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Pulsar contribution to high energy cosmic rays

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Abstract. We show that assuming a simple CR acceleration scenario, where all the pulsar rotational energy is transformed into CR particles of the highest available energy at a given moment, one obtains particle fluxes of the order of the observed ones. The slope of CR energy spectrum for $E>10^{16}$eV would be determined by a power-law distribution of their initial periods and the spectrum flattening – by the decay of the pulsar magnetic field.

1. Introduction

The origin of cosmic rays (CR) in the energy region ~$10^{14\text{-}15}$-$10^{18\text{-}19}$eV seems to be most unclear. Lower energy particles are probably accelerated by the diffusive shock wave mechanism on shocks induced by Galactic supernovae explosions in the interstellar medium. The test particle approximation of this process is very well understood (with most problems solved analytically) and progress in the non-linear treatment has been continuing. (A troubling thing, however, is the non-detection of TeV gamma-rays from SNRs, while predictions say the opposite).

CR with energies higher than those from the region mentioned above, i.e. with $E>10^{18}$-10^{19}eV, might be of extragalactic origin and as such could be accelerated by shocks in huge relativistic jets associated with e.g. radiogalaxies. Anyway, arguments concerning their anisotropy and their propagation through the intergalactic sea of the microwave (and other) radiation, give us useful and relevant constraints on sites of their origin.

However, virtually nothing certain can be said about the origin of the intermediate energy CR. In principle, they could be just as well of Galactic as of extragalactic origin. Here, we consider the former possibility, with Galactic pulsars (or phenomena associated with them) being responsible for the particle acceleration. The idea is not new, as it has not been difficult to estimate from the energetics point of view, that they release to the surroundings enough of their rotational energy to account for the intermediate energy CR pool. Also high energy of a *single* particle could, in principle, be achieved from a simple estimation (E~$qvBR$).

Doubts have been risen, however, whether pulsars could produce power-law energy spectra as required by observations (power law spectrum is usually attributed to a many-step acceleration mechanism, whereas here it would be the large scale electric field responsible for acceleration). Moreover, if they were to produce the very high energy particles with $E\approx10^{18}$-10^{19}eV a significant anisotropy associated with the Galactic plane should be expected, contrary to observations. In this paper we show that the two above arguments may not be quite true. We calculate the CR energy spectra that may be produced by the pulsar population in the Galaxy and obtain power-law in several orders of magnitude. Also the anisotropy should not be significant if the accelerated particles were heavy nuclei (iron) and/or there was a large magnetic halo in our Galaxy.

2. Assumptions of the model

We assume that particles are accelerated in the large scale electric field produced by the pulsar magnetic moment rotation. At a given time the energy of each produced particle equals $q\phi$,

$$\phi(t)=\frac{R^3}{2c^2}B\Omega(t)^2=6.6\frac{B(G)}{P^2(s)}Volts \qquad (1)$$

where ϕ is the maximum potential drop available at time t in the model of a rotating magnetic moment, R –is the neutron star radius (10 km), B – magnetic field at the star magnetic equator, Ω - the angular velocity of rotation. We assume that all the rotation energy loss

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$$dE_{rot}/dt = -I\Omega\dot{\Omega} = -\frac{R^6B^2\Omega^4}{6c^3}$$

is transformed into energetic particles, so that their production rate $Q(E)$ equals

$$Q(E) = \frac{dE_{rot}}{dt \cdot q\phi} = \frac{R^3B\Omega^2(t)}{3qc}$$

Such a scenario has also been considered by Blasi et al. (2000). The acceleration should probably have to occur outside the light cylinder in order to make the particle energy losses for synchrotron and curvature radiation negligible (Venkatesan at al., 1997). If the pulsar magnetic field did not change with time, it follows from the above formulas that the energy spectrum of the emitted particles during its lifetime would be

$$\frac{dN}{dE} = \frac{Ic^2}{qR^3B}E^{-1} = \frac{I\Omega_o{}^2}{2E_{\max}}E^{-1} = \frac{E_o^{rot}}{E_{\max}}E^{-1} \qquad (2)$$

where $E_o^{rot} = \frac{1}{2}I\Omega_o^2$ is the initial rotation energy of the pulsar and $E_{max}=q\phi$ is the particle energy at the initial time.

