125. We adopt the same parameterizations as 2FGL for these sources, while left free the spectral parameters of 5 2FGL sources that were either nearby or had a significant residual when assuming the 2FGL values: 2FGL J2333.3+6237, 2FGL J2257.5+6222c, 2FGL J2239.8+5825, 2FGL J2238.4+5902, 2FGL J2229.0+6114. In addition, we added 4 sources not included in 2FGL which will be described in Section § 3.1.

3. Results

3.1. Spatial Analysis

Because of the wide and energy-dependent point-spread function of the LAT, nearby sources must be carefully modeled to avoid bias during a spectral analysis. Therefore, before analyzing Cas A, we performed a dedicated search for nearby point-like sources not included in the 2FGL catalog. We did so by adding sources in the background model at the positions of significant residual test statistic (TS, which follows the same definition as that in Nolan et al. 2012) until the residual TS < 25 within the entire pointlike ROI. Table 1 lists the four significant new sources found in this study. We have not found any counterparts for the new sources yet.

Figure 1 shows a count map above 800 MeV of the region surrounding Cas A. The relatively bright source coincident with the SNR Cas A has a TS value of ∼ 600. First, we used pointlike to fit the position of this source and test for any possible spatial extension. The best fit position of the source, in Galactic coordinates, is \( l, b = 111°74, -2°12 \), with a statistical uncertainty of 0′:01 (68% containment). To account for the systematic error in the position of Cas A, we added 0′:005 in quadrature as was adopted for the 2FGL analysis (Nolan et al. 2012).

This location is only 0′:02 away from the central compact object (CCO) (Pavlov & Luna 2009), as shown in Figure 2. This confirms that the GeV source is most likely the \( \gamma \)-ray counterpart of the Cas A SNR. Following the method described in Lande et al. (2012), we used a disk spatial model to fit the extension of Cas A. We found that the emission was not

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\(^2\)The diffuse model gal_2year_p7v6_v0.fits and isotropic template isotrop_2year_P76_source_v0.txt can be obtained through the FSSC.
significantly spatially extended ($\text{TS}_{\text{ext}} = 0.1$) and has an extension upper limit of 0.1 at 95% confidence level. Note that this upper limit is larger than the shell of Cas A.

### 3.2. Spectral Analysis

We performed a spectral analysis of Cas A in the energy range from 100 MeV to 100 GeV using \texttt{gtlike}. We first fit Cas A with a power-law spectral model and found an integral flux of $(6.17 \pm 0.43_{\text{stat}}) \times 10^{-11}$ erg cm$^{-2}$s$^{-1}$ in the energy range from 100 MeV to 100 GeV and a photon index of $\Gamma = 1.80 \pm 0.04_{\text{stat}}$. The results are consistent with the previous analysis of [Abdo et al. (2010a)]

We then tested for a break in the spectrum of Cas A by fitting the spectrum with a smoothly-broken power-law spectral model

$$
\frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right)^{-\Gamma_1} \left( 1 + \left( \frac{E}{E_b} \right)^{\frac{\Gamma_2 - \Gamma_1}{\beta}} \right)^{-\beta}.
$$

Here, $N_0$ is the prefactor; $E_0$ is a fixed energy scale (taken to be 1 GeV); $E_b$ is the break energy; $\Gamma_1$ and $\Gamma_2$ are the photon indices before and after the break, respectively; $\beta$ is a small, fixed parameter that describes the smoothness of the transition at the break (taken to be 0.1).

We tested for the significance of this spectral feature using a likelihood ratio test:

$$
\text{TS}_{\text{break}} = 2 \log(\mathcal{L}_{\text{SBPL}}/\mathcal{L}_{\text{PL}})
$$

where $\mathcal{L}$ is the Poisson likelihood of observing the given data assuming the best-fit model. We obtained $\text{TS}_{\text{break}} = 48.2$, indicating that the break is significant. The resulting spectral parameters are quoted in Table 2.

We then computed a spectral energy distribution (SED) in 8 bins per energy decade by fitting the flux of Cas A independently in each energy bin (the lowest 6 bins were combined into 3 bins). The SED of Cas A, along with the all-energy spectral fit, is plotted in Figure 3. Statistical upper limits are shown in energy bins where TS of the flux is less than 4. These upper limits are calculated at 95% confidence level using a Bayesian method (e.g., Helene 1983).
We estimated the systematic errors on the spectrum of Cas A due to uncertainty in our model of the Galactic diffuse emission and due to uncertainty in our knowledge of the IRFs of the LAT.

