Investigating the Vela SNR's Emission of Electron Cosmic Rays with CALET at the International Space Station

Holger Motz for the CALET collaboration

Waseda University, Faculty of Science and Engineering, Global Center for Science and Engineering, Okubo 3-4-1, Shinjuku, Tokyo, Japan

Introduction

No direct assignment of cosmic rays to an individual astrophysical source has been achieved so far, because the direction information is lost in propagation. A possibility to study a few sources are TeV energy electrons, which are limited in range by energy loss, with the following supernova remnant (SNR) source as candidates [1]:

- Vela SNR: distance ~ 0.3 kpc , age ~ 11 kyr
- Monogem SNR: distance ~ 0.3 kpc , age ~ 86 kyr
- Cygnus Loop: distance ~ 0.44 kpc , age ~ 20 kyr

The total energy emitted by each SNR in electron cosmic rays above 1 GeV is estimated to be on the order of $Q_{0_{SNR}} \sim 10^{48}$ erg [1].

In this work we study what range is preferred for $Q_{0_{SNR}}$, and what limits can be set on it, based on the latest all-electron spectrum measured by CALET [2].

Electron and Positron Flux Parametrization

$$\Phi_e^- = C_e E^{-(\gamma_e - \Delta\gamma_e)} \left(1 + \left(\frac{E}{E_b}\right)^{\frac{\Delta\gamma_e}{s}}\right)^s e^{-\left(\frac{E}{E_{cut_d}}\right)} + \frac{C_s}{C_{norm}} \Phi_{s(e^-)} + \Phi_{pulsars} + \Phi_{nearSNR}$$

$$\Phi_e^+ = \frac{C_s}{C_{norm}} \Phi_{s(e^+)} + \Phi_{pulsars}$$

- Distant SNR: Power law with a soft spectral break at low energy, and a high-energy exponential cut-off at $E_{cut_d} = 1$ TeV representing radiative energy loss of high energy electrons. (Parameters: normalization C_e, index γ_e, break position E_b and index change $\Delta\gamma_e$ are free, softness $s = 0.05$ is fixed)
- Secondary positron ($\Phi_{s(e^+)}$) and electron ($\Phi_{s(e^-)}$) fluxes: From DRAGON calculations of nuclei spectra with rescale factor. (Parameter: C_s/C_{norm})
- Pulsar flux $\Phi_{pulsars}$ as source of the positron excess: Combined flux of nearby (<1 kpc) and young (1 Myr) pulsars from ATNF catalog [3], using given age, position and initial energy. Analytic calculation of CR propagation, diffusion time is age minus release time delay. (Parameters: spectral index, cut-off energy, acceleration efficiency, release time delay common for all pulsars)
- Flux $\Phi_{nearSNR}$ from nearby SNR: Calculated with DRAGON as a point source, power law index γ_i same as for nuclei in the used propagation model. Spectrum normalized to $Q_{0_{SNR}} = 10^{48}$ erg over 1 GeV integrated over the injection duration, rescaled for best fit and limit calculation.

Best Fit and Limit Calculation

Fit to CALET ($\Phi_e^- + \Phi_e^+$) and AMS-02 (Φ_e^+) for $E > 10$ GeV, using sum of both χ^2.

For CALET data systematic uncertainties treated by fitting a weight w for the energy dependent 1σ deviation $\Delta(E)$ for each type of systematic error with known energy dependence (Normalization, tracking, charge selection, electron identification, Monte Carlo). Fit function shifted by $w\Delta(E)$, each squared weight added to the total χ^2.

To derive the limit on $Q_{0_{SNR}}$, the parameter is increased in iteratively smaller steps (down to 10^{45} erg) up to the value were χ^2 exceeds the 95% CL threshold.

Propagation Models

Parameters determined by comparison of nuclei spectra calculated with DRAGON [4] with experimental data of proton spectrum and B/C ratio.

Spectral hardening of the nuclei spectra explained by a soft break in the slope of the diffusion coefficient with rigidity.