The above spectrum would also describe the particle production spectrum (per 1 pulsar) at the equilibrium $Q(E)$ if all pulsars were being produced at a constant rate in time, with the same Ω_o and B

$$Q(E) = \frac{1}{t_{\max}}\frac{dN}{dE}$$

where t_{max} is the maximum time when pulsar contributes to CR production (t_{max} has to be assumed finite, otherwise the total number of produced particles diverges to infinity). As pulsars are being born with various initial periods P_o and B, the actual CR production spectrum in the Galaxy can be calculated by integration of (2) with weights equal to the number of pulsars borne with given P_o and B.

There is, however, evidence that B may decay in time (e.g. old pulsars have low magnetic fields). Adopting that $B(t) = B_o \exp(-t/t_d)$ we obtain that the CR production rate at the equilibrium for pulsars born with fixed P_o and B_o equals

$$Q(E) = \frac{1}{\varepsilon\, t_{\max}}\left[\frac{AE^2}{(\sqrt{1+AE^2}-1)\sqrt{1+AE^2}} - 1\right] \qquad (3)$$

where another energy scale ε has appeared

$$\varepsilon = \frac{3q^2}{2ct_d} = 2.28\cdot 10^{-32}\mathrm{eV}\cdot \mathrm{Z}^2\left(\frac{10^7\,yrs}{t_d}\right)$$

and the constant A equals

$$A = \left(\frac{E_{\max}}{\varepsilon E_o{}^{rot}}\right)^2\left(1+\frac{\varepsilon E_o{}^{rot}}{E_{\max}{}^2}\right)$$

It can be derived that for $E \to E_{max}$

$$Q(E) \to \left(\varepsilon\, t_{\max}\sqrt{A}\right)^{-1}\cdot E^{-1}$$

and for $E \to 0$

$$Q(E) \to \left(\varepsilon\, t_{\max}\right)^{-1}.$$

The energy E^* where the change of slope occurs is $E^*=A^{-1/2}$. If $\varepsilon E_o^{rot}/E_{\max}^2 << 1$ (which is fulfilled if $\left[B_{12}/P_o(s)\right]^2 >> 2.2$, i.e. probably true for most pulsars) then $E^* = 4.2\cdot 10^{13}eV\,\frac{10^7\,yrs}{t_d}\cdot\frac{Z}{B_{12}}$ which corresponds to $E^* \cong 10^{15}$eV for iron nuclei, B=10^{12}eV and t_d=10^7 years. Let us note that for a given decay time t_d, the change of the slope in the production spectrum occurs at an energy E^* dependent on B_o only.

The production spectrum $Q(E)$ for any given P_o and B_o is much flatter than that needed for the observed CR. However, after integration over distributions of P_o and B_o we can obtain much steeper production spectrum of high energies. For a fixed B_o and a distribution of P_o, $f(P_o)dP_o$, we have for large energies

$$Q(E) \cong \int_{P_{\min}}^{P_{\max}} \frac{E^*}{E} f(P_o)dP_o = \frac{E^*}{E}\int_{P_{\min}}^{\sqrt{b/E}} f(P_o)dP_o \qquad (4)$$

where $b = 2\pi^2 ZR^3B_o/c^2$.

For the simplest case, $f(P_o)=(P_2-P_1)^{-1}=const$ (with $P_1=P_{min}$ and $P_2=P_{max}$)

$$Q(E) \to \frac{E^*}{E}\frac{\sqrt{\frac{b}{E}-P_1}}{P_2-P_1} \approx E^{-3/2} \qquad (5)$$

for $P_1 << \sqrt{b/E}$. Let us note that the integration over a distribution of B_o does not change this energy dependence. This is still flat enough but for $\sqrt{b/E}$ approaching P_1 the spectrum steepens ($Q(E) \to 0$ for $E \to E_{max}=b/P_1^2$).

A more realistic $f(P_o)$ would probably be something similar to a gamma distribution that is

$$f(P_o) = C\cdot P_o{}^{s-1}e^{-qP_o}$$

Introducing this form into (4), we have for high energies (small P_o)

$$Q(E) \to \frac{E^*}{E}\int_0^{\sqrt{b/E}} CP_o{}^{s-1}dP_o = \frac{A}{s}\,\frac{E^*}{E}\left(\frac{b}{E}\right)^{\frac{s}{2}} \approx E^{-\left(1+\frac{s}{2}\right)} \qquad (6)$$

Also here, the integration over B_o distribution does not change this high energy dependence. Thus, adopting an appropriate value of s, one can obtain the necessary slope of the production spectrum at its high energy end.

