Are there pulsars in the knee ?

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Abstract

Recent findings indicate that the Monogem Ring supernova remnant (SNR) and the associated pulsar PSR B0656+14 may be the 'Single Source' responsible for the formation of the sharp knee in the cosmic ray energy spectrum at \( \sim 3\) PeV. We estimate the contribution of the pulsar B0656+14 to the cosmic rays in the PeV region and conclude that the pulsar cannot contribute more than 15% to the cosmic ray intensity at the knee. Therefore it cannot be the dominant source there and an SNR is still needed.

We also examine the possibility of the pulsar giving the peak of the extensive air shower (EAS) intensity observed from the region inside the Monogem Ring. The estimates of the gamma-ray flux produced by cosmic ray particles from this pulsar indicate that it can be the source of the observed peak, if the particles were confined within the SNR during a considerable fraction of its total age.

We also estimate the contribution of Geminga and Vela pulsars to cosmic rays at the knee.

1 Introduction

A few years ago we suggested the 'Single Source Model' to explain the remarkable sharpness of the knee in the cosmic ray energy spectrum at \( \sim 3\) PeV [1,2], a feature noticed even in the first publication on this subject, 46

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years ago \[\text{[3]}\]. The model is based on the assumption that a single, relatively recent and nearby supernova remnant contributes significantly to the cosmic ray intensity at PeV energies. The sharpness is due to the cutoff in the energy spectrum of cosmic rays accelerated by SNR. Comparing the shape of the energy spectrum of cosmic rays from the Single Source and its total energy content with the model of SNR acceleration and the propagation of cosmic rays through the ISM \[\text{[4]}\] we derived a likely interval of distance (230-350 pc) and age (84-100 kyear) for the Single Source \[\text{[5]}\].

On the basis of our estimates of distance and age we calculated the possible flux of high energy gamma rays from the Single Source and found that it is unlikely to be observed at sub-GeV and TeV gamma rays with gamma telescopes of the present sensitivity \[\text{[5]}\]. Among the sources which would satisfy these limits of distance and age we indicated the Monogem Ring and Loop I \[\text{[6]}\].

Recently, Thorsett et al. \[\text{[7]}\], using the triangulation technique found the distance of the pulsar PSR 0656+14 associated with the SNR Monogem Ring. It is 288±30 pc and its spin-down age is \(\sim\)110 kyear, both of which are in remarkable agreement with our estimates for the Single Source \[\text{[5]}\]. Thorsett et al. themselves claimed that the SNR Monogem Ring and its associated pulsar PSR 0656+14 can be the Single Source responsible for the formation of the knee.

Armenian physicists have studied the sky near the Monogem Ring in the sub-PeV and PeV range using the EAS technique and found a 6\(\sigma\) excess of the EAS intensity in one of their angular bins \[\text{[8]}\]. Since their bin of 3\(^\circ\) × 3\(^\circ\) is narrower than the size of the SNR it is thought that the excess is not due to the extended source, but to a discrete source, viz. the pulsar.

In this paper we analyse the possibility of the pulsar PSR B0656+14, associated with the SNR Monogem Ring, being the Single Source responsible for the knee and also see to what extent the EAS excess (the ‘Armenian peak’) could come from the same object.

2 Contribution of an isolated pulsar to the knee

At the beginning we consider the pulsar as an isolated neutron star. The energy spectrum of cosmic rays is calculated as

\[
\frac{dN}{dE} = \int_0^T \frac{c}{4\pi} \frac{d^2N}{dt dE} S(t, T, E) \rho(t, T, E, R) dt
\]

(1)

Here \(E\) is the particle energy, \(c\) is the speed of light, \(t\) is the time since the creation of the pulsar and \(T\) is its spin-down age. \(\frac{d^2N}{dt dE}\) is the particle
emission rate, $S(t, T, E)$ is the survival probability against escape from the Galaxy and $\rho(t, T, R, E)$ is the density of cosmic ray particles at a distance $R$ from the source, emitted and observed at the time $t$ and $T$ respectively. Details of the calculations are given in [9]. Calculations have been made for the energy spectrum of protons ($Z = 1$) and oxygen nuclei ($Z = 8$), (assuming that oxygen nuclei could, in fact, be taken from the pulsar surface and accelerated by it). The result is shown in Figure 1.

Figure 1: The energy spectrum of cosmic rays from PSR B0656+14 observed at the present time and compared with the Single Source model of the knee [1, 2]: full line - total energy spectrum of cosmic rays; dashed line: energy spectrum of the Single Source, dotted line: energy spectrum of protons accelerated by B0656+14, dash-dotted line - the same spectrum for oxygen nuclei. The knee in the actual spectrum is at $logE(GeV) \approx 6.5$, close to our pulsar prediction for oxygen.

