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Origin of energetic cosmic rays
II. The possibility of a contribution from pulsars

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Abstract. The form of the primary cosmic ray spectrum expected from pulsars is derived using the model of Ostriker and Gunn for pulsar characteristics and experimental data on pulsar frequencies. It is found that in the energy range 10^{14} eV to 10^{16} eV (ie in the region covering the break in the primary spectrum) the majority of cosmic rays could come from pulsars. The shape of the spectrum is such as to go some way towards explaining the rapid change of slope which is found to occur at about 3×10^{15} eV. The pulsar contribution appears to cease above 3×10^{16} eV and some other source is necessary here; similarly other sources are needed below about 10^{14} eV.

1. Introduction

In the previous paper (Bell *et al* 1974, referred to as I), attention was given to a model for cosmic ray production in which it was assumed that the sources all produced energy spectra ($N(E) = AE^{-\gamma}$) in which γ was constant, independent of energy. In the present work we examine the primary cosmic ray spectrum expected from particular sources, pulsars, for which this condition does not obtain. The object is to take a model of pulsar mechanism (that of Ostriker and Gunn 1969) together with such experimental data on pulsars as are available, including their likely rate of production in the galaxy, and use this to make a quantitative prediction of the expected primary spectrum at the earth.

In the present work the energies considered are largely above 10^{14} eV. The energy interval considered (10^{14}–10^{20} eV approximately) is sufficiently wide that one may suppose that a single mechanism is not necessarily responsible and, as will be seen, we consider pulsars as potential sources of cosmic rays only below about 10^{17} eV, a limit that comes from the adopted theory.

One of the essential problems arising when the cosmic rays with highest energies (above 10^{17}–10^{18} eV) are considered is the nature of the objects which are able to accelerate particles to such gigantic energies. Quantitative arguments which are often put forward that these cosmic rays can originate in pulsars (despite problems concerning the magnitude of the energy involved) do not seem to stand against detailed analysis as will be demonstrated. It has been shown (Karakula *et al* 1972) that the almost ideal isotropy of the cosmic rays with energies above 10^{18} eV is not in agreement with their entirely galactic origin, since the smearing out by the magnetic fields in the galaxy is not sufficient, and extra-galactic particles are required. However, the contribution of galactic

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pulsars should be at least two orders of magnitude higher than that from extra-galactic ones because if pulsars are neutron stars their frequency should be on average proportional to the density of matter.

In general it may be said that, if cosmic rays are extra-galactic in origin, then because of inverse square law effects, the frequency of the objects producing them must be several orders of magnitude higher, in relation to the matter density, in extra-galactic space than in the galaxy. It can be remarked that the indications that cosmic rays with the highest energies are extra-galactic are therefore an argument against any objects originating in the process of normal stellar evolution being sources of those cosmic rays.

2. Predictions of the model

According to the theory of Ostriker and Gunn the energy spectrum of cosmic rays produced by a pulsar depends on its age. In the early stage, when the gravitational losses dominate, the relation is

$$N_1(E)\,\mathrm{d}E = 6{\cdot}5\times10^{73}\frac{P\,\mathrm{d}P/\mathrm{d}t}{\epsilon_e^2}E^{-2{\cdot}5}\,\mathrm{d}E \tag{1}$$

with E in eV, and in the later stage, when magnetic losses dominate:

$$N_2(E)\,\mathrm{d}E = 1{\cdot}38\times10^{15}\frac{I^{1/2}}{(P\,\mathrm{d}P/\mathrm{d}t)^{1/2}}E^{-1}\,\mathrm{d}E. \tag{2}$$

