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# Vela as a source of cosmic rays responsible for the formation of the knee in the energy spectrum

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**Abstract.** The sharpness of the knee in the cosmic ray (CR) energy spectrum observed at an energy of 3-4 PeV can be caused by the contribution of a relatively young and nearby single source. The application of the models for the acceleration and propagation of CR in the Galaxy allows us to estimate the limits for the distance to the source and its age. The Vela cluster containing supernova remnants (SNR) and pulsar is within these limits. The paper presents additional arguments based on the anisotropy and the structure of the CR energy spectrum at PeV energies and above in favour of the Vela SNR ( and, possibly, the associated pulsar ) being such a single source responsible for the formation of the knee.

## 1. Introduction

The Single Source Model (SSM) was suggested in 1997 for the explanation of the remarkable sharpness of the knee in the size spectrum of extensive air showers (EAS) at a primary energy of about 3-4 PeV [1]. Its basis is an obvious non-uniformity in space and time of the CR source distribution: supernova remnants (SNR), pulsars etc., as well as of the interstellar medium (ISM) properties. On the basis of accumulated statistics it is expected that the probability of a relatively close and young SN explosion at distances up to 300 pc from the Sun and of the age up to  $10^5$  years is rather high ( $\sim 1$ ).

The division of the all-particle energy spectrum into two components - that from many distant and old sources and that from a single nearby and young source is a simplification of the real situation, but such a scenario let us describe the main features of the observed spectrum and put forward a possible identification of the assumed single source.

## 2. Identification of the single source

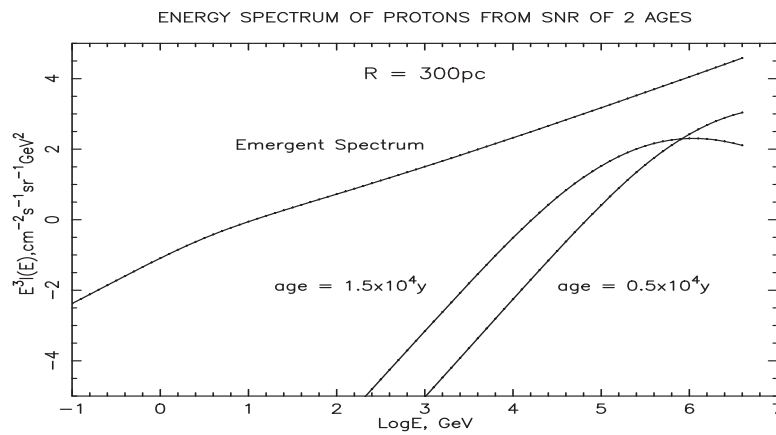
### 2.1. The distance and the age

The identification of the source can be made by a comparison of the observed spectrum with model calculations performed for different ages and distances from the source to the observer in the solar system. Our first calculations were made assuming that such a source is a SNR and based on the ideas that CR are confined within its expanding shell until the moment when such trapping ability weakens and CR begin to leave the shell and go out into interstellar space [2,3]. In the paper [4] where we used these ideas we postulated that this escape occurs when the shock wave expanded up to the radius of 100 pc. Before that the confinement lasted up to 80 kyears and after that the accelerated particles begin to diffuse, interact with atoms of the



interstellar medium during propagation and eventually escape from the Galaxy. Our calculations [5] show that the energy spectra of accelerated particles depend on time. They have a power law shape with exponents varying from 2.0 at the initial stage of SNR expansion to  $\sim 2.55$  at the end of it. The overall energy spectrum of particles emergent from the SNR has also the power law shape up to the knee with the exponent of  $\sim 2.15$ . Comparing the results of our calculations with the energy spectrum of the single source derived from the experimental data we estimated the limits of the possible distances  $R$  and ages  $T$  for the SNR as  $250 < R < 400$  pc and  $85 < T < 115$  kyears [6]. American astronomers have found that these limits are satisfied for the SNR Monogem Ring associated with the pulsar B0656+14 [7].

In later works it was shown that there is probably no such strong confinement and high energy particles may begin to leave the shell soon after the explosion [8]. For such a model the age of the unknown SNR becomes shorter. In the extreme case of the instant release of all accelerated particles it is  $5 < T < 35$  kyears, but the distance of the SNR remains the same, i.e.  $250 < R < 400$  pc. These new limits are satisfied for the SNR Vela being located at a distance of  $273 \pm 33$  pc and having an age of about 11 kyears.



