STUDYING THE SGR 1806-20/C11 1806-20 REGION USING THE FERMI LARGE AREA TELESCOPE

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ABSTRACT

The region around SGR 1806-20 and its host stellar cluster C11 1806-20 is a potentially important site of particle acceleration. The soft γ-ray repeater and C11 1806-20, which also contains several very massive stars including a luminous blue variable hypergiant LBV 1806-20, are capable of depositing a large amount of energy to the surroundings. Using the data taken with the Fermi Large Area Telescope (LAT), we identified an extended LAT source to the southwest of C11 1806-20. The centroid of the 1–50 GeV emission is consistent with that of HESS J1808-204 (until now unidentified). The LAT spectrum is best-fit by a broken power law with the break energy \( E_b = 297 \pm 15 \) MeV. The index above \( E_b \) is \( 2.60 \pm 0.04 \) and is consistent with the flux and spectral index above 100 GeV for HESS J1808-204, suggesting an association between the two sources. Meanwhile, the interacting supernova remnant SNR G9.7-0.0 is also a potential contributor to the LAT flux. A tentative flux enhancement at the MeV band during a 45 day interval (2011 January 21–March 7) is also reported. We discuss possible origins of the extended LAT source in the context of both lepton and hadronic scenarios.

Key words: cosmic rays – ISM: individual objects (SNR G9.7-0.0, HESS J1808-204, W31) – pulsars: individual (SGR 1806-20) – stars: magnetars

1. INTRODUCTION

Magnetars are neutron stars with very high surface magnetic fields and frequent starquakes (Duncan 1998). Unlike rotation-powered neutron stars, magnetars are powered by their strong magnetic fields, instead of their spin-down energy (Duncan & Thompson 1992). The typical magnetic field of magnetars is >10^{14} G; however, the discovery of a low-magnetic-field SGR 0418+5729 put the lower limit to be 7.5 \times 10^{12} G (Rea et al. 2010).

During the past decade, more than 100 γ-ray pulsars (mostly young pulsars and millisecond pulsars) have been identified through their γ-ray pulsation, thanks to the unprecedented sensitivity at the 100 MeV–>300 GeV energy range of the Fermi Large Area Telescope (LAT; Abdo et al. 2013) and multiwavelength observations. On the other hand, soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs), both thought to be manifestations of magnetars, have not been seen at energies above several hundred kiloelectronvolts.

Most of the known >20 SGRs and AXPs\(^5\) are located at low Galactic latitudes (Olausen & Kaspi 2014), where the γ-ray contamination by the strong Galactic diffuse emission is severe. Also, in many cases, the presence of known supernova remnants (SNRs), molecular clouds, and/or energetic pulsars in the magnetars’ neighborhood impose source confusion in hard γ-ray bands. Meanwhile, a series of gigaelectronvolt bright SNR–molecular cloud (MC) association systems have been discovered with LAT (e.g., Abdo et al. 2009, 2010a, 2010b, 2010c; Castro et al. 2013; Xing et al. 2014; Araya 2015; Liu et al. 2015). Therefore, whether magnetars are intrinsically dark in MeV–GeV energies, or their GeV pulsations are just buried under the γ-ray backgrounds, is still unclear. Abdo et al. (2010d) analyzed the first ∼17 months of LAT data of 13 magnetars and did not find convincing evidence for γ-rays from any of the magnetars.

SGR 1806-20 was first discovered to be a source of soft γ-ray bursts (Laros et al. 1986) and its bursts were found to be recurrent (Atteia et al. 1987; Laros et al. 1987). It is also famous for its 2004 December 27 giant flare (Hurley et al. 2005). The persistent X-ray counterpart of SGR 1806-20, AX 1805.7-2025, was discovered by Murakami et al. (1994) with ASCA. The X-ray pulsation with a period of 7.47 s was determined by Kouveliotou et al. (1998) and a spin-down rate of ∼2.6 \times 10^{-3} \text{s yr}^{-1} was found. Woods et al. (2000) used a series of RXTE observations to investigate the spin evolution of SGR 1806-20 and found that SGR 1806-20 contains a significant timing noise. The spin history was refined by many investigations (e.g., Mereghetti et al. 2000; Woods et al. 2007). The latest long-term (years) spin history was reported by Younes et al. (2015) with a spin-down rate of ∼2.53 \times 10^{-3} \text{s yr}^{-1}, which is larger than the historical values measured in 1995.

