THE ASTROPHYSICAL JOURNAL, 162:L181–L186, December 1970

PULSARS AND VERY HIGH-ENERGY COSMIC-RAY ELECTRONS

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Received 1970 June 8; revised 1970 September 19

ABSTRACT

In the study of the propagation of cosmic-ray electrons, the use of a continuous source distribution is not valid in the range of very high energies. The electron spectrum in that energy range depends on the age and distance of a few local sources. It is shown that if the far-infrared background discovered recently exists in the Galaxy, the very high-energy electrons observed at Earth probably all come from the source Vela X, and a cutoff energy at about 2×10^3 BeV is predicted. Implications on the propagation of cosmic rays in the Galaxy are discussed.

The primary difficulty in the astrophysical study of cosmic rays is that they are mixed thoroughly in the interstellar magnetic field, so that information from cosmic rays relate to all sources at once. Thus in the past one could not learn from the cosmic-ray data what happened in a particular source, nor could the information about a single source predict an observable effect on cosmic rays. This position, however, has changed with the discovery of pulsars and the detection of cosmic-ray electrons with very high energies. We shall show in this Letter that if the far-infrared radiation discovered recently (Shivanandan, Houck, and Harwit 1968; Houck and Harwit 1969; Muehlner and Weiss 1970) exists in the Galaxy, then a major part of the very high-energy cosmic electrons detected recently by Anand, Daniel, and Stephens (1969) is probably originating from the single source Vela X, and the intensity and spectrum of these energetic electrons should provide direct information about this pulsar. A positive prediction of the above suggestion is a sharp cutoff of the cosmic-electron spectrum at $\sim 2 \times 10^3$ BeV.

In a recent article Lingenfelter (1969) considered the contribution of pulsars and radio supernova remnants to the intensity of local cosmic-ray nuclei. The flux from these discrete sources is, unfortunately, smeared out by the background (cosmic rays originating from the distant part of the Galaxy). Thus little information about pulsars can be learned from the nucleus component of cosmic rays. But the situation is quite different for the case of high-energy electrons, which suffer serious energy losses in interstellar space. The loss rate is given by $dE/dt = -bE^2$, where $b = 8 \times 10^{-26} (W_{\text{ph}} + W_h)$ $(\text{eV sec})^{-1}$. The quantities W_{ph} and W_h are respectively the energy density of the ambient photons and the magnetic field in eV cm^{-3}. The energy of an electron in interstellar space varies as $E(t) = E_0(1 + bE_0t)^{-1}$. Consequently, electrons of energy E must be produced at a time t less than $(bE)^{-1}$ ago and from sources not much farther away than $(2D/bE)^{1/2}$, where D is the diffusion coefficient for cosmic-ray propagation in the interstellar space. Obviously, as the observed energy becomes large, the number of possible sources for electrons with this energy becomes correspondingly small. So in the study of the propagation of cosmic-ray electrons there are three energy ranges. In the range of lowest energies where radiation loss is negligible, the leakage approach with a continuous source distribution gives approximately correct results. In the medium-energy range where the radiative lifetime is shorter than the effective leakage lifetime, the leakage approach should be replaced by the diffusion approach (Shen 1967; Jokipii and Meyer 1968; Berkey and Shen 1969; Jones 1970). In the range of very high energies the electrons can come from only a few sources, and the time between the arrival of the flux from two successive source events becomes longer than the time during which a source can contribute maximum (and approximately constant) flux at Earth. In that case the use of a

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continuous, time-independent source distribution is not valid, and the electron spectrum at Earth depends on the age and distance of these few sources. The critical energies separating these three ranges depend on the radiation intensity in the Galaxy and the distribution of local discrete sources. We shall illustrate this point by estimating the electron flux from the distant part of the Galaxy and from local sources.

