Neutrons, gamma-rays and neutrinos from the Galactic Centre

Włodek Bednarek
Department of Experimental Physics, University of Łódź, ul. Pomorska 149/153, 90-236 Łódź, Poland

Abstract

We propose that the observed excess of cosmic rays at $\sim 10^{18}$ eV, reported by the AGASA and SUGAR groups from the direction of the Galactic Centre, can be due to the neutrons produced by heavy nuclei injected from a very young pulsar. By normalization of the calculated neutron flux to the flux observed in the cosmic ray excess, the neutrino and gamma-ray fluxes at the Earth are predicted. We discuss their observability by a 1 km^2 neutrino detector of the IceCube type and future γ-ray Cherenkov telescopes.

1. Introduction

The AGASA and SUGAR experiments reported the existence of an extended excesses of cosmic rays (CRs) over a narrow energy range $10^{17.9} - 10^{18.3}$ eV from directions close to the Galactic Centre (GC) and the Cygnus region [6,2]. The GC region (inner ~ 50 pc) is rich in many massive stellar clusters with up to more than 100 OB stars [7]. These stars should explode soon as supernovae, which presence in the GC (10^3 supernovae in the past 10^5 years) is suggested by the observations of the diffuse hot plasma emitting X-rays. Since it is expected that pulsars are formed in explosions of such massive stars, the GC region should contain many young pulsars, some of them being as young as $10^3 - 10^4$ yrs. We assume that at least one of these young pulsars has been born with the parameters allowing acceleration of iron nuclei to energies $\sim 10^{20}$ eV, and production of $\sim 10^{18}$ eV neutrons from their disintegration.

2. A pulsar inside a molecular cloud

We investigate the scenario in which a very young pulsar is formed in a core collapse of the type Ib/c supernova immersed within a high density medium of the GC region. The particles, accelerated by this pulsar, escape into the surrounding and diffuse in the magnetic field of the cloud, suffering collisions with the matter (see [1]). We discuss the case of a pulsar immersed in a huge molecular cloud with the radius $R_{\rm c} = 10$ pc, the density $n_{\rm c} = 10^3$ cm^{-3}, and the magnetic field

---

pp. 2509–2512

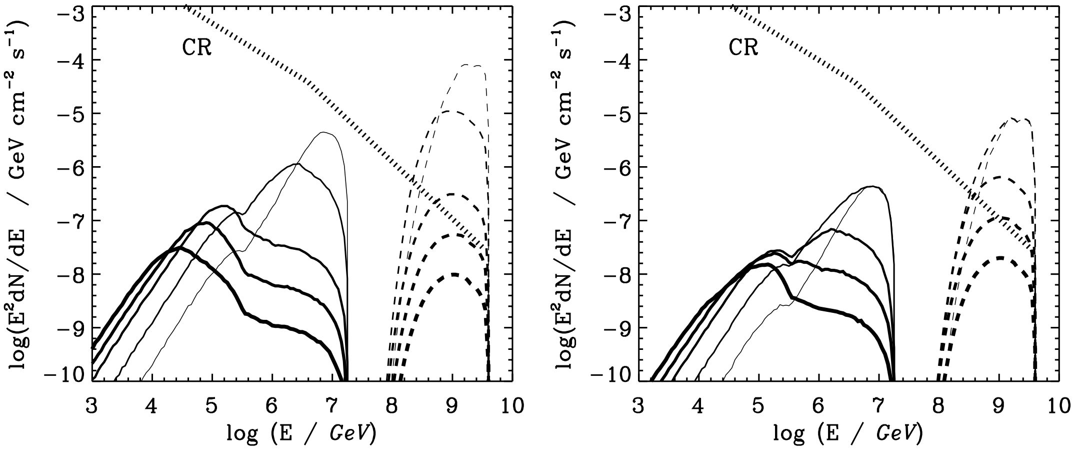

Fig. 1. The differential spectra of neutrons (dashed curves) and γ-rays (full curves) expected from the Galactic Centre at the Earth at the time $10, 10^2, 10^3, 3\times10^3$, and 10^4 yrs (from the thinnest to the thickest curve) after the formation of the pulsar. The thick dotted curve shows schematically the observed cosmic ray spectrum within the 20° circle.

$B_{\rm c} = 10^{-4}$ G, and in an extended high density region inside the GC with $R_{\rm c} = 50$ pc, $n_{\rm c} = 10^2$ cm^{-3}, and $B_{\rm c} = 3 \times 10^{-5}$ G.