Injection spectrum is a single index (γ_i) power law with exponential cut-off at R_{cut} common for all primary nuclei species.

Diffusion coefficient depending on position (increasing exponentially with galactic radius r, distance from galctic plane z) and rigidity:

$$D(r, z, R) = D_0 \max\left\{e^{(r-r_n)/r_s}, 1\right\} \max\left\{e^{(z-z_n)/z_s}, 1\right\} \left(\frac{R}{R_0}\right)^{\delta_l} \left(1 + \left(\frac{R}{R_b}\right)^{\frac{\delta_l - \delta_h}{s}}\right)^{-s}$$

Four distinct models (A,B,C,X) to cover a wide range in local diffusion speed.

Common parameter values: $R_0 = 4$ GV, $\delta_l = 0.5$ (Kraichnan turbulence), $r_n = 2$ kpc (galactic bulge), $z_n = 0.15$ kpc (inner disk).

Model	Description	D_0 $[10^{28}\text{cm}^2/\text{s}]$	$D_{0(sol)}$ $[10^{28}\text{cm}^2/\text{s}]$	r_s [kpc]	L [kpc]	z_s [kpc]	R_b [TV]	δ_h	s	v_a [km/s]
X	Very low diffusion fits helium spectra	0.16	1.31	3.0	6	0.6	1.0	0.01	0.3	18
A	Low diffusion	0.66	2.58	4.5	3	1.8	0.5	0.2	0.05	0
B	Medium diffusion	1.32	5.35	4.5	6	3.5	0.5	0.2	0.05	0
C	High diffusion	1.78	7.22	4.5	6	5.3	0.5	0.2	0.05	0

Table 1. Propagation model parameters.

