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# Vela as the Source of Galactic Cosmic Rays above 100 TeV

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We modeled the contribution of the young supernova remant Vela to the local cosmic rays taking into account the effect of the Local superBubble and an anistropic diffusion. We recovered the knee observed in the CR spectrum at energy of 3-5 PeV. By the contribution of Vela and an older local source of 2-3 Myr supernova we were able to explain the CR spectrum from TeV to 100 PeV.

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## 1. Introduction

The measured energy spectrum of cosmic rays (CRs) extends smoothly over more than 11 decades as a nearly featureless power law, $I(E) \propto E^{-\beta}$. One of its most prominent features is the knee, a break in the all-particle energy spectrum at the energy $E_k \simeq 4\,\mathrm{PeV}$, which was discovered by Kulikov and Khristiansen in the data of the MSU experiment already in 1958 [1]. The second knee corresponds to a change in the spectral slope of the all-particle energy spectrum at $\simeq 5 \times 10^{17}$ eV where the slope hardens by $\Delta\beta \simeq 0.2$. There is a general consensus that the knee in the total CR spectrum at $E_\mathrm{k} \simeq 4\,\mathrm{PeV}$ coincides with a suppression of the primary proton and/or helium flux, and that the composition becomes increasingly heavier in the energy range between the knee and $10^{17}$ eV [2, 3, 4, 5].

Explanations for the origin of the knee fall in two main categories, connecting it either with a change in the propagation or the injection of CRs. In the first case, the knee energy may either corresponds to the rigidity at which the CR Larmor radius $R_\mathrm{L}$ is of the order of the coherence length $l_\mathrm{c}$ of the turbulent magnetic field in the Galactic disk [6, 7]. Alternatively, the knee corresponds to a transition between the dominance of pitch angle scattering to Hall diffusion or drift along the regular field [8, 9, 10]. In both cases, the energy dependence of the confinement time changes which in turn induces a steepening of the CR spectrum [11, 8, 9, 10, 6, 7]. In the second class of models, the knee is connected to properties in the injection spectrum of the Galactic CR sources. For instance, the knee might correspond to the maximal rigidity to which CRs can be accelerated by the population of Galactic CR sources dominating the CR flux below PeV [12, 13, 14]. Alternatively, the knee may be caused by a break in the source CR energy spectrum at this rigidity [15, 16]. A variant of this model is the suggestion that the spectrum below the knee is dominated by a single, nearby source and that the knee correspond to the maximal energy of this specific source [17, 18]. All these models lead to a sequence of knees at $ZE_\mathrm{k}$, a behaviour first suggested by Peters [19].

In the isotropic diffusion approximation one defines a scalar diffusion coefficient which depends on energy as $D(E) = D_0(E/E_0)^\delta$. Measurements of the Boron and Carbon fluxes especially by the AMS-02 experiment are consistent with Kolmogorov turbulence, i.e. $\delta = 1/3$, at rigidities above $\sim 100\,\mathrm{GV}$ [20]. The normalisation $D_0$ is only weakly constrained using measurements of stable nuclei, but can be restricted considering the ratio of radioactive isotopes as, e.g., $^{10}$Be/$^{9}$Be: Fitting successfully these ratios requires values of the normalisation constant $D_0$ in the range $D_0 = (3-8) \times 10^{28}\mathrm{cm}^2/\mathrm{s}$ at $E_0 = 10\,\mathrm{GeV}$ [21, 22, 23]. For typical magnetic field strengths of order $\mu$G and maximal length scales of fluctuations in the turbulent field of order 10 pc, numerically calculated diffusion coefficients are two orders of magnitude below this value for $D_0$. Since $D$ scales for Kolmogorov turbulence as $D \propto B^{-1/3}$, the magnetic field strengths $B$ would have to be scaled down by a factor $10^{-6}$ to obtain agreement between the two approaches. This discrepancy can be resolved, if the diffusion is sufficiently anisotropic and the magnetic field contains a non-zero component perpendicular to the Galactic disk [24]. As a result, the number of sources contributing to the locally observed flux is reduced by two orders of magnitude. Thus only few sources contribute to the local CR flux at energies above 200 GeV.