In the relations, P is the period of the pulsar at time t, $\mathrm{d}P/\mathrm{d}t$ is its rate of change, and I and ϵ_e are the moment of inertia and ellipticity. Equating equations (1) and (2) shows that change from the first to the second stage occurs at an energy

$$E_z = \frac{1{\cdot}31\times10^{39}}{\epsilon_e^{4/3}I^{1/3}}\left(P\frac{\mathrm{d}P}{\mathrm{d}t}\right) \tag{3}$$

which can be estimated from the properties of pulsars measured experimentally. As can be seen, the energy spectra of cosmic rays can be expressed as a function of E_z. Following Ostriker and Gunn, the maximum energy of the emitted cosmic rays can be expressed in terms of E_z:

$$E_{\mathrm{max}} = 4{\cdot}06\times10^{11}E_z^{1/3}. \tag{4}$$

The final spectrum of cosmic rays emitted by the pulsar can thus be written:

$$\begin{aligned} N(E,E_z) &= 5\times10^{34}\left(\frac{I}{\epsilon_e^2}\right)^{1/3}\frac{1}{E_z^{1/2}E}, && E<E_z \\ &= 5\times10^{34}\left(\frac{I}{\epsilon_e^2}\right)^{1/3}\frac{E_z}{E^{2{\cdot}5}}, && E_z<E<E_{\mathrm{max}}. \end{aligned} \tag{5}$$

The total energy emitted by the pulsar during its lifetime then follows as

$$E_{\mathrm{tot}} = \int_0^{E_{\mathrm{max}}} N(E,E_z)E\,\mathrm{d}E \simeq 1{\cdot}5\times10^{35}\left(\frac{I}{\epsilon_e^2}\right)^{1/3}E_z^{1/2}. \tag{6}$$

3. Average energy spectrum of cosmic rays from pulsars

Values of E_z can be calculated for all pulsars with known values of $\mathrm{d}P/\mathrm{d}t$. We assume the values $I = 1{\cdot}4 \times 10^{45}\ \mathrm{g\,cm^2}$ and $\epsilon_e = 2 \times 10^{-4}$, which are appropriate to the Crab pulsar, to apply to all pulsars and, using the data on P and $\mathrm{d}P/\mathrm{d}t$ from the review of Manchester and Taylor (1972), we obtain the observed frequency distribution of E_z given in figure 1. The approximation involved in using identical values of I and ϵ_e for all pulsars is not too serious in view of the lack of sensitivity of the various cosmic ray quantities to these parameters and, in any case, the expected range of values is small.

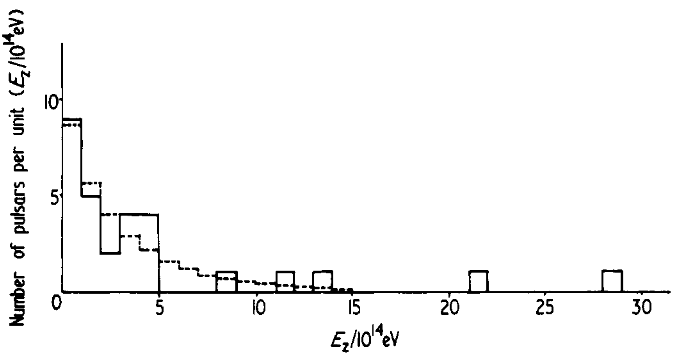

Figure 1. The observed distribution of pulsars as a function of breaking point energy E_z. The broken histogram shows the empirical fit, $f(E_z/10^{14}\ \mathrm{eV})$, multiplied by the total number of pulsars plotted.

The distribution can be approximated by the relation:

$$f(x) = 0{\cdot}306x^{-0{\cdot}133} \exp(-0{\cdot}284x) \tag{7}$$

which is normalized to $\int f(x)\,\mathrm{d}x = 1$ where $x = E_z/10^{14}$ eV. Assuming that the distribution is an unbiased sample of the population of pulsars in the galaxy, the average energy spectrum emitted per pulsar can be calculated from equations (5) and (7):

$$N(E) = \int_0^\infty N(E, E_z) f(E_z/10^{14})\,\mathrm{d}E_z/10^{14}. \tag{8}$$

The energy spectrum obtained is given in figure 2. The broken histogram marks the spectrum expected when absorption in the supernova shell is taken into account as discussed by Barrowes (1971). In the present paper the absorption was estimated assuming that the mass of the shell is equal to 2·2 solar masses and that the velocity of expansion is $10^4\ \mathrm{km\,s^{-1}}$ (see Cameron 1971). From equation (8) the mean total energy per pulsar and the mean maximum energy can also be calculated:

$$E_t = \int_0^\infty E_{\mathrm{tot}}(E_z) f(E_z/10^{14})\,\mathrm{d}E_z/10^{14} = 7{\cdot}5 \times 10^{59}\ \mathrm{eV}$$

and

$$E_m = \int_0^\infty E_{\mathrm{max}}(E_z) F(E_z/10^{14})\,\mathrm{d}E_z/10^{14} = 2{\cdot}4 \times 10^{16}\ \mathrm{eV}.$$