To probe the uncertainties due to the modeling of Galactic diffuse emission we use a series of alternative models (de Palma et al. 2013). These models differ from the standard one in the sense that 1) adopt different gamma-ray emissivities for the interstellar gas, different gas column densities, and use a different approach for incorporating spatially extended residuals; 2) vary a select number of important input parameters of the model (Ackermann et al. 2012a): the H I spin temperature, the cosmic-ray source distribution, and height of the cosmic-ray propagation halo; 3) allow more freedom in the fit by separately scaling components of the model in four Galactocentric rings. Although these models do not span the complete uncertainty of the systematics involved with Galactic diffuse emission modeling, they were selected to probe the most important systematic uncertainties.

At low energy (< 1 GeV), our uncertainty in the modeling of the Galactic diffuse emission leads to significant uncertainty in the spectral analysis of Cas A, because the integrated intensity of the diffuse emission on the scale of the energy dependent point spread function of the LAT becomes comparable with the flux of the source. By examining the residual maps after fitting, we found that the standard diffuse model overshoots the data for a region \(\sim 2^\circ\) from Cas A (Figure 4), and this can lead to underestimated upper limits in the SED calculation.

This overestimation of diffuse count is most likely due to uncertainty in modeling the gamma-ray emission from the molecular complex associated with NGC 7538 and Cas A in the Perseus arm (e.g., Abdo et al. 2010b). The alternative diffuse models provide a qualitatively better fit of this region when the normalization of each Galactocentric ring was left free, since the increased degrees of freedom allow us to better scale the Galactic diffuse model for this specific region. The improvement can be seen in Figure 4 which shows a residual map with the standard diffuse model and an improved residual map with one of the alternative diffuse models.

Even though there is significant systematic uncertainty in the spectral model of Cas A at lower energies, TS_{break} was greater than 20 using all of the alternative diffuse models and is therefore robust against this systematic uncertainty.

We estimated the systematic error due to uncertainty in the IRFs using the method described in Ackermann et al. (2012b). Following this method, we set the pivot in the bracketing IRFs at 2 GeV, near the spectral peak in our SED. Again, we found the spectral
break to be robust against uncertainty in IRFs.

The systematic errors on the estimated spectral parameters due to both systematic uncertainties are included in Table 2.

Fig. 1.— *Fermi*-LAT count map of the region surrounding Cas A ($20^\circ \times 20^\circ$) from 800 MeV to 100 GeV. This plot is smoothed by a Gaussian kernel of size 0:1. Also shown are the 2FGL sources included in our background model (blue crosses) and the new sources we added in (green stars).

4. Discussion

In Figure 3, the new spectral data points measured with the *Fermi*-LAT are overlaid with those from Paper I. The newly-measured spectrum is consistent with the previous result, except that most of the new data points lie slightly above the old measurement. This is likely due to the changed event classifications and improved IRFs of the LAT as well as
Table 1. New sources added to the ROI

<table>
<thead>
<tr>
<th>Name</th>
<th>TS</th>
<th>$l$ (deg.)</th>
<th>$b$ (deg.)</th>
<th>Flux $(10^{-8} \text{ ph cm}^{-2}\text{s}^{-1})$</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source 1</td>
<td>35.0</td>
<td>120.10</td>
<td>1.41</td>
<td>1.96±0.53</td>
<td>2.24±0.10</td>
</tr>
<tr>
<td>Source 2</td>
<td>31.7</td>
<td>118.59</td>
<td>-1.14</td>
<td>0.89±0.40</td>
<td>2.04±0.15</td>
</tr>
<tr>
<td>Source 3</td>
<td>25.6</td>
<td>113.16</td>
<td>-0.28</td>
<td>0.66±0.31</td>
<td>1.92±0.16</td>
</tr>
<tr>
<td>Source 4</td>
<td>24.8</td>
<td>105.82</td>
<td>2.89</td>
<td>1.39±0.65</td>
<td>2.12±0.14</td>
</tr>
</tbody>
</table>

Note. — The spectral and spatial parameters of the new sources found in the region surrounding Cas A. $l$ and $b$ are the Galactic longitude and latitude of the source and TS is the significance of the detection of the source (in the energy range from 100 MeV to 100 GeV). The sources were modeled with a power-law spectral model and the flux is computed from 100 MeV to 100 GeV.