It is remarkable that the spectrum of cosmic rays has a very sharp peak at a rigidity of 0.25 PV, i.e. a rigidity close to that of the knee. It is the maximum rigidity of the particles emitted by the pulsar at the present time (neglecting the time for light to travel). The energy density contained in the proton and oxygen spectra is the same and equal to $1.9 \cdot 10^{-6} eV cm^{-3}$. Despite the fact that we normalized the energy transferred to the cosmic rays to the total loss of the rotation energy the cosmic ray energy density turns out to be small compared with the value of $\sim 2.24 \cdot 10^{-4} eV cm^{-3}$ needed to form the knee in the SS model [5]. If, instead of energy density,
we compare the intensity at the knee needed to ensure the observed cosmic ray flux and intensity in the peak for \( Z = 8 \), the difference becomes smaller, but it is still rather large \( (\approx 7) \). We conclude, therefore, that the pulsar PSR 0656+14, if it is considered as an isolated neutron star, can contribute up to \( \sim 15\% \) to the formation of the knee, due to the sharpness of its energy spectrum and the closeness of its peak rigidity to the needed value of 0.4 PV, but it seems not to be able to produce enough cosmic rays to be the dominant source of the knee.

3 The EAS intensity peak in the Monogem Ring region and the possibility of associating it with the pulsar B0656+14

3.1 Observation of the peak

Since the Monogem Ring SNR is located in our Local Superbubble, with its low gas density, and it is not discrete, but an extended source, which occupies a substantial part of the sky with an angular size of about 25°, then we do not expect a measurable flux of high energy gamma quanta from it \[5\]. However, Armenian physicists looking for regions with an excessive flux of EAS at PeV energies have found such a domain within the Monogem Ring SNR \[8\] (the ‘Armenian peak’). Their search bin had a size 3° × 3°, which is not point-like, but definitely smaller than the size of the Monogem Ring SNR itself. The magnitude of the excess was about 6 standard deviations and therefore appears well founded statistically.

The immediate idea, to be examined now, is that inside such an extended object as the Monogem Ring SNR there is an additional discrete source of high energy cosmic rays, which gives this excess. The most plausible discrete source within the SNR is the pulsar, specifically PSR B0656+14. Though the position of the peak is displaced from the present pulsar position, it is reasonable to analyse the probability of this pulsar producing the observable peak. The inevitable diffusive scattering of particles from the SNR and pulsar means that the Armenian peak must be due to gamma rays or neutrons.

It should be remarked that results of the experimental observation of the Monogem region is controversial. The Armenian finding is the only positive result of a search, supported marginally by the Moscow University group \[10\], other people found nothing \[11, 12, 13, 14, 15, 16, 17, 18\]. Therefore our estimates related to the Armenian peak are purely conventional, i.e.
they have a meaning if the excess of EAS found by Armenian physicists really exists.

3.2 Particles from an isolated pulsar

From the data published in [8], we estimate a flux of particles giving rise to an observed EAS peak as $(1.2 \pm 0.4) \times 10^{-13} \text{cm}^{-2}\text{s}^{-1}$. If these showers are produced by gamma quanta, their energy for the shower size $N_e > 10^6$ at 3200 m above sea level should be more than 1.07 PeV [19]. If the showers are produced by neutrons, their energy must be higher and for $N_e > 10^6$ at Aragats level should exceed 2.5 PeV [20].

Since the pulsar B0656+14 is at a distance of about 300 pc from the solar system, then if the observed gamma quanta or neutrons are produced by protons from it, they can be born only 900 years ago, i.e. at the present epoch. From the results presented in §2 it is clear that the pulsar B0656+14, if it is an isolated neutron star (i.e. the particles can diffuse freely from it), cannot give particles above its peak energy of 0.25 PeV at the present epoch. Higher energy particles produced in the past would have the necessary higher energy but they have already diffused for a long time and their density in the vicinity of the pulsar at the present epoch is very low. Heavier nuclei, if they are accelerated by this pulsar, and have higher total energy at the present time, cannot help, since they have even smaller energy per nucleon in the peak of their energy spectrum (Figure 1).

Therefore, if the pulsar B0656+14 is isolated it cannot give the Armenian peak at energies above 1 PeV.

3.3 Particles from the pulsar associated with a SNR

There is a way to include into consideration higher energy particles born in the past, but which, however, produce gamma quanta or neutrons at the present time and this is to associate the pulsar with a SNR, since they were both born in the same SN explosion and reject the assumption that the pulsar can be regarded as isolated. In this way we allow the produced particle to be trapped in the SNR in the usual manner for SNR-accelerated particles [4, 21, 22]. The pulsar created as a result of the explosion is located within the shell close to the SNR morphological center. We now assume that cosmic rays accelerated by the pulsar are also confined for the same time as those from the SNR. They are all released much later, begin to diffuse from internal regions of the SNR and eventually escape from the Galaxy. Their density in the vicinity of the pulsar is still high. In the process of diffusion
through the ISM they produce gamma quanta which can be seen now. This is the scenario.

