PROCEEDINGS OF SCIENCE

Modeling of the Cosmic Ray Flux at the Knee

Gwenael Giacinti[a,b,*] **and Dmitri V. Semikoz**[c]

[a] *Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai 201210, People's Republic of China*
[b] *School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China*
[c] *Astroparticule et Cosmologie, Université de Paris Cité, CNRS, F-75013 Paris, France*

E-mail: gwenael.giacinti@sjtu.edu.cn, dmitri.semikoz@apc.univ-paris7.fr

The origin of the knee in the cosmic ray (CR) spectrum is still unknown after 65 years of studies. Here, within the framework of anisotropic CR diffusion models, we show that the knee is a time-dependent feature, and that the flux in this region contains major contributions from one or a few nearby recent CR sources. We calculate the propagation of CRs in the Jansson-Farrar galactic magnetic field model, after injecting them at discrete sources in the disc of the Galaxy. Anisotropic diffusion plays a key role in reconciling the large diffusion coefficient required for CR escape from the Galaxy with the measured value of the Galactic magnetic field. The main difference with the isotropic diffusion case is a significant reduction of the number of sources that contribute to the CR flux in any given location in the Galaxy. As a result, few sources dominate the local flux at the knee. The contribution from the strongest source is found to vary between 10% and 80%, on a time scale of hundreds of thousands of years.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

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1. Introduction

A pronounced change in the cosmic ray spectrum, called the "cosmic ray knee", occurs at the energy $E_{\mathrm{k}} \simeq 4\,\mathrm{PeV}$. At this energy, its spectral index changes from $\beta \simeq 2.7$ below, to $\beta \simeq 3.1$ above E_{k}. This feature was discovered in 1958, but since then, its nature is still the subject of discussions. They are divided in two main categories: Either the knee is linked to the properties of cosmic ray sources, or it is linked to those of cosmic ray propagation. For the second scenario, one possibility was suggested in Refs. [1, 2], where the knee energy corresponds to the rigidity at which the cosmic ray Larmor radius is of the order of the correlation length, L_{c}, of the turbulent magnetic field in the Galactic disc.

In this work, we propose a new model of anisotropic cosmic ray propagation in our Galaxy [3], where cosmic rays are injected at discrete transient sources in the Galactic disc and propagated individually in a model of the Galactic magnetic field. Our new model can be used to study future gamma-ray and neutrino data in great detail.

2. Model

Cosmic-ray fluxes at GeV energies, as well as Fermi-LAT gamma-ray data, can be well described by isotropic cosmic ray diffusion models like GALPROP [4, 5]. However, the diffusion coefficient required to reproduce the measured B/C ratio is very high: $D_0 \approx 3 \cdot 10^{28}$ cm^2/s at GeV energies. Indeed, in isotropic turbulence without any large-scale magnetic field, such a value for D_0 would correspond to a turbulent magnetic field strength of $B \approx 3 \cdot 10^{-11}$ G [6], whereas the observed Galactic magnetic filed strength is several orders of magnitude higher, $B \sim 1\,\mu$G [9]. This conceptual problem has to be solved in some way. One obvious solution is to take into account the regular magnetic field of our Galaxy. In this case, the propagation of cosmic rays is anisotropic with essentially two diffusion coefficients, one along the regular field, $D_{||}$, and the other in the perpendicular direction, $D_{\perp}$. If both the regular and turbulent magnetic fields are of same order (μG scale), $D_{||}$ will be responsible for the escape of cosmic rays from our Galaxy [6]. The main difference between isotropic and anisotropic diffusion models is that the number of locally contributing sources at any point in our Galaxy is reduced in the anisotropic case, because of the small value of $D_{\perp}$. This effect should increase the clumpiness and inhomogeneity of the sea of PeV cosmic rays in our Galaxy.

At GeV energies, where all Galactic SNe contribute to the cosmic ray flux, the anisotropic diffusion model is not distinguishable from the isotropic one. The difference in their predictions for local cosmic ray observables lies in the fluctuations of the local cosmic ray flux, which are always small even in the anisotropic case, due to the large number of sources contributing to the flux at GeV energies. The same is true for gamma-ray observations, in which local fluctuations are further smoothed by the integration over the line of sight.