SGR 1806-20 is a member of the cluster of giant massive stars C11 1806-20 (Fuchs et al. 1999; Corbel & Eikenberry 2004; Figer et al. 2005), which is located within the giant Galactic H ii complex W31 (Corbel & Eikenberry 2004). Bibby et al. (2008) determined that C11 1806-20 has a distance of 8.7^{+1.0}_{-0.8} kpc from us (which is consistent with a lower limit of 9.4 kpc set by Svirski et al. 2011). Among the members of this stellar cluster is a luminous blue variable (LBV) hypergiant LBV 1806-20, which generates tremendous wind powering the radio nebula G10.0-0.3 at its core (Gaensler et al. 2001; Corbel & Eikenberry 2004). C11 1806-20 also hosts four Wolf–Rayet

\(^5\) McGill magnetar catalog: http://www.physics.mcgill.ca/~pulsar/magnetar/main.html.
(WR) stars and four OB supergiants (Eikenberry et al. 2004; Figer et al. 2005). In the cluster, each WR star generates relatively intense wind, with a mass-loss rate of $\sim 10^{-5.2}$–$10^{-4.2} M_\odot$ yr$^{-1}$ and a terminal velocity of $(1.2$–$3.1) \times 10^6$ m s$^{-1}$ (see Table 4 of Nugis & Lamers 2002).

A radio nebula in W31, G10.0-0.3 (Kulkarni et al. 1994) which has a luminosity of $10^{32}$ erg s$^{-1}$ at the distance of 8.7 kpc (Bibby et al. 2008), is believed to be powered by LBV 1806-20 where the radio flux peaks (Gaensler et al. 2001; Kaplan et al. 2002), while analyses of Cerro Tololo Inter-American Observatory (CTIO) infrared, Chandra X-ray, and Inter-Planetary Network (IPN) $\gamma$-ray data for SGR 1806-20 confirmed the magnetar position to be off the center of G10.0-0.3 (Hurley et al. 1999; Eikenberry et al. 2001; Kaplan et al. 2002). Also, VLA observations of G10.0-0.3 showed no evidence of a blast wave or a supernova explosion because of a centrally condensed, time-varying morphology and an extraordinarily steep spectrum (Kulkarni et al. 1994; Vasisht et al. 1995; Frail et al. 1997). Therefore, Gaensler et al. (2001) doubted the putative SNR nature of this radio nebula and suggested that no known SNR is associated with SGR 1806-20.

HESS J1808-204, detected at the TeV band, has an extended feature similar in scale and orientation to that of G10.0-0.3, and hence they are argued to be associated with each other (Rowell et al. 2012). Its 0.5–5 TeV energy flux of $1.3 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ can readily be explained by the intense stellar wind from LBV 1806-20 from an energetic point of view (Rowell et al. 2012). At Fermi/LAT energies, a “confused” source, 2FGL J1808.5-2037c (Nolan et al. 2012) is cataloged at the southern edge of HESS J1808-204 (see Figure 1 of Rowell et al. 2012), while an updated Fermi/LAT catalog (3FGL; Acero et al. 2015) shows a “confused” source, 3FGL J1809.2-2016c, to the northeast of Cl’ 1806-20. This highlights the complexity of the megaelectronvolt–gigaelectronvolt emission from this region, and a dedicated investigation using all available LAT data is crucial to identify the origin of high-energy $\gamma$-ray emission.

SNR G9.7-0.0, which is a shell-type non-thermal SNR (Friel et al. 1994; Brogan et al. 2006), is separated from Cl’ 1806-20 by only 0$^\circ$.35 as projected on the sky. However, its distance from us of 4.7 kpc (Hewitt & Yusef-Zadeh 2009) is inconsistent with that of Cl’ 1806-20, making it impossible for them to be related to each other. The MC interaction of this SNR has been confirmed by the detection of a nearby OH(1720 MHz) maser (Hewitt & Yusef-Zadeh 2009), and hence it is a potential candidate for $\gamma$-ray emission.

In this work, we explore the MeV–GeV emission in the field of SGR 1806-20/Cl’ 1806-20 by using approximately seven years of Fermi/LAT data with the latest instrumental responses and background models. Then, we compare its morphology and spectrum to those of HESS J1808-204 (which is associated with G10.0-0.3). We also examine the correlation between the long-term temporal behavior of LAT flux and the X-ray outburst history of SGR 1806-20. In turn, we provide some insight into the possible origin(s) of the $\gamma$-rays.

2. OBSERVATION & DATA REDUCTION

We performed a series of binned maximum-likelihood analyses for a $20^\circ \times 20^\circ$ ROI centered at R.A. = 18$^h$08$^m$11$^s$.277 and decl. = $-20^\circ$.2852$^\prime$.82 (J2000), which is the centroid of 1–50 GeV emission around 3FGL J1809.2-2016c (see Section 3.1). We used the data obtained by LAT between 2008 August 4 and 2015 September 3. The data were reduced and analyzed with the aid of the Fermi Science Tools v10r0p5 package. In view of the complicated environment of the Galactic plane region, we adopted the events classified as Pass8 “Clean” class for the analysis so as to better suppress the background. The corresponding instrument response function (IRF) “P8R2. CLEAN_V6” is used throughout the investigation.

Considering that we include photons with energies of 60–300 MeV, and that we are investigating a crowded region on our Galactic plane, we focused on the events belonging to either “FRONT” or “PSF3” partition for better spatial resolution. In those cases that favor spectral resolution and/or photon statistics more than spatial resolution, we adopted “FRONT” data instead of “PSF3” data. We further filtered the data by accepting only the good time intervals where the region-of-interest (ROI) was observed at a zenith angle less than 90° so as to reduce the contamination from the albedo of Earth.

