ORIGIN OF COSMIC RAYS*

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Presented is a model in which cosmic electrons (> 100 MeV) are produced by pulsars, and cosmic protons and alpha particles are accelerated by shock waves in supernova envelopes. It is argued that neither mechanism by itself can produce both the observed protons and electrons at energies above a few hundred MeV. But supernova accelerated electrons could constitute the majority of cosmic electrons with energy below about 10 MeV.

1. Introduction. From cosmic-ray measurements above the earth's atmosphere (e.g., P. Meyer, 1969) it has been found that the cosmic electron intensity per unit energy at energies from a few hundred MeV to several hundred GeV is about 1% to 2% of the corresponding proton intensity in the same energy region. This result does not seem to be an obvious consequence of any of the proposed cosmic-ray acceleration mechanisms - supernova vs pulsar. For example, for supernova-models (e.g. Colgate and Johnson, 1960) cosmic ray particles are accelerated by a shock wave from a supernova explosion moving in the outer layers of the presupernova star. Charge neutrality implies that electrons and protons at the same radial distance from the explosion's center should be accelerated to the same velocity. In such a model, the ratio $(e/p)_\gamma$ of electron-to-proton intensities per unit γ at the same Lorentz factor γ is about one. This is related to the ratio of $(e/p)_E$ of electrons - to - protons intensities per unit energy at the same energy E by the relation

$$(e/p)_E = (M_e/M_p)^{\Gamma-1}\,(e/p)_\gamma$$

if the electron and proton differential intensities vary as $\gamma^{-\Gamma}$. Here $\Gamma = 2.7$ is the spectral index of high energy cosmic rays (Meyer, 1969). (This relation can be obtained from the definition $dn/d\gamma = K\gamma^{-\Gamma}$ and $E = m\gamma$ since $(e/p)_\gamma = K_e/K_p$ and $dn/dE = KE^{-\Gamma}m^{\Gamma-1}$.) Thus in the supernova model (in which electrons and protons are accelerated to the same velocity) we obtain $(e/p)_E \approx 3 \times 10^{-6}$ a value much lower than the observed ratio in cosmic rays $(e/p)_E \approx 2 \times 10^{-2}$.

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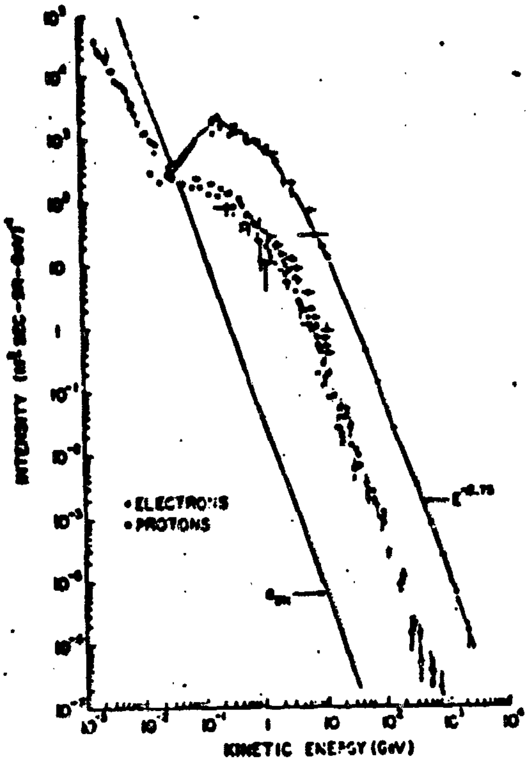
Pulsar accelerator mechanisms run into similar difficulties. If pulsar generated low frequency waves accelerate matter in the supernova remnant (Gold, 1969 ; Kulsrud et al, 1972), it follows that $(e/p)_E \equiv 10^3$ in the energy range 10^{10} to 10^{12} eV. This ratio $(e/p)_E$ is much larger than the observed ratio in this energy region. Particle acceleration can take place in electric fields close to the pulsar (Goldrich and Julian, 1969). In this model protons and electrons pass thru about the same accelerating potential and are accelerated to the same energies. If the pulsar remains uncharged this mechanism implies $(e/p)_E \approx 1$. Crab nebula observations give the bound $(e/p)_E > .1$ since if all known energy losses of the Crab (synchrotron emission and expansion) are compared with the maximum power which can be supplied by the rotating neutron star, one finds that the present energy given to protons in the nebula cannot exceed that given to electrons by more than a factor of ten (Borner and Cohen, 1973). The inequality is a consequence of the possibility that acceleration efficiencies can be less than unity. All these considerations imply that pulsar accelerated particles cannot reproduce the observed $(e/p)_E$ ratio of cosmic rays.

