Galactic Propagation of Cosmic Rays from Individual Supernova Remnants

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1. Question|

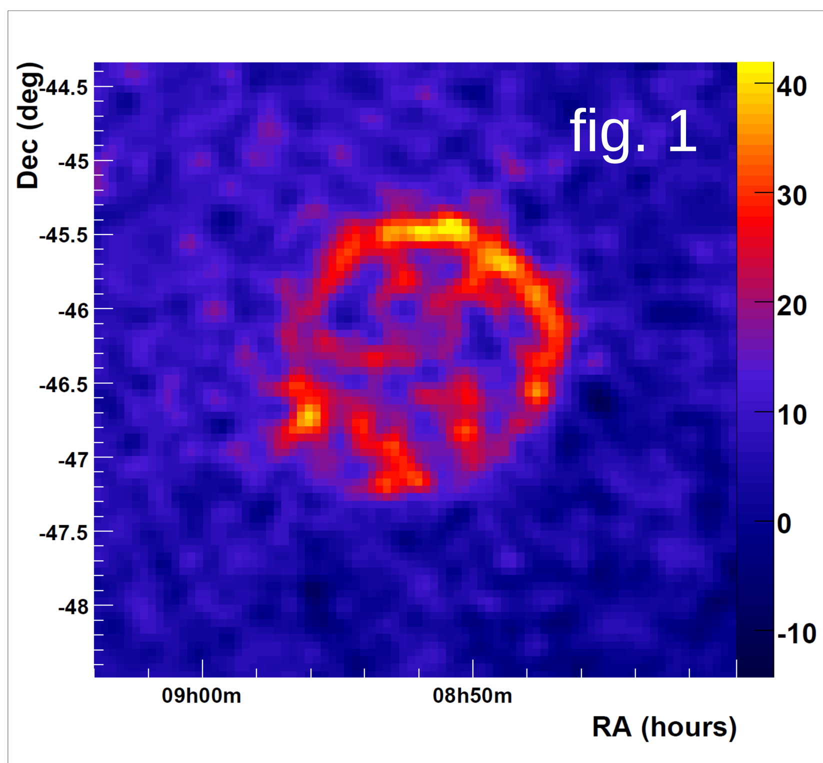
Can predicted cosmic ray spectra of supernova remnants explain the cosmic ray observations (<PeV) at Earth?

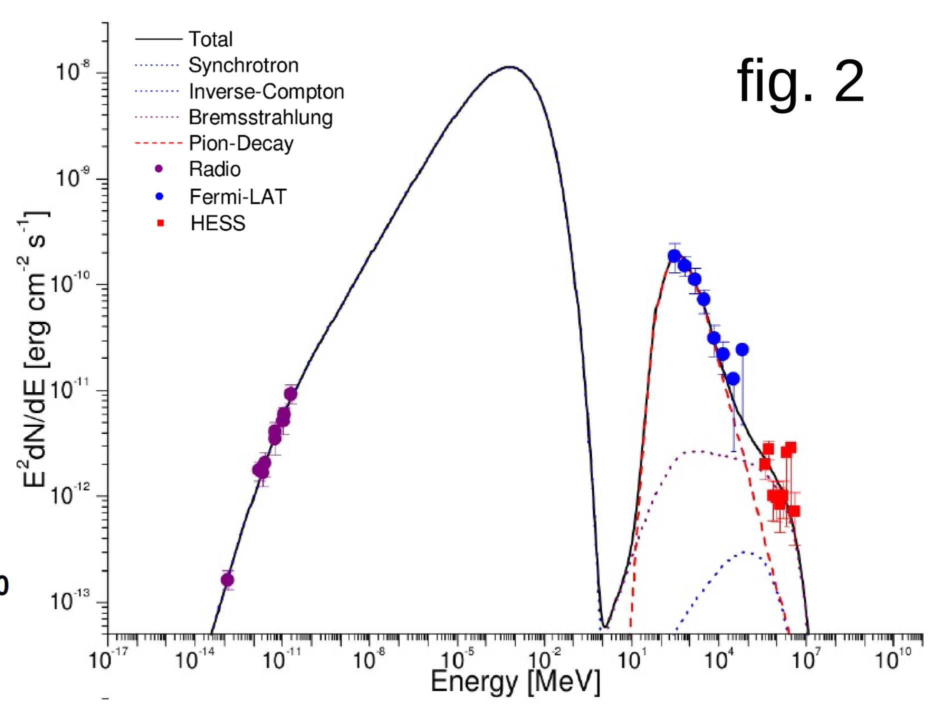
2. Source Spectra|

Proton spectra $j_p(E)$ of supernova remnants (SNRs) are determined by fitting predicted gamma ray fluxes to measured data (see fig. 1 and 2). *E* refers to the kinetic energy. We use proton spectra (single power laws) which were derived accordingly using a one zone SNR model [1]. The normalization of the source spectra is fixed by a condition to the proton luminosity $L_p = E_{tot}/t_{diff}$ based on the corresponding total energies E_{tot} (listed in [1]) and the time scale t_{diff}~10^4 yrs of diffusive escape of protons from SNRs [3]. L_p and $j_p(E)$ are 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 the speed of light *c*, proton mass *m* and the radius *R* of the SNRs.





