A Survey of Supernova Remnants Detected by *Fermi*-LAT

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The Fermi Gamma-ray Space Telescope has firmly identified GeV emission from more than a dozen supernova remnants (SNRs) in its first years of operation. Long thought to be capable of supplying the high energy cosmic rays in the Galaxy, SNR shocks are ideal sites to study cosmic-ray acceleration. Here we review the SNRs detected by Fermi-LAT, and discuss their properties. The population of detected remnants spans a large range of ages and environments, allowing for a comparative study of acceleration efficiency. The inclusion of gamma-ray data in multi-wavelength models improves our general understanding of these SNRs, constraining physical parameters including the magnetic field, gas density and energetics.

Gamma-ray Supernova Remnants

Supernova remnants (SNRs) have long been thought to be the main sources of Galactic cosmic rays (CRs). By accelerating particles in their expanding shock waves, ~10% of the supernova kinetic energy is thought to be transferred into CR nuclei up to energies ~3x10^{15} eV. *Fermi*-LAT has now identified more than a dozen SNRs, summarized in the table below. Observations are reaching the spectral and spatial sensitivity to disentangle leptonic (inverse Compton/IC and bremsstrahlung) and hadronic (pion decay) emission mechanisms, directly probing the CRs accelerated by SNRs.

Fermi-LAT Identified SNRs

Classes are emerging as Fermi identifies an increasing number of SNRs. Bright SNR/MCs are the most numerous class. These SNRs have evolved past the wind-blown bubble of their massive progenitor, and are directly interacting with dense clouds. The large target mass of the cloud provides a natural explanation for the high luminosity.

Young SNRs are the second most numerous class. Historical SNRs Cas A and Tycho have flat spectra, while more aged SNRs Vela, Jr. and RX J1713.7-3946 peak in the TeV. Spectral differences could reflect differing emission mechanisms (hadronic vs leptonic) or changes in the spectrum of accelerated CRs with time.

As the sensitivity of Fermi has increased, a third class of faint SNRs has been identified. These SNRs, such as the Cygnus Loop (right), have evolved in a low-density ISM, and their relative dimness can be explained by the lower density of surrounding gas.

	SNR name	Index 1	Index 2	E_{break} (GeV)	Age (kyr)	Ref.
Young	Cassiopeia A	−2.1±0.1	−2.4±0.2*	>100	0.33	[2]
	Tycho	−2.3±0.2	−2.0±0.5*	–	0.44	[3]
	Vela, Jr.	−1.9±0.2	−2.1±0.2*	–	0.7	[4]
	RX J1713.7−3946	−1.5±0.1	−2.1±0.1*	–	1.6	[5]
	Puppis A	−2.0±0.1	–	–	3.7	[6]
	Cygnus Loop	−1.83±0.06	−3.2±0.2	2.4±0.3	~20	[7]
	S147	1.4±0.5	2.5±0.2	1.0±0.8	30	[8]
	W49B	−2.18±0.04	−2.9±0.2	4.8±1.6	~4	[9]
	CTB 37A	−2.28±0.1	–	–	~15	[10,16]
Middle-Aged	G349.7+0.2	2.0±0.1	–	–	14	[10]
	3C391	2.35±0.16	–	–	7	[10]
	W30	2.1±0.1	2.7±0.1	2.4±1.2	25	[10,11]
	IC 443	−1.93±0.03	−2.56±0.11	3.25±0.6	10-30	[12]
	W44	−2.1±0.1	−3.0±0.2	1.9±0.5	20-40	[13]
	W28	−2.1±0.3	−2.74±0.1	1.0±0.2	35-150	[14]
	W51C	−1.97±0.08	−2.44±0.09	1.9±0.2	20-40	[15]

*Index is taken from TeV ACT measurements.

