Origin of Cosmic Electrons from About 10^2 to 10^6 GeV

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The origin of high-energy cosmic electrons is considered. It is found that electrons of energies $\lesssim 10^3$ GeV could have been produced by local supernovae associated with known radio remnants. At higher energies, observations of muon-poor air showers indicate the existence of electrons at 10^6 GeV which may have originated entirely from the supernova Vela X.

Meyer and Muller[1] have recently presented new measurements of cosmic electrons which, together with earlier measurements by Anand, Daniel, and Stephens,[2] extend the observed spectrum of these particles up to about 750 GeV with no obvious change of spectral index. At these energies, because of synchrotron and Compton losses in interstellar space, the discrete-source nature[3] of the cosmic rays may have observable effects. In the present Letter we wish to investigate these effects in the light of the new data, and to suggest that in the energy region where muon-poor air showers are produced, unambiguous evidence may already exist for a discrete source of cosmic electrons.

Because of the synchrotron and Compton losses, the electron spectrum from a point source has a sharp high-energy cutoff at an energy where the radiation loss time equals the age of the source. Such a sharp cutoff is typical of an instantaneous and localized emitting region, and differs from the smooth and gradual steepening of the spectrum which occurs if electrons are produced by a continuous source distribution. The absence of any cutoff in the electron spectrum up to at least 750 GeV then implies the existence of an upper limit on the ages of all sources which could contribute to the observed electron flux at this energy. The cutoff energy E_c for a point source is independent of the propagation mode of the particles or their production spectrum, and at energies where the E^2 dependence of synchrotron and Compton losses is valid, it satisfies the relation

$$c\sigma_T(W_{ph}+B_\perp^2/4\pi)E_c t = (mc^2)^2, \tag{1}$$

where σ_T is the Thompson cross section, t is the age of the source, W_{ph} is the sum of the photon energy densities in interstellar space, and $B_\perp$ is the component of the interstellar magnetic field perpendicular to the velocity vector of the electrons.

For a typical interstellar magnetic field of a few microgauss, the E^2 dependence of synchrotron losses is valid up to at least 10^{20} eV, since the quantum nature of the electron and the effect of radiation reaction become important at much higher energies only.[4] For Compton scattering, the E^2 dependence of the energy loss is valid for energies less than $E_T = (mc^2)^2/\epsilon_r$, where ϵ_r is the energy of the incident photon.[5] At higher energies, the electrons tend to lose a major fraction of their energy in a single Compton collision, so that the scattering process should be considered as a sudden loss, characterized by a lifetime T_c which is energy dependent and given by

$$T_c = (c\sigma W_{ph}/\epsilon_r)^{-1}, \tag{2}$$

where σ is the Klein-Nishina cross section.[6]

The principal components of the interstellar photon field are visible photons with an energy density ~ 0.45 eV cm^{-3}, 3°K blackbody photons with energy density 0.25 eV cm^{-3}, and possibly far-infrared photons with energy density <3 eV cm^{-3}. For the visible field $\epsilon_r \simeq 3$ eV and $E_T \simeq 80$ GeV. For 3°K photons, $\epsilon_r \simeq 9\times10^{-4}$ eV, and, if the far-infrared background peaks at 1 mm, $\epsilon_r \simeq 10^{-3}$ eV, so that for both the blackbody and far-infrared fields $E_T \simeq 2.5\times10^5$ GeV.

We have evaluated the radiation loss time T_c for both Compton and synchrotron losses in a variety of photon and magnetic fields. For synchrotron losses, $T_c = 4\pi(mc^2)^2(Ec\sigma_T B_\perp)^{-1}$. For Compton losses, $T_c = (mc^2)^2(Ec\sigma_T W_{ph})^{-1}$ if $E < E_T$ and $T_c = (c\sigma W_{ph}/\epsilon_r)^{-1}$ if $E > E_T$. The results are summarized in Table I. As can be seen, above ~ 100 GeV the effects of visible photons are negligible and the main contribution to Compton loss at these energies comes from 3°K and far-infrared

TABLE I. Cosmic electron lifetimes in years against energy loss by synchrotron radiation and Compton collisions.