Let us assume that pulsars accelerate iron nuclei in its wind zone in the mechanism called magnetic slingshot [5]. The maximum energies of the nuclei are determined by the magnetic field energy per particle in the pulsar wind zone, $E_{\rm Fe} = B^2(r_{\rm LC})/8\pi n_{\rm GJ}(r_{\rm LC}) \approx 1.8 \times 10^{11} B_{12} P_{\rm ms}^{-2}$ GeV, where $P = 10^{-3} P_{\rm ms}$ s is the pulsar period, $B = 10^{12} B_{12}$ G is the pulsar's surface magnetic field, $n_{\rm GJ} = B(r_{\rm LC})/(2ecP) \approx 3.3 \times 10^{11} B_{12} P_{\rm ms}^{-4}$ cm^3 is Goldreich & Julian density, $r_{\rm LC} = cP/2\pi \approx 4.77 \times 10^6 P_{\rm ms}$ cm, and c is the velocity of light. The nuclei can escape from the supernova envelope after a year from the supernova explosion for typical parameters of the supernova, i.e the mass of the envelope $M_{\rm env} = 3M_\odot$, and its expansion velocity $v_{\rm env} = 3 \times 10^8$ cm s^{-1}. The iron nuclei, diffusing in the magnetic field of the high density medium in the GC region, interact with the matter producing neutrons, neutrinos, and γ-rays.

The equilibrium spectrum of iron nuclei in the cloud, is calculated by integrating over the activity time of the pulsar, $dN/dE = \int_{t_0}^{t_{\rm obs}} (dN/dEdt)\, K e^{-c(t_{\rm obs}-t)/\lambda} dt$, where $t_0 = 1$ yr, K gives the part of nuclei produced at the time t which are still present inside the cloud at the time $t_{\rm obs}$. λ is the mean free path for collision of the iron nuclei with the matter of the cloud. The value of K is estimated from $K = (R_{\rm c}/D_{\rm dif})^3$, where $D_{\rm dif} = (r_{\rm L} ct/3)^{1/2}$ is the diffusion distance of iron nuclei in the magnetic field of the cloud, and $r_{\rm L}$ is the Larmor radius of the iron nuclei with energy $E_{\rm Fe}$. The part of iron nuclei confined within the molecular cloud, interact with a relatively dense medium suffering disintegrations and losing energy on pion production. The pions decay into neutrinos and

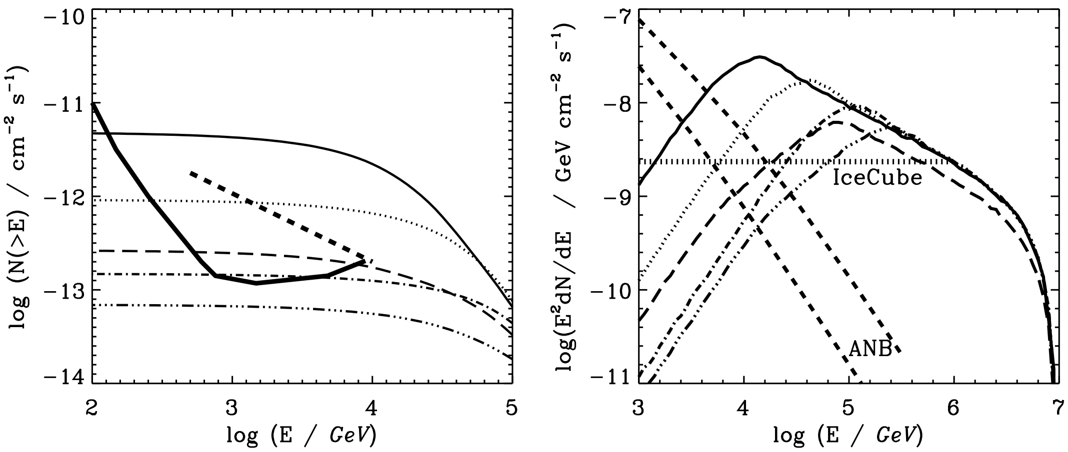

Fig. 2. The integral spectra of γ-rays produced in hadronic interactions of iron nuclei with the matter of the molecular cloud at the Galactic Centre for the models: I (full curve), II (dotted), III (dot-dashed), and IV (dot-dot-dot-dashed), and V (dashed). The thick-dashed and full curves show the sensitivity of the HEGRA System and planned CANGAROO III, HESS, and VERITAS systems (a 50-hour exposure). The differential spectra of muon neutrinos produced in this same process (on the right). The dashed curves indicate the atmospheric neutrino background within 1° of the source and the dotted line shows the 3 yr sensitivity of the IceCube detector.

γ-rays. We calculate the differential spectra of neutrons (from disintegrations of the iron nuclei), muon neutrinos, and γ-rays (from inelastic collisions of iron) for the pulsar with the surface magnetic field $B_{12} = 6$ (typical for the observed radio pulsars) and the initial period $P_{\rm ms} = 2$.