Table 2. Spectral Results for Cas A

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>$\Delta_{\text{stat}}$</th>
<th>$\Delta_{\text{sys,diffuse}}$</th>
<th>$\Delta_{\text{sys,IRFs}}$</th>
<th>$\Delta_{\text{sys}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy flux $(10^{-11} \text{ erg cm}^{-2}\text{s}^{-1})$</td>
<td>4.69</td>
<td>0.38</td>
<td>+0.03/-0.73</td>
<td>+0.45/-0.36</td>
<td>+0.45/-0.81</td>
</tr>
<tr>
<td>$\Gamma_1$</td>
<td>0.89</td>
<td>0.29</td>
<td>+0.46/-1.00</td>
<td>+0.32/-1.37</td>
<td>+0.55/-1.70</td>
</tr>
<tr>
<td>$E_{\text{break}}$ (GeV)</td>
<td>1.72</td>
<td>0.40</td>
<td>+0.62/-0.17</td>
<td>+1.20/-0.87</td>
<td>+1.35/-0.89</td>
</tr>
<tr>
<td>$\Gamma_2$</td>
<td>2.17</td>
<td>0.09</td>
<td>+0.06/-0.02</td>
<td>+0.08/-0.05</td>
<td>+0.10/-0.05</td>
</tr>
</tbody>
</table>

Note. — Spectral fit of Cas A assuming a smoothly-broken power-law spectral model. Energy flux is quoted from 100 MeV to 100 GeV. $\Delta_{\text{stat}}$ is the statistical error; $\Delta_{\text{sys,diffuse}}$ is the estimated systematic error due to uncertainties in modeling the Galactic diffuse emission; $\Delta_{\text{sys,IRFs}}$ is the estimated systematic error due to uncertainty in our knowledge of the IRFs of the LAT. $\Delta_{\text{sys}}$ is derived by adding the two components of systematic errors in quadrature.
Fig. 2.— *Fermi*-LAT best-fit localization of Cas A (shown as a green cross, also shown is the error ellipse at 68% confidence level, calculated by adding statistical and systematic errors in quadrature), overlaid with VLA 20 cm radio map of the Cas A SNR (Anderson & Rudnick 1995). The central compact object is shown as a yellow star. Also shown are best-fit positions obtained by MAGIC (Albert et al. 2007) and VERITAS (Acciari et al. 2010).
Fig. 3.— The spectral energy distribution of Cas A. The black points include statistical error only and the blue cross points include both statistical and systematic errors added in quadrature. The black upper limits consider only statistical effects and are calculated at 95% confidence level using a Bayesian method. We plot an upper limit instead of a data point when $TS < 4$. Blue upper limits have included systematic uncertainties. The red line is the best-fit spectral model assuming a smoothly-broken power law. The dark shaded region represents the statistical error on the spectral fit and the lightly shaded region represents the systematic and statistical errors added in quadrature. Also shown are the spectral points measured in Paper I (green points).
Fig. 4.— Weighted residual count maps (unsmoothed) in the energy range 100 MeV to 100 GeV after fitting with (a) standard diffuse model and (b) one of the alternative diffuse models. The weighted residual $s$ is calculated as $s = (N_{\text{obs}} - N_{\text{mdl}})/\sqrt{N_{\text{mdl}}}$, where $N_{\text{obs}}$ and $N_{\text{mdl}}$ are observed count and model count, respectively. The location of Cas A is indicated by the black cross. The contours correspond to integrated intensity of the CO line and represent the column-density distribution of the molecular complex associated with NGC 7538 and Cas A (this is the same CO intensity map of the Perseus arm with the same velocity range of integration as described in Abdo et al. 2010b). The CO map was smoothed using a Gaussian kernel of $0\arcmin.5$. Contours of 8, 29, and 50 K km s$^{-1}$ are shown.
updated background models. In Paper I, we argued that the GeV–TeV gamma rays detected from Cas A can be interpreted in terms of either a leptonic or a hadronic model. In these models, cosmic-ray electrons and protons (and ions) are accelerated in Cas A and produce the gamma-ray emission. In what follows, we revisit the gamma-ray emission models and then discuss the new LAT spectrum.

The synchrotron X-ray filaments found at the locations of outer shock waves indicate efficient acceleration of cosmic-ray electrons at the forward shocks (Hughes et al. 2000; Gotthelf et al. 2001; Vink & Laming 2003; Bamba et al. 2005; Patnaude & Fesen 2009). Moreover, X-ray studies with Chandra suggest that electron acceleration to multi-TeV energies also takes place at the reverse shock propagating inside the supernova ejecta (Uchivama & Aharonian 2008; Helder & Vink 2008). The detections of TeV gamma rays with HEGRA (Aharonian et al. 2001), MAGIC (Albert et al. 2007) and VERITAS (Acciari et al. 2010), established the acceleration of multi-TeV particles in the remnant. Because of the small radius of 2.5′ of Cas A, these experiments lacked the angular resolution to determine the spatial distribution of the gamma rays and the sites of particle acceleration.