As can be seen from figure 2 knowledge of the exact value of the maximum energy is not

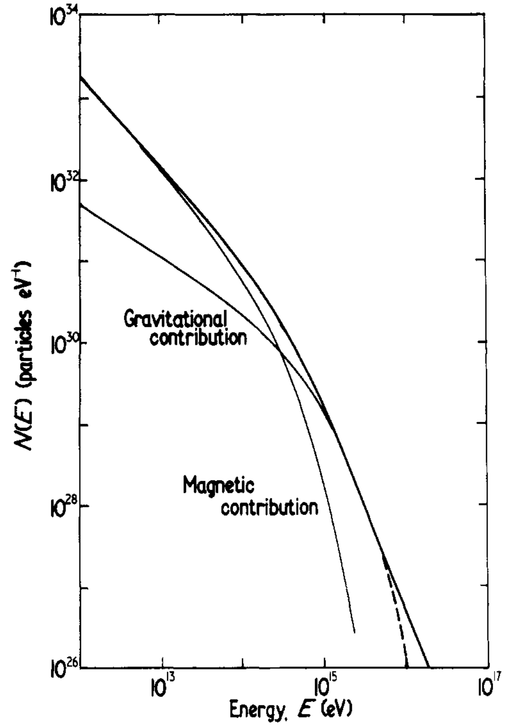

Figure 2. The average energy spectrum emitted per pulsar.

important since in the early stages when the particles with highest energies are produced the absorption by the shell is dominant.

A variety of estimates for the frequency of supernova explosions exists; a reasonable rate for the galaxy is one in 26 years (Tamman 1970) and we assume a uniform distribution throughout the galactic disc (15 kpc radius and 300 pc average thickness).

In order to calculate the form of the expected energy spectrum it is now necessary to assume a lifetime for the particles in the galaxy. In the present work we adopt a confinement time of $\tau = 2 \times 10^6$ yr independent of energy. This value is chosen from the measurements of spallation products at much lower energies and is assumed to be valid at the energies in question here.

The resulting predicted primary spectrum observed at 'local' points in the galaxy is given in figure 3. Also shown is the experimental spectrum with slope $-2{\cdot}7$ obtained by extrapolation of the data from direct measurement below 2×10^{12} eV (Ryan *et al* 1972) and the various experimental data on the primary spectrum obtained in measurements on cosmic rays in the atmosphere.

The spectrum C of Bradt *et al* (1965) is as quoted in that work. In fact EAS measurements of the size spectrum of recorded showers show the 'kink' indicated in B and discussed at length in I.

It is immediately seen that the contribution from pulsars calculated by us is, in the region of 10^{16} eV, of the same order of magnitude as that observed experimentally. Such a fact is rather encouraging; it should be noted particularly that the input information has all been taken directly from astronomical data without preconceived ideas as to what cosmic ray intensities would result.

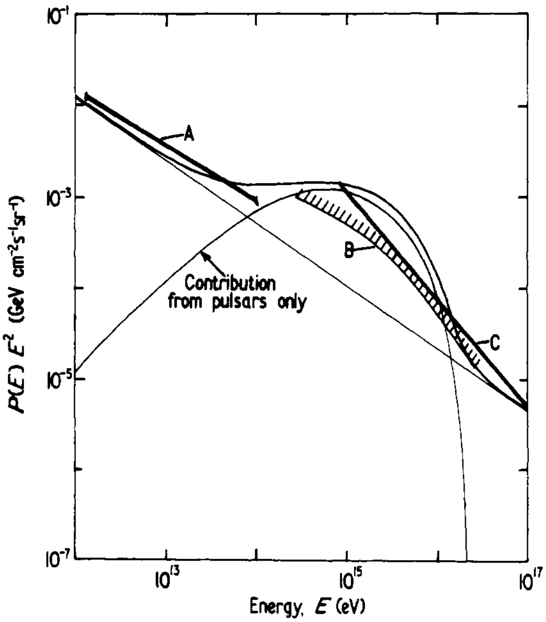

Figure 3. The total cosmic ray energy spectrum obtained under the assumptions stated in the paper. The spectrum from pulsars is marked together with a spectrum with differential slope −2·7. The sum of the two is also plotted. The experimental points are taken from: A, indirect analysis muon measurements; B, analysis of EAS data by Hillas (1972), the line represents the lower limit for the intensity; C, EAS measurements of Bradt *et al* (1965).