In the energy range between 200 GeV and 100 TeV a 2–3 Myr old local supernova (SN), or a complex of neighboring old SN, can dominate the local CR flux, as shown in Refs. [25, 26, 27]. A local SN event of the same age was deduced from $^{60}$Fe found in sediments in the ocean crust of the Earth [28, 29, 30] and on the Moon [31]. Such a local SN is able to to resolve the anomalies which were found recently by CR experiments. This includes the energy dependence of the proton to helium ratio, the breaks in the energy spectrum of primary nuclei at the rigidity 200 GV, the positron excess, and the ratio $R \simeq 2$ of positron to antiproton fluxes, see Refs. [25, 26, 27] for details.

The phase of the CR dipole amplitude is constant between $\simeq 20$ TeV and 100 PeV, except for abrupt flip by 180° at $\simeq 200$ TeV. Similarly, the dipole amplitude is approximately constant above and below 200 TeV. This behaviour of the dipole anisotropy suggests that two CR sources located in the two opposite hemispheres relative to the local magnetic field line dominate the CR flux below and above this energy [32]. We suggest in this work that Vela, a 11 kyr old supernova remnant (SNR)at the distance 270 pc, is the source dominating the local CR flux above 200 TeV. We study the expected CR flux from Vela, which is connected with the Solar system by a magnetic field line in models of the global Galactic magnetic field as, e.g., the Jansson–Farrar model [33]. If this source would be indeed directly connected to the Solar system by a magnetic field line, its flux would however overshoot the locally measured one by 3 orders of magnitude in case of anisotropic diffusion. Such an excess is avoided, if one takes into account that the Earth is located inside the Local Superbubble. We use a simplified model for the structure of the magnetic field inside the Local Superbubble similar to the one of Refs. [34, 35], and follow individual CR trajectories solving the Lorentz equation. Despite of using a simplified model for the Local Superbubble we obtain a good description of the fluxes of individual groups of CR nuclei in the knee region and above. Adding additionally the CR flux from the 2–3 Myr old source, the CR spectra in the whole energy range between 200 GeV and the transition to extragalactic CRs are described well combining the fluxes from only these two local sources.

## 2. Theoretical framework

### 2.1 Local Bubble and the geometry of the local magnetic field

The model used for the local magnetic field is very similar to the one used in [52], we apply an exponential damping of the bubble magnetic field at $z_{bub} \approx \pm 3\,\mathrm{pc}$ to ensure the decaying of the bubble magnetic field from the top and the bottom. The strength of the regular magnetic field depends only on the radius and is set to $B_{\mathrm{in}} = 0.1\mu G$ inside the bubble, $B_{\mathrm{sh}} = 8 - 12\mu G$ in the wall, and $B_{\mathrm{out}} = 1 - 3\mu G$ outside the bubble. The Sun is assumed to be at the centre of the LB, while Vela is situated at the coordinates : $r_{\mathrm{vela}} = 0.29\,kpc, l_{\mathrm{vela}} = -3.37^\circ, b_{\mathrm{vela}} = 263.94^\circ$. We interpolate the transition between different magnetic field regimes by logistic functions $T(r)$, with a transition width parameter $w_{i=1,2}$. we set

$$T_1 = [1 + \exp\left(-\frac{r-R+w/2}{w_1}\right)]^{-1}, T_2 = [1 + \exp\left(-\frac{r-R-w/2}{w_2}\right)]^{-1}$$

For $s = \frac{y}{|y|}$, the regular magnetic field $B_{\mathrm{reg}} = (B_{\mathrm{x}}^2 + B_{\mathrm{y}}^2 + B_{\mathrm{z}}^2)^{1/2}$ is given

For $r < R$

$$B = B_{\mathrm{in}}(1-T_1) + B_{\mathrm{sh}}T_1] \begin{pmatrix} s \times \sin(\vartheta) \\ -s \times \cos(\vartheta) \end{pmatrix} exp(-z^2/z_{\mathrm{bub}}) + B_{\mathrm{out}}(1 - exp(-z^2/z_{\mathrm{bub}})),$$

And for $r > R$

$$B = B_{\rm sh}(1-T_2) + B_{\rm out}T_2] \begin{pmatrix} s\times\sin(\vartheta) \\ -s\times\cos(\vartheta) \end{pmatrix} exp(-z^2/z_{\rm bub}) + B_{\rm out}(1-exp(-z^2/z_{\rm bub})),$$

The turbulent magnetic field is taken to be randomly directed with modes distributed between $L_{\rm min} = 1$ AU and $L_{\rm max} = 25$ pc according to an isotropic Kolmogorov power spectrum.