<u>2. Discussion.</u> Here we present a model in which the bulk of the cosmic protons (alpha particle) are accelerated by shock waves in supernova envelopes while cosmic electrons are produced mainly by electromagnetic processes associated with pulsars. Such a decoupling of electrons from protons allows in principle a wide range of e/p ratios. The observed $(e/p)_E$ ratio in cosmic rays then determines the relative contributions of pulsars and supernovae to cosmic rays in the galaxy. Another consequence of the decoupling of electrons from protons is that the cosmic ray electrons and protons need not have the same energy spectra. As we shall see below, this consequence is not in conflict with the observational data.

The cosmic electron and proton measurements from about 10^6 to 10^{12} eV are plotted in Figure 1. Much of this data has been recently summarized by McDonald et al (1972). The proton measurements above 10 GeV were made by Ryan et al (1972) while the electron data above 100 GeV are from Meyer and Muller (1971). As can be seen from Figure 1, above about 100 MeV the electron intensity is less than the proton intensity at the same energy.

The electron-to-proton ratio, however, does not appear to be constant. At 1 GeV, $(e/p)_E \approx 3 \times 10^{-2}$; at 100 GeV $(e/p)_E \approx 0.4 \times 10^{-2}$. Because of the uncertainty in the measurements (mainly in the electron data) this variation may not be highly significant. Also, synchrotron and Compton losses in interstellar space may lead to an $(e/p)_E$ ratio which decreases with increasing energy even if this ratio is a constant at injection. Nonetheless, the electron and proton data does not conflict with our contention that electrons and protons come from different sources. Regarding the data in Figure 1, therefore, we propose that above a few hundred MeV the majority of electrons are produced by pulsars while protons of all energies are accelerated by shock waves in supernova envelopes. According to a recent study (Ilovaisky, and Lequeux, 1972) the mean interval between supernova outbursts in the galaxy is about 50 years.

Therefore, in order to supply 4×10^{40} ergs sec^{-1}, the average cosmic-ray energy released by a supernova should be about 6×10^{49} ergs. This energy is consistent with models (Colgate, and White, 1966) of shock acceleration of cosmic rays in supernova explosions, as these models provide a total cosmic ray energy of at least 10^{50} ergs.



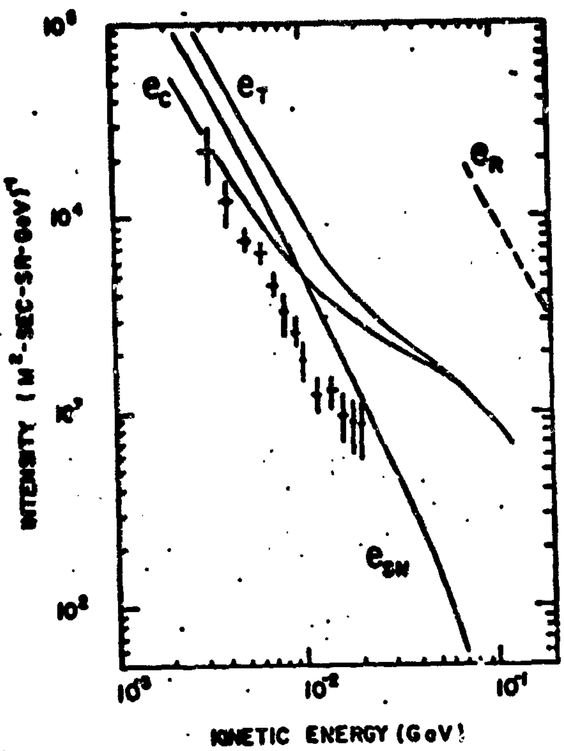


Figure 1 - Cosmic Ray proton and electron spectra at earth.

Figure 2 - Cosmic electron spectra at low energies.

Let us now consider again the data of Figure 1. The line labelled e_{SN} represents the interstellar electron spectrum that would result from acceleration by shock waves in supernova envelopes. This intensity has the same spectrum as that of the high energy protons (i.e. $E^{-2.75}$), but according to equation (1), its absolute normalization is reduced by a factor $(m_p/m_e)^{1.75}$. The intensity e_{SN} is clearly negligible in comparison with the observed electron intensity above about 100 MeV. In our model, this latter intensity is almost entirely due to acceleration in pulsars. In the 2 to 10 MeV region, however, electrons from supernovae may constitute the majority of cosmic electrons in interstellar space.

The possibility of a generic link between low energy electrons and ultrarelativistic protons was first recognized by Bronstein and Cline (1966) who pointed out that if one limits the discussion to electrons below 10 MeV, the ratio (e/p) is indeed close to unity. This is a consequence of the present model in which low energy electrons are accelerated by supernovae. But since the overall picture at the low energies is complicated by the existence of additional sources of electrons including an unknown contribution from pulsars at low energies, further observations will be of interest.