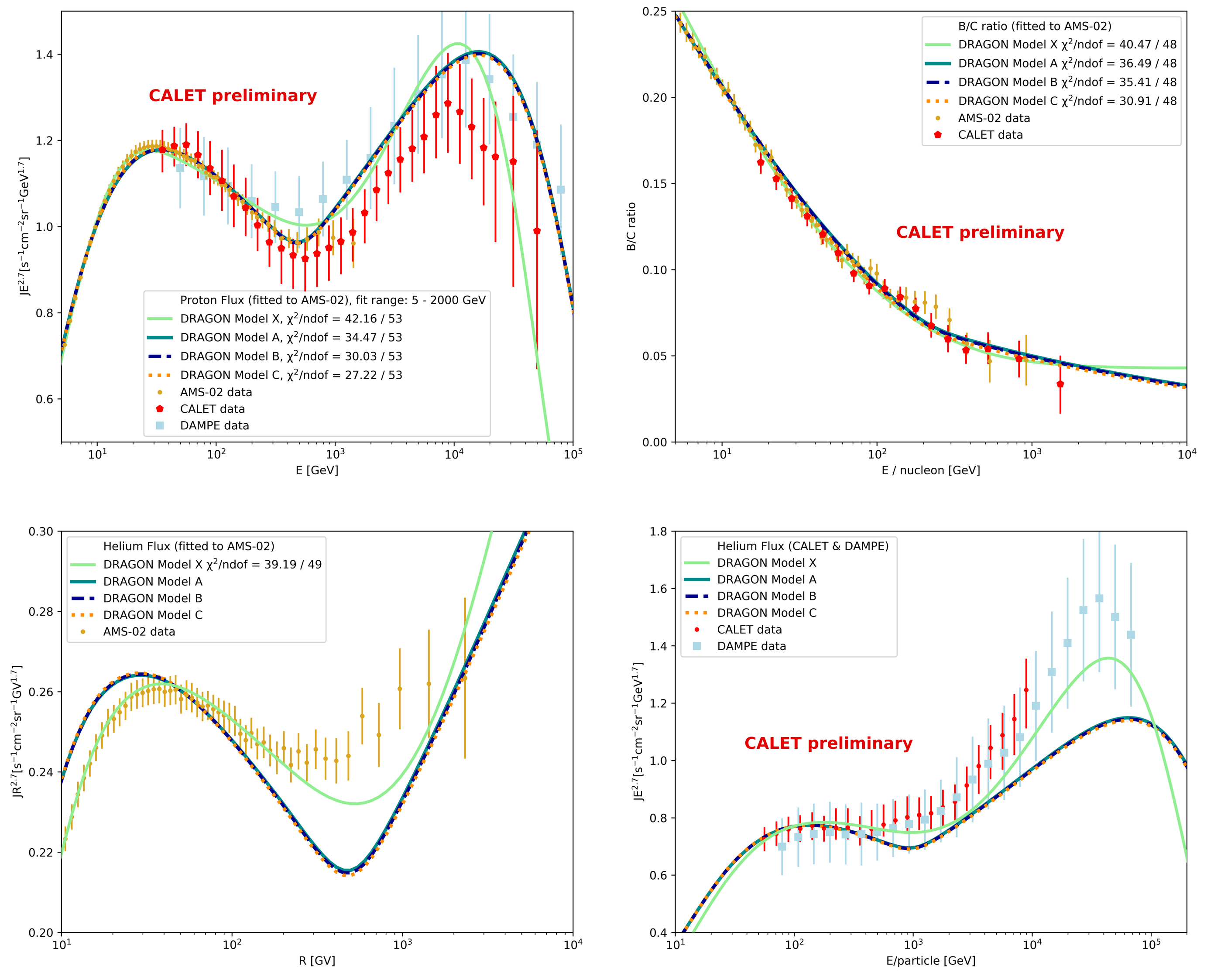


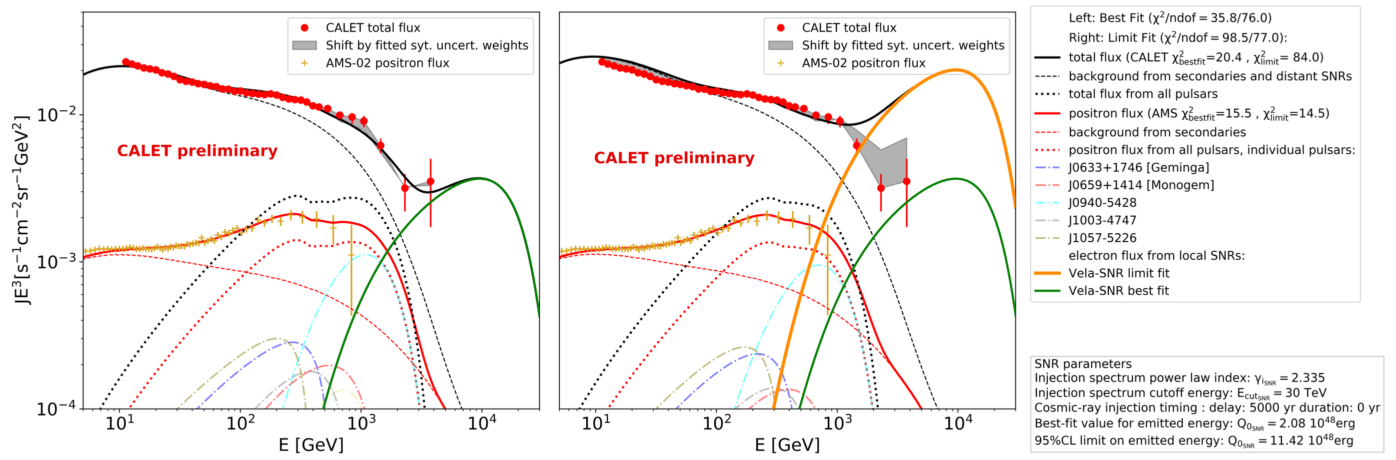
Figure 1. Comparison of the DRAGON calculation results to measurements. Normalization and solar modulation fitted to AMS-02 data. Models A,B,C reproduce proton spectrum and B/C ratio, Model X simultaneously reproduces the helium spectrum within experimental errors.