To find, however, the particle production rate in the whole energy region, we have to adopt a distribution of the initial magnetic fields, B_o, and integrate over it (which has to be done numerically). Following many other authors we assumed that the variable $x=logB_o$ has a Gaussian distribution $g(B_o)$, with σ=0.4. Such assumptions are justified by analysis of the observed pulsar population (e.g. Lorimer et al., 1993). We have done calculations for several different values of $\bar{x}$ (between 12 and 13).

What is the actual CR production rate it is not certain, as we would have to know the CR lifetime $T(E)$ in the Galaxy as a function of energy. Here we adopt that $T(E)$ has a

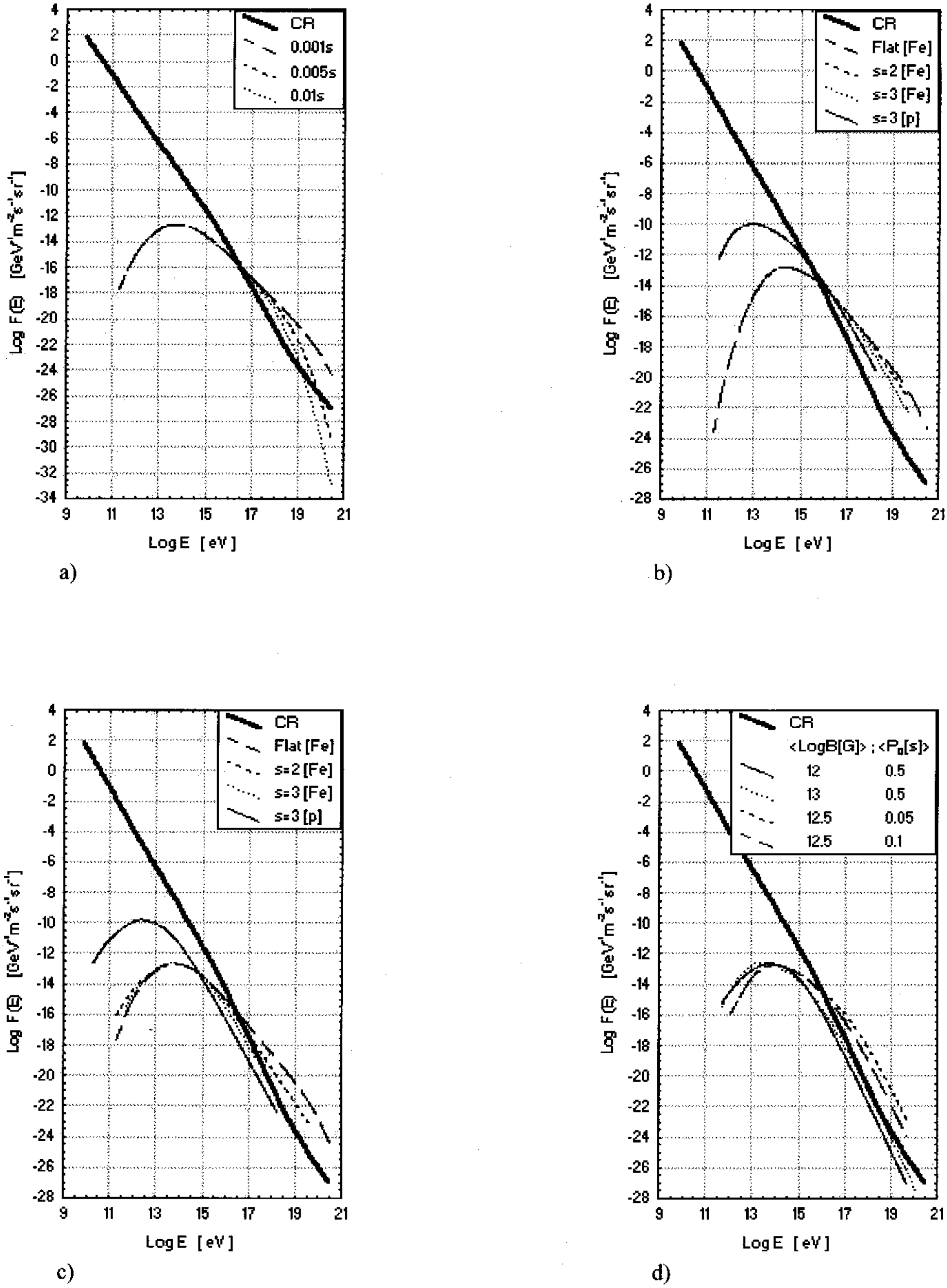

Fig.1. CR energy spectra. Thick line – the observations. All other lines are predictions of our model with t_d=10^7 years.