In the diffusion approach the contribution to the density of local cosmic-ray electrons from a point source $Q_i = K_i(t)f_i(E)$ at a distance r_i is (Berkey and Shen 1969)

$$N_i(E) = \int_{(bE)^{-1}}^{0} \frac{K_i(t)f_i[E/(1 - bEt)] \exp(-r_i^2/4Dt)}{(4\pi Dt)^{3/2}(1 - bEt)^2} dt . \quad (1)$$

If the period during which the source actively generates cosmic rays is much shorter than either the propagation time $r_i^2/2D$ or the age of the source (a condition satisfied by all pulsars; we shall return to examine this point in more detail later), then equation (1) reduces to

$$N_i(E) = Q_i(E)R_i(E,r_i,t_i) , \quad (2)$$

where $Q_i(E) = \int dt' K_i(t') f_i(E)$ is the total number of cosmic-ray electrons produced at energy E by the source in its lifetime:

$$R_i(E,r_i,t_i) = (4\pi Dt_i)^{-3/2}(1 - bEt_i)^{\alpha-2}\exp(-r_i^2/4Dt_i) \quad \text{for } E < E_i = (bt_i)^{-1} \quad (3)$$

and

$$R_i(E,r_i,t_i) = 0 \quad \text{for } E > E_i = (bt_i)^{-1} , \quad (4)$$

where t_0 is the age of the source and α the injection spectra index. E_i is the "turnoff" energy such that no electrons from the source can reach Earth with energy higher than E_i. In comparison with the photon flux from a star, in equation (2) $N_i(E)$ corresponds to the apparent brightness of the source, $Q_i(E)$ to the absolute brightness, and R_i is analogous to $(4\pi r_i^2)^{-1}$.

The total electron intensity at Earth is given by the summation of $N_i(E)$ from all sources. Sources beyond 1 kpc can be justifiably represented by a time-independent continuous distribution (Lingenfelter 1969); their contribution (which is small) to local high-energy-electron intensity will be considered later. For local sources, pulsars are the obvious candidates. Among the fifty pulsars whose data have been compiled by Maran (1970), the rate of change of period $\dot{p}$ has been measured for fifteen of them, and for two of them a reasonable upper limit of $\dot{p}$ is given. The age (or its lower limit) of these seventeen pulsars can thus be estimated by $p/2\dot{p}$ with adequate accuracy (Pacini 1968; Ostriker and Gunn 1969). The turnoff energy E_i and the propagation factor $R_i(E)$ for them are listed in Table 1. The two values of b used in calculation correspond to two different photon intensities in the Galaxy ($b = 10^{-25}$ eV^{-1} sec^{-1} represents a blackbody radiation of 2.7° K, a stellar photon density of 0.2 eV cm^{-3}, and an average magnetic field of 4 microgauss; $b = 1.3 \times 10^{-24}$ represents an additional 13 eV cm^{-3} in the far-infrared range). The distance to the pulsars is either taken from Prentice and ter Haar (1969) or computed from the dispersion measure according to their method. In regard to the dependence of R_i and E_i of the pulsars on the parameters, we note that with the exception of Vela X and the Crab the argument $r_i^2/4Dt_i$ in the exponential of R_i for all pulsars is less than one at $D = 10^{29}$ cm^2 sec^{-1}. Hence the relative contributions to the local cosmic rays from the older pulsars are insensitive to the distance of the pulsar or the details of propagation in interstellar space. Instead, the flux depends only on the age and varies as $t_i^{-3/2}$. (This is rather fortunate, since, apart from the uncertainties involved in the estimation of D and r_i, the distance to the pulsar refers to the present position of the star. Pulsars may well have large runaway velocities, in which case for an old pulsar the distance at present would be different from that at the star's earlier epoch, during which most of the cosmic rays were produced.) As for the two young pulsars, at present the flux from the Crab is entirely negligible. The flux from Vela X is more than one order of magnitude lower than that from the other pulsars if the data used in Table 1 are accurate and if cosmic-ray production from all sources is equal. But one should notice that, unlike other pulsars, the flux from Vela X is extremely sensitive to the speed of diffusion of cosmic rays in the Galaxy. Changing the value of D by a factor of 2, for example, would change the flux from Vela X by several orders of magnitude. We will return to this point.