The low energy electron data and calculated spectra are given in Figure 2. The data points and the curve e_c are taken from the paper of Simmett and McDonald (1969). The curve e_c is the interstellar electron intensity that would result from the collisions of nuclear cosmic rays with interstellar gas (the principal production mechanisms are $\pi^{\pm}$decay and knock-on collisions). The curve e_{SN} is the supernova electron intensity corrected for ionization losses in interstellar space (using an exponential path length distribution with a mean path of 4 g cm^{-2}). As can be seen from Figure 2, the sum e_t of e_c and e_{SN} has approximately the same spectral shape as the observed intensity but its absolute normalization is greater by a factor of about 3 to 4. Because both the quiescent low-energy electron intensity (shown in Figure 2) and the enhanced quiet-time (non-flare) fluxes of these particles (which amount to increases in intensity by factors up to 4 without change in spectrum) have been interpreted as galactic in origin (Simmett and McDonald 1969) spectrum e_t shown in Figure 2 could in fact be equal to the interstellar electron intensity below about 10 MeV. This result is also consistent with the apparent lack of gredients in the electron density in interplanetary space in the vicinity of 1 A.U. (Fisk and Van Hollebeke, 1972).

If the electron intensity in interstellar space below - 10 MeV is close to the curve e_t in Figure 2, the contribution of pulsars at these energies must be quite small. The dashed line e_R in Figure 2 represents an extrapolation to low energies of the interstellar electron spectrum as deduced from the observed galactic nonthermal radio background (Webber, W.R. et al, (1972). The radio background, however, determines the electron spectrum down to about 200 MeV only. It is possible therefore that the spectrum e_R flattens or cuts off at about 100 MeV, so that its contribution below 10 MeV could in fact be negligible. Since such a flattening or cutoff is not due to any of the known energy loss processes in interstellar space, it probably is caused by an intrinsic cutoff in the source itself.

In summary we have presented a model for the origin of cosmic rays in which cosmic protons and alpha particles (but not electrons) are accelerated by shock waves in supernova envelopes. Since this mechanism is expected to produce identical velocity spectra for all cosmic-ray particles, it conflicts with the observed electron-to-proton ratio in that the predicted ratio is smaller by almost 4 order of magnitude than that observed. Identical velocity spectra, however, are entirely consistent with observations of cosmic alpha particles. We have proposed that cosmic electrons (but not proton) above about 100 MeV are produced primarily by pulsars, either in the pulsar magnetosphere, or in the nebular remnant of the supernova. We have argued that it is unlikely that both cosmic protons and electrons are accelerated by pulsars because these objects are expected to produce an electron-to-proton ratio which is greater by at least 2 orders of magnitude than that observed. Electrons of supernova origin are negligible in comparison with electrons from pulsars above about 100 MeV the observed electron intensity may have been primarily produced in supernovae envelopes by the same mechanism that produces ultra-relativistic protons and nuclei. These low-energy electrons may also contain contribution from the products of collisions of nuclear cosmic rays with the interstellar gas.

References

Borner, G. and Cohen, J. M., Physics of Dense Matter, IAU Symposium No. 53, Boulder, Colorado, in press (1972).

Brunstein, K. A. and T. L. Cline, Nature, 209, 1186 (1966)

Colgate, S. A. and Johnson, M. H., Phys. Rev. Letters, 5, 235 (1960).

Colgate, S. A. and White, R. H., Astrophys, J., 143, 626 (1966).

Gold, T., Nature, 221, 25 (1969).

Goldrick, K. and Julian, W. (1969) Ap. J. 157, 869

Goldstein, M. L., Ramaty, B. and Fisk, L. A., Phys. Rev. Letters, 24,(1970).

Ilovaisky, S. A. and Lequeux, J., Astronomy and Astrophysics, to be published, (1972).

Kulsrud, R. M., Ostriker, J. P. and Gunn, Phys. Rev. Letters, 28, 636 (1972).

McDonald, F. B., Cline, T. L. and Simmett, G. M., Geophys, J., Res., 77, 2213 (1972).

Meyer, P., Ann. Rev. Astron, Astrophys. 7, 1, (1969).

Meyer, P. and Muller, D., Conf. Papers, Twelfth Int. Conf. on Cosmic Rays, Robert, Tasmania, Australia, 1971 (unpublished), Vol. 1, p. 117, paper OG-36.

Ryan, M. J., Ormes, J. F. and Balasubrahmanyan, V. K., Phys. Rev. Letters, 28, 985 (1972).

Simmett, G. M. and F. B. McDonald, Astrophys, J., 157, 1435 (1969).

Webber, W. R., Lezniak and Damle, S. V., Geophys, J., Res., to be published (1972).