Identification vs. Association

We established whether gamma-ray emission is *associated* by overlap within the SNR's radio extension, or truly *identified* with the SNR, based on several criteria:

• SOURCE EXTENSION. Resolving the source size is an unambiguous way of identifying SNRs. Of the 12 extended sources identified in 2FGL, 6 are SNRs. To date 10 SNRs have resolved spatial extensions with the LAT [4,5,6,7,8,12,13,14,15]. As the LAT sensitivity increases with time, particularly at high energies, an increasing number of faint SNRs should be resolvable. Of the 274 Radio SNRs in Green's Catalog [17], just less than half have sizes >20 arcminutes and may be resolved by the LAT.

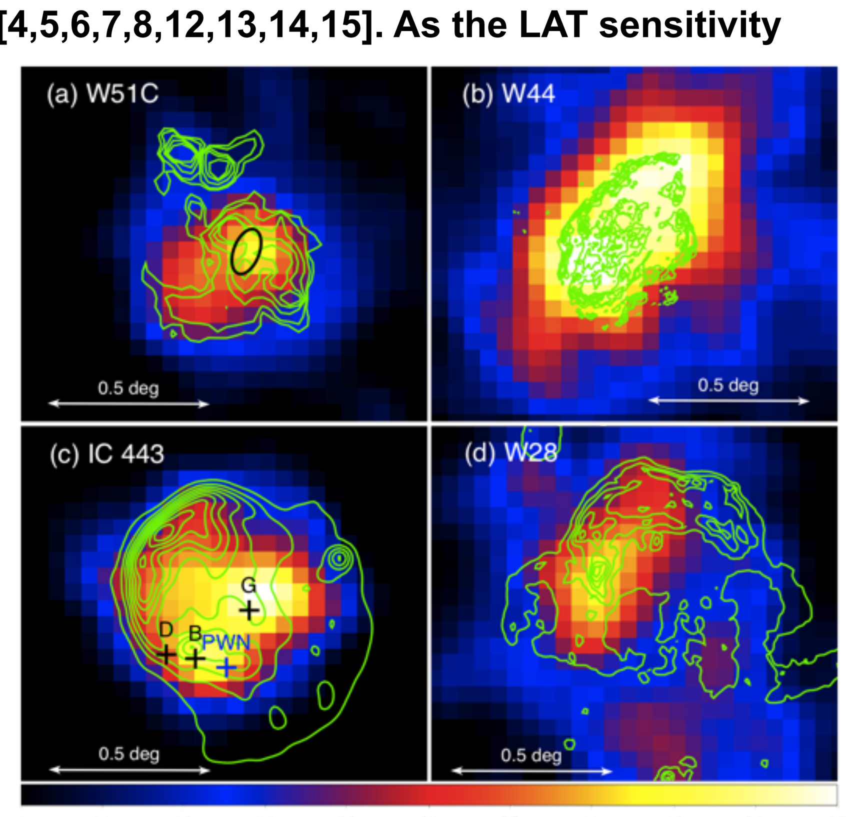

Figure 1. Fermi-LAT count maps of four extended SNR/MCs, using front events at 2-10 GeV. VLA radio contours are superposed. A black ellipse in panel (a) represents the location of shocked CO clumps. The black crosses in panel (c) are the locations of shocked clumps with OH masers. The position of the PWN is marked in panel (c).

• NONE-VARIABLE. No change in gamma-ray flux is expected or has been observed for any SNR. Variability typifies high-mass binary systems or extragalactic sources. One 2FGL association has been ruled out as an SNR based on blazar-like variability.

• RULING OUT PSRs/PWNe. For those cases in which neither the pulsar phase nor an extended source size can be resolved, an identification with the SNR can still be established by ruling out the PSR and PWN. For example, the central compact object of Cas A is too poor in energy to produce gamma-ray emission. While relatively few PWNe have been identified with the LAT, TeV and radio observations can be used to constrain the maximum emission in the Fermi LAT band. PWNe also have smaller sizes than the SNR.

Properties of GeV-bright SNRs

The Second Fermi Large Area Telescope Catalog (2FGL) detected 1873 sources at energies from 0.1-100 GeV, using 2 years of data: 89 sources overlap with the radio extension of an SNR; ~45% are estimated to be chance coincidences; 20 of these are firmly established as a PSR, PWN or high-mass binary; 10 SNRs are identified by spatially extension. The remaining 42 SNRs with 2FGL associations hint at the large population of GeV-bright SNRs which have not yet been firmly identified.