For subtracting the background contribution, we have included the Galactic diffuse background (gll_iem_v06.fits), the isotropic background (iso_P8R2_CLEAN_V6_PSF3_v06.txt for “PSF3” data or iso_P8R2_CLEAN_V6_FRONT_v06.txt for “FRONT” data) as well as all other sources cataloged in 3FGL within 25° of the ROI center in the source model. We set free the spectral parameters of the 3FGL sources within 7° of the ROI center in the analysis. For the 3FGL sources beyond 7° of the ROI center, their spectral parameters were fixed at the catalog values.

In spectral and temporal analysis, we required each energy-bin and time-segment to attain a signal-to-noise ratio $>$3$\sigma$ for a robust result. For each energy-bin or time-segment dissatisfying this requirement, we placed a 2$\sigma$ upper limit on its flux.

3. DATA ANALYSIS

3.1. Spatial Analysis

The test-statistic (TS) maps of the field around 3FGL J1809.2-2016c for “PSF3” data are shown in Figure 1, where all 3FGL catalog sources except 3FGL J1809.2-2016c are subtracted. The morphologies in 0.2–50 GeV and 1–50 GeV are both ellipse-like, with a major axis of $\sim 45^\circ$ anti-clockwise from the north. The peak detection significance is $\sim 27\sigma$ in 0.2–50 GeV and $\sim 15\sigma$ in 1–50 GeV. The 95% confidence regions of centroids determined on these two maps overlap more than one-third of the area of each other. They also overlap more than one-third of the area of the extents of HESS J1808-204. The centroid at 1–50 GeV is positionally consistent with SGR 1806-20/Cl’ 1806-20, and both 0.2–50 GeV and 1–50 GeV centroids are positionally consistent with SNR G9.7-0.0 as well as its maser. The 1–50 GeV centroid is taken to be the center of our ROI.

In order to examine whether the centroid position is significantly dependent on the energy band, we also created TS maps with the minimum energy cut ($E_{\text{cut,min}}$) shifted to 1.5, 2, 2.5, and 3 GeV, and the maximum energy cut shifted to 500 GeV. The contours of detection significance (4, 4.5, 5, 5.5$\sigma$) determined on the 2.5–500 GeV TS map are overlaid on both panels of Figure 1. The centroid distances, measured from...
the SNR G9.7-0.0 center and SGR 1806-20/Cl* 1806-20 respectively, as functions of the $E_{\text{cut,min}}$ are shown in Figure 2.

The centroid at the $E_{\text{cut,min}}$ of 200 MeV is almost equidistant (~0°.19) from the SNR G9.7-0.0 center and SGR 1806-20/Cl* 1806-20. As the $E_{\text{cut,min}}$ increases from 200 MeV to 2.5 GeV, the distances of the centroid from the SNR G9.7-0.0 center and from SGR 1806-20/Cl* 1806-20 remain essentially constant ($\chi^2 < 5$ for 4 dof). Nevertheless, one noticeable thing in 2.5–500 GeV is that, the detection significance at HESS J1808-204 and SGR 1806-20/Cl* 1806-20 is $\gtrsim 5.5\sigma$ while the detection significance at SNR G9.7-0.0 and its OH maser is $\lesssim 4.5\sigma$.

Figure 1. TS maps in 0.2–50 GeV (top) and 1–50 GeV (bottom), respectively, where all neighboring 3FGL catalog sources except 3FGL J1809.2-2016c are subtracted. On each map, the 95% confidence region of the centroid is indicated as a black thick cross, and the FWHM of the PSF is illustrated by a golden dashed circle. Both panels are overlaid with the magenta contours of detection significance (4, 4.5, 5, 5.5$\sigma$) determined in 2.5–500 GeV. The position and extents of HESS J1808-204, described as a thick brown ellipse, are taken from Rowell et al. (2012). The position and dimension of SNR G9.7-0.0, described by a green thick circle, are taken from Brogan et al. (2006), and the position of its OH maser, indicated as a green “X”, is taken from Hewitt & Yusef-Zadeh (2009). The position of SGR 1806-20/Cl* 1806-20, indicated as a gray diamond, is taken from Israel et al. (2005).

With the $E_{\text{cut,min}}$ further pushed to 3 GeV, the entire feature appears to be resolved into two separated clumps, each of which has a significant detection (3.3–$3.4\sigma$). Although the “dip” between their centroids is not statistically significant ($\sim 2.5\sigma$), it is noticeable that the regions of these two clumps are respectively coincident with HESS J1808-204 and SNR G9.7-0.0. In order to quantify the significance of two emission sites resolved in this energy band, we performed two tests: we re-made the TS map with the brighter clump modeled as an additional point source and subtracted, and we found that the residual at the other clump still has a detection significance of $\sim 3.0\sigma$; in a likelihood ratio test, we found that a model with two point sources (representing the two clumps respectively) is preferred over that with a single point source (representing the brighter clump) by $\sim 3.0\sigma$. Therefore, we have strong evidence for the two-emission-site morphology at energies $\gtrsim 3$ GeV.