**Figure 1.** The energy spectrum of CR from the SNR which exploded at a distance of 300 pc from the Sun, 5 or 15 kyear ago. The Figure demonstrates that the maximum contribution to the CR flux is at PeV energies, i.e. in the region of the knee. The emergent spectrum is also shown for comparison.

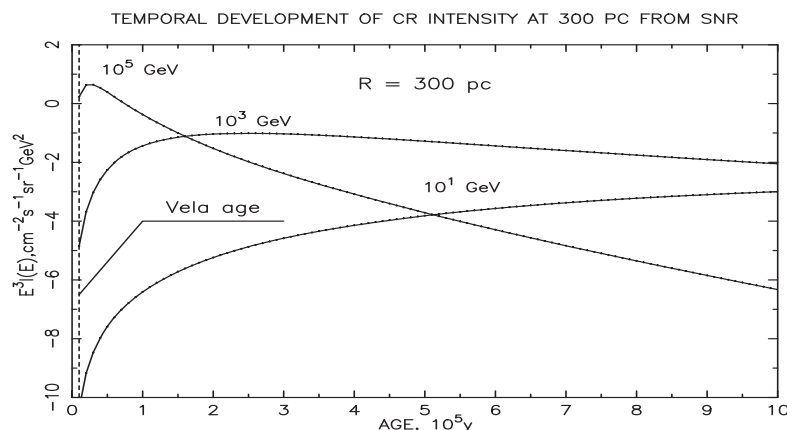
Direct calculations made with an updated model of SNR acceleration show that a SN with the distance and the age similar to Vela gives the maximum contribution to the CR flux in the PeV region close to the observed knee (Fig.1)

Calculations show that such a young SNR has a relatively rapid temporal variability. With time its CR energy spectrum becomes softer, with almost no PeV particles when its age approaches  $10^3$  kyear (Fig.2)

## 2.2. Anisotropy of the CR flux

The Vela cluster is a complex and rather extended source which includes the main SNR (Vela SNR), pulsar B0833-45 with its nebula (VelaX+PWN) and one more (weak) SNR (Vela Jr). It is located in the Galactic Plane, in the third Quadrant:  $\ell \sim 265^\circ, b \sim -3^\circ$ . Due to the proximity of this source to the Solar System one may expect an excess of the CR flux close to the direction towards this source, especially for high energy CR with their least deviation in the Galactic magnetic fields.

In our paper [9] the position of Vela on the celestial sphere was compared with the position of intensity excesses in Equatorial and Galactic coordinates for CR of different energies (Fig.3).



**Figure 2.** The temporal evolution of the CR spectrum from a SNR at 300 pc from the Sun. Differential CR intensities at 3 energies:  $10^1$ ,  $10^3$  and  $10^5$  GeV are shown. The age of Vela is shown by the vertical dashed line at 11 kyear. The Figure demonstrates the rapid softening of the spectrum within the time range of several hundred kyears.