a) flat distribution of P_0, values of P_1 are shown in the insert; P_2=1s, <log B_0>=12.1; iron nuclei,

b) comparison of spectra for the flat and two gamma distributions of P_0, for the same <P_0>=0.05s; <log B_0>=12.1; the solid line is for protons,

c) the same as Fig.1b but for <P_0>=0.5s,

d) predictions for gamma function with s=3.86 for iron nuclei.

power-law form $T(E)=2\cdot 10^{7}\left(E/1.5GeV\cdot Z\right)^{-0.27}$, which roughly fits the low energy data (≤1GeV/n) and the particle lifetime at ~10^{19}eV with a very big (20-50 kpc) Galactic halo (Giller and Zielinska, 2000). To compare the predicted CR fluxes produced by pulsars, we have to assume the CR confinement volume and the pulsar production rate, *q*. We have adopted V=1.2*10^{68}cm^3. All our predicted fluxes are drawn for *q*=1/100 years.

3. Results of calculations

We have calculated the expected CR energy spectra for various values of the parameters describing $f(P_o)$ and $g(B_o)$. Fig.1a. shows the results for iron nuclei for the homogeneous (flat) $f(P_o)$ between P_1 and P_2, for several values of P_1 (other parameters given in the Figure caption). The high energy behaviour, described in the previous paragraph (formula (5) and the discussion below) is well seen. It is seen also that small initial P_o predict a too flat CR spectrum, but for P_1=10 ms the slope fits (roughly) that of the data at ~10^{18}eV. Note that the absolute magnitude can easily be shifted by factor of 10 or so, due to the uncertainly of the *qT/V* product.

Fig.1b. represents a comparison of the calculated spectra for the flat distribution of P_o and the gamma distribution with *s* =2 and 3. All P_o distributions are for the same $\overline{P_o}=50ms$. As discussed before the steepest spectrum is that for *s* =3, but it is still slightly too flat. Also at E ≥10^{18}eV we predict disturbingly too many particles. This can be, however, overcome by diminishing $\overline{P_o}$, as it is shown in Fig.1c., where for the gamma distribution with *s* =3 we obtain ~ three orders of magnitude less particles at E~10^{17}eV.

As discussed in the previous paragraph (formula 6), to get the observed slope (3.2), we need to have 1+*s*/2+0.27=3.2, i.e. *s* =3.86. The results for this value of *s* are presented in Fig.1d. The case with <log*B*>=12 and $\overline{P_0}$ =0.5s reconstructs very well the slope above ~10^{16}eV. For <log*B*>=13 and the same $\overline{P_0}$ =0.5s also the absolute flux fits the observations in a large energy region. Such a rather large $\overline{P_o}$ has been deduced from the analysis by Narayan (1987) (see also Narayan and Ostriker, 1990). Calculations for smaller $\overline{P_0}$, s=3.86 and <log*B*>=12.5 are also shown. We see that for the chosen parameters in Fig.1d. all spectra have the required slope above ~10^{16}eV. This slope decreases at lower energies (as does that of the observed spectrum) due to the decay of the magnetic field and eventually at $\leq 10^{14}$eV the finite t_{max} comes into play and causes the flux to fall.

4. Conclusions

If CR with E >10^{15}eV were to have nothing to do with the acceleration by pulsars it would be a strange coincidence that the fluxes predicted here for the most simple scenario, would coincide with observations. The predicted pulsar parameters at birth are close to those derived from observations of their Galactic population.

If this model was true the CR slope (γ=3.2) at E≥10^{16}eV would be determined by the distribution of pulsar initial periods (~$P_0^{3.86}$ at small P_0). Its flattening at ~3*10^{15}eV would be caused by decaying magnetic fields (t_d~10^7yrs).

If the produced particles were mainly iron nuclei then they should be quite well confined to the Galaxy at least up to ~10^{19}eV (e.g. Giller et al., 1994).

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