TABLE 1

COSMIC-RAY PARAMETERS OF PULSARS

Source	t(10^{14} sec)	r(10^2 pc)	$R_i(0)$ (10^{-66} cm^{-3})	E_i(BeV)
PSR 0329........	1.8	5	0.43	4.2 (55)
PSR 0531........	2.9×10^{-4}	17	$\sim10^{-900}$	2.6×10^4 (3.4×10^5)
CP 0808..........	>32	1.3	0.05	$<$ 0.24 (<3.1)
AP 0823..........	1.6	$>$ 9	0.50	4.8 (62)
PSR 0833........	3.6×10^{-3}	4	0.08	2.1×10^3 (2.8×10^4)
PSR 0834........	1.3	4	0.70	5.9 (77)
PSR 0950........	5.5	0.6	0.04	1.4 (18)
PSR 1133........	1.6	1.3	0.45	4.8 (63)
PSR 1451........	$>$ 0.44	2.5	$\leq$ 3.3	<18 (<228)
PSR 1508........	0.71	$>$ 6	$\leq$ 1.7	11 (141)
PSR 1642........	0.31	1.6	5.8	25 (321)
PSR 1749........	0.34	10	2.5	23 (294)
PSR 1919........	6.35	2.5	0.06	1.2 (16)
PSR 1929........	0.97	1.5	1.1	7.9 (103)
PSR 1933........	0.29	>20	$\leq$ 0.2	26 (334)
PSR 2016........	1.9	3	0.4	3.9 (51)
PSR 2045........	0.89	4	1.2	8.6 (112)
MP 0254*........	0.81	$>$ 5	$\leq$ 1.5	10 (123)
MP 0736*........	0.56	4	2.4	14 (179)
MP 1240*........	0.60	11	1.6	13 (167)
MP 1449*........	0.13	>10	$\leq$ 3.1	59 (770)
MP 1604*........	0.72	2	1.6	11 (139)
MP 1944*........	0.77	5	1.5	10 (130)

NOTE.—Propagation factor R_i and turnoff energy E_i of the pulsars are calculated with $D = 10^{29}$ cm^2 sec^{-1} and $b = 1.3 \times 10^{-24}$ eV^{-1} sec^{-1} or $b = 10^{-25}$ eV^{-1} sec^{-1} (the corresponding E_i is in parentheses). Asterisk denotes short-period pulsars whose rate of change of period has not been measured; parameters of these pulsars are therefore very crude estimations. Except for PSR 0531, PSR 0833, PSR 1933, and probably MP 1449, the relative contribution from a given pulsar is insensitive to the distance of the pulsar or the diffusion coefficient.

The relative contributions from the pulsars whose $\dot{p}$ have not been measured are more difficult to estimate because of the uncertainty of their age. According to the theory of rotating neutron stars, the age of a pulsar is approximately given by $p^2/2K_0$, where $K_0 = p\dot{p}$ is proportional to the effective magnetic moment of the star (see Ostriker and Gunn 1969, for example). For illustration we have estimated E_i and R_i for the pulsars of unknown $\dot{p}$ by taking $K_0 = 1.4 \times 10^{-15}$ sec, the average value of $p\dot{p}$ for pulsars of measured $\dot{p}$. Those which can contribute electrons at Earth with energy higher than 10 BeV when the far-infrared is present are listed in Table 1.

The electron flux from the distant sources can be estimated by considering the contribution from a doughnut-shaped source distribution of outer radius $a_1 \approx 10$ kpc, inner radius $a_2 \simeq 1$ kpc, thickness $Z = 0.3$ kpc, and a total production rate $Q(E)$. In the

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isotropic-diffusion approximation the equilibrium intensity at the center of the ring is (Shen 1969)

$$\begin{aligned} N(E) &\approx N_0(E)\,(1 - a_2/a_1) && (E \ll E_1) \\ &\approx N_0(E)\,[1 - (E/E_2)^{1/2}]\,(E_1/E)^{1/2} && (E_1 \ll E \ll E_2) \qquad (5) \\ &\approx N_0(E)\,(E_1E_2/E^2)^{1/2}\,e^{-(E/E_2)} && (E \gg E_2)\,, \end{aligned}$$

where $E_1 = 2D/ba_1^2$, $E_2 = 2D/ba_2^2$, and $N_0(E) = (a_1Z/\pi D)Q(E)$.