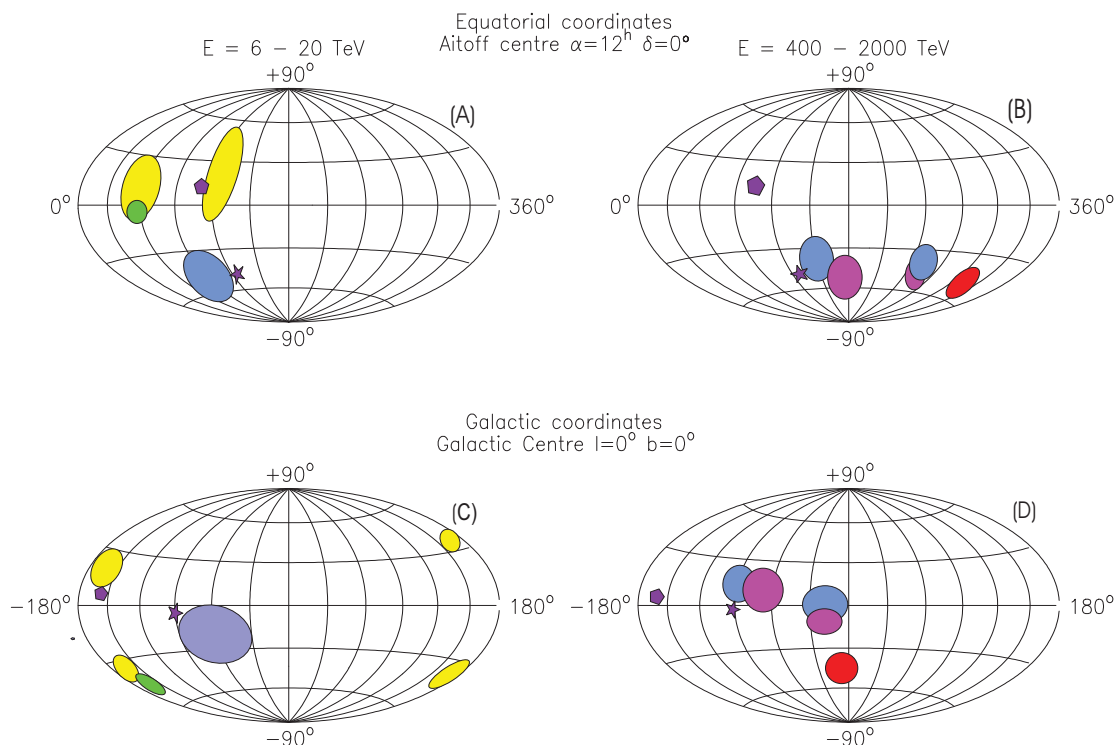
It is seen that the position of intensity excesses for CR of PeV energies approaching the energy of the knee tends to the direction towards Vela. The small difference of the Vela SNR and the nearest intensity excess coordinates can be related to the slightly smaller energy of the studied CR (0.4 - 2 PeV) than the energy of the knee ( $\sim 3$  PeV) or to the local magnetic field the effect of which is difficult to estimate without precise knowledge of its regular and turbulent components.

### 2.3. Application of the difference method for the anisotropy study

The confirmation of the possible role of the Vela SNR in the formation of the knee was found by the application of a new difference method developed for the study of anisotropy [10]. The idea of the method is that the energy spectrum of CR from a nearby and young source will be different from the background spectrum of CR particles from more distant and old sources. Accordingly, the characteristics of extensive air showers (EAS) produced by CR from such a source should be different from those from background showers. One should look for the direction in which the difference between the characteristics of showers arriving from one side of this direction and from the opposite side is a maximum. It is postulated that such a direction is the direction towards our single source.

A search of this sort has been applied to the data base of EAS detected with the GAMMA array. The array is made by an international collaboration and is located at the Aragats mountain in Armenia [10]. The data used for the analysis include about  $3.38 \cdot 10^6$  EAS with the total number of charged particles  $N_{ch} > 10^5$  and zenith angles  $\Theta < 40^\circ$ , which correspond to the threshold primary energy of about 0.4 PeV. The parameter used for the comparison of the characteristics of EAS arriving from the direct and opposite directions was the shower age. The maximum difference was found for the direction with Galactic coordinates  $\ell = 277^\circ \pm 3^\circ, b = -5^\circ \pm 3^\circ$  (Figure 4).

Taking into account the extended profile of Vela and the possible deviation of CR particles in the Galactic magnetic fields the agreement of these coordinates with the coordinates of Vela can be regarded as very satisfactory.



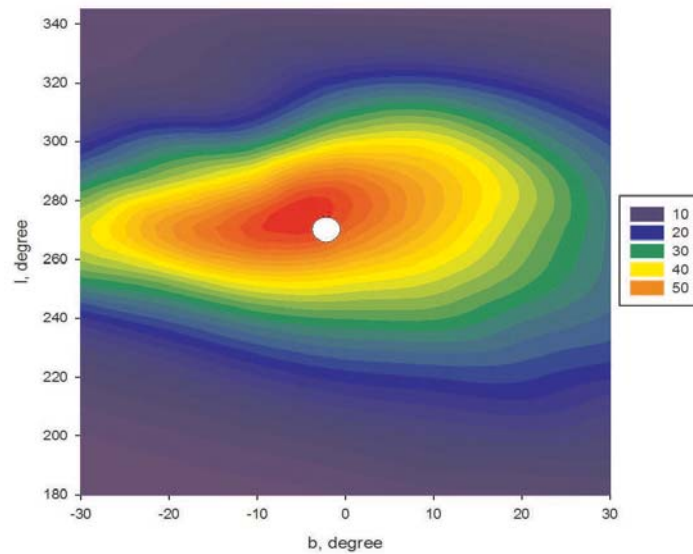
**Figure 3.** Schematic maps of CR excesses in Equatorial (A,B) and Galactic (C,D) coordinates for two energy domains: 6 - 20 TeV (A,C) and 400 - 2000 TeV (B,D). The excess regions in the MILAGRO and ARGO-YBJ experiments nearly overlap and are shown in yellow. Super-Kamiokande - green, IceCube - blue, IceTop - magenta for 400 TeV CR, red for 2000 TeV. The dark pentagon indicates the position of the Monogem Ring SNR, the dark star - the position of Vela X.