We calculate energy spectra of cosmic rays accelerated by the pulsar B0656+14 and observed now at the Earth assuming that the confinement time is the fraction of the pulsar age. The results are shown in Figure 2. It is seen that as the instant when cosmic rays are released from confinement approaches the present moment, the higher energy cosmic rays remain within the region between the pulsar and the Earth and can be the potential source of observed gamma quanta. Comparison with Figure 1 shows the ‘value’ of the SNR trapping: particles above the knee (at 3 PeV) have now a higher intensity and thus this model is better able to explain the observation of particles of these high energies in practice.

3.4 Gamma rays from the pulsar associated with the SNR

We have calculated the expected flux of gamma quanta with energy above 1 PeV as the integral along the line of sight for gamma quanta produced in PP-collisions of protons accelerated by the pulsar with the hydrogen atoms of the ISM:

\[
F(> 1\text{PeV}) = \int_0^R 2cdr \int_{1\text{PeV}}^{E_{\text{max}}} dN \frac{dE}{dE} \rho_{cr} \sigma_{in} n_\gamma(> 1\text{PeV}) \rho_{\text{ISM}} dE
\]  

Here \(\frac{dN}{dE}\) is the energy spectrum of cosmic rays emitted by the pulsar, confined during the time \(t_{\text{conf}} = \Delta \ast \text{age,}\) then released and, until the present time, survived after escape and diffusion (Figure 2). \(\sigma_{in}\) is the inelastic cross-section of PP collisions, \(n_\gamma(> 1\text{PeV})\) is the multiplicity of gamma quanta with energy above 1 PeV, \(\rho_{\text{ISM}}\) is the mean density of the target gas in the ISM, taken as \(3 \cdot 10^{-3} \text{cm}^{-3}\) since B0656+14 is situated in our Local Superbubble with its low gas density, \(c\) is the speed of light.

Calculation of the flux for \(\Delta = 0.8\) gives a value of \(3.7 \cdot 10^{-15} \text{cm}^{-2} \text{s}^{-1}\), which is less than the experimental value \(\sim 10^{-13} \text{cm}^{-2} \text{s}^{-1}\) by more than an order of magnitude. However, the calculations show a strong dependence of the gamma ray flux on the value for the time when the cosmic rays were released from confinement. For instance, if \(\Delta = 0.95\) the flux rises up to \(2.0 \cdot 10^{-13} \text{cm}^{-2} \text{s}^{-1}\) and exceeds the experimental value by the factor of \(\sim 2\). For \(\Delta = 0.99\) the flux is \(2.2 \cdot 10^{-12} \text{cm}^{-2} \text{s}^{-1}\), which is by an order of magnitude higher than the previous value.

We have also calculated the spectra of gamma quanta from interactions of nuclei, accelerated by the pulsar and shown that they are about 2 times higher than that for protons.
Figure 2: The energy spectrum of cosmic rays from the pulsar B0656+14 observed at the Earth, calculated for different times $t_{conf}$, during which cosmic rays were confined within the SNR shell and after that they were released, begin to diffuse through the ISM and escape from the Galaxy. Dashed lines indicate the contribution from the cosmic rays accumulated during the confinement time, dotted lines show the contribution from the pulsar since the end of the confinement. Full lines show the total spectrum composed of these two. The spectra are shown for the confinement time lasting (a) 0.2; (b) 0.4; (c) 0.6 and (d) 0.8 times the pulsar age.
Estimates show that electron inverse compton scattering on photons of the microwave background radiation or on X-ray quanta emitted by SNR and neutrons produced in charge exchange $pp \rightarrow nX$ reactions or released from disintegrated cosmic ray nuclei cannot be the particles which give rise to the observed EAS peak [9]. The summary of our estimates are shown in Figure 3.

