Galactic Propagation of Cosmic Rays from Individual Supernova Remnants

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1. Question|

Can predicted cosmic ray spectra of supernova remnants explain the cosmic ray observations (<PeV) at Earth?

2. Source Spectra|

- Proton spectra j_p of N=20 supernova remnants (SNRs) from fit to gamma ray fluxes [1] (see fig. 1, 2).
- Proton luminosity L_p and j_p connected via

$$L_p = cR^2 \int_{10\,\mathrm{MeV}}^{10^9\,\mathrm{MeV}} dE\, E \sqrt{1-\left(\frac{mc^2}{E+mc^2}\right)^2}\, j_p(E)$$

with kinetic energy E, speed of light c, proton mass m, radius R of SNR.

- Time scale t_{diff}~10^4 yrs of diffusive escape from the SNRs [3].
  → normalization of j_p fixed by total energy E_{tot} i.e. $L_p = E_{tot}/t_{diff}$.

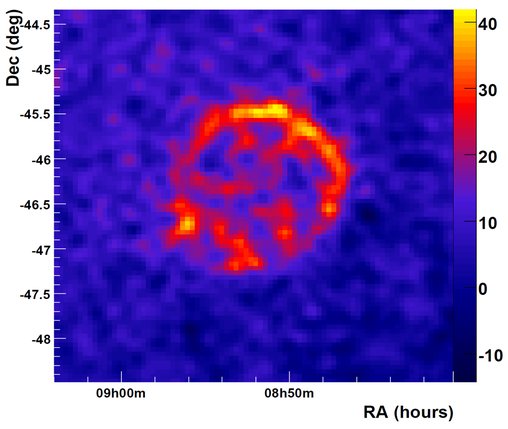

Fig. 1: Gamma ray image of the SNR Vela Jr for energies higher than 0.5 TeV taken from [2].

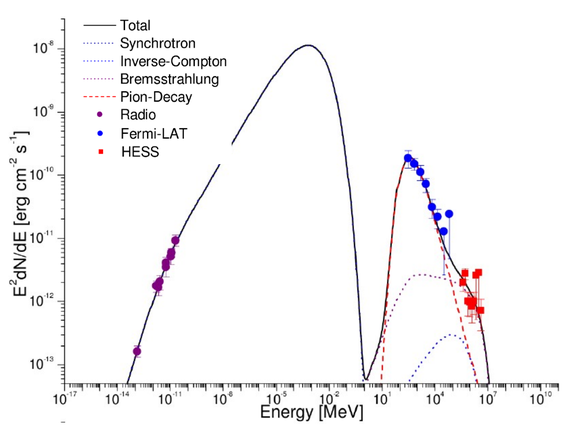

Fig. 2: Modeled spectral energy distributions of W28 for a hadronic scenario as presented in [1].

3. Propagation|

- Effects of galactic propagation on j_p simulated with GALPROP [4, 5]:
  - *standard* settings of GALPROP [4],
  - galactic volume: 10 kpc³,
  - simulation grid size: 1 kpc and 0.1 kpc along the x/y and z coordinate axis.
- *<dF/dE>:* average proton spectrum from M=50 sets of N=20 SNRs. SNRs located at $\boldsymbol{r}_{cgp}$ which is the grid-point closest to a random positions drawn from the SNR-distribution in [4]
  → prediction for observed CR spectrum.
- SNRs modeled as delta functions: $\delta(\boldsymbol{r}-\boldsymbol{r}_{cgp})$.

4. Results|

Fig. 3:

- Spectral index γ of proton spectrum reproduced (10 GeV to ~50 TeV) .
- Higher γ predicted for energies E > 50 TeV.