E (GeV)	$\epsilon_r = 3$ eV $W_{ph} = 0.45$ eV cm^{-3}	$\epsilon_r = 10^{-3}$ eV $W_{ph} = 0.25$ eV cm^{-3}	$W_{ph} = 1$ eV cm^{-3}	$B_\perp = 2\times10^{-6}$ G	$B_\perp = 7.5\times10^{-7}$ G
10^2	3×10^7	1.6×10^7	4×10^6	2×10^7	1.4×10^8
10^3	10^8	1.6×10^6	4×10^5	2×10^6	1.4×10^7
10^4	5×10^8	1.6×10^5	4×10^4	2×10^5	1.4×10^6
10^5	4×10^9	1.6×10^4	4×10^3	2×10^4	1.4×10^5
10^6	...	3×10^4	7×10^3	2×10^3	1.4×10^4
10^7	...	1.6×10^5	4×10^4	2×10^2	1.4×10^3

photons. However, since the existence of the far-infrared background is not conclusively established and the mean interstellar magnetic field could be as low as 10^{-6} G,[7] an upper limit of $\sim 1.5\times10^6$ yr on the ages of the electron sources is adequate to account for the lack of cutoff in the electron spectrum up to 10^3 GeV. This upper limit is not necessarily inconsistent with the mean age of cosmic rays as determined in their matter traversal,[8] so that electron measurements at higher energies are required to establish the possible discrete-source nature of cosmic electrons. However, with a magnetic field of 2×10^{-6} G,[9] and a combined energy density in 3°K and far-infrared photons of 1 eV cm^{-3}, 10^3-GeV electrons would have to be produced by sources younger than $\sim 3\times10^5$ yr. If these sources were supernova explosions, evidence for their existence could be found among the known radio remnants of supernovae or in the available sample of pulsars.

Based on the most recent observational data, the only known pulsars younger than 3×10^5 yr are NP0531 and PSR0833, the fast pulsars in the Crab Nebula and the Vela X supernova remnant. It is very unlikely that cosmic rays from the Crab Nebula have reached Earth, since if they did, they would have had to stream at velocities close to c. Therefore, among the pulsar sample, only Vela X could be a potential source younger than 3×10^5 yr.

A list of the observable radio remnants of supernovae has been compuled by Milne.[10] The maximum observable lifetime of a radio remnant is $\sim 7\times10^4$ yr. Thus all known supernova remnants could, in principle, contribute to the observed cosmic electron flux at $\sim 10^3$ GeV, but it is unlikely that the very distant objects could make a significant contribution. The ten supernova remnants, which, according to Milne, are at distances less than 1 kpc are listed in Table II. We also give the estimated ages from the relation[10] $D(\text{pc}) \simeq 3(Rt)^{2/5}$, where D is the diameter of the remnant and $R \simeq 10^{-2}$ events/yr is the rate of supernova explosions in the region sampled by Milne's survey (about half the galaxy). At the same rate, the cylindrical volume of radius 1 kpc centered at Earth should contain an additional couple of dozen unobservable supernova remnants with ages ranging from 7×10^4 to 3×10^5 yr. Since all these supernovae could contribute to the observed flux up to $\sim 10^3$ GeV, the existence of a single dominant source of cosmic electrons can only be established by measurements at higher energies. With the exception of muon-poor air showers, such measurements are not available at the present time.

Muon-poor air showers[11] are indicative of an initial electromagnetic interaction at the top of the atmosphere. Such showers are observed up to primary energies of about 2×10^6 GeV with a possible cutoff at higher energies[12] and require a primary flux of $(6^{+4}_{-3})\times10^{-9}$ quanta m^{-2} sec^{-1} sr^{-1} at energies greater than 8×10^5 GeV.[13] As can be seen from Table I, at 10^6 GeV the dominant energy loss is synchrotron radiation in a field of 2

TABLE II. Distances and ages of supernova remnants.