Results for Vela-only Study

Only Vela as the dominating source in the TeV region is added to the background.

Two scenarios: Continuous injection with constant intensity over a duration and burst-like release after a delay. Studied parameter space for each:

- propagation models: X, A, B, C
- duration/delay: 0, 1, 2, 5, 10 kyr
- spectrum cut-off energy: 10, 20, 30, 50, 100, 200 TeV



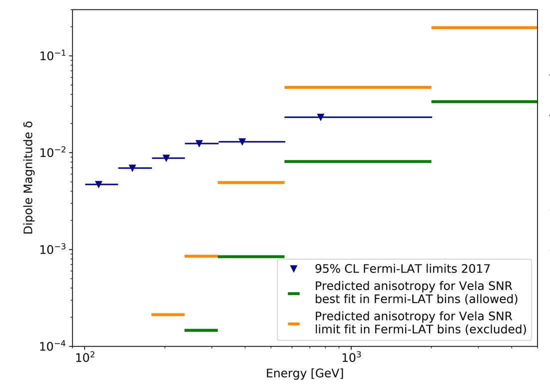


Figure 2. Top: Example of best fit (left) and limit fit (right) for 5 kyr delay, 30 TeV cut-off energy, Model X. The fitted weights of the systematic uncertainties contribute 4.05 (26.2) to χ^2 of best (limit) fit. Left: Comparison of the anisotropy for the model with the 2017 Fermi-LAT anisotropy limit [5]. The best fit is allowed (anisotropy below the limit), the limit fit is excluded (above the limit), i.e. a stricter limit from anisotropy exists.

Model	duration [kyr] 0	1	2	5	10	delay [kyr] 1	2	5	10
	Best-Fit Q_0 $[10^{48}$ erg]								
X	0.37 – 0.58	0.44 – 0.58	0.43 – 0.65	0.52 – 0.76	0.93 – 1.33	0.54 – 0.79	0.47 – 0.67	1.84 – 2.59	2875 – 4037
A	0.35 – 0.49	0.34 – 0.48	0.33 – 0.48	0.33 – 0.46	0.42 – 0.59	0.36 – 0.51	0.32 – 0.46	0.42 – 0.60	5.68 – 8.10
B	0.55 – 0.78	0.52 – 0.77	0.50 – 0.71	0.44 – 0.62	0.37 – 0.53	0.51 – 0.72	0.45 – 0.65	0.37 – 0.54	0.55 – 0.77
C	0.70 – 1.01	0.92 – 1.01	0.62 – 1.02	0.57 – 0.83	0.41 – 0.61	0.58 – 0.92	0.58 – 0.85	0.43 – 0.65	0.37 – 0.51
	95%CL-Limit Q_0 $[10^{48}$ erg]								
X	1.83 – 2.44	1.92 – 2.56	2.04 – 2.71	2.63 – 3.47	4.62 – 6.10	2.59 – 3.41	2.35 – 3.10	10.6 – 13.9	21365 – 28612
A	1.40 – 1.75	1.39 – 1.74	1.38 – 1.74	1.40 – 1.79	1.87 – 2.43	1.50 – 1.91	1.37 – 1.73	2.00 – 2.62	41.3 – 56.2
B	2.06 – 2.48	1.98 – 2.38	1.90 – 2.29	1.68 – 2.05	1.60 – 2.00	1.92 – 2.34	1.75 – 2.12	1.57 – 1.94	3.19 – 4.17
C	2.73 – 3.27	2.60 – 3.12	2.48 – 2.97	2.11 – 2.54	1.73 – 2.13	2.47 – 2.97	2.25 – 2.70	1.74 – 2.11	1.88 – 2.42

Table 2. Result overview for the Vela-only study. Each cell shows the range of $Q_{0_{SNR}}$ with variation of the cut-off energy (mostly 10 TeV highest, 200 TeV lowest value). Fermi-LAT anisotropy limit [5] comparison: Best fits allowed for Model X, A, B (partly), all excluded for Model C. All limit fits are excluded, thus the limits from anisotropy are stricter.

