ORIGIN OF COSMIC RAY ELECTRONS

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ABSTRACT

Electrons ($e^-$) in cosmic radiation are believed to be produced by the interactions of cosmic ray nuclei with interstellar space. $e^+$ production spectrum had been calculated using a new set of invariant cross sections for the production of pions and kaons. In the case of $e^-$, a primary component had been added as the secondary $e^-$ produced along with $e^+$ in the galaxy. The equilibrium spectra of both $e^+$ and $e^-$ were calculated and compared with the observations. An empirical relation is given for the energy loss rate due to inverse-Compton scattering, which connects smoothly the Thompson and Klein-Nishina regimes. It is found that a simple power law injection spectrum for $e^-$ can not explain the observed $[e^+/(e^+ + e^-)]$ ratio, and one requires a spectral flattening below about 8 GeV. Flat $e^-$ spectrum similar to that in Crab supernova with a spectral break by one power around 5 GeV could explain both the observed spectrum and the $[e^+/(e^+ + e^-)]$, suggesting that the sources of cosmic ray $e^-$ are supernovae energized by pulsars.

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INTRODUCTION

Though electron component constitutes only about one percent of the total cosmic radiation, it provides a valuable tool to understand the propagation of cosmic rays and the physical state of the space where cosmic rays spent most of their time. This stems from the fact that electrons being light leptons, suffer less energy loss, by which their energy spectrum is considerably modified during propagation in the galaxy. The major energy loss processes they undergo are different from those of the nucleonic components. Below 1 GeV, Bremsstrahlung process is important and the radiation arising from this process contributes to a large fraction of the non-thermal background radiation in the $\gamma$-ray regime. At higher energies, the dominant energy loss mechanisms are the synchrotron radiation and inverse-Compton scattering, while screening ambient magnetic and radiation fields respectively. While the energy loss due to these processes is proportional to the square of the electron energy, the former one leads to the emission of non-thermal radio background in the Galaxy over a broad band of frequencies and the latter one elevates the energy of ambient photons to X and $\gamma$-ray energies. Thus, the knowledge of the electron component plays an important role in the understanding of the origin and propagation of cosmic rays, as well as on the origin of non-thermal radiation and the physical state of the region where this radiation comes from.

The electron component consists of both positive and negative particles. They are the end products of the decay of unstable particles, like pions and kaons, which are produced by the interaction of cosmic ray nucleons with the interstellar gas. If this process is the major source of $e^+$ and $e^-$, it is expected that the abundance of $e^+$ and $e^-$ should be nearly equal, with a small positive excess. However, the observations clearly show a large excess of $e^-$, suggesting that most of the observed $e^-$ are of primary origin. Estimates of the production spectrum of $e^+$ in the Galaxy were carried out in the past (e.g., Daniel & Stephens, 1976; Protheroe, 1982; Moskalenko & Strong, 1998). The production spectrum was re-examined in this investigation, by parameterizing the invariant cross-sections for the production of pions and kaons in proton-proton collisions. Knowing the $e^+$ production spectrum, one could determine the equilibrium spectrum using propagation models and applying all energy loss mechanisms accurately. In this context, an attempt was made to connect the energy loss rate through inverse-Compton scattering between the two regimes, namely, the Thompson limit and the extreme Klein-Nishina limit. A comparison of the calculated equilibrium spectrum was then made with the observations after applying solar modulation. At high energies, where
solar modulation does not modify the spectrum, it provides information on the propagation including the physical state of the propagating region. At low energies where modulation is important, this component gives the absolute magnitude of the modulation. These aspects are described in this paper.

The observed spectrum of e⁻ is steeper than that of the nucleonic component and it is essential to determine the equilibrium spectra of cosmic-ray nuclei composed of these sources which produce them. Therefore, differences in the type of production spectrum of e⁻ and the sources which produce them. Consequently, differences in input production spectrum for e⁻ in this investigation and the equilibrium spectra, determined using the propagation and modulation parameters, obtained from the e⁺ investigation, calculated spectra were then compared with the observation to draw important conclusions relating the origin of electrons in cosmic rays. These deductions were cross-checked using the \(|e^+/(e^++e^-)|\) as a function of energy.