On the contrary, at PeV energies, the situation is quite different. The escape time of cosmic rays from the Galaxy is decreased by, e.g., a factor 100 for Kolmogorov turbulence. Moreover, the number of sources which are able to accelerate cosmic-rays to PeV energies is expected to be dramatically smaller than at low energies, possibly reduced by a factor 10 or even 100. Indeed, state-of-the-art studies of cosmic-ray acceleration at supernova remnant shocks suggest nowadays

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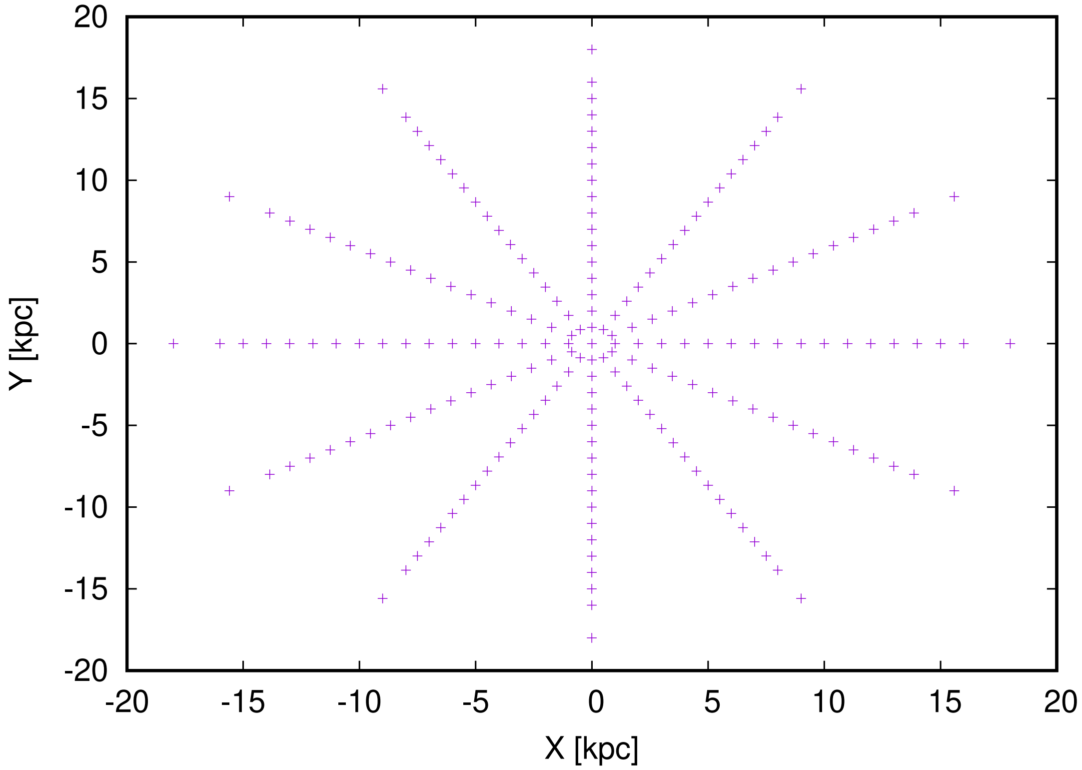

Figure 1: Locations of the reference sources, in the Galactic disc, in our model.

that only a small fraction of all supernovae should be able to accelerate cosmic-rays up to the knee or beyond, see for example [7, 8].

As a result, at PeV energies, the two models are very different. In the isotropic model, the PeV cosmic ray distribution in the Galactic disc is still homogeneous with only small local fluctuations. On the contrary, our anisotropic model predicts large fluctuations at PeV energies, as well as a significant reduction of the global diffuse gamma-ray flux compared to the contribution from individual gamma-ray sources.