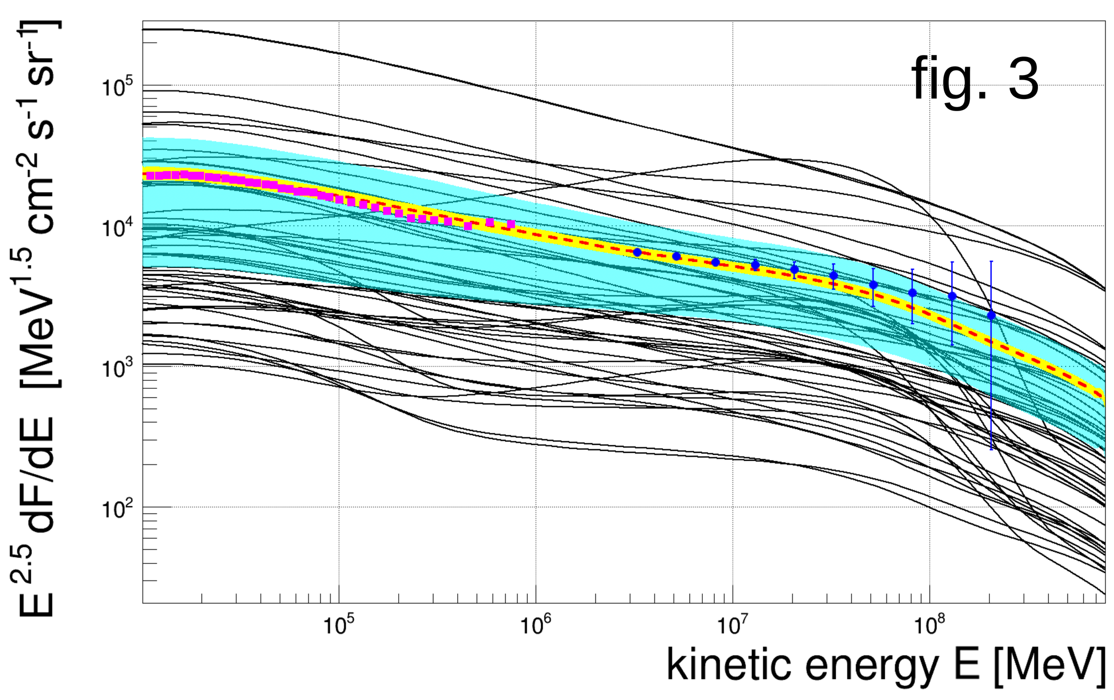
Gamma ray image of the SNR Vela Jr for energies higher than 0.5 TeV (left) taken from [2]. Model spectral energy distributions of W28 for a hadronic scenario as presented in [1].