Equation (5) shows explicitly that the radiation loss cuts off contributions from distant sources at high energy ($E > E_2$), and the flux from local sources becomes important. At low energy ($E \lesssim E_1$), all sources inside 1 kpc contribute on the average only $a_2/a_1 \approx 10$ percent to the intensity of local cosmic-ray electrons.

Recent experiments have extended the spectrum of cosmic-ray electrons up to 670 BeV (Anand *et al.* 1969). The spectral index is 2.6 below 200 BeV and steepens somewhat above it. Let us first consider the case of $b = 10^{-25}$ (eV sec)$^{-1}$, i.e., the case in which the infrared radiation does not exist in the Galaxy. The contribution from the continuous background starts to drop off at $E_2 \simeq 100$ BeV, and the electrons produced by nearby sources take over. As shown in Table 1, when the energy goes up, the electron flux from each pulsar starts to turn off one by one according to its age. At about 1000 BeV only electrons produced by Vela X and the Crab (which contributes very little) are fresh enough to reach Earth. Since if $D \leq 10^{29}$ cm^2 sec^{-1} the propagation factor R of Vela X is an order of magnitude less than that of the other young pulsars, it is tempting to postulate a sharp drop of electron intensity between 500 and 1000 BeV. But this conclusion is far from secure. The ages of the pulsars whose rates of change $\dot{p}$ have not been measured are only crude estimates, the electron flux from Vela X is extremely sensitive to D, and furthermore it is always possible that hidden supernova remnants of age less than 5×10^5 years (hence which may contribute electrons of energy greater than 500 BeV at Earth) exist nearby. In view of these uncertainties, one could only say that if future observation shows a sharp drop in the electron spectrum at the energy corresponding to 10^{-25} (eV sec)$^{-1}$ multiplying the age of the youngest pulsar next to Vela X (likely to be MP 1449), then it would indicate that no radiation field stronger than the 2.7° K blackbody emission exists in the Galaxy, and the diffusion coefficient D is probably smaller than 2×10^{29} cm^2 sec^{-1}.

Let us now consider the case that a strong infrared flux exists in the Galaxy. Then the present data on cosmic-ray electrons already provide interesting implications, and clear-cut evidence will be expected in the future observations. In the presence of a 13 eV cm^{-3} radiation field the electron flux from distant sources starts to drop off at a few BeV, and (except for the Crab and Vela X) the pulsars with measured $\dot{p}$ all turn off below 30 BeV. Granting the uncertainties involved in the estimation of age, none of the pulsars with unknown $\dot{p}$ is likely to contribute electrons of energy higher than 100 BeV at Earth. Of course, cosmic-ray sources do not always show up as observable pulsars (radiation from pulsars is likely to be anisotropic), but if the observed high-energy electrons were from a hidden source, the source must have an age less than 3×10^4 years and be within a radius of $\sim$500 pc. It seems unlikely that such a young and close cosmic-ray source would not show up as an observable radio remnant. Furthermore, if one assumes a supernova rate of 10^{-2} year^{-1} in the Galaxy, the probability of having a supernova explosion younger and closer than Vela is $\sim$0.1. Thus it seems reasonable to propose Vela X as the principal source of the electrons above 100 BeV if the far-infrared radiation exists. Then one expects a cutoff of the electron spectrum at $\sim 2 \times 10^3$ BeV corresponding to the age of the Vela pulsar. (If future observations covering the whole spectral range in the far-infrared indicate a radiation density higher than 13 eV cm^{-3}, the cutoff energy will be correspondingly lower.)

For Vela X to contribute significantly to the present cosmic-ray intensity, the flux from that source must reach Earth with a diffusion coefficient greater than 10^{29} cm^2 sec^{-1} (see eq. [3]). Such a value of D is compatible with the study of the interstellar magnetic field (Wentzel 1969) but is much higher than that obtained recently by Ramaty, Reames, and Lingenfelter (1970). Based on the closed-disk model (in which cosmic rays diffuse isotropically within the disk but will not return after entering the halo), they have deduced an upper limit of 3×10^{27} cm^2 sec^{-1} for the diffusion coefficient from the anisotropy measurement of cosmic rays. If the far-infrared radiation exists and if $D \leq 3 \times 10^{27}$ cm^2 sec^{-1}, the detection of 500-BeV electrons at Earth implies a cosmic-ray source with an age of less than 4×10^4 years and located within 70 pc. The probability that a supernova event occurred within this range and duration is $\sim$0.01. Since the propagation of cosmic rays along the field line is probably faster than the perpendicular diffusion caused by the random walk of field lines, it is possible that diffusion from a source located at a magnetic line passing near the solar system is faster than the average value of D indicated. But a discrepancy by a factor of more than 30 is still hard to account for. These difficulties, however, can be reconciled in other propagation models. In any case, the turnoff energy of a source depends only on the age of the source and radiation density in space. The detection of a cutoff of cosmic electrons at $\sim 2 \times 10^3$ BeV will provide not only a strong support to the existence of the far-infrared radiation but also important information on the propagation of cosmic rays.