Galactic source number	Distance (kpc)	Age (10^4 yr)	Name
G41.9 − 4.1	0.7	3.2	CTB 72
G74.0 − 8.6	0.6	3.5	Cygnus loop
G89.1 + 4.7	0.8	2.3	HB 21
G117.3 + 0.1	0.9	4.7	CTB 1
G156.4 − 1.2	0.6	3.2	CTB 13
G160.5 + 2.8	0.8	2.7	HB 9
G180.0 − 1.7	0.7	4.3	S149
G205.5 + 0.2	0.6	4.6	Monoceros
G263.4 − 3.0	0.4	1.1	Vela X
G330.0 + 15.0	0.4	3.8	Lupus loop

$\times 10^{-6}$ G. With such a field, a source younger than 2000 yr is required to produce electrons at this energy. The measured magnetic field along the line of sight to PSR0833, however, is only 0.75×10^{-6} G. If $B_\perp$ in the containment region of the 10^6-GeV electrons is equal to this value, the source of these electrons only has to be younger than 1.4×10^4 yr, a requirement that is well met by the supernova Vela X. Synchrotron losses will in fact truncate the electron spectrum from the supernova at about 1.5×10^6 GeV, in good agreement with the absence of muon-poor air showers of sizes greater than $\sim 2 \times 10^6$, corresponding to primary energies $\sim 2 \times 10^6$ GeV. Since Compton losses in the Klein-Nishina regime do not produce an absolute cutoff, even if the photon density is 1 eV cm^{-3} these losses will not significantly affect the intensity of the very high-energy electrons.

Except for the Vela supernova remnant, the age of which is better determined from pulsar observations,[14] the ages of the other remnants given in Table II are quite uncertain. Since all of these objects are more distant than Vela X and none is expected to be younger than 2×10^4 yr, the most likely source of 10^6-GeV electrons at Earth is Vela X. The younger, historically observed supernovae such as the Crab are all too distant to compete effectively with Vela X if their cosmic electron outputs are comparable.

We proceed now to investigate the consequences of a model in which Vela X is the only source of electrons at high energies. Based on considerations of chemical composition and anisotropy, it can be shown[8] that the bulk of the nuclear cosmic rays are produced by a distribution of sources and not by a single source. We can put an upper limit on the contribution of Vela X to the cosmic-ray background by considering the upper limit on the sideral anisotropy. The anisotropy from a point source may be approximated by r/ct, where r is the distance to the source and t is its age. With a distance of 400 pc and an age of 10^4 yr. the anisotropy from Vela X is ~ 0.15. An upper limit[15] of 10^{-3} on the anisotropy of all cosmic rays implies therefore that the ratio of the cosmic-ray flux from Vela X to the total flux cannot be greater than $\sim 7 \times 10^{-3}$.

