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COSMIC-RAY ELECTRONS AND POSITRONS

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ABSTRACT

Measurements of cosmic-ray electrons and positrons address a number of significant astrophysical questions concerning the nature and distribution of sources in the galaxy, and the characteristics of cosmic ray propagation in the galactic disk and halo. The abundance of positrons may also carry the signature of unusual pair production processes or dark matter particle decays. We shall review the body of information available, including recent results from the HEAT collaboration. We describe constraints on the source energy spectrum of electrons, which appears to have the same shape as that of nuclear cosmic rays, and we discuss the evidence that positrons are predominantly if not exclusively of interstellar secondary origin. Finally, we emphasize the need for several key observations that are required in the future in order to resolve the remaining questions.

INTRODUCTION

Electrons, distinct by their low mass and leptonic nature, are a relatively rare and somewhat enigmatic component of the cosmic rays. It is still not understood why there are so few electrons (~ 1% of the proton intensity at GeV energies), but it is well known from measurements of the relative abundances of negative electrons and positrons, that the much more abundant negative electrons must predominantly come from primary sources.* Radio observations have shown that supernova remnants are the most likely source candidates, and recent measurements in the x-ray and gamma-ray region, have indicated one shell-type supernova remnant (SN 1006) as a likely accelerator of electrons up to very high energy, around 100 TeV (Koyama et al, 1995; Tanimori et al, 1998). In lieu of more detailed knowledge, one usually assumes that negative electrons are accelerated along with protons and nuclei, and likely, with the same energy spectrum. The origin of positrons, on the other hand, is generally attributed to secondary production in the galaxy, mostly from proton-proton hadronic interactions that lead to positive pions. Whether there are, in addition, primary contributions to the positron intensity, remains a subject of ongoing research.

During propagation from their sources, electrons are affected by electromagnetic interactions. Their low mass permits significant energy losses due to bremsstrahlung with the interstellar gas, inverse Compton scattering off photons, and synchrotron emission in the magnetic fields of the galaxy. Compton interactions with the cosmic microwave background preclude electrons from traversing intergalactic distances. Thus, electrons are the only cosmic ray species for which extragalactic contributions are excluded with certainty. The shape of the energy spectrum of the *observed* electron flux is sensitive to the parameters of the propagation process, such as diffusion coefficient, distribution of sources, size of the galactic halo, re-acceleration in interstellar space, etc. All observers since the 1970's agree that the

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*In this paper, we shall use the term "electrons" for the sum of particles regardless of charge; otherwise we will use the terms "negative electrons" or "positrons".

measured electron energy spectrum above ~ 10 GeV is considerably steeper than that of all other co ray species, and that this steepening is most likely a consequence of radiative energy losses du propagation.

In the following, we shall discuss these issues in more detail, review recent measurements their interpretation, and comment on the promise of future investigations.

PROPAGATION OF ELECTRONS

It has been often suggested, with good reason, that electrons are an excellent probe for study the containment and propagation of cosmic rays in the galaxy. Let us briefly summarize the pertin quantities. The energy loss rate dE/dt of electrons for both synchrotron and inverse Compton proce increases with the square of the electron energy E; hence these are the dominant processes at high ener

$$\frac{dE}{dt} = -kE^2 \text{ with } k = C\left(w_{ph} + \frac{<B^2>}{8\pi}\right)$$

The constant C equals 10^{-16} if the energy densities of photons and the magnetic field, w_{ph} $B^2/8\pi$, are measured in eV/cm^3 and dE/dt in GeV/sec. If an electron of initial energy E_o is observed energy E after time t, it follows from (1) that $E_o = E/(1-kEt)$. The quantity $t = 1/kE$ is referred to as radiative lifetime, i.e. the time after which an electron of very large initial energy has reached the ene E. For diffusive isotropic propagation, with diffusion coefficient D, the electron travels the distance $(2D\tau)^{1/2} = (2D/kE)^{1/2}$ during its lifetime. If D depends on energy, the pathlength is λ $=\left(\int_E^\infty \frac{2D(E')dE'}{kE'^2}\right)^{1/2}$. It is instructive to compare λ with the dimensions of the galactic containment reg

We assume that the sources of electrons, with differential source energy spectrum $\propto E^{-\gamma_o}$ are distrib over the galactic disc, which has a scale size ("thickness") d, but that the containment volume inclu galactic halo of scale size h; h>>d. Qualitatively, one then predicts three regions for the *observed* ene spectrum dn/dE.