In the following, as an example of Galactic magnetic field model, we take the state-of-the-art Jansson-Farrar model (JF12) [9, 10]. The original turbulent magnetic field strength was overestimated in this model, leading to an overestimation of the cosmic ray confinement time in the Galaxy. In order to reproduce the measured B/C ratio, we reduce the value of the turbulent magnetic field strength by a fixed factor everywhere in the Galaxy, according to the results of our previous studies [1, 2]. In the following, we use the outer scale $L_{\rm max} = 25$ pc for the turbulence.

We define the locations of "reference sources" in the Galactic disc at $z = 0$, up to a Galactocentric radius $R = 18$ kpc. See Fig. 1 for their locations. These fixed reference source locations provide a good sampling of the Galactic disc.

We propagate individual cosmic rays in the JF12 model, after injecting them at these designated locations. For each reference source, we calculate 10^3 cosmic ray trajectories at each of the following five energies: $E = 1, 3, 10, 30$, and 100 PeV. We save the cosmic ray positions in space at fixed, logarithmically-spaced moments in time between 30 yr and 30 Myr. This provides us with reusable

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samples of cosmic ray positions from reference sources, and at given reference times after escape from these sources.

In any of our simulations, we generate randomly the locations and ages of all the SNe that occured within the last 30 Myr in the Galaxy. We assume that there are on average 3 SNe per century, and that their distribution in the Galaxy follows the formula used in our previous works [1, 2]. For each SN, we then search for the nearest "reference source" in the above list. We then move the locations of its 10^3 cosmic rays to the actual location of the SN, by doing a small translation of the cosmic ray locations along the Galactocentric radius, and a slight rotation around the Galactic center, such that the location of the reference source is moved to the location of the actual source. We calculate the locations of the cosmic rays according to the actual age of the SN, by interpolating their locations in the two nearest time bins. In this way, we can calculate the cosmic ray flux coming from any source in the Galaxy, at any point in space and time. This allows us to simulate the evolution with time of the cosmic ray distribution in the Galaxy at $\sim (1 - 100)$ PeV energies.

In order to calculate the cosmic ray flux at any point in the Galactic disc, we divide it in $(100\,\mathrm{pc})^3$ bins up to a radius of 20 kpc in the Galactic plane and up to $z = \pm 400$ pc from the Galactic plane. We calculate the cosmic ray density in each bin assuming that the original cosmic ray flux injected at each source follows a power law $E^{-\alpha}$ up to a maximum energy E_{max}, and that the total energy deposited in cosmic rays by each SN is 10^{50} erg between 1 GeV and E_{max}.

We find that, at the Earth position (8.2 kpc from the Galactic center), 90 % of the cosmic ray flux at PeV energies comes from sources that are simulated from the 4 nearest "reference sources" around the Earth. Since we are mostly interested in studying the cosmic ray flux at the Earth here, we simulate, for a greater precision, 10^4 cosmic ray trajectories from each of these 4 reference sources, instead of the 10^3 trajectories used for the other reference sources.

3. Results

In the upper row of Fig. 2, we show two examples of cosmic ray distributions in the Galactic disc at $E = 1$ PeV, averaged over the altitudes $-100\,\mathrm{pc} < z < 100\,\mathrm{pc}$. The upper left panel corresponds to the case where only 1.6% of all SNe contribute to the cosmic ray flux at this energy, whereas the upper right panel corresponds to the case where 10% of SNe contribute. In both panels, we plot the relative cosmic ray fluxes, normalized to the value measured at Earth. The color bars are in $log10$ scale, i.e., the value "0" corresponds to the flux at the Earth.

In the case with the source density of 1.6% of all SNe, we assume that the sources inject cosmic rays with a power law spectrum $\propto E^{-\alpha}$ with $\alpha = 2.2$ and $E_{max} > 1$ PeV. In this case, the time-averaged value of the cosmic ray flux at Earth at $E = 1$ PeV has a value similar to the value measured by the KASCADE experiment. If we use the same injected spectrum for the case with 10% of SNe, the calculated cosmic ray flux overshoots the KASCADE data by a factor 6 at 1 PeV. However, this is only 3 times larger than the cosmic ray proton flux measured by IceTop. One way to make our calculated flux consistent with a source density of 10% of SNe is to take an injected spectrum with $\alpha = 2.3$. In this case, the calculated spectrum at PeV energies is between the KASCADE and IceTop data points.