Let us assume that the same upper limit is applicable to the electron component at energies where Compton and synchrotron losses are negligible. By using a demodulated electron intensity[16] of 15 electrons (m^2 sec sr GeV$)^{-1}$, we find that the electron intensity from Vela X at this energy should not exceed 10^{-1} electrons (m^2 sec sr GeV$)^{-1}$. By extrapolating this intensity to higher energies, we find that a differential spectral index $\Gamma = 2.4 \pm 0.05$ is required to yield an integral flux of $(6^{+4}_{-3}) \times 10^{-9}$ electrons (m^2 sec sr$)^{-1}$ above 8×10^5 GeV. If the cosmic-ray anisotropy should turn out to be less than 10^{-3}, Γ should be less than 2.4 ± 0.05, whereas if we underestimated the electron modulation at 3 GeV or if the ratio of the electron to proton outputs at the same energy is higher for Vela X than for the general cosmic-ray background, Γ is larger than 2.4 ± 0.05. By extrapolating the intensity of 10^{-1} electrons (m^2 sec sr GeV$)^{-1}$ to 750 GeV with a spectral index of 2.4, we get an intensity of 1.8×10^{-7} electrons (m^2 sec sr GeV$)^{-1}$. This is lower by about an order of magnitude than the flux of $(1.75^{+1.75}_{-0.75}) \times 10^{-6}$ electrons (m^2 sec sr GeV$)^{-1}$ observed[1] at this energy. It is therefore plausible that more than one supernova contributes to the $\lesssim 10^3$-GeV electron flux, and, as discussed above, the remnants listed in Table II are likely candidates. The spectra from these objects will be cut off at various energies, depending on the ages of the sources and the photon and magnetic fields in interstellar space. As can be seen from Tables I and II, these cutoffs should in general lie in the 10^3- to 10^5-GeV range. In order that Vela X should produce all the electrons at 750 GeV, and only 7×10^{-3} of the electrons at 3 GeV, the production spectrum of electrons from this supernova has to be flatter than 2. In this case, the air-shower data require that the source spectrum of the supernova should steepen at some higher energy or that the interstellar photon density be larger than 1 eV cm^{-3}. Both these possibilities cannot be ruled out at the present time.

We have recently discussed in detail the various propagation modes of cosmic rays in the interstellar medium.[17] If cosmic rays from Vela X propagate by ordinary three-dimensional diffusion, the mean free path l is of the order $r^2/ct \simeq 50$ pc. If cosmic rays propagate by compound diffusion, l can be as small as $(r^4/10ct)^{1/3} \sim 100$ pc. Both these values are not inconsistent with the anisotropy and the matter traversal of cosmic rays.[17]

In summary, while there seems to be some evidence for the discrete-source nature of the cosmic electron intensity at $\lesssim 10^3$ GeV, there are good indications that muon-poor air showers are produced by electrons from Vela X alone. A model in which the necessary flux of 10^6-GeV electrons reaches Earth from Vela X is consistent with electron measurements at lower energies (~3 GeV), a differential spectral index at the source of ~2.4, and the upper limit on sidereal anisotropy of cosmic rays. Within this model, Vela X produces about 10% of the observed electrons at 750 GeV with the remaining flux being produced by local supernovae with observable radio remnants.

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Single-Particle Distributions of π Mesons Produced in K^-p Interactions at 9 GeV/c*

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We present distributions of transverse momentum squared and of longitudinal momentum in the laboratory, center-of-mass, and projectile frames for pions produced in K^-p interactions at 9 GeV/c. Comparisons made with the corresponding distributions published by other laboratories for pion production in K^+p, π^+p, pp, and π^-p interactions indicate that in the proton fragmentation region the distributions for pions produced from K^-p interactions at 9 GeV/c have not yet reached a limiting behavior.

A number of physicists have suggested that the cross section ($d\sigma/dP_\parallel dP_\perp^2$) for producing a given type of particle at a given point in momentum space approaches a limit as the energy of the interaction increases.[1] Here $P_\parallel$ indicates the momentum of the particle parallel to the beam and $P_\perp$, the momentum perpendicular to the beam. There has been much speculation on the rate at which this limit should be approached for various types of interactions. With apologies to the theorists who would like to see the invariant distributions, we present some single-particle distributions for pions produced in K^-p interactions at 9 GeV/c in a form that facilitates comparison with corresponding distributions published by other laboratories for pion production in K^+p, π^+p, pp, and π^-p interactions.[2-4]

The data for the K^-p interactions at 9 GeV/c are from an exposure of 100 000 pictures taken in the Brookhaven National Laboratory (BNL) 80-in. bubble chamber. The film has been scanned twice and events of all topologies have been measured. The plots we present represent about half of our available data. The statistical errors in the regions of high statistics are typically less than 5%. The uncertainties indicated for our