To further investigate the 0.2–50 GeV morphology of 3FGL J1809.2-2016c, we followed the scheme adopted by Hui et al. (2011). We produced a γ-ray count-map where all 3FGL catalog sources except 3FGL J1809.2-2016c are subtracted, and then computed a brightness profile along the major axis of the ellipse-like feature. We also simulated an expected point-like source with the same spectrum as 3FGL J1809.2-2016c. The result is shown in Figure 3. To examine the source

Figure 2. Centroid distances, measured from the SNR G9.7-0.0 center and SGR 1806-20/Cl* 1806-20, respectively, as functions of the $E_{\text{cut,min}}$. At the $E_{\text{cut,min}}$ of 3 GeV, the entire feature is resolved to be two separated clumps (with an $\sim 3.0\sigma$ significance), so there are two data points on each panel, where the gray one is for the fainter (less significant) clump.
extension, we have fitted the profile with a single Gaussian. It yields an FWHM of $1.65 \pm 0.22$ ($\chi^2 = 2.51$ for 12 dof), exceeding that of the simulated point source, $0\degree.83$, by $>3.5\sigma$. We repeated this exercise for the minor axis of the ellipse-like feature, and obtained a FWHM of $1.53 \pm 0.19$ ($\chi^2 = 3.40$ for 12 dof). This also exceeds that of the simulated point source by $>3.5\sigma$. These suggest that the MeV–GeV emission from 3FGL J1809.2-2016c is extended along both major and minor axes.

Since the feature around 3FGL J1809.2-2016c is extended with the major and minor axes consistent within the tolerance of statistical uncertainties, we replaced the “confused” point source 3FGL J1809.2-2016c with a circularly extended source in the source model for subsequent analyses. We named it Fermi J1808.2-2029, assigned it a single power law (PL), and attempted uniform disks of different radii. They are centered at the $1–50$ GeV centroid (our ROI center), which is determined with better spatial resolution and sufficient photon statistics. The values of the In(likelihood) in $0.2–50$ GeV for “FRONT” data are tabulated in Table 1. We determined the radius to be $0\degree.65_{-0.09}^{+0.05}$ and this morphology is preferred over a point-source model by $>15\sigma$. Therefore, we modeled Fermi J1808.2-2029 as a uniform disk with $0\degree.65$ radius, in subsequent analyses.

### 3.2. Spectral Analysis

To construct the binned spectrum of Fermi J1808.2-2029, we performed an independent fitting of each spectral bin, adopting “FRONT” data. We examined how well the $0.2–50$ GeV spectrum can be described by, respectively, a simple PL

$$\frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right)^{-\Gamma} ,$$

an exponential cutoff power law (PLE)

$$\frac{dN}{dE} = N_0 \left( \frac{E}{E_0} \right)^{-\Gamma} \exp \left( \frac{-E}{E_c} \right) ,$$

and a broken power law (BKPL)

$$\frac{dN}{dE} = \begin{cases} N_0 \left( \frac{E}{E_0} \right)^{-\Gamma_1} & \text{if } E < E_b, \\ N_0 \left( \frac{E}{E_0} \right)^{-\Gamma_2} & \text{otherwise}. \end{cases}$$

For each spectral bin, we assigned Fermi J1808.2-2029 a PL model. The results of spectral fitting are tabulated in Table 2, and the spectral energy distribution is shown in Figure 4.

In $0.2–50$ GeV, the likelihood ratio test indicates that PLE is preferred over PL by $\sim6.5\sigma$. A PLE model yields a photon index of $\Gamma = 2.09 \pm 0.08$ and a cutoff energy of $E_c = 3628 \pm 1017$ MeV. BKPL is preferred over PL by $\sim8.0\sigma$, and the TS value BKPL yields is higher than that of PLE yields by $\sim26$. Despite the poorly constrained index
### Table 2
\(\gamma\)-ray Spectral Properties of Fermi J1808.2-2029 as Observed in 0.2–50 GeV by Fermi/LAT

| Model | Parameter | Value          |
|-------|-----------|----------------|
| **PL** | \(\Gamma\) | 2.44897 ± 0.027259 |
|       | Flux (\(10^{-9}\) photons cm\(^{-2}\) s\(^{-1}\)) | 160.924 ± 4.72334 |
|       | TS         | 1409.07        |
| **PLE** | \(\Gamma\) | 2.09236 ± 0.0835688 |
|       | \(E_0\) (MeV) | 3627.92 ± 1017.36 |
|       | Flux (\(10^{-9}\) photons cm\(^{-2}\) s\(^{-1}\)) | 157.55 ± 4.85607 |
|       | TS         | 1450.93        |
| **BKPL** | \(\Gamma_1\) | -0.414013 ± 0.714715 |
|       | \(\Gamma_2\) | 2.60408 ± 0.0442632 |
|       | \(E_0\) (MeV) | 296.947 ± 14.6352 |
|       | Flux (\(10^{-9}\) photons cm\(^{-2}\) s\(^{-1}\)) | 156.085 ± 5.48364 |
|       | TS         | 1476.96        |