![Figure 3: Fluxes of gamma-quanta ($\gamma$) and neutrons ($N$) from PP and FeP collisions of protons and iron nuclei emitted by the pulsar B0656+14 as a function of $\Delta$ - a fraction of the total pulsar age during which the emitted particles are confined within a SNR. The inverse scattering of electrons ($e$) contributes much less (shown by the dotted arrow). The dashed lines indicate the experimental limits of the flux found in [8].](image)

4 Discussion

We conclude that although the pulsar B0656+14 cannot be the dominant source supplying cosmic rays in the knee region, it alone accelerates protons which can produce gamma quanta observable as an excess EAS intensity in the Armenian peak. Certainly cosmic rays from the associated SNR Monogem Ring can contribute to this intensity. The only condition is that cosmic rays from this pulsar should be confined by the associated SNR during a considerable fraction of its age.
4.1 Position of the Armenian peak and the pulsar B0656+14

There is a potential difficulty in the association of the Armenian peak with the pulsar. It is the mutual position of the region where the EAS intensity peak is observed, the pulsar position and the direction of its proper motion. Chilingarian et al. remark that despite the fact that their intensity peak is inside the Monogem Ring SNR it is displaced from the pulsar position by 8.5°. It is rather far. Moreover, if the excess EAS intensity is due to the interaction of cosmic rays produced by the pulsar in the past, then the direction of its proper motion should be away from the region where it was in the past. On the contrary, the direction of B0656+14’s proper motion is towards the region of the peak.

However, even if everything is correct, our scenario with a long confinement could give an explanation for the possible misalignment of the pulsar and the Armenian peak. The diffusion radius of PeV protons reached in a few ky years is about 100 pc and a sphere of this radius can be seen from a distance of 300 pc at an angle of about 20°. It means that PeV cosmic rays have overcome the parent pulsar and its proper motion is not necessarily connected with the regions of the highest cosmic ray density. Within the sphere the density of cosmic rays is presumably uniform and any kind of local ISM density perturbation or a local molecular cloud could create the excess intensity of gamma quanta.

4.2 The connection between the pulsar and the SNR

The confinement of high energy cosmic rays by the SNR raises other interesting problems: how can the Monogem Ring SNR, which according to our model accelerates cosmic rays only up to 0.4 PeV rigidity, trap and confine for a long time particles with rigidities up to 10^5 PeV? A possible idea for such a scenario is that SNR with their large sizes and moderate magnetic fields are efficient in the acceleration of relatively large fluxes of particles up to moderate sub-PeV and PeV energies, whereas a pulsar which has much higher magnetic fields in a much smaller volume, can accelerate smaller fluxes of particles reduced further by beaming, but up to much higher super-PeV energies. It means again that the pulsar B0656+14 and, probably, other pulsars, might be serious contenders for the sources of cosmic ray particles beyond the knee, discussed often as the so called ‘second component’ of cosmic rays in two- or three-component models [23, 24, 25, 26, 27].
4.3 Possible contribution of other pulsars to the knee

It is well known that some pulsars emit energetic gamma rays (see [28] for a review). Bhadra examined the possibility for pulsars to form the knee and concluded that Geminga and Vela are the most likely candidates [29]. We calculated energy spectra of cosmic rays produced by these pulsars, considering them as isolated pulsars; they are shown in Figure 4.

Since Geminga is older than B0656+14 (its age is $3 \cdot 10^5$ y), its maximum rigidity will be 0.19 PV, therefore it could contribute to the knee energies only if it accelerates iron nuclei. In this case there is no room for the ‘second knee’ in the interval 10-20 PeV found by us and included in the Single Source Model as an ‘iron peak’.

![Figure 4: Energy spectra of cosmic rays produced by the Geminga and Vela pulsars. Full line: Geminga, accelerating iron nuclei, dashed line: Vela, accelerating protons.](image)

Vela is much younger (\( \sim 10^4 \) year). Its maximum rigidity is right in the knee region of \( \sim 2.8 \) PV, so that it could contribute even by accelerating protons. The intensity can be adjusted by introducing the efficiency of conversion of the pulsar rotation energy to the accelerated particles at the level of 10%, which is a reasonable value. However, the Vela pulsar is associated with a young SNR and most likely its accelerated cosmic rays are still confined in the SNR shell.
5 Conclusions

We examined the possible contribution of several pulsars to the intensity of cosmic rays at the knee region. We conclude that the pulsar B0656+14 can contribute, but cannot be the dominant source in the knee responsible for its formation. Its contribution to the intensity of the Single Source, needed to form the sharp knee, does not exceed 15%. The SNR associated with the Monogem Ring, rather than the pulsar, still remains the most likely Single Source which gives the dominant contribution to the formation of the cosmic ray energy spectrum in the vicinity of the knee.

We have also examined the possibility of the pulsar B0656+14 giving the peak of the EAS intensity, observed from the region inside the Monogem Ring. The estimates of the gamma-ray flux produced by cosmic ray protons from this pulsar evidence that it can be the source of the observed peak, if the protons were confined within the SNR during a considerable fraction (0.89-0.94) of its total age.

Other possible mechanisms for the production of particles which could give rise to the Armenian peak were also examined, but they were found improbable.

Geminga and Vela pulsars seem to be unlikely contributors at the knee.

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