In the above discussions we have assumed that the bulk of cosmic rays has been produced within a short period after the supernova event. Thus, electrons of energy higher than $(bt_i)^{-1}$ cannot come from sources of age t_i. That most of the cosmic rays must be generated immediately after the supernova event is quite evident. Take the Crab pulsar as an example: Its total rotational energy at present, 914 years after its birth, is about 10^{49} ergs (compared with the estimated 3×10^{51} ergs of energy carried away by the magnetic-dipole radiation within the first year; see Ostriker and Gunn 1969). Even if all this energy could be converted to the particle energy, the cosmic-ray density in the Galaxy would still be less than what had been observed, provided the birth rate of the pulsar is no higher than one per 10 years and the confinement time of cosmic rays is no longer than 10^8 years. The energy density of the observed high-energy electrons is, however, very small ($N_e(E > 100$ BeV$) \simeq 5 \times 10^{-16}$ ergs cm^{-3}; see Anand *et al.* 1969). Because a rotating neutron star does continuously generate relativistic particles, one might suspect that these electrons could come from the continuous production of many old pulsars. We shall show this is not the case. According to the neutron-star theory developed by Pacini (1968) and Ostriker and Gunn (1969), the energy loss from the star became dominated by the magnetic-dipole radiation a short time (about 10^2 years) after the beginning. The luminosity of the radiation then decreases as the rotation of the star slows down:

$$L_m(t') = L_0(1 + t'/\tau_m)^{-2}\,. \tag{6}$$

For the Crab pulsar, if the origin of time t' is chosen to be the present, i.e., about 10^3 years after the explosion, then $L_0 = 10^{38}$ ergs sec^{-1} and $\tau_m = 1300$ years. These figures will be used to estimate the contribution to the present local cosmic-ray density from the continuous production of the pulsars.

Since the relativistic particles draw their energy from these long-wavelength electromagnetic waves, one expects

$$Q_i(t') = \alpha L_0(1 + t'/\tau_m)^{-2}\,, \tag{7}$$

where α is the conversion factor from electromagnetic energy to particle energy. If we substitute equation (7) into equation (1) and notice that $\tau_m \ll \frac{1}{4}r^2/D$ for all pulsars, we find the contribution to the local cosmic-ray electrons from the continuous production of a pulsar with age older than $(bE)^{-1}$ to be

$$N_i(E) \approx a L_0 \tau_m \beta(E) S_i(E)\,, \tag{8}$$

where

$$S_i(E) = \frac{\tau_m}{bEt_i^2[1-(bEt_i)^{-1}]}\left(\frac{bE}{4\pi D}\right)^{3/2} \exp\left(-\frac{r_i^2 bE}{4D}\right) \tag{9}$$

and $\beta(E)$ represents the fraction of the particle's energy in the form of electrons with energy higher than E.

After summation of N_i over all the pulsars with age older than 8×10^{12} sec (the cutoff time of a 100-BeV electron at $b = 1.3 \times 10^{-24}$ eV^{-1} sec^{-1}), we have N_e (> 100 BeV) $\approx a\beta(100 \text{ BeV}) \times 10^{-19}$ ergs cm^{-3}. Thus the continuous production from the old pulsars cannot account for the observed high-energy electrons.

The author is very grateful to Dr. S. P. Maran for sending him the pulsar table. He also wishes to thank Dr. R. Ramaty for a stimulating discussion. This research was supported in part by NASA grant 5514-52-13969.

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