For the external magnetic field we considered a regular magnetic field along the galactic arms (the x coordinate) $B(r) = B(x)$ with a total amplitude of 3 $\mu$G this is the simplest case wich holds as a first approximation since the simulation scale still small compared the galactic magnetic field scales usuly studied. In this configuration the turbulent magnetic field strength is set as follows. For $r > R - w/2 : B_{\rm turb} = B_{\rm reg}/2$, and for $r < R - w/2 : B_{\rm turb} = B_{\rm reg} * 5$

## 2.2 Injection spectrum

We use as CR injection spectrum for Vela a broken power law in rigidity with an exponential cut off at the rigidity $\mathscr{R}_{\rm max} = 3\times10^{15}$ V,

$$\frac{dN}{dE} \propto \begin{cases} E^{-2}, & \text{if} \quad E < ZE_{\rm br} \\ E^{-2.9}\exp(-E/(ZE_{\rm max})), & \text{if} \quad E \geq ZE_{\rm br}. \end{cases} \tag{2.1}$$

Where $E_{\rm br} = 1$ PeV and $E_{\rm max} = 3$ PeV in a such way to be consistant with heavy nuclei flux. The normalisation of the spectra for different groups of CR nuclei will be fixed such that the propagated fluxes at Earth agree with observations.

The injection spectrum steepens at $\mathscr{R}_{\rm br} = 1$ PV by $\Delta\beta = 0.9$. Such a steepening is motivated e.g. by the analysis of Ref. [15] Including strong field amplification as suggested by Bell and Lucek [39, 40].

## 2.3 Calculation of the flux

In order to compute the flux, we injected 30.000 protons per energy at the position of Vela and propagated them for 12.000 yr. We calculated the CR density $n(E)$ in three regions of interest averaging the CR densities between 8 to 12 kyr: Around the source, on the bubble wall, and inside the bubble. The CR flux $F(E) = c/(4\pi)n(E)$ was then computed from the CR densities in the considered volumes, as defined in [52]

For energies below 100 TeV we deduced the flux from earlier times and higher energies using the scaling relation for the flux inside the bubble :

$$(E_{\rm low}/E_{\rm high})^{1/3} \approx t_{\rm early}/t_{\rm now} \tag{2.2}$$

And on the wall, we could'nt use the same method because particles of lower energy simulated $E$ =0.1 PeV reach the bubble wall before being in their diffusive mode the relation does not apply anymore. To have a hint on how should the flux be supressed at lower energies, we computes the flux at 1 kpc from the source after 100kyr in a bubble like gemoetry using the equation (2.2) and then we computed the ratio : $F(E = 1\times10^{14})/F(E = E_{low})$ for $E_{low} = 1\times10^{13}$ eV, $E_{low} = 2.15\times10^{13}$ eV and $E_{low} = 4.64\times10^{13}$ eV and then we deduced the flux in the wall of our simulation at $E_{low}$ from the flux at $E = 1\times10^{14}$ eV by keeping the same ratios.

## 3. Proton flux from Vela

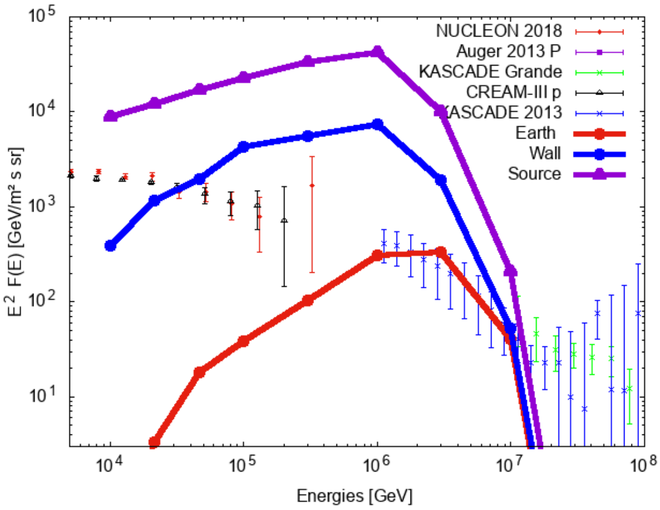
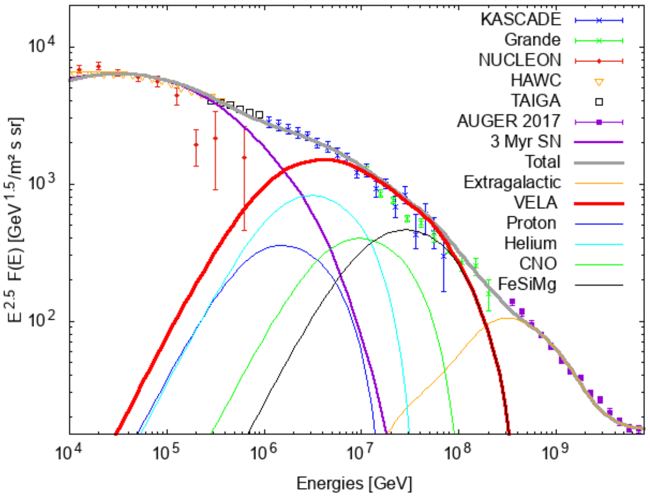