The large distance to the GC, $D_{\rm GC} \approx 8.5$ kpc, effects on the expected fluxes of neutrons and γ-rays measured at the Earth. The fluxes of neutrons and γ-rays are reduced by the factor $\exp(-D_{\rm GC}/\lambda)$, where λ is the mean free path for neutrons or γ-rays. Fig. 1 shows the fluxes of neutrons and γ-rays observed on Earth at different times after pulsar formation for the case of the pulsar with the previously mentioned initial parameters and two different media in the GC region, i.e. the case of the molecular cloud (on the left), and the case of a more extended and lower density region around the GC (on the right). Fig. 1 shows also the observed spectrum of cosmic rays (CR) within the 20° circle. It is found that only pulsars born within the last $\sim 3 \times 10^3$ yrs are able to produce fluxes of neutrons which exceed the CR limit, provided that they accelerate nuclei with the efficiency $\xi = 1$.

3. Discussion and Conclusion

The SUGAR group estimates the flux of particles responsible for the reported excess in the energy range $10^{17.9} - 10^{18.5}$ eV as $(9 \pm 3) \times 10^{-14}$ m^{-2} s^{-1} [2].

If this excess is caused by neutrons, then their expected flux can be compared with the observed one, giving the efficiency of iron acceleration, ξ. Basing on this normalization, the fluxes of neutrinos and gamma-rays at the Earth can be predicted. We consider five different sets of parameters describing our scenario: model (I) R $= 10$ pc, $n = 10^3$ cm^{-3}, $B_{\rm c} = 10^{-4}$ G, $t_{\rm obs} = 10^4$ yr; (II) $t_{\rm obs} = 3\times 10^3$ yr and other parameters as above; (III) $t_{\rm obs} = 10^3$ yr and other parameters as above; (IV) R $= 50$ pc, $n = 10^2$ cm^{-3}, $B_{\rm c} = 3\times 10^{-5}$ G, $t_{\rm obs} = 10^4$ yr; and (V) $t_{\rm obs} = 3\times 10^3$ yr and other parameters as in (IV). It is assumed in all these models that the pulsar is born with $B = 6\times 10^{12}$ G and $P_{\rm o} = 2$ ms. From the above normalization we derive the value of the parameter ξ: ≈ 1 for model I, 0.18 (II), 0.03 (III), 0.3 (IV), and 0.09 (V). Using these estimates for ξ, the expected fluxes of γ-rays and muon neutrinos are predicted. The integral spectra of γ-rays from the GC region are presented in Fig. 2, together with the sensitivities of the present HEGRA telescope system and the planned next generation telescopes, i.e. CANGAROO III, HESS, VERITAS. The γ-ray fluxes in the energy range 1-10 TeV predicted in the models, (I) $\sim 2.1\times 10^{-12}$ cm^{-2} s^{-1}, (II) $\sim 2.1\times 10^{-13}$ cm^{-2} s^{-1}, and probably also in (IV) $\sim 8\times 10^{-14}$ cm^{-2} s^{-1}, should be observed by the future systems of Cherenkov telescopes. Models III and V predict fluxes below the sensitivity limit of these Observatories.

Fig. 2 shows also the muon neutrino and anti-neutrino spectra expected in this model. At energies > 10 TeV, these spectra are above the 3 yr sensitivity limit of the planned IceCube neutrino detector. We estimate the number of muon neutrino events during one year in the IceCube detector basing on the calculations of the likelihood for observing such neutrinos by a detector with a surface area of 1 km^2 [4]. The IceCube detector should detect a few up to several neutrinos per year from the GC region provided that the excess of cosmic rays at $\sim 10^{18}$ eV is caused by neutrons [1]. Detection of predicted neutrino fluxes from the GC (or lack) will also constrain the recent model of extremely high energy cosmic ray production by pulsars [3], since the parent iron nuclei have to be accelerated to energies $\sim 10^{20}$ eV in order to inject neutrons with energies $\sim 10^{18}$ eV.

4. References

1. Bednarek W. 2002, MNRAS 331, 483
2. Bellido J.A. et al. 2001, Astropart.Phys. 15, 167
3. Blasi P., Epstein R.I., Olinto A.V. 2000, ApJ 533, L123
4. Gaisser T.K., Grillo A.F. 1987, Phys.Rev. D 39, 1481
5. Gunn J., Ostriker J. 1969 PRL 22, 728
6. Hayashida N. et al. 1999, Astropart.Phys. 10, 303
7. Morris M., Serabyn E. 1996, ARA&A 34, 645