#### Figure 4
SED of Fermi J1808.2-2029/HESS J1808-204. The upper limits are at the 2\(\sigma\) confidence level. The blue lines illustrate the best-fit BKPL model (solid) as well as the range allowed by a 1\(\sigma\) uncertainty (dashed) in 0.2–50 GeV. Sandwiched between the two red dashed curves is the 0.4–4 TeV HESS flux allowed by a 1\(\sigma\) uncertainty (see Figure 2 of Rowell et al. 2012).

\[\Gamma_1 = -0.41 \pm 0.71\] below the spectral break, the spectral break and the index above the break are well constrained to be \(E_0 = 297 \pm 15\) MeV and \(\Gamma_2 = 2.60 \pm 0.04\). The spectrum above \(E_0\) is steeper than that below \(E_0\) by >4\(\sigma\).

Extrapolating the BKPL model to 0.4–4 TeV, we obtain an estimated flux consistent with the H.E.S.S. measurements (reported by Rowell et al. 2012), within the tolerance of statistical uncertainties (see Figure 4).

#### 3.3. Temporal Analysis

In order to examine the long-term variability of Fermi J1808.2-2029, we divided the first \(\sim 6.9\) years of Fermi/LAT observations into 14 180 day segments. A binned maximum-likelihood analysis of “PSF3” data in 60 MeV–50 GeV was performed for each individual segment. We assumed a PL model for Fermi J1808.2-2029. The temporal behavior of the photon flux of Fermi J1808.2-2029 is plotted with the X-ray outburst history of SGR 1806-20, taken from GCN Circulars and Collazzi et al. (2015), altogether in Figure 5(a).

The \(\chi^2\) test indicates that the photon flux deviates from a uniform distribution at a confidence level of \(\sim 99.98\%\) (\(\chi^2 = 39.03\) for 13 dof), but the temporal variability shows no correlation with the X-ray outburst history of SGR 1806-20. Noticeably, the photon flux from MJD55582.655 to MJD55762.655 in the \(\sim 302–347\) days after the X-ray outburst at MJD55281 is greater than the \(\sim 6.9\) year average of the best-fit horizontal line by \(>4.0\) times its statistical error. If we randomly generate 14 data points of a Gaussian probability distribution with a mean and standard deviation based on the observed light-curve, in each of the 10\(^6\) Monte-Carlo simulations, the chance probability to obtain at least one data point different from the average by >4 times its statistical error is <0.1\%. This might indicate that our detection of the flux increment is not an occasional chance event.

In order to examine the gradualness or abruptness of such a flux increment, we divided the data \(\sim 122–572\) days after that X-ray outburst into 10 45 day segments, and performed a binned maximum-likelihood analysis for each segment. The temporal behavior of the photon flux is shown in Figure 5(b). The photon flux from MJD55582.655 to MJD55627.655 (in the data \(\sim 302–347\) days after that X-ray outburst) is higher than the \(\sim 6.9\) year average by \(\sim 4.3\) times its statistical error. Since the photon flux within these 45 days is even higher than those in the \(\sim 302–482\) days after that X-ray outburst by \(\sim 2.0\) times the statistical error, the flux increment is more likely to be abrupt.

In order to quantify the change of the photon flux and the spectral shape in the data \(\sim 302–347\) days after that X-ray outburst, we repeated the binned maximum-likelihood analysis in these 45 days with “FRONT” data of energies 200 MeV–50 GeV. As a result, a PL yields a signal-to-noise ratio of \(\sim 6.0\sigma\), which is sufficiently high for us to claim a significant detection, with a photon index of \(\Gamma = 2.72 \pm 0.24\) and a photon flux of \((2.20 \pm 0.39) \times 10^{-7}\) photons cm\(^{-2}\) s\(^{-1}\). The additional spectral parameters in PLE/BKPL are not statistically required based on a likelihood ratio test (<1\(\sigma\)). Compared to the approximately seven year average values of BKPL parameters shown in Table 2, the 200–300 MeV spectral shape becomes steeper at a >4\(\sigma\) level, the 0.3–50 GeV photon index is consistent with the approximately seven year average within the tolerance of statistical uncertainties, and the flux rises by \(\sim 1.6\) times the statistical error. In order to further check the robustness, we repeated the aforementioned analysis with the spectral parameters of the Galactic diffuse background and isotropic background fixed at the approximately seven year averages. As a result, the photon index and photon flux are both altered by only \(\lesssim 5\%\).

We confirm a genuine LAT flux enhancement of Fermi J1808.2-2029 within the 45 days. Since the ratio of the flux increment to the statistical error drops from \(\sim 4.3\) at >60 MeV to \(\sim 1.6\) at >200 MeV and the 200–300 MeV spectral shape becomes much steeper in these 45 days, we infer that almost the entire enhancement occurs at energy <400 MeV.