One can clearly see in Fig. 2 that our calculated distribution of PeV cosmic rays in the disc is substantially more patchy and inhomogeneous than any of the predictions from standard Galactic

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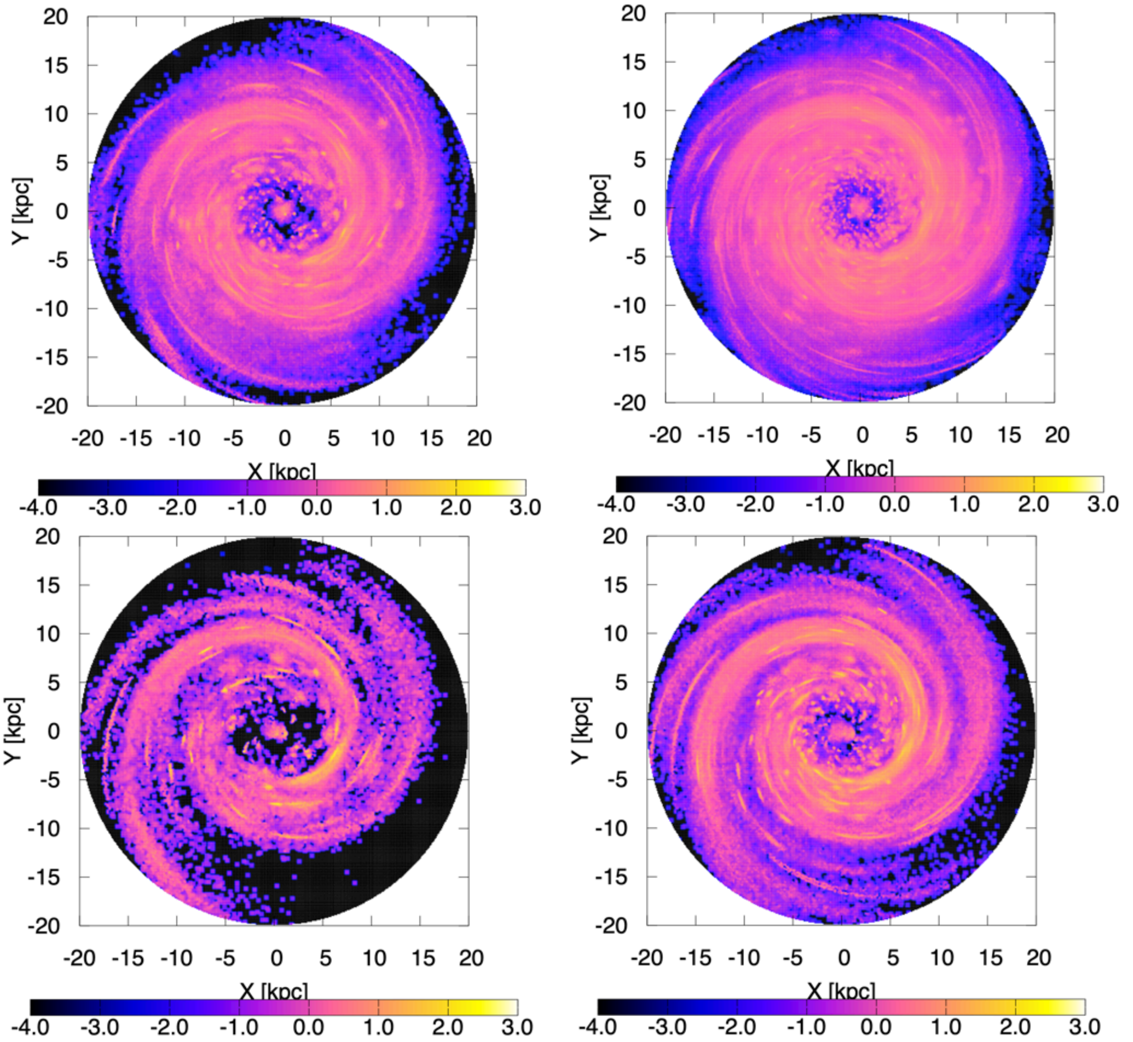