Below about 10^{14} eV the contribution from pulsars is too small and other sources must be postulated. It is this region which is discussed in a following paper (III). If a spectrum with slope −2·7 from other sources (perhaps novae) is allowed then from figure 3 it can be seen that the summed predicted spectrum is in fair agreement with the observations; in particular it explains quite well the 'kink' at a few times 10^{15} eV and also the decrease in slope in the region 10^{13}–10^{15} eV which was tentatively suggested by Wdowczyk and Wolfendale (1973).

We have, thus, an alternative explanation of the break in the spectrum to that put forward in I and the present assumption of an energy independent confinement time is at variance with the diffusion arguments outlined there (in which the confinement time falls above about 3×10^{15} eV). In actual fact the observed spectrum could be due to a combination of a steepening source spectrum produced by the pulsar mechanism and a decreasing confinement time as described in I.

4. Inclusion of heavy nuclei

The spectrum due to pulsars presented in figure 3 is related to protons. In fact the mechansim of Ostriker and Gunn can also accelerate heavier nuclei and to energies correspondingly higher ($E_{\max} \propto A^{1/3}Z^{2/3}$). If these heavier nuclei are not fragmented before they leave the source then they should be observed above 10^{16} eV. The possibility that these very energetic primary cosmic rays are heavier than protons does not appear to be ruled out by the present experimental data. Although the measured fluctuations of the N_μ/N_e ratio (for a summary see Adcock *et al* 1968) and the age parameter fluctuations (Catz *et al* 1973) indicate that at 10^{15} eV protons dominate in good accord with the pulsar hypothesis, these experiments allow very little to be said about the energy region above 10^{16} eV. Some observations on cosmic rays in that energy region could in fact be more easily understood if heavier nuclei were to dominate at 10^{17} eV. For example, the problem of high multiplicities in EAS interactions, a result inconsistent with the predictions of scaling in very high energy collisions, would be eased considerably if heavy nuclei were allowed in this region (see Wdowczyk and Wolfendale 1973). In the region 10^{16}–10^{17} eV where, on the hypothesis that heavy nuclei as well as protons may originate in pulsars, a transition from protons to heavies would be expected, there is a measure of support from the recent work of Firkowski *et al* (1973). Here the measured density spectrum of muons is flatter than expected for a purely proton source.

Above 10^{18} eV the heavy nuclei from galactic pulsars should fall rapidly in intensity and presumably extra-galactic particles will take over. Some, slight, evidence in favour of this transition comes from the discrepancy between the energy spectrum obtained at Haverah Park (Andrews *et al* 1971) and Yakutsk (Diminstein *et al* 1972): the spectrum observed at Haverah Park is steeper as would be expected for a device which is more sensitive to muons, and thus to the heavy component. It should be remarked, however, that the evidence for large fluxes of heavy particles above 10^{16} eV is not strong.

5. Conclusions

The analysis made in the present work shows that the pulsar mechanism of Ostriker and Gunn combined with experimental data on pulsar frequencies gives a cosmic ray spectrum which is rather close to observation in the energy range 10^{14}–10^{16} eV if the primaries are considered to be protons. The rapid change of slope observed in this energy region is moderately well reproduced by this spectrum.

Below 10^{14} eV some other source of particles is required, such as novae (see paper III in this series).

Above 10^{16} eV it is conceivable that heavy nuclei, accelerated in pulsars, contribute and there is some circumstantial evidence supporting this idea, as far as about 10^{18} eV. At still higher energies it is likely that the particles originate either in peculiar objects in extra-galactic space or that they are of cosmological origin.

Acknowledgments

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