### 4. DISCUSSION

Fermi J1808.2-2029 is extended mainly toward the southwest direction (see Figures 1 & 3). Its emission region partly coincides with SNR G9.7-0.0 and partly coincides with SGR

\[\text{http://gcn.gsfc.nasa.gov/gcn3_archive.html}\]
1806-20/C1* 1806-20. The association between Fermi J1808.2-2029 and HESS J1808-204, where the latter has been associated with the radio nebula G10.0-0.3, is suggested by the connection of 300 MeV–4 TeV spectrum by a PL (see Figure 4).

Leptonic particles can be accelerated in the outer gap (outer magnetosphere) region and/or pulsar wind region of a neutron star, and can then produce γ-rays through the curvature radiation process and inverse-Compton scattering (IC) of soft photons (Aharonian et al. 2012; Lyutikov et al. 2012; Harding & Kalapotharakos 2015). Hadronic particles are mostly accelerated by SNR shocks, and then collide with protons in MCs to produce γ-rays through neutral-pion-decay (Ackermann et al. 2013). Leptonic cosmic-rays generally emit γ-rays at lower energies than hadronic cosmic-rays due to synchrotron cooling of leptons.

There are abundant infrared and optical photons within Cl* 1806-20 (see Balman et al. 2003; Israel et al. 2005; Kosugi et al. 2005; Rea et al. 2005), and cosmic microwave background photons are everywhere. These both can be seed photons for leptonic cosmic-rays to produce γ-ray emission through IC. NANTEN survey reveals some CO clouds positionally consistent with the 1–50 GeV centroid and/or 0.2–50 GeV centroid of Fermi J1808.2-2029 (see Figures 4(f) and 17 of Takeuchi et al. 2010). These clouds can be collision sites for hadronic cosmic-rays to produce γ-ray emission. During the searching process for the magnetar SGR 1806-20 in the MeV–GeV band, distinguishing between γ-rays produced by leptonic and hadronic cosmic-rays is an important issue.

4.1. Hadronic Scenario

4.1.1. Relactions with SNR G9.7-0.0

The spectrum of Fermi J1808.2-2029 has a turnover at energies below 1 GeV, consistently with the Fermi/LAT spectra of shell-type SNRs interacting with MCs such as W51C, W44, IC 443, and W28 (see Figure 3 of Abdo et al. 2009; Figure 3 of Abdo et al. 2010b; Figure 3 of Abdo et al. 2010c; Figure 3(a) of Abdo et al. 2010a). Therefore, significant γ-ray contribution from shell-type SNR G9.7-0.0 is suggested.

In 0.2–50 GeV, the most preferable spectral model for Fermi J1808.2-2029, BKPL, yields a spectral index Γ2 well within the range for GeV sources of SNR–MC hadronic interaction (see Table 3 of Liu et al. 2015). Integrations adopting the BKPL parameters in Table 2 give γ-ray energy fluxes of $F(\gtrsim E_0) \sim 2.19 \times 10^{-10} \text{ erg cm}^{-2} \text{s}^{-1}$ and $F(1–100 \text{ GeV}) \sim 9.88 \times 10^{-11} \text{ erg cm}^{-2} \text{s}^{-1}$. Assuming that Fermi J1808.2-2029 is just next to SNR G9.7-0.0 (at a distance of ~4.7 kpc from us), we obtain γ-ray luminosities of $L(\gtrsim E_0) \sim 5.80 \times 10^{35} \text{ erg s}^{-1}$ and $L(1–100 \text{ GeV}) \sim 2.61 \times 10^{35} \text{ erg s}^{-1}$. Both the $L(1–100 \text{ GeV})$ and $L(\gtrsim E_0)$ are well within the ranges of luminosities for SNRs, according to Table 3 of Liu et al. (2015) and Bamba et al. (2015) respectively.

However, the γ-ray spectra of many GeV-detected SNRs have a spectral break at a few gigaelectronvolts (Acero et al. 2016), in contrast to the PL connection of 300 MeV–4 TeV spectrum of Fermi J1808.2-2029/HESS J1808-204. Noticeably, the 2.5–500 GeV detection significance at SNR G9.7-0.0 and its OH maser drops to $\lesssim 4.5 \sigma$ (cf. Figure 1), and the region of HESS J1808-204 is totally inconsistent with that of SNR G9.7-0.0. Therefore, the interacting SNR G9.7-0.0 can only account for the γ-ray emission from 200 MeV to several gigaelectronvolts, but is unlikely to contribute significantly to the emission at energies above several gigaelectronvolts.

4.1.2. Relations with Cl* 1806-20

There are a number of MCs along the line of sight toward Fermi J1808.2-2029 and Cl* 1806-20, including MC 73 and MC 16, whose distances are consistent with that of Cl* 1806-20, i.e., ~8.7 kpc (Corbel & Eikenberry 2004; Takeuchi et al. 2010). They can be collision sites for hadronic cosmic-rays from Cl* 1806-20 to produce γ-ray emission.