Figure 2: Distributions of $E = 1$ PeV (upper row) and $E = 10$ PeV (lower row) cosmic ray protons in the Galactic disc at a given time, as seen from above. In the left panels, we assume that 1.6% of all SNe accelerate cosmic rays to PeV, and in the right panels, we assume that 10% of SNe accelerate to PeV. The cosmic ray fluxes are normalised to the value measured at Earth, and the color bar are in log10 scale.

cosmic ray propagation models, especially those relying on isotropic cosmic ray diffusion. The case with 10% of SNe (lower panel) is much smoother in large parts of the Galactic disc than the case with 1.6% of SNe (upper panel), but it is still very far from the usually smoother predictions from existing Galactic cosmic ray propagation models.

In the lower row of Fig. 2, we provide the same calculations at 10 PeV, above the energy of the knee. One can clearly see that the situation there is even more extreme than at 1 PeV. The cosmic ray distribution in the Galaxy becomes increasingly more patchy and inhomogeneous. Only a few young SNe contribute to the cosmic ray flux in the Galaxy in the case with 1.6% of SNe (upper panel). A bigger number contribute in the case with 10% of SNe, though still small enough not to give a smooth distribution of cosmic rays. Cosmic ray densities vary by more than four orders of magnitude depending on the observer position and time, even at the same distance from the Galactic

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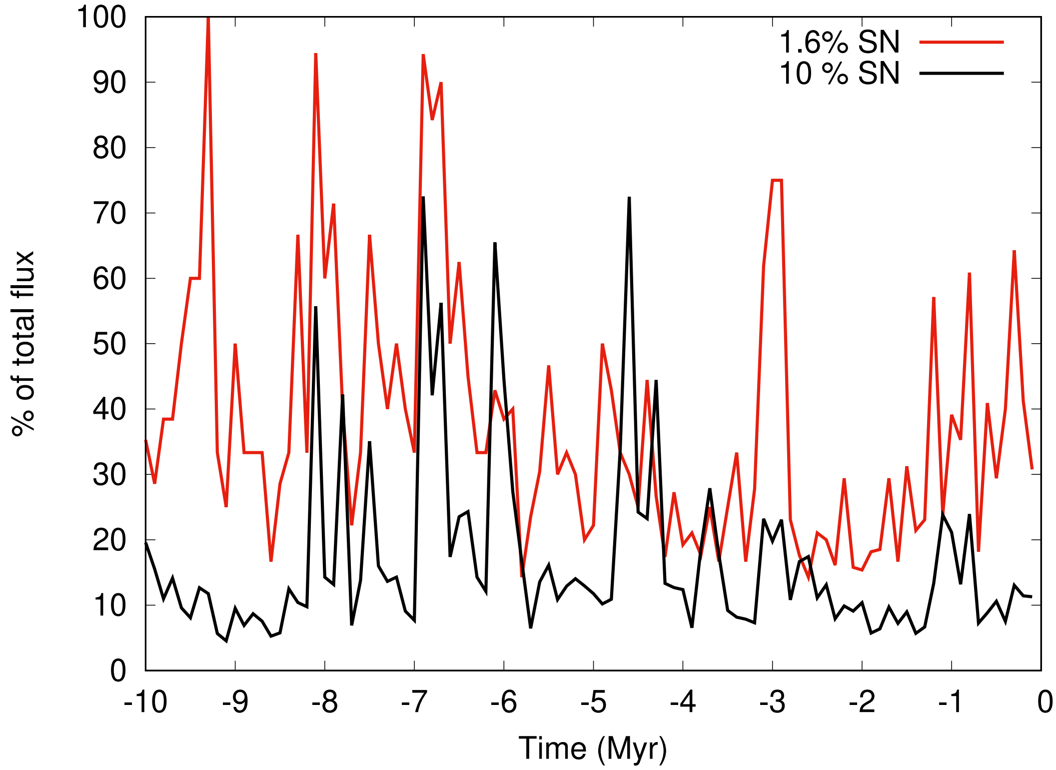

