OG 3.2.14

Propagation of Cosmic Ray Electron Component in the Galaxy

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Abstract
A detailed calculation has been carried out to determine the energy spectrum of positrons in the Galaxy. These calculations are compared with the observed spectrum and useful information on the magnitude of modulation is obtained. In the case of electrons, a source spectrum has been added and constraints has been set on the spectrum. It is shown that the charge-sign effect on solar modulation is required. Finally, a consistency check has been made by comparing the estimated fraction of positrons with the observed data.

1 Introduction:

The cosmic ray electron component is one of the rarer species constituting only about one percent of the total cosmic radiation. Being light leptons, they undergo severe energy loss during propagation in the Galaxy, resulting in considerable modification of their energy spectra. By examining the observed energy spectra of these particles, one can obtain valuable information on the propagation of cosmic rays and the physical state of the volume of space, where cosmic rays spent most of their time. The major energy loss processes they undergo are different from those of the nucleonic components of cosmic rays. Below 1 GeV, the Bremstrahlung process is important and the radiation arising from this interaction with interstellar gas contributes to a large fraction of the non-thermal background radiation in the gamma ray regime below about 100 MeV. At higher energies, the dominant energy loss mechanisms are the synchrotron radiation and inverse Compton processes, when traversing through ambient magnetic and radiation fields respectively. While the energy loss due to these processes is proportional to the square of their energy, the former one leads to emission in a broad band of non-thermal radio background in the Galaxy and the latter one raises the energy of the ambient photons to gamma ray energies. Thus knowledge of the cosmic ray electron component plays an important role not only in the understanding of the origin and propagation of cosmic rays, but also on the origin of the non-thermal radiation and the physical state of the region from where this radiation comes.

The electron component consists of both positive and negative particles. They are also produced by the interaction of cosmic ray nucleons with the interstellar gas during their propagation, as the end product of the decay of unstable particles, such as pions and kaons, created in these interactions. If this is the major source of these particles, then it is expected that their abundance should be nearly equal with a small positive excess. However, the observations show a large excess of electrons, suggesting that most of the negatrons are accelerated in the cosmic ray sources along with the nucleons. This makes the positron a very important component of cosmic rays. It is also experimentally very challenging to detect positrons against a vast background of cosmic ray protons. Many calculations were carried out in the past to determine the energy spectrum of cosmic ray positrons arising from the interaction of cosmic ray nucleons in the Galaxy (eg: Daniel & Stephens,1975; Protheroe, 1982; Moskalenko & Strong, 1998). In his paper, the production of secondary electrons in the Galaxy is re-examined, by making use of the available cross sections for the production of pions and kaons, and propagate them using the simple Leaky Box Model for cosmic rays.

2 Production of Secondary Electrons:

I summarize below the steps taken to carry out this calculation. The available cross sections for the production of pions and kaons of both signs have been reanalyzed to parameterize the invariant cross section for the inclusive reactions. It is assumed that the invariant cross section for the production of π^+ in p-p collision is the same as for the production of π^- in n-p collisions. This assumption was also extended to kaon production and the error resulting by neglecting the associated production of K^+ near threshold energies is negligible, as the contribution from kaons is very small at these energies. Though the interstellar medium (ISM) contains only 10% helium by number, the effect of the Fermi momentum of target nucleons has been incorporated (Stephens, 1997), which is not a small effect at low energies. Muon spectra from the decay of pions and kaons were obtained using two body decay kinematics; only the $K \rightarrow \mu + \nu$ channel was used with proper branching ratio. Finally, the electron spectrum from muon decay has been carefully evaluated.

In order to obtain the pion and kaon production spectra, one needs to know the cosmic ray nucleon spectra in the interstellar space. For this purpose, steady state propagation calculation was carried out for H, D, 3He, 4He and C and O nuclei by incorporating all other heavy nuclei as equivalent to C and O. It was assumed that the injection spectrum of the primary nuclei is a power law in rigidity and the propagation time is rigidity dependent above 3.5 GV (Stephens & Streitmatter, 1998). The resultant spectra for P, He, C and O were compared with observation after modulating them to make sure that there was no error due to normalization. The interstellar nucleon spectra were then grouped under protons and neutrons on the basis of the mass to charge ratio of each element. This approach is fully justified as the product of interaction cross section for a nucleus and the number of participating nucleons is nearly the same as the product of the total number of interacting nucleons and the p-p cross section; in fact, this is strictly true for α - p interaction. A similar estimate made for the target composition showed that the cosmic ray nucleon interaction with target helium needs to multiplied by 3.17 to take into account the increase in the interaction cross section and the number of participating nucleons from the interacting nucleus. Notice hat this factor is < 4.0, because of the proton interaction is enhanced only by the increase in the cross section. By the above approach, the production spectra of both the electrons and positrons in the ISM was obtained. In this calculation, contribution from knock-on electrons were not considered, as the results will be presented only above 100 MeV.