**PRODUCTION OF SECONDARY ELECTRONS**

Major part of the electrons produced by the collisions of cosmic-ray nuclei with the interstellar medium (ISM) comes from the decay of pions. In order to calculate the spectra of pions and kaons resulting from cosmic-ray interactions, it is essential to determine the equilibrium spectra of cosmic-ray nuclei composed of these sources which produce them. This was obtained in the framework of leaky-box model as described by Stephens and Streitmatter (1983). In this investigation, I made use of the latest cross-sections given by Webber (private communication) employed time as the variable, rather than the matter traversal. Calculations were carried out for H, C, He, C and O nuclei by incorporating all other heavy nuclei as equivalent to C and O. It was assumed that the injection spectral shape of primary nuclei is a power law in rigidity with a spectral index of -2.2. The resultant spectra of p, He, C and O were subjected to solar modulation and compared with the observed data. This was needed to make sure that there was no error due to normalization.

The cosmic-ray nuclei in the ISM were considered to be bare nuclei and were grouped under protons and neutrons, by using the calculated spectra and the charge to mass ratio of all nuclei (Stephens, Streitmatter, 2000). The production spectra of pions and kaons were then determined by making use of the inclusive invariant cross-section for producing them \((E d^3 \sigma / d p^3)\). The parameterization of \(E d^3 \sigma / d p^3\) for the production of pions in p-p collisions has the following form, which provides a good fit to the data:

\[
\frac{E d^3 \sigma}{d p^3} = A w(s)(1 - X_R)^{\gamma} p_t \exp[-B w'(s)p_t] \]

where \(X_R\) is the ratio of total energy of the particle to the available energy in the center of mass system. \(s\) is the square of the total 4-momenta of the projectile and the target, \(s_{th}\), the threshold value of \(s\), and \(p_t\) the transverse momentum. The functions \(w(s), w'(s)\) and \(z(p_t)\) are defined below:

\[
w(s) = A_1 (1 - s_{th}/s)^{-A_2} \quad \text{for} \quad s_{th}/s \geq C_1
\]
\[
w(s) = A_1 (s/4m_p^2)^{B_2} \quad \text{for} \quad s_{th}/s < C_1
\]
\[
1.0 \quad \text{for} \quad s \leq C_2
\]
\[
1.0 \quad \text{for} \quad s > C_2
\]
\[
z = D_1 - D_2 p_t + w(p_t)
\]
\[
w(p_t) = D_3 [p_t^2 - 0.81] \quad \text{for} \quad p_t > 0.9 \text{ GeV/c}
\]
\[
0.0 \quad \text{for} \quad p_t \leq 0.9 \text{ GeV/c}
\]

In the case of kaons, the parameterization obtained by Badhwar and Stephens (1977) was used. The constants required for the above equation are given in Table 1. The procedure used to carry out the calculations of the above parameterization are given below. It was assumed that \((E d^3 \sigma / d p^3)_{+1}\) in n-p collisions is the same as for \((E d^3 \sigma / d p^3)_{-1}\) in p-p collisions. This assumption was extended to kaons. The error resulting from neglecting associate production of K⁺ near threshold energies is negligible, as the contribution from kaons at these energies is very small. Though the ISM contains only 10% helium by number, the effect on momentum of target nucleons is important and it had been incorporated (Stephens, 1997). Muons from the decay of pions and kaons were obtained using two body decay kinematics. In the case of kaons, only the channel from muon decay

The calculated values are shown in Fig. 1. The helium abundance abundance density \(n_e\) is about 5. The resulting spectra of

**PROPAGATION**

Leaky-box model

The steady state form of the propagation equation

\[
\frac{dN(E, t)}{dt} = \frac{\partial}{\partial t} \int dE \sigma(E, p) \frac{dN(E, p)}{dE dp} = \frac{\partial}{\partial t} \int dE \sigma(E, p) \frac{dN(E, p)}{dE dp} + \int dE \frac{dN(E, p)}{dE dp} \frac{dE \sigma(E, p)}{dE dp} = 0
\]

The first term on the left hand side is the escape term. The second term is the sum of ionization and ionization losses. The leakage term is of the form of the continuous escape term and the sum of the different continuous escape time \(T_{esc}\) has been deduced from the data (Stephens and Streitmatter, 1983).