Figure 1: Flux of protons as function of energy computed inside the bubble centred on the Sun's position, on the bubble wall and around the source.

In Fig. 1, we show the normalised proton flux in the bubble wall, inside the bubble and around the source. We can see that for high energies ($E_p > 10^{16}$ eV) the bubble is transparent, since the Larmor radius ($R_L \sim 100$ pc) of such protons is large compared to the thickness of the bubble wall. For energies below 1 PeV, particles start to be trapped in the wall and the flux inside the bubble is increasingly suppressed.



(a) All particles

Figure 2: The all-particles flux from Vela and from the 2–3 Myr SN and the extragalactic contribution from Ref. [44] together with experimental data from NUCLEON [41], HAWC [45], TAIGA [46], CREAM [42], KASCADE and KASCADE Grande [5], and AUGER [47].

From Fig. 2, we see that the all-particles flux fits well the experimental data up to $10^{17}$ eV. In the energy range above $10^{17}$ eV, the extragalactic contribution becomes important which we model following Ref. [44].

We computed the total energy output of Vela from the normalisation of the simulated data to the experimental ones: The relative energy fraction in protons found is 0.065, the one of helium 0.15, of carbon 0.055 and of iron 0.045, respectively. We obtain then as total energy output in CRs $3.7\times10^{49}$ erg. The total kinetic energy of the Vela supernova calculated in Ref. [49] is $1.4\times10^{50}$ erg. We note also that the CR acceleration efficiency of Vela should be high, as it is expected in the scenario of strong magnetic field amplification of Refs. [39, 40].

## 4. Conclusions

In the standard diffusion picture it is assumed that Galactic CRs form a smooth, stationary "sea" around the Galactic disk. Evidence for this assumption comes from $\gamma$-ray observations, which indicate a rather small variation of the parent CR populations below $\approx 100$ GeV throughout the Galaxy outside of several kpc from the Galactic center [50]. Going to higher energies, CRs escape faster and thus the number of CR sources contributing to the local flux diminishes. In order to match the required diffusion coefficient with micro-gauss magnetic fields observed in the local Galaxy the CR propagation should be strongly anisotropic [24]. Then the number of CR sources decreases by a factor 100 relative to the case of isotropic diffusion. As a result, the CR flux should be dominated by few local CR sources except for the lowest energies.

In this work, we have examined the suggestion put forward in Refs. [17, 18] that the spectrum below the knee is dominated by CRs accelerated in the Vela SNR and that the knee corresponds to the maximal energy of this source. As an important improvement compared to these earlier studies, we have taken into account that the Sun is located inside the Local Superbubble and that CRs propagate anisotropically. Without the influence of the Local Superbubble, the CR flux from Vela at the position of the Sun would overshot the observed one by 3 order of magnitude, because the Sun and Vela are connected by field lines of the regular magnetic field. Using a CR injection spectrum with a break $\Delta\beta \simeq 0.9$ at $E_{\rm br} = 1$ PeV as motivated by studies of Ref. [15], we have obtained a good description of the flux of individual groups of CR nuclei both in the knee region and above. Adding additionally the CR flux from the 2–3 Myr old source suggested in Ref. [25, 26, 27], the CR spectra in the whole energy range between 200 GV and the transition to extragalactic CRs are described well combining the fluxes from only these two Galactic sources.

Finally, we stress that, there is an important question to be addressed is how strong the dipole anisotropy from Vela will be reduced, since the magnetic field on the bubble wall is almost 10 times higher then the sourrounding one, particles will more easily diffuse on the wall and occupate a larger volume around the bubble. Last but not least, we note that the suggestion from Ref. [35] that the Galactic soft neutrino component [51] in the ICeCube data is produced by CRs interacting in the wall of a superbubble fits well in the scenario presented here, as explained in Ref. [53]

The reliability of our model on the differents parameters in actually studied, results will be published soon.

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