It is widely considered that diffusive shock acceleration (DSA: see e.g., Malkov & O’C Drury 2001, for a review) operating at the forward shocks is responsible for the energization of the cosmic-ray particles. Most DSA models, which provide predictions of gamma-ray spectra of SNRs, focus on the acceleration at the forward shock (e.g., Ellison et al. 2010; Morlino & Caprioli 2012). Recently, newly-developed non-linear DSA models have included the effects of acceleration of particles at reverse shocks and their subsequent transport (Zirakashvili & Ptuskin 2012). Zirakashvili et al. (2013) have demonstrated that about 50% of the gamma-ray flux at 1 TeV from Cas A can be contributed by the reverse-shocked medium. Although the nonthermal X-ray filaments and knots in the reverse-shock region are interesting sites of particle acceleration (Uchivama & Aharonian 2008), we assume that the gamma-ray emission comes predominantly from the forward shock region. Note that our discussion on leptonic versus hadronic emission would not be greatly affected by this assumption, because we allow for parameter space that is relevant also for the reverse-shocked regions.

The gamma-ray emission models are constrained by the gas and radiation density and by the magnetic field in the gamma-ray production region. We assume the simplest model where cosmic rays are distributed uniformly in the shell of the remnant. The fluxes of bremsstrahlung and π⁰-decay gamma-ray emission scale linearly with the average gas density \(\propto \bar{n}\). Likewise the IC flux is proportional to the radiation energy density \(\propto U_{\text{ph}}\) as long as IC scattering is in the Thomson regime. The synchrotron flux scales as \(\propto B^{s+1/2}\) for a fixed density of electrons with a power-law index of \(s\). The magnetic field only indirectly affects
the gamma-ray flux by determining the amount of relativistic electrons that are required to
produce the observed synchrotron radio emission. This in turn can be used to calculate the
bremsstrahlung and IC fluxes. Therefore the gamma-ray flux constrains the magnetic field
in the shell (Cowsik & Sarkar 1980).

The outer shock waves are currently propagating into a dense circumstellar wind. The
density behind the blastwave is estimated as \( n_\text{H} \sim 10 \text{ cm}^{-3} \) from the measured hydrodynamical
quantities such as shock velocities (Laming & Hwang 2003). The radiation field for IC
scattering is dominated by far infrared (FIR) emission from the shock-heated ejecta, char-
acterized by a temperature of 100 K and an energy density of \( \sim 2 \text{ eV cm}^{-3} \) (Mezger et al.
1986). Using the gas and infrared densities, which are well constrained from the multiwave-
length data, it was shown in Paper I that bremsstrahlung by relativistic electrons dominates
the leptonic component below \( \sim 1 \text{ GeV} \), and IC/FIR becomes comparable to bremsstrahlung
above 10 GeV, for the assumed electron acceleration spectrum \( Q_e(E) \propto E^{-2.34} \exp(-E/E_m) \)
with \( E_m = 40 \text{ TeV} \) (Vink & Laming 2003). The power-law index was set to match the
radio-infrared spectral index of \( \alpha = 0.67 \) (Rho et al. 2003), since both the GeV gamma-ray
emission and the radio synchrotron emission sample similar electron energies. We note that
the IC scattering of FIR exceeds IC of cosmic microwave background by a factor of \( \sim 3 \) at
10 GeV.

Figure 5 compares the leptonic model presented in Paper I with our new LAT mea-
surement. The magnetic field \( B = 0.1 \text{ mG} \) used in the leptonic model is consistent with
\( B = 0.08-0.16 \text{ mG} \) estimated by Vink & Laming (2003) who interpreted the width of a syn-
chrotron X-ray filament as the synchrotron cooling length. The field is somewhat lower than
\( B \approx 0.3 \text{ mG} \) estimated by Parizot et al. (2006) who took into account a projection effect.
Unlike the TeV band where the electrons responsible for the gamma-ray emission suffer from
severe synchrotron losses, the gamma-ray spectral shape near 1 GeV does not depend on
the magnetic field. This can be seen, for example, in Araya & Cui (2010) who employed
different magnetic field strengths (by a factor of 6) between two radiation zones.