Assuming that Fermi J1808.2-2029 is just next to Cl* 1806-20 (at a distance of ~8.7 kpc from us), we obtain γ-ray luminosities of $L(\gtrsim E_0) \sim 1.99 \times 10^{36} \text{ erg s}^{-1}$ and $L(1–100 \text{ GeV}) \sim 8.95 \times 10^{35} \text{ erg s}^{-1}$. The $L(1–100 \text{ GeV})$ is marginally within the range for GeV sources of SNR–MC hadronic interaction, while the $L(\gtrsim E_0)$ is beyond the range of 0.1–100 GeV luminosities for SNRs. We assume the average number density of protons in MCs near Cl* 1806-20 to be 100 cm$^{-3}$, which is appropriate for MC 73 and MC 16 (see Corbel & Eikenberry 2004). The cross section area of proton–proton collisions is $\sim 10^{-26} \text{ cm}^2$, and the angular diameter of
the cloud is $\sim 0.15$, which corresponds to $\sim 20$ pc at 8.7 kpc. We also assume the $\gamma$-ray conversion efficiency for each individual proton–proton collision to reach the maximum of 0.1. Hence, we inferred the $\gamma$-ray conversion efficiency of cosmic-ray energy to be $\sim 7.0 \times 10^{-6}$ and the required power from a nearby cosmic-ray accelerator to be $P_{\text{CR}}^{\text{local}} \sim 2.8 \times 10^{41}$ erg s$^{-1}$.

A typical supernova explosion releases energy of a canonical amount of $\sim 10^{51}$ erg, and its remnants can vigorously accelerate cosmic rays for $>5$ kyr (Dermer & Powale 2013), with an efficiency of $\sim 10\%$ for converting kinetic energy to nonthermal cosmic-ray energy (Ginzburg & Syrovatskii 1964). Therefore, the energy budget $P_{\text{CR}}^{\text{local}} \sim 2.8 \times 10^{41}$ erg s$^{-1}$ is so high that even a combined contribution from several SNRs inside or around Cl* 1806-20, if they exist, cannot supply it.

Even if SGR 1806-20 is a gigaelectronvolt emitting magnetar, it normally accelerates leptons but not hadrons, like other $\gamma$-ray pulsars (see Abdo et al. 2013). Therefore, it is reasonable to exclude SGR 1806-20 as a major hadronic source of Fermi J1808.2-2029.

Rowell et al. (2012) constrained the total kinetic energy of all stellar winds from Cl* 1806-20 to be $L_{\text{wd}} > 10^{38}$ erg s$^{-1}$, which is dominated by LBV 1806-20 and/or the four WR-stars. Assuming that the entire cluster is the energy source of Fermi J1808.2-2029, we obtain an efficiency of cosmic-ray production of $P_{\text{CR}}^{\text{local}} / L_{\text{wd}} < 3000$. Therefore, there is no evidence for the combined stellar wind of all Cl* 1806-20 members to be the major source.

Regardless of the cosmic-ray origin(s), the proton density ($\sim 100$ cm$^{-3}$) in MCs near Cl* 1806-20 is far from being sufficient to cause the observed $\gamma$-ray emission. It follows that a purely hadronic scenario does not support the adjacency between Fermi J1808.2-2029 and this cluster at all.

### 4.2. Leptonic Scenario

The analyses of XMM-Newton observations determined the spin-frequency of SGR 1806-20 on 2011 March 23 to be $\nu = 0.129838$ Hz, and the average spin-down rate from 2005 July to 2011 March to be $\dot{\nu} = 1.35 \times 10^{-11}$ Hz s$^{-1}$ (Younes et al. 2015). Hence, we obtain a spin-down power of $L_{\text{rd}} \sim 6.92 \times 10^{34}$ erg s$^{-1}$. Adopting the same $\nu$ and $\dot{\nu}$, we also obtain a surface magnetic-field strength of $B_{f} \sim 5.03 \times 10^{15}$ G at the pole. Hence, we can estimate the power of magnetic-field decay to be $L_{\text{bf}} > 10^{38}$ erg s$^{-1}$ (see Zhang 2003). Here, we have $L_{\text{bf}} > 10 L_{\text{rd}}$, which is consistent with the prediction for magnetars by Duncan & Thompson (1992). Assuming that SGR 1806-20 is the energy source of Fermi J1808.2-2029, we obtain $\gamma$-ray conversion efficiencies of $L(>E_{\gamma})/L_{\text{rd}} \sim 29$ and $L(>E_{\gamma})/L_{\text{bd}} < 2.0$. Assuming that the entire cluster is the energy source of Fermi J1808.2-2029, we obtain a $\gamma$-ray conversion efficiency of $L(>E_{\gamma})/L_{\text{rd}} < 0.02$. Therefore, the total kinetic energy of all stellar winds from Cl* 1806-20 can easily account for the emission detected at Fermi J1808.2-2029, while the energy loss of SGR 1806-20 alone, which mostly arises from magnetic energy, can only contribute to a small component of the emission.