Figure 3: Fraction of the total cosmic ray flux at Earth at $E = 1$ PeV that comes from the source with the highest contribution to this flux as a function of time. The red line corresponds to a source density of 1.6% of all SNe, and the black line corresponds to 10% of SNe.

center. At these energies, only a few SNe dominate the cosmic ray flux at almost any location of the Galaxy, including at the position of the Earth.

In Fig. 3, we plot the fraction of the cosmic ray flux at Earth at $E = 1$ PeV which is due to the source with the largest contribution to this flux. In the case of a source density equal to 1.6% of all SNe (red line), the contribution from the source with the highest flux to the total flux at Earth varies between 20% and almost 100%. In this case, the total number of sources having a non-zero contribution to the flux at Earth in our simulations varies around 100 at any given time, although most of them provide only a very small contribution to it. For a source density equal to 10% of SNe (black line), the contribution from the source with the highest flux can still be up to about 70% of the total flux, but, most of time, it stays at the level of 10%. In this case, the total number of sources having a non-zero contribution to the flux at Earth in our simulations varies around 1000.

At $E = 10$ PeV, the contribution of the source with the largest flux varies between 50% and 100% in both cases, however in the case of 1.6% of SNe, it remains close to maximum for a significant fraction of the time.

4. Discussion and conclusion

We have presented here a new model of anisotropic cosmic ray propagation in our Galaxy around PeV energies, where cosmic rays are injected stochastically at individual transient sources in

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the Galactic disc and propagated individually in Galactic magnetic field models. With our code, we can simulate the full 3-dimensional distribution of $\sim$ PeV cosmic rays in the Galaxy as a function of time. As a result, we can simultaneously study the contribution from individual sources and the global diffuse cosmic ray flux, as well as estimate its local time and space fluctuations.

The widely-used isotropic cosmic ray diffusion models require a diffusion coefficient that is two orders of magnitude larger than those expected for cosmic rays diffusing in pure isotropic turbulence with $\sim \mu$G strengths [6]. Anisotropic cosmic ray diffusion models, such as ours, allow to remove this major tension by making cosmic rays escape along the regular Galactic magnetic field direction in the halo. We used here the state-of-the-art Jansson-Farrar Galactic magnetic field model [9, 10], with a reduced turbulent component. This allows our model to satisfy the constraints on the cosmic ray confinement time from the B/C ratio [1, 2] with standard $\sim \mu$G Galactic magnetic field strengths. However, this leads to major changes in the distribution of PeV cosmic rays in our Galaxy.

In particular, we find that our model has two important consequences. First, the cosmic ray flux in the Galaxy is highly inhomogeneous in space, at PeV energies and above. For practical applications, this means that the standard assumption in gamma-ray astronomy that the line-of-sight emission should be proportional to the summed-up gas density along the line-of-sight does not hold anymore at such energies. Second, the cosmic ray flux at PeV energies can contain a dominant contribution from one single source, due to the small number of sources contributing to the flux at any point in the Galaxy, and in particular at the position of the Earth. At 10 PeV energies, this is almost always guaranteed due to the even smaller number of sources contributing to the flux.

Thus, we expect the cosmic ray distribution in our Galaxy to be strongly inhomogeneous at $\sim$ PeV energies and beyond, and we expect that the local high-energy cosmic ray flux at any point in the Galactic disc displays strong fluctuations with time.

We also expect our findings to have important consequences for the predicted secondary $\gtrsim$ 100 TeV gamma-ray and neutrino emissions from our Galaxy. These emissions should therefore be substantially more patchy and clumpy in our model than in the usual predictions from isotropic cosmic ray propagation models.

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