Also shown in Figure 5 is the hadronic model presented in Paper I. To achieve a
better match with the new measurement, the normalization of the model spectrum is in-
creased by 27% from Paper I. The model was calculated for a proton spectrum of \( Q_p(p) \propto p^{-2.1} \exp(-p/p_m) \)
with an exponential cutoff at \( c p_m = 10 \text{ TeV} \), where \( p \) denotes momentum of
accelerated protons. The total proton content amounts to \( W_p (> 10 \text{ MeV c}^{-1}) \approx 4 \times 10^{49} \text{ erg} \),
which is less than 2% of the estimated explosion kinetic energy of \( E_{\text{sn}} = 2 \times 10^{51} \text{ erg} \)
(Laming & Hwang 2003; Hwang & Laming 2003).

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3 The shocked ejecta gas can contribute to the gamma-ray emission. The baryon density in the shocked
Paper I already showed that the leptonic model cannot fit the turnover well at low energies because the bremsstrahlung component that is dominant over IC below 1 GeV has a steep spectrum. Note that the spectral shape of the bremsstrahlung component copies the electron spectrum with spectral index $s = 2.34$, which in turn is determined from the radio-infrared spectral index of $\alpha = 0.67$ (Rho et al. 2003). If we use a steeper power law for the electron energy distribution based on a global spectral index of $\alpha = 0.77$ in the radio wavelengths (Baars et al. 1977) or a spectral shape with curvature that reproduces the hardening ($\alpha = 0.77 \rightarrow 0.67$) in the integrated spectrum, the discrepancies between the bremsstrahlung model and the Fermi-LAT data become even larger. Araya & Cui (2010), who reported the results of Fermi-LAT analysis of Cas A independently, also showed that the electron bremsstrahlung with such a steep electron index could not explain the Fermi-LAT spectrum. However, uncertainties in the Galactic diffuse emission at low energies prevented a definitive conclusion regarding the inconsistency between the bremsstrahlung model and the gamma-ray data. In this paper, a more detailed investigation of these uncertainties at low energy now confirms the hadronic origin of the GeV $\gamma$-ray emission from Cas A. The new LAT spectrum can be described by a broken power law with a second power-law index of $\Gamma_2 = 2.17 \pm 0.09$. A comparison between the LAT spectrum and the TeV $\gamma$-ray spectra suggests that additional steepening between the LAT and the TeV bands is necessary. Indeed, the TeV $\gamma$-ray spectra measured with HEGRA, MAGIC, and VERITAS are consistent with a power law with a photon index of $\Gamma_{TeV} = 2.5 \pm 0.4_{\text{stat}} \pm 0.1_{\text{sys}}$, $\Gamma_{TeV} = 2.3 \pm 0.2_{\text{stat}} \pm 0.2_{\text{sys}}$, and $\Gamma_{TeV} = 2.61 \pm 0.24_{\text{stat}} \pm 0.2_{\text{sys}}$, respectively, which are somewhat steeper than the second index $\Gamma_2 = 2.17 \pm 0.09$ of the LAT spectrum. However, given the relatively large statistical uncertainties of the TeV $\gamma$-ray fluxes, we refrain from solidifying the presence of the cutoff. If confirmed, efficient acceleration of particles to PeV energies in Cas A is questioned.

The Fermi-LAT results on two historical SNRs, Tycho’s SNR (Giordano et al. 2012) and Cas A, support hadronic scenarios for these objects. Tycho’s SNR is the remnant of a Type Ia supernova, while Cas A is that of a core-collapse SN (specifically Type IIb). This indicates that both Type Ia and core-collapse SNRs can convert a substantial fraction of their kinetic expansion energies into cosmic-ray energies, and makes SNRs energetically favorable candidates for the origin of Galactic cosmic rays. Recently, direct spectral signatures of the $\pi^0$-decay emission have been found in two middle-aged SNRs interacting with molecular clouds: W44 and IC 443 (Ackermann et al. 2013; Giuliani et al. 2011). Although spectroscopic evidence for the $\pi^0$-decay emission from Cas A is not as strong as these two cases, our ejecta is similar to that in the forward shock region. Therefore, the total proton content estimated here can be interpreted roughly as a sum of the cosmic-ray contents in the forward shock region and that in the reverse-shocked ejecta.
results presented in this paper demonstrate the importance of the gamma-ray measurements of SNRs below 1 GeV.

Fig. 5.— Gamma-ray spectrum of Cas A together with the emission models. The Fermi, MAGIC, and VERITAS points are plotted as filled circles, triangles and open circles, respectively (Albert et al. 2007; Acciari et al. 2010). The Fermi spectral points include both statistical and systematic errors. The curves show a leptonic model for $B = 0.12$ mG (dashed line) and the hadronic model from Paper I with its normalization increased by 27% (solid line).

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