3 Propagation and Results:

The equation describing the propagation of electrons is written as (Stephens, 1990a)

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

The first term on the right hand side is the energy loss term, consisting of ionization, synchrotron and inverse Compton losses, the integral term is due to Bremstrahlung, which is not a continuous energy loss process, the next term is the loss due to escape and the last term is the production term. In the case of continuous energy loss processes, proper derivatives are carefully considered, including the change in the inverse Compton loss term at higher energies. The ionization and Bremstrahlung terms were properly modified to take care of the ISM composition. The above equation was then solved by the Runge Kutta technique until $\partial N(E)/\partial t \rightarrow 0$, to achieve a steady state situation. The production term is described in the previous section and in the case of negatrons, an additional source term was introduced, which is a power law spectrum. The cosmic ray escape time was taken from the work of Stephens and Streitmatter (1998) to be equivalent to 15.9 g/cm^2 of ISM traversed by relativistic nuclei for an interstellar density of 0.3 hydrogen atom/cc. The resultant spectrum was then subjected to solar modulation in order to compare with the observation.

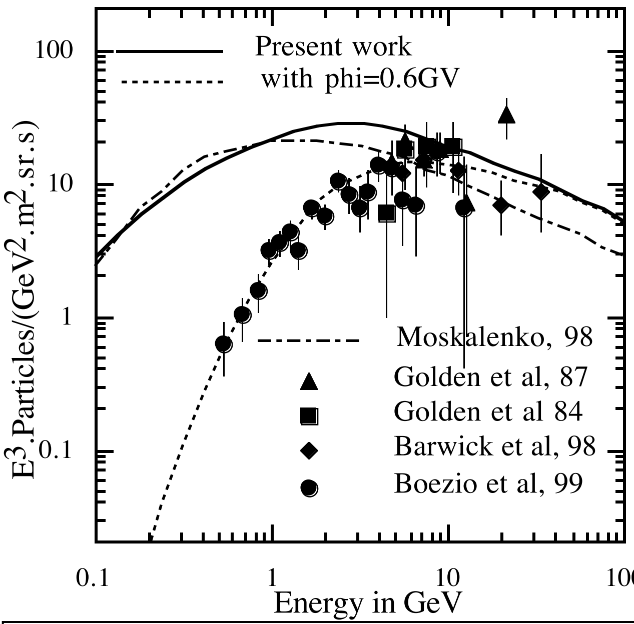

Fig. 1. Energy spectrum of cosmic ray positrons.

In Figure 1, the observed positron spectra measured over the last two decades are shown (Golden et al, 1984, 1987, Barwick et al, 1998, Boezio et al, 1999). There is considerable spread in the data above 4 GeV. The solid curve shown in this figure is the equilibrium spectrum of positrons in the ISM from this calculation. This estimate differ from that of Moskalenko & Strong (1998) [MS], as shown by dashed dotted curve, both in shape and in absolute intensity. The present ISM spectrum was modulated with a modulation parameter phi=0.6 GV and this is shown by the dashed curve. The agreement between this curve and the observed data is very good. From this, it is inferred that our present understanding of the absolute modulation is indeed correct. A better constraint can be set on this when the existing differences among data points are reduced.

The calculated electron spectra are shown in Figure 2 along with the data up to a TeV . The solid curve is the calculated ISM spectrum using an additional primary source term, which is equivalent to the spectrum without energy loss, but with energy independent escape, namely, $250E^{-2.55}$ electrons /(m^2.s.sr.GeV). In order to fit the low energy data, one needs to modulate this ISM spectrum with a higher value of phi=0.8 GV. Above 4 GeV, this spectrum agrees with the set of data with low flux values. Thick dashed curve shown here is by using a source spectrum of the type $175E^{-2.4}$. This ISM spectrum is in agreement with the high energy data as well as with that estimated by MS, which deviates at low energies as can be noticed by the dash-dotted curve. This ISM spectrum was modulated with phi=0.7 GV in order to get a good fit to the data. The fact that one requires a larger solar modulation for electrons compared to positrons to fit the spectra measured by the same experiment (Boezio et al, 1999) during the positive polarity cycle, indicates that there is a noticeable charge sign effect. However, there is uncertainty in determining the