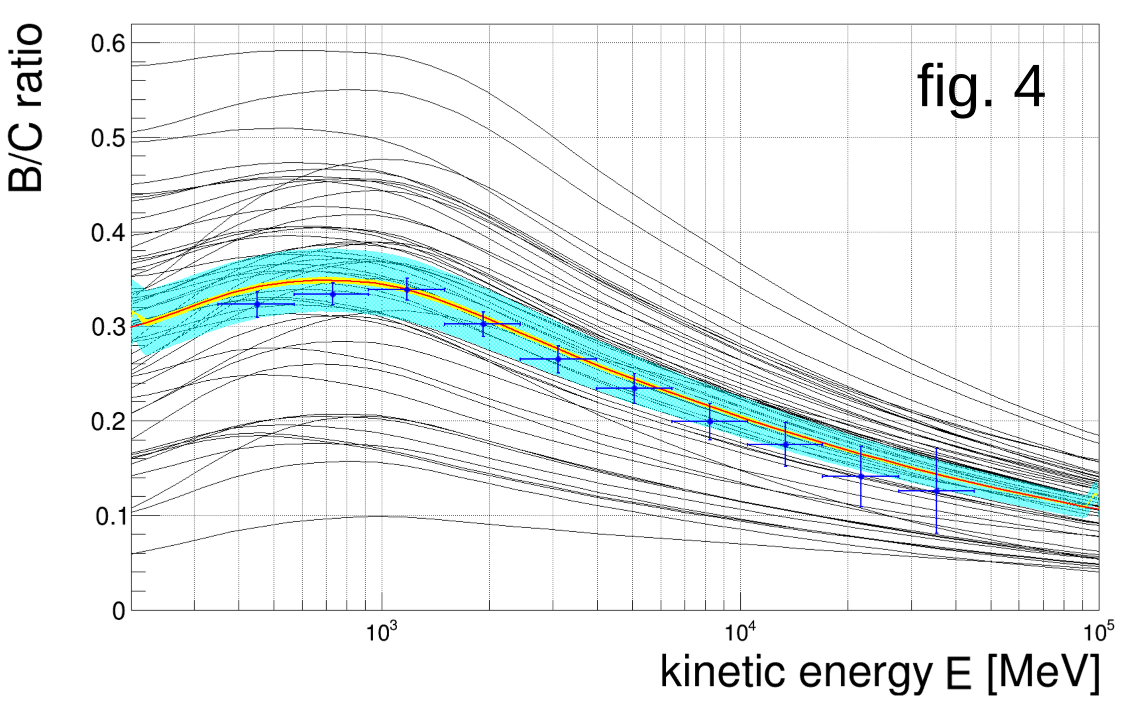
3. Propagation|

The effects of the galactic propagation on the cosmic ray (CR) spectra are computed using GALPROP [4, 5]. In our approach, SNRs are model as delta functions $\delta(\mathbf{r}-\mathbf{r}_{cgp})$ located at a point $\mathbf{r}_{cgp}$ on the simulation grid. This grid is created within GALPROP during the numerical evaluation. We calculate the average proton spectrum <*dF/dE*> from 50 sets of *N*=20 SNRs placed at grid points closest to a random positions drawn from the spatial SNR distribution taken from [4]. This procedure is necessary to derive a realistic prediction for the observed CR spectrum because the SNRs are continuously emitting CRs in the simulations - while their activity cycle in nature is limited. Our 3D simulations are based on the standard settings of GALPROP (see default *web run* [4]), but with a galactic volume of 10 kpc³ and a grid size of 1 kpc and 0.1 kpc along the x/y and z coordinate axis, respectively.

4. Results|

The spectral index of the predicted proton spectrum <*dF/dE*> reproduces the observations for energies between 10 GeV and ~50 TeV reasonably well, but is steeper at higher energies (see fig. 3). As the observed SNRs provide ~70 % of the measured CR flux, the simulations have been upscaled by a factor α=1.45 to account for a contribution of yet unresolved SNRs. Additionally, the experimental data of PAMELA [11] and CREAM [7] in fig 3 have been shifted up and down, respectively, by the corresponding systematic uncertainties to allow for a smooth continuation from low to high energies.
As can be seen in fig. 4, the Boron to Carbon (B/C) ratio in our model reproduces the measurements [8], correctly.





In black simulated proton spectra (left) and isotopic ratios B/C (right) of 50 sets of 20 SNRs with random positions are given. The corresponding mean values <*dF/dE*> (red) and the error (yellow band) as well as the spread (blue band) are displayed. The blue dots show measured data from CREAM [7] (left) and AMS -01 [8] (right). The magenta curve present the observations by PAMELA [11] (left). See text for further details.

5. Discussion|

The spectral behavior of the CR proton spectrum is reproduced in the energy range from 10 GeV to ~50 TeV. As the SNR sample extracted from [1] is not statistically complete, missing SNRs may cause the deviation of the spectral index at *E*>50 TeV. For instance in [8] additional flat spectrum SNRs are discussed which could be included in this analysis in the future.
Scaling <dF/dE> up by a factor of α=1.45 brings the model predictions in reasonable agreement with the data. Taking into account that in total *N*=20 SNRs have been used, this hints that ~αN=30 *comparable* SNRs would be needed in our sample to reproduce the energy budget of the CR flux. In this context it should be noted that according to [9] already 274 SNRs are known out of which ~30 emit gamma rays. This is an indication that: (a). **the majority of the SNRs missing in our sample are less luminous and thus can only contribute with a factor of 1.45 to our analysis** or (b). that the CR luminosities as predicted in [1] are too optimistic.
The **agreement of the predicted B/C ratio with observations** suggests that the parameter settings used in our simulations are well suited to predict the propagation of cosmic rays in the galaxy.

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

To further explore if source spectra of SNRs based on gamma ray observations result in a consistent prediction of the observed galactic CRs, we plan to: (a). include additional SNRs, (b). implement an inhomogeneous grid in GALPROP to improve the spatial resolution and (c.) include individual τ_{diff} values for each of the SNRs in the analysis.

References|

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