In the case of kaons, the Klein-Nishina limit

\[
dE \sigma \frac{dN}{dt} = 1.0184 - 3.605
\]

Here, \(\epsilon\) and \(\rho\) One can notice from the table below 14.6/\(\epsilon\) with star light photons from these two regions:

\[
dE \sigma \frac{dN}{dt} = 6.313
\]

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Table 1: Constants in the set of equations (1)

<table>
<thead>
<tr>
<th>A</th>
<th>A₁</th>
<th>A₂</th>
<th>B</th>
<th>B₁</th>
<th>B₂</th>
<th>C₁</th>
<th>C₂</th>
<th>D₁</th>
<th>D₂</th>
<th>D₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>79.0</td>
<td>0.35</td>
<td>2.65</td>
<td>4.60</td>
<td>0.3</td>
<td>0.6</td>
<td>0.35</td>
<td>26</td>
<td>4.0</td>
<td>1.45</td>
<td>1.2</td>
</tr>
<tr>
<td>72.5</td>
<td>0.72</td>
<td>0.90</td>
<td>4.10</td>
<td>0.0</td>
<td>0.0</td>
<td>0.31</td>
<td>-</td>
<td>5.0</td>
<td>0.9</td>
<td>0.27</td>
</tr>
<tr>
<td>83.0</td>
<td>0.57</td>
<td>1.82</td>
<td>4.35</td>
<td>0.0</td>
<td>0.0</td>
<td>0.27</td>
<td>-</td>
<td>4.5</td>
<td>1.2</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Only the channel $K \rightarrow \mu + \nu$ was considered with proper branching ratio. Finally, the electron spectrum had muon decay was evaluated and results for energies $\geq 10$ MeV are given.

The calculated production spectra of e$^+$ and e$^-$ resulting from the collisions of cosmic-ray nuclei with ISM are shown in Figure 1. They are given per unit hydrogen density in the ISM, which takes into account the helium abundance also, as described earlier. These spectra peak at about 30 MeV, where the ratio of e$^+$ to e$^-$ is about 5. This ratio decreases on either side of the peak, reaching an asymptotic value of 1.4 at large energies. The asymptotic spectral slope is approximately the same as that of the cosmic ray nucleons. One needs to examine at low energies, the role of delta production, the target nucleus effect and the production of electrons by knock-on process.

**PROPAGATION OF ELECTRONS**

Leaky-box model had been used for the propagation of the electron component, and the equation describing the propagation can be written as (Stephens, 1990)

$$\frac{\partial N(E,t)}{\partial t} = \frac{\partial}{\partial E} \left\{ N(E,t) \frac{dE}{dt} \right\} - \int_0^1 \left[ N(E) - N\left(\frac{E}{1-v},t\right) \right] \psi_{rad}(v)dv - \frac{N(E,t)}{T_{es}(E)} + Q(E,t)$$

(2)

The first term on the RHS is the energy loss term, consisting of ionization, synchrotron and inverse-Compton scattering. The integral term is for the Bremsstrahlung loss, which is not a continuous energy loss. In the use of ionization and Bremsstrahlung, the composition of ISM, consisting of 80% neutral hydrogen, 10% neutral helium and 10% helium nuclei, had been taken into account. Further, proper derivatives in energy of the continuous energy loss term had been carefully incorporated for the different expressions corresponding to the different composition. The next term is due to particle escape from the confinement region and the escape time $T_{es}$ has a constant value of $T_{es}^* = 30$ Myr below 2.7 GV and is $T_{es}^*(2.7/E)^{0.5}$ above 2.7 GV, determined from the abundance of radio clock nuclei (Streitmatter and Stephens, 2000) and B/C ratio (Stephens and Streitmatter, 2000).

In the case of inverse-Compton scattering, the energy loss in the two regions, Thompson limit and the Klein-Nishina limit, are given here (Blumenthal and Gould, 1970).

$$\frac{dE}{dt} = 1.0184 \times 10^{-16} E^2 \rho [1.0 - 0.03425 \ln(E < \epsilon >) / GeV/s \quad \text{for} \quad E \leq 14.599/\epsilon$$

(3)

$$\frac{dE}{dt} = 3.065 \times 10^{-12} \rho \left[ \ln(E < \epsilon >) - 7.1525 \right] / GeV/s \quad \text{for} \quad E \geq 3193.3/\epsilon$$

(4)

Here, $\epsilon < \epsilon >$ and $\rho$ are the mean energy and the energy density of the photons in eV and eV/cc respectively. One can notice from the above equations, that in the Thompson limit, the energy loss is proportional to $E^2$ and below $14.6/\epsilon$, $\epsilon > GeV$ and there is a large gap between these two regions. In the case of scattering with star light photons, the $E^2$ dependence is valid only below about a GeV. The empirical fit that connects these two regions is,

$$\frac{dE}{dt} = 6.313 \times 10^{-16} \rho \left[ E < \epsilon > \right]^{0.661} / GeV/s \quad \text{for} \quad 14.599/\epsilon < E \leq 3193.3/\epsilon$$

(5)

This expression provides the missing link between these two extreme regions, and the derivatives at the cross-over energies show good continuity.