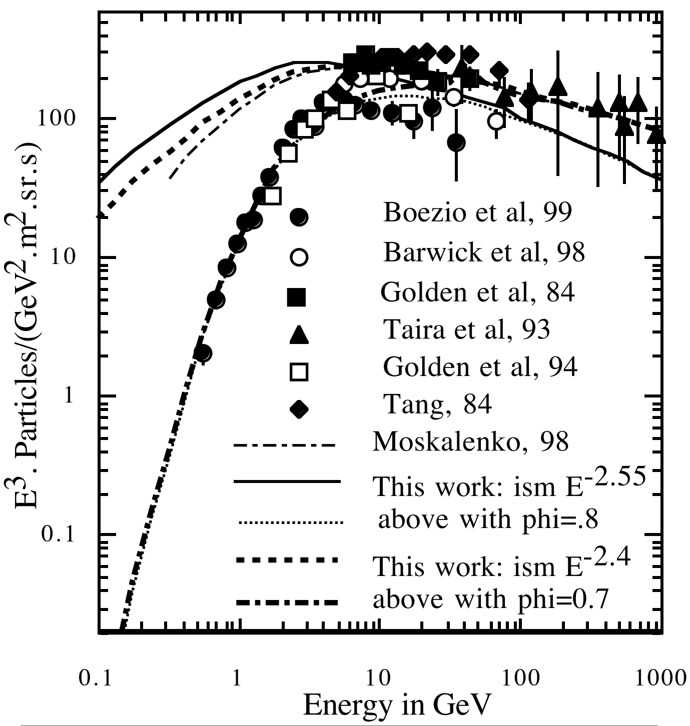

Fig. 2. Energy spectrum of cosmic ray

absolute magnitude of this effect, due to the scatter of data at high energies and the choice to introduce an additional primary source spectrum for electrons. It is also seen that one requires for electrons a steeper primary spectrum than for the nucleons (Stephens, 1990; Boezio et al, 1999). The magnitude of this difference can be estimated with reliability when high energy spectrum is measured accurately.

The recent data on the fraction of positrons are shown in Figure 3 along with theoretical curves. The calculated curve by Protheroe (1982) and by MS are for the ISM, the former one (dashed curve) does not agree with the entire data and the latter one (dash-dotted curve) agrees with data below 5 GeV. The present calculations (dotted and solid curves) includes solar modulation with phi=0.6 GV for positrons and phi=0.7 & 0.8 GV for electrons with flat and steep primary spectra respectively. These curves pass through low and high energy data, but fail to go through the intermediate data points. It is interesting to point out that none of the theoretical curves when modulated can reproduce the observed fraction, which decreases sharply between 1 and 5 GeV. One needs to understand the implication of the behaviour of the data in this energy range.

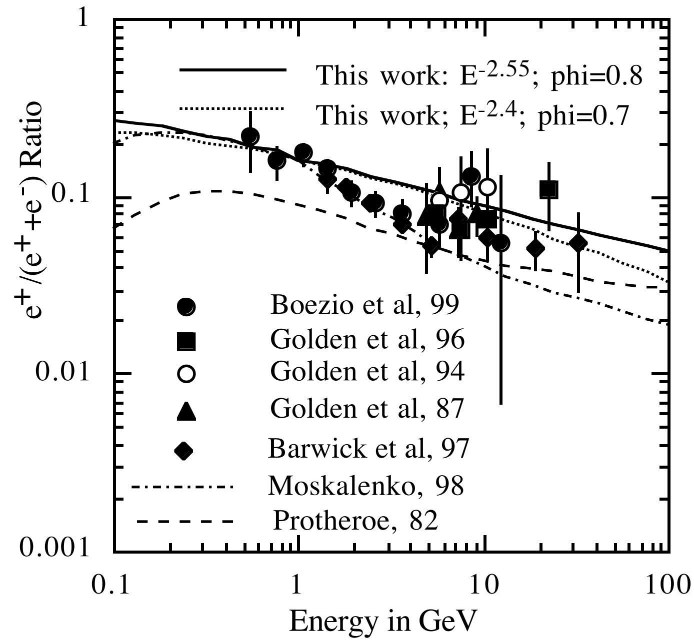

Fig. 3. Positron fraction vs Energy

Acknowledgements: Part of this work was carried out while I was at NASA/GSFC, where it was supported by NASA RTOP 353-87-02 through USRA. I thank Dr. R.E. Streitmatter for the kind hospitality during my stay and providing excellent computational facility to work at home.

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