References

[1] T. Kobayashi, Y. Komori, K. Yoshida, and J. Nishimura. The Most Likely Sources of High-Energy Cosmic-Ray Electrons in Supernova Remnants. *Astrophys. J.*, 601:340–351, January 2004.

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[4] Daniele Gaggero et al. Three-Dimensional Model of Cosmic-Ray Lepton Propagation Reproduces Data from the Alpha Magnetic Spectrometer on the International Space Station. *Phys.Rev.Lett.*, 111(2):021102, 2013.

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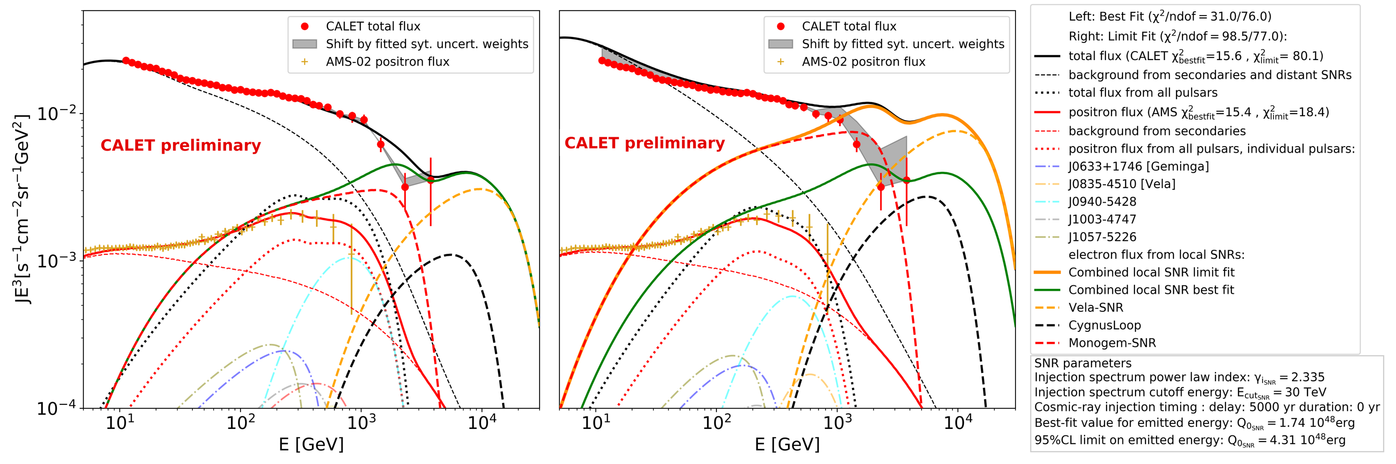
Results for Three-Nearby-SNR Study

The combined flux from all three nearby SNR significantly contributing in the TeV region (Vela, Monogem and Cygnus Loop) is added to the background.

Except age and position, the three SNR are assumed to have identical properties.

Same range of parameters as in the Vela-only study.



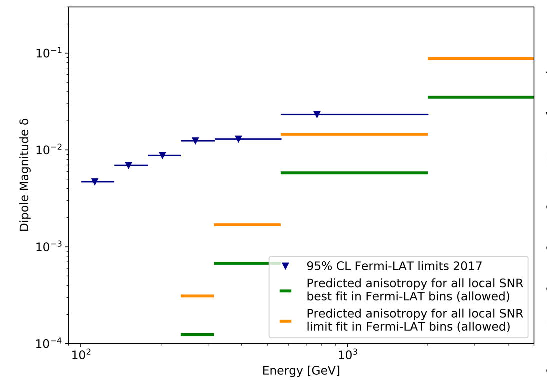


Figure 3. Top: Example of best fit (left) and limit fit (right) for 5 kyr delay, 30 TeV cut-off energy, Model X. The fitted weights of the systematic uncertainties contribute 1.96 (28.9) to χ^2 of best (limit) fit. Left: Comparison of the anisotropy for the model with the 2017 Fermi-LAT anisotropy limit [5]. Both the best fit and the limit fit are allowed (anisotropy below the limit), i.e. the limit from CALET spectral data is stricter than the Fermi-LAT anisotropy limit.