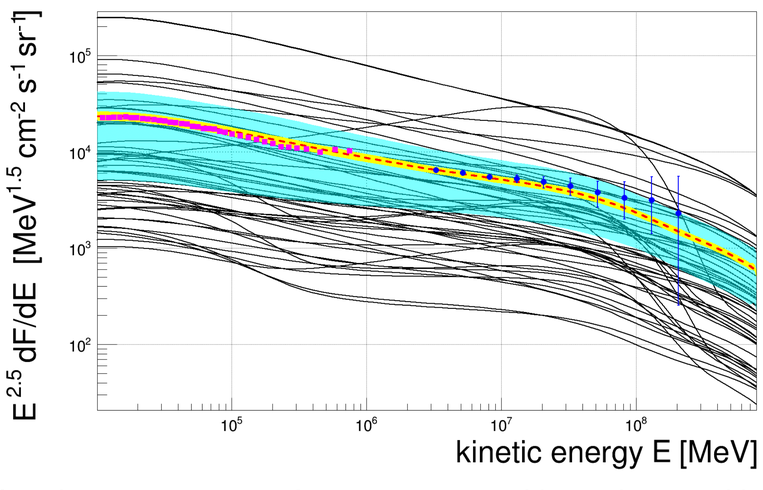

Fig. 3: Simulated proton spectra of 50 SNRs sets with random positions (black). Mean values <*dF/dE*> (red) and their errors (yellow band) as well as the spread (blue band) are displayed. Blue dots show measured data from CREAM [7], the magenta curve present the observations by PAMELA [11] (left).

- Simulated SNRs provide ~70 % of measured CR flux.
- Simulations upscaled by α=1.45
  → account for unresolved SNRs.
- PAMELA [11] and CREAM [7] data shifted up and down, respectively, by systematic uncertainties
  → smooth continuation from low to high energies.

Fig. 4:

- Boron to Carbon (B/C) ratio measurements [8] reproduced.

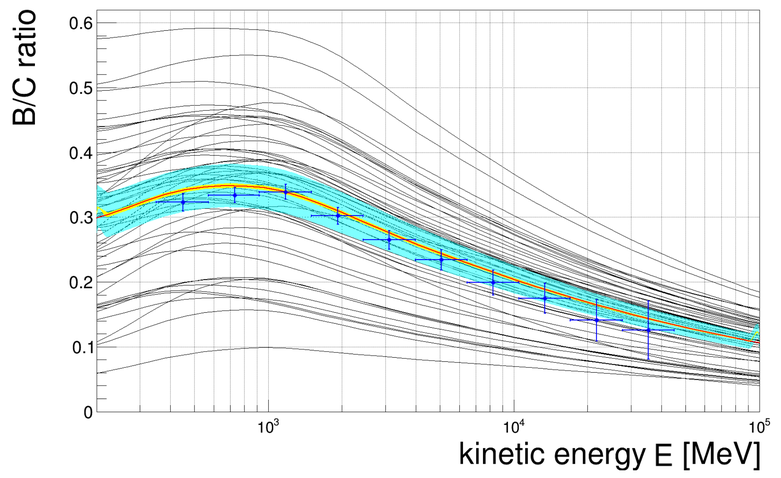

Fig. 4: Simulated B/C ratios of 50 SNRs sets with random positions (black). Mean values (red) and their errors (yellow band) as well as the spread (blue band) are displayed. Blue dots show measured data from AMS-01 [8].

5. Discussion|

- Spectral behavior of CR proton spectrum is well described (10 GeV to ~50 TeV)
  → support for theory of CR origin in SNRs [12].
- B/C ratio fits data
  → simulation settings well suited for galactic propagation.
- SNR sample is not statistically complete
  → steeper spectrum (E>50 TeV)?
  → Include flat spectrum SNRs (e.g. from [8]).
- Scaling of <dF/dE> by a factor of α=1.45 needed to match energy budget of CR data:
  → (I) All missing SNRs only contribute with a factor of 1.45,
  → (II) CR luminosities as predicted in [1] are too optimistic.

Gamma ray observations suggest that SNRs provide a sufficient energy budget to explain the observed flux of galactic cosmic rays (<PeV).

Outlook: (I) include additional SNRs, (II) implement inhomogeneous grid in GALPROP, (III) include individual τ_{diff} values for each of the SNRs in the analysis.

6. Acknowledgments|

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7. References|

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