The steady state solution to the Eq.(2) was obtained by the method of Runge- Kutta technique until $\frac{dE}{dt}(E)=0$. In this equation, the production term $Q(E)$ is described in the previous section. For this
calculation, the interstellar density of hydrogen was taken to be 0.2 atom/cc corresponding to 7.9 Myr (Streitmatter and Stephens, 2000), as obtained from the study of radio-clock isotopes. The value of the effective perpendicular component of the interstellar magnetic field was taken to be 3 μ G. This includes the variation over the regions in the halo, where cosmic rays are confined. Similarly, the mean density was taken to be 0.3 eV/cc. I have also considered a case, in which the mean magnetic field and photon density were assumed to be 5 μ G and 0.5 eV/cc respectively, representing the values in the halo at large energies, where lifetime due to energy loss is small, one needs to consider the effect of nearby stars. This can not be examined by using the leaky-box model and requires the solution of diffusion equation in space and time.

Fig. 1. The calculated production spectra of electrons and positrons in the ISM from the interaction of cosmic ray nuclei are shown perpendicular to unit $n_H$.

![Production Rate vs Kinetic Energy](image1.png)

RESULTS

Positron spectrum

The observed positron spectrum measured during the last two decades is shown in Figure 2. The values in this figure are multiplied by $E^3$. Only CAPRICE results (Boezio et al, 2000) are available below a few GeV and one can notice considerable spread in the data above about 4 GeV. In this figure and in the two figures the combined HEAT data (Barwick et al, 1998) are plotted as reported by Muller (2000). The short-dashed curve marked as A and the dash-dotted curve marked as B in this figure are the integral spectra obtained from this calculation for the two sets of energy loss parameters describing the confinement, which includes a part of the Halo (Curve A), and the Disk (Curve B). They differ in energies due to the change in the physical state of the region, relating to magnetic field and starlight photon density. These spectra also differ from that of Moskalenko and Strong (1998) at low energies, due to difference in the estimated production spectra, and at high energies due to the propagation effects.

Fig. 2. The calculated positron spectra are compared with the observation. The flux values are multiplied by $E^3$. The upper curves are for the interstellar spectra, while the lower ones are at the Earth.

![Positron Flux vs Kinetic Energy](image2.png)

Electron spectrum

The modulated electron energized by the solar wind used for the solar constant of 580 MV. It can be accurately determined at high latitudes and used for the following in the region. The observed values correspond to Curve C.

Fig. 3. The calculated electron spectrum was used for the solar constant of 580 MV. It can be accurately determined, and the following in the region. The observed values correspond to Curve C.
Origin of Cosmic Ray Electrons

The calculated spectra are shown by the solid and long-dashed Curves A and B. Spherically symmetric model was used for the solar modulation and the curves in the figure correspond to an equivalent modulation parameter of 0.9 MV. It can be seen that both the modulated Curves A and B agree with the observation within the uncertainties of the measurements. It is clear from this figure that one needs to measure the $e^+$ spectrum accurately at high energies in order to distinguish between different models, whether the observed positrons come from their time mostly inside the disk (Curve B) or they stay mostly in the extended halo region (Curve A).

The following investigation, the physical parameters relevant to the extended confinement region, which correspond to Curves marked as A in Figure 1, are only used.

**Electron spectrum**

![Electron spectrum graph](image)

**Fig. 3.** The calculated electron spectra are compared with the observation. The flux values are multiplied by $E^3$. The upper curves are spectra in the ISM and the lower ones are spectra near the Earth.