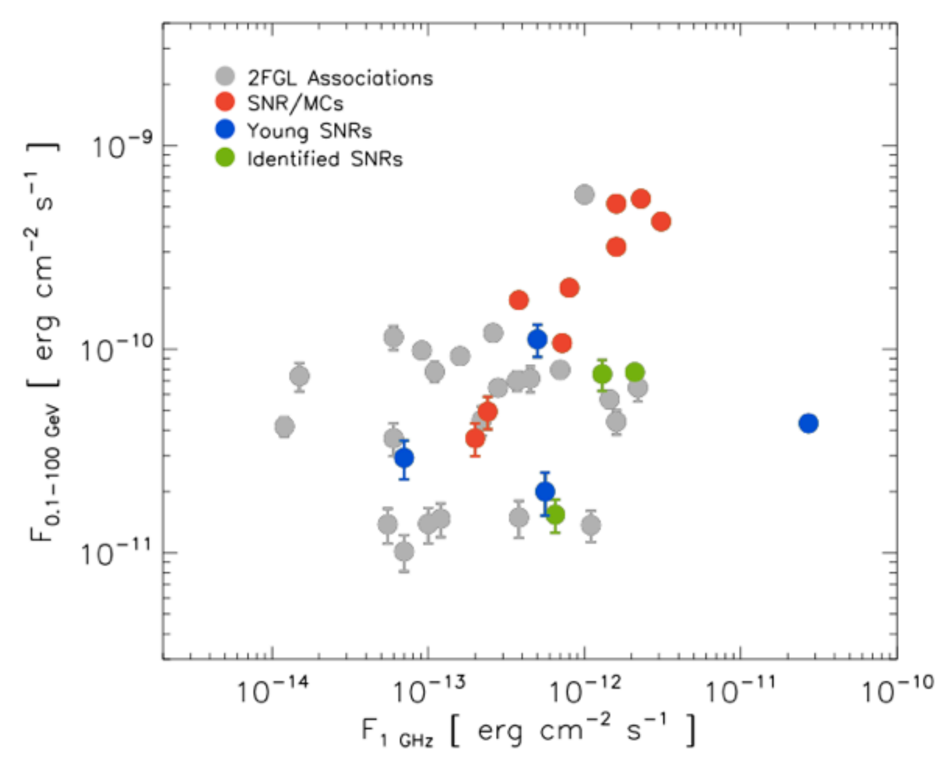

Figure 2. Synchrotron radio (1GHz) flux vs. gamma-ray (0.1-100 GeV) flux. Large scatter is seen for all 2FGL-detected SNRs, however a correlation can be seen for the subset of identified SNRs known to be interacting with molecular clouds.