#### 2.4. The contribution of the Vela pulsar

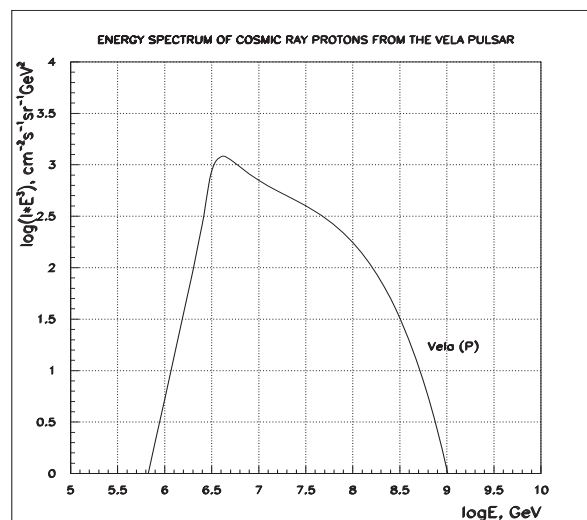
The pulsar B0833-45, which is a consequence of the SN explosion, can also contribute to the total CR flux from Vela. The energy spectrum of protons from this pulsar has been calculated by us in [11]. It occurs that the 'peak' of the intensity in coordinates  $\log E^3 I$  vs  $\log E$  appears right at the energy of the knee at 3-4 PeV (Fig.5). If this pulsar can accelerate other nuclei as well as protons then irregularities of the spectra at higher energies above the knee might be expected. In particular, it is likely that a peak with a considerable fraction of iron nuclei might appear at energies of about 50-80 PeV. At energies above 100 PeV the contribution of the pulsar ceases and one would expect a steepening of the spectrum.

The experimental situation at energies above the knee is ambiguous. Most experiments demonstrate a flattening of the spectrum at an energy above 20 PeV, which may be caused by the end of the contribution from nuclei of the CNO group. The experiment GAMMA showed the existence of a sharp peak at an energy in the range 50-80 PeV, which can be caused by the contribution of iron nuclei [12]. The experiments Tunka-133 [13], Yakutsk [14] and Ice-Top [15] do not observe such a sharp peak, but a small increase of the intensity at these energies exists in their data. The experiment KASCADE-Grande does not show an irregularity in the spectrum at 50-80 PeV [16]. However, all experiments show a steepening at energies above 100 PeV, which can be interpreted as the end of the contribution from the single source.

Therefore, there is a high probability that both the Vela pulsar and the Vela SNR contributes to the total CR flux emitted by this source, but so far this statement cannot yet be regarded as a firm proof.



**Figure 4.** The contour plot for the distribution of the parameter (called  $\chi^2/J$  in [10]) which describes the difference of the EAS age distributions for the direct and opposite directions, in Galactic coordinates. Contours of different colors correspond to different levels of this parameter (see inset: largest values painted red correspond to the largest difference of age distributions). The white spot at the plot center shows the position of Vela which is remarkably close to the position of the maximum difference in the EAS age distributions.



**Figure 5.** Energy spectrum of protons produced by the Vela pulsar [9].

### 3. Conclusion

Although with reservations it can be stated on the basis of:

- estimates of the distance and the age of the source,
- the data on the CR anisotropy at PeV energies,
- the application of the difference method for the study of the anisotropy,
- the possible existence of the intensity peak in the CR energy spectrum at an energy of 50-80

PeV caused by primary iron nuclei,  
that it is very likely that the Vela cluster (SNR and pulsar) is the CR source responsible for the formation of the knee in the locally measured energy spectrum.

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