Model	duration [kyr] 0	1	2	5	10	delay [kyr] 1	2	5	10
	Best-Fit Q_0 $[10^{48}$ erg]								
X	0.33 – 0.50	0.35 – 0.57	0.36 – 0.55	0.44 – 0.71	0.70 – 1.21	0.43 – 0.70	0.41 – 0.67	1.38 – 2.23	2.05 – 3.17
A	0.27 – 0.40	0.27 – 0.37	0.26 – 0.39	0.25 – 0.37	0.31 – 0.45	0.28 – 0.41	0.25 – 0.38	0.31 – 0.45	1.08 – 1.70
B	0.40 – 0.61	0.40 – 0.59	0.38 – 0.57	0.34 – 0.50	0.29 – 0.45	0.39 – 0.56	0.35 – 0.51	0.30 – 0.44	0.39 – 0.58
C	0.54 – 0.81	0.52 – 0.86	0.50 – 0.73	0.43 – 0.66	0.33 – 0.50	0.51 – 0.71	0.43 – 0.68	0.35 – 0.53	0.29 – 0.40
	95%CL-Limit Q_0 $[10^{48}$ erg]								
X	1.38 – 1.89	1.44 – 1.97	1.52 – 2.09	1.85 – 2.55	2.67 – 3.58	1.85 – 2.55	1.70 – 2.34	3.94 – 5.05	4.82 – 5.63
A	1.32 – 1.05	1.05 – 1.33	1.05 – 1.33	1.07 – 1.38	1.34 – 1.77	1.12 – 1.44	1.03 – 1.32	1.41 – 1.89	4.62 – 6.43
B	1.48 – 1.78	1.45 – 1.75	1.40 – 1.70	1.26 – 1.55	1.20 – 1.50	1.40 – 1.70	1.29 – 1.56	1.17 – 1.45	1.83 – 2.44
C	1.91 – 2.30	1.89 – 2.26	1.81 – 2.17	1.58 – 1.90	1.33 – 1.63	1.78 – 2.13	1.64 – 1.96	1.32 – 1.59	1.34 – 1.75

Table 3. Result overview for the three SNR study. Each cell shows the range of $Q_{0_{SNR}}$ with variation of the cut-off energy (mostly 10 TeV highest, 200 TeV lowest value). Fermi-LAT anisotropy limit [5] comparison: Best fits allowed for Model X, A, B (partly), C (partly). Limit fits for Model A, 10 kyr delay and Model X, 5 & 10 kyr delay are allowed, others excluded.

Conclusions

From fitting the calculated flux from nearby SNR to CALET data it is found that for most studied propagation, release timing and spectral cut-off conditions:

- The preferred range for the energy emitted by a SNR in electron cosmic rays above 1 GeV is several 10^{47} erg with a majority of best-fit cases allowed (Model X,A: all ; Model B,C: partial) by the Fermi-LAT anisotropy constraint.
- 95%CL limits on the order of a few 10^{48} erg can be set on this emission.

The exception are conditions of delayed release and low propagation speed (Model A, 10 kyr delay and Model X, 5 & 10 kyr delay ; red in Tables 2 and 3):

- The best fit energy may exceed 10^{48} erg significantly.
- No strong limit can be set on the Vela SNR alone, but if considering the combined flux from all the nearby SNR limits of $\sim 5 \times 10^{48}$ erg can be set.
- These limits are stricter than those from Fermi-LAT anisotropy data.

motz@aoni.waseda.jp

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