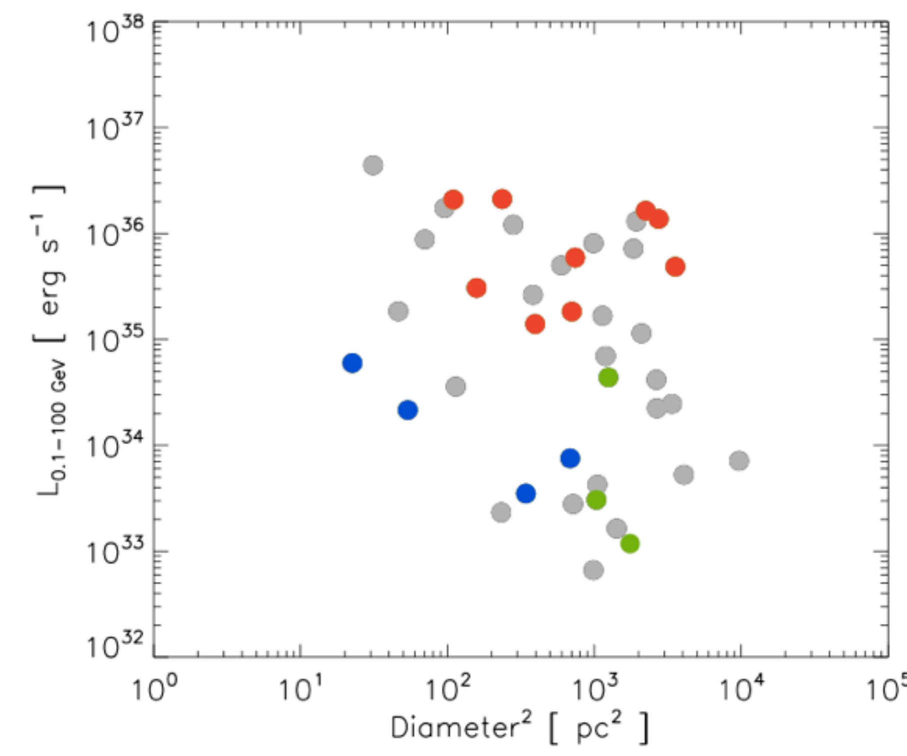

Figure 3. Gamma-ray luminosity plotted as a function of diameter squared (using the radio size). Among identified SNRs, those interacting with molecular clouds are brighter than young SNRs and those evolving in the diffuse ISM.

The correlation between radio and GeV observed for SNR/MCs (Fig. 2) suggests a physical link. SNR/MCs are also more luminous than other LAT-identified SNRs (Fig. 3). The diameter^2 traces SNR age, as the Sedov age is related to its radius as t ~ R$^{2.5}$ [1]. The luminosity of SNR/MCs is so high that IC scattering off the CMB becomes unlikely. Assuming a ~10% efficiency for CR acceleration and an electron-to-proton ratio K_{ep} =0.01, the luminosity of IC is only ~10^{34} erg s^{-1}. This is at least an order of magnitude below the faintest SNR/MC [1]. π^0-decay origin is favored over bremsstrahlung for these sources, unless K_{ep} ~ 1.

Non-thermal Modeling of Cygnus Loop

The Cygnus Loop is an evolved SNR, but not interacting with dense clouds [18]. The gamma-ray morphology is well-matched to X-ray and Hα filaments [8]. The radio is generally well-correlated, but not for all regions. Non-thermal modeling constrains the environment density, magnetic field, and energy in CRs. Bremsstrahlung models cannot fit both the GeV and radio breaks. IC models are viable, but require B<2 μG, and a low gas density ~0.02 cm^{-3} to suppress Bremsstrahlung emission. A π^0-decay model gives a good fit with a total power in CRs of ~3x10^{48} erg (5 cm^{-3}/n_H). This is <1% of the SNe kinetic energy, whereas Cas A and Tycho require ~10%. Either Cygnus Loop was an inefficient accelerator, or CRs have escaped by this late time. The presence of a break at ~2 GeV is suggests the latter.