![Energy in GeV](image)

**Fig. 4.** The calculated $[e^+/(e^++e^-)]$ by various models are compared with the observation.

The electron spectrum measured during the last two decades is plotted in Figure 3. As in the case of $\nu$, the flux values are multiplied by $E^3$. There is large scatter of data above 7 GeV. It has been observed that one could fit the observed $e^-$ spectrum using a simple power law injection spectrum with a spectral index of -2.4 (Stephens, 1999). However, this required a larger modulation parameter than for the $e^+$. The observed non-thermal radio spectrum in the Galaxy indicates that the electron spectrum in the ISM should become much flatter below about a few GeV (e.g. Daniel and Stephens, 1975; Rockstroh and Webber, 1978). Therefore, injection spectra which flatten below a few GeV had been examined. In the first case, a spectrum of the type, $80E^{-2.0}$ electrons / (m$^2$.sr.s.GeV), which is the production spectrum multiplied by $T_0^{4}$, $4\pi$ and was used for $E \leq 7$ GeV. This spectrum was assumed to steepen to a slope of -2.5 above 7 GeV. The resulting equilibrium spectrum is shown by Curves B in Figure 3, along with the modulated spectrum, using the same absolute modulation as in the case of $e^+$. One can notice that the spectrum fits the data well. However, it is hard to explain a spectral break of $\Delta \beta = 0.5$ from a source. Therefore, an alternate source spectrum was also considered in this investigation.
In the case of pulsar driven supernova remnants, like the Crab nebula, the electron spectrum in the core is very flat. The relationship between the radio spectral index, \( \alpha \), and the electron spectral index, \( \beta \), is given by \( \beta = 1 + \alpha \). Since the radio spectral index of Crab nebula is \(-0.27\) (Bietenholz et al., 1997), an electron spectrum of the type, \( 50E^{-1.54} \) electrons \( / (m^2 sr s GeV) \) for \( E \leq 4.5 \) GeV was considered, and the source spectrum above this energy due to energy loss at the source. The resultant equilibrium spectrum is then steeper by one power above this energy due to energy loss at the source. The resultant equilibrium spectrum is then steeper by one power above this energy due to energy loss at the source. The result of this is shown by dash-dotted Curve A in Figure 3 and the modulated spectrum is shown by solid Curve A which fit the data well. For a comparison, the estimated \( e^- \) spectrum in the ISM by Moskalenko and Strong (1998) is also shown. This appears to be steeper at lower energies than both types of spectra considered. In this investigation, as in the case of \( e^+ \), one needs to improve the quality of \( e^- \) observation beyond about 2 GeV to remove possible systematic uncertainty and to draw very meaningful deductions.

**Positron fraction**

In Figure 4 is shown the observed fraction of positrons, \( \frac{[e^+/(e^+ + e^-)]}{(e^+ + e^-)} \), as a function of energy. The dotted curve in this figure is due to Moskalenko and Strong (1998) for the ISM. The upper Curves A and B are the calculated ISM ratio, which are obtained using two kinds of injection spectra discussed earlier. The lower Curves are the modulated ones, which differ from the ISM values. It has been pointed out by (Stephens, 1999) that a single power law injection spectrum for \( e^- \) can not reproduce the sharp decrease of the observed \( \frac{[e^+/(e^+ + e^-)]}{(e^+ + e^-)} \). Injection spectra with double power law seem to fit the data well. However, it is interesting to notice that the source spectrum similar to that in the Crab remnant reproduces the data, including the sharp kink around 3 GeV and the flattening of the ratio above 5 GeV. One may point out that there is no need to invoke the decay of SUSY particles to understand the observed flattening of the \( \frac{[e^+/(e^+ + e^-)]}{(e^+ + e^-)} \). Further, the source spectral shape of electrons as inferred from the observations is different from that of nucleon component. From this analysis, one finds a natural explanation that the positron component is supplied by one kind of supernova. The above conclusions clearly indicate the need for measuring accurately the positron fraction over a broad band of energy, not only to search for source of \( e^+ \) production, but also to understand the primary sources of \( e^- \).

**REFERENCES**


**INTRODUCTION**

Over 40 years, we have known of the existence of cosmic-ray interstellar \( p^\#s \) and \( p^-\)s in the higher energy range. The higher energy portion of the spectrum of \( p^-\)s has not been studied as much as \( p^\#s \) due to technical difficulties. The signal from \( p^-\)s as an excess over the background counts is a potential clue to the origin of the neutrino event. The signal from \( p^-\)s as an excess over the background counts is a potential clue to the origin of the neutrino event. The signal from \( p^-\)s as an excess over the background counts is a potential clue to the origin of the neutrino event.

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