Whereas, synchrotron cooling generally makes leptonic cosmic-rays difficult to produce $\gamma$-ray photons of a few gigaelectronvolts or above via synchrotron radiation. It follows that normal stellar winds from Cl* 1806-20 cannot explain the strong emission at energies above a few gigaelectronvolts and the gigaelectronvolt–teraelectronvolt PL connection. However, with the reduced synchrotron losses for high-energy IC emitting electrons, pulsar wind nebulae (PWNes) can maintain their high gigaelectronvolt–teraelectronvolt $\gamma$-ray fluxes for timescales exceeding the lifetime of their progenitor pulsars (Tibolla et al. 2011). Most terelectronvolt-detected PWNe are associated with pulsars of high spin-down power $>10^{36}$ erg s$^{-1}$ (Halpern & Gotthelf 2010). Although the spin-down power of SGR 1806-20 is an order of magnitude lower than this threshold, the major mechanism of energy injection for a magnetar is the rapid decay of its strong magnetic field (Duncan & Thompson 1992), which may account for the PWN-required power for SGR 1806-20.

Assuming that the loss of magnetic energy of SGR 1806-20 is the major source for the emission at energies $>4$ GeV, an integration adopting the BKPL parameters in Table 2 yields a $\gamma$-ray conversion efficiency of $L(>4\text{ GeV})/L_{\text{bd}} < 0.41$. Therefore, SGR 1806-20 alone is sufficient to generate a PWN, which may account for the flux at energies $>4$ GeV. Furthermore, the gigaelectronvolt–teraelectronvolt spectral connection is also consistent with this PWN scenario. Noticeably, the photon index 2.39 $\pm$ 0.19 of HESS J1808-204 (Rowell et al. 2012) is consistent with the photon index 2.65 $\pm$ 0.19 of HESS J1713-381 (Aharonian et al. 2008), which is a terelectronvolt PWN produced by the magnetar CXOU J171405.7-381031 (Halpern & Gotthelf 2010). Similarly to SGR 1806-20, CXOU J171405.7-381031 has a spin-down power of $L_{\text{rd}} \sim 4.2 \times 10^{34}$ erg s$^{-1}$, a surface magnetic-field strength of $B_{f} \sim 9.6 \times 10^{14}$ G at the pole (Halpern & Gotthelf 2010) and hence the power of magnetic-field decay $L_{\text{bf}} > 10^{36}$ erg s$^{-1}$ (see Zhang 2003). A major uncertainty of this scenario is that there is no firmly identified PWN in this region, as the leptonic and/or hadronic nature of HESS J1808-204 is currently unclear (Rowell et al. 2012).

At around 2011 January 21, the LAT flux of Fermi J1808.2-2029 started an abrupt yet dramatic enhancement with a slight spectral steepening, which lasted for $\lesssim 45$ days. It is unlikely to be associated with any X-ray outburst of SGR 1806-20. As the enhancement is constrained to occur at energies $\lesssim 400$ MeV, we interpret that the enhanced emission is mostly leptonic. Furthermore, according to the third catalog of AGNs detected by the Fermi/LAT (3LAC; Ackermann et al. 2015), there is no discovered AGN within 3° from the center of Fermi J1808.2-2029. Therefore, we speculate the possibility of an independent $\gamma$-ray outburst of SGR 1806-20 occurring at around that epoch.

### 5. SUMMARY

Fermi J1808.2-2029/HESS J1808-204 has intense $\gamma$-ray emission, with the spectrum from 300 MeV to 4 TeV well described by a PL model of photon index $\Gamma = 2.60 \pm 0.04$. In terms of the energy budget, the emission from 200 MeV to several gigaelectronvolts is easily accounted for by SNR G9.7-0.0 interacting hadronically with an MC and/or leptonic particles in stellar winds from Cl* 1806-20. We speculate the possibility that the emission from several GeV to 4 TeV is leptonic and dominated by a PWN powered by the magnetic-field decay of SGR 1806-20. Such a “hybrid” scenario is also consistent with the morphologies we observed: the centroid at the $E_{\text{cut},\text{min}}$ of 200 MeV is almost equidistant from the SNR G9.7-0.0 center and SGR 1806-20/Cl* 1806-20; in 3–500 GeV, the entire feature is resolved to be two separated clumps (with an $\sim 3.0\sigma$ significance), whose regions are,
respectively, coincident with HESS J1808-204 and SNR G9.7-0.0.

We confirm that an abrupt yet dramatic enhancement of 60–400 MeV (probably leptonic) LAT flux of Fermi J1808.2-2029 occurs from 2011 January 21 to March 7. Whether it is caused by the magnetar SGR 1806-20 or not remains an open question. Therefore, we strongly encourage the pulsation search of SGR 1806-20 using Fermi/LAT data within these 45 days.

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