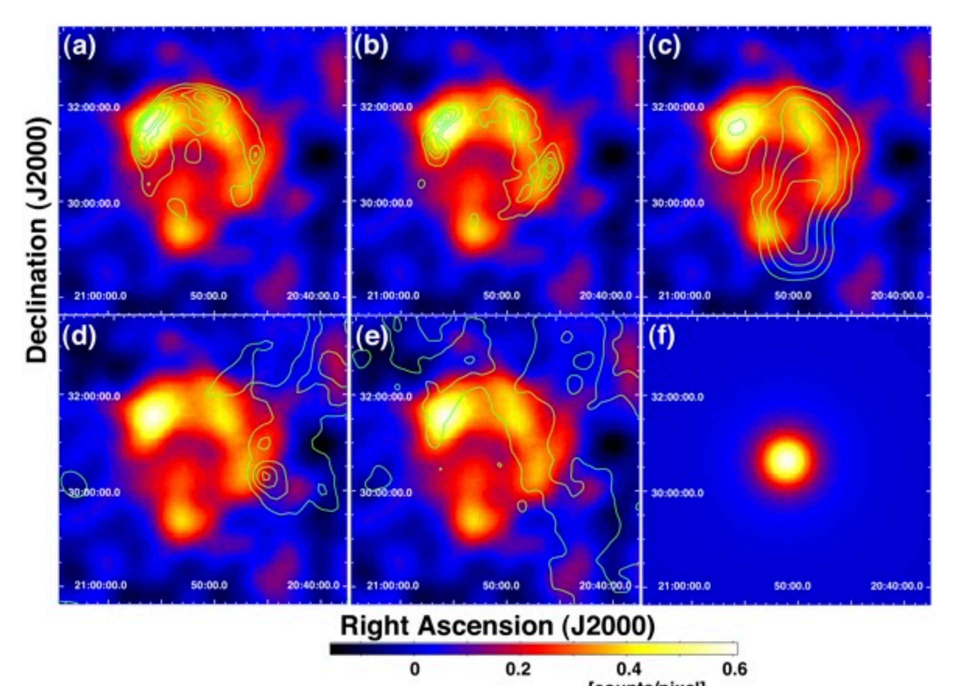

Figure 4. Background-subtracted counts maps at 0.5-10 GeV [8]. Contours correspond to images of: (a) X-rays, (b) Hα, (c) Radio, (d) CO, (e) HI, (f) the LAT PSF.

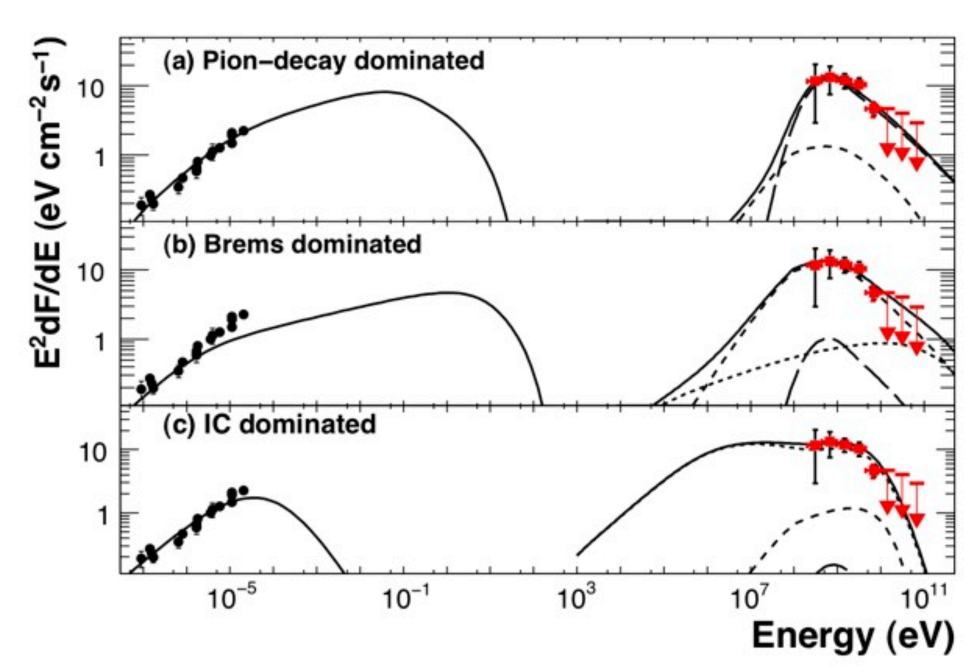

Figure 5. Multi-band spectral fits to radio and gamma-ray emission [8]. All models show different combinations of π^0 decay (long-dash), bremsstrahlung (dash), and IC (dotted).

Conclusions

***Fermi*-LAT has identified a large sample of gamma-ray SNRs over a range of ages and environments. GeV luminosity appears to provide separation between newly established classes. A possible correlation between radio and gamma-ray fluxes for SNR/MCs is presented. Work is underway to systematically catalog SNRs with Fermi, and better constrain the contribution of SNRs to Galactic CRs throughout their evolution.**

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