(a) Low energies; λ(E)>h:

The observed spectrum is determined by diffusive escape from the halo; radiative energy losses insignificant. Thus, $dn/dE \propto D^{-1}E^{-\gamma_o}$. If D is independent of energy, the observed spectrum has same slope as the source spectrum.

(b) High energies; λ(E) <d:

The propagation of electrons is dominated by radiative energy losses. In this energy region, elect cannot escape from the galactic disk before losing most of their energy. Now we have dn/dE $E^{-(\gamma_o+1)}$. The spectral index is exactly one unit larger than that of the source spectrum independent of D. If E is very large, the discrete nature of sources in the disk becomes a lim factor, and another scale length, ℓ; the average distance between sources becomes a limiting fa One expects a sharp drop-off of the observed electron intensity if $\lambda < \ell$.

(c) Intermediate energies; h>λ(E)>d:

The containment volume now depends on energy: electrons of initial energy, E, can only fill a v of scale λ(E). The observed energy spectrum will be steeper than the source spectrum, but will affected by any energy dependence of D. An exact solution of the propagation equation for cylindrical symmetry by Dogiel (1990) gives $dn/dE \propto D^{-1/2}E^{-(\gamma_0+0.5)}$.

Thus one predicts a steepening of the observed spectrum over a characteristic range of energies. The spectral slope γ may vary from γ_0 (at low energy, and D independent of energy) to a maximum value $\gamma = \gamma_0 + 1$ (provided $\lambda > \ell$). One usually defines two "break energies" E_1 and E_2, corresponding to $\lambda(E_1) = h$ and $\lambda(E_2) = d$, respectively. The values of these energies depend critically on the value of the diffusion coefficient and its energy dependence. If we accept the general assumption that the measured electron spectrum (which will be discussed below) is fully steepened to a power law index γ_0+1 at energies above about 30 GeV, then E_2 could at most be $E_2 \approx 30$ GeV. For this value of E_2, and with h =10kpc, =1kpc, and k=0.25×10^{-16} GeV^{-1} sec^{-1} in the halo, but k=1.0×10^{-16} GeV^{-1} sec^{-1} in the disk, one would obtain $E_1 \approx 1$ GeV and D = 1.4×10^{28} cm^2/sec if the diffusion were energy independent. With the more realistic assumption that the diffusion coefficient reflects the $E^{-0.6}$ behavior of the propagation pathlength deduced from nuclear composition data, i.e., assuming $D(E) = D_o\,(E/1GeV)^{0.6}$, we would obtain $E_1 \approx 0.01$ GeV, and $D_o = 7.5 \times 10^{26}$ cm^2/sec. Thus, in this case the break at E_1 would occur at very low energies where bremsstrahlung and ionization energy losses cannot be ignored and where solar modulation obscures the interstellar spectrum. Further, the change in spectral slope at E_2 would be quite small, $\Delta\gamma \approx 0.2$, and difficult to observe.

Of course, there are more parameters that can and perhaps must be introduced. These include anisotropic diffusion, convection, and re-acceleration in interstellar space. Others are solar modulation and bremsstrahlung losses at low energy, and Klein-Nishina corrections to the inverse Compton formula. But the more serious challenge is for the observer: one must obtain data on the electron spectrum which are accurate enough to permit a determination not only of the average spectral index γ, but also of its variation $\gamma(E)$ over a large range of energies. Only then will it be possible to derive decisive constraints on the propagation process.

THE MEASUREMENTS

Observations of electrons have been notoriously difficult because of their low intensity requiring, in particular at high energies, rather large detectors, and because of the need of effective discrimination against proton-induced background. While virtually all instruments use electromagnetic calorimeters, the observation of just the longitudinal shower profile has in general been insufficient to reject all proton-induced showers. More successful were measurements where the details of the initial stages of the shower could be visually observed in emulsions (Kobayashi et al, 1999, and earlier work of this group) or where an imaging calorimeter was used for detailed observation of both the longitudinal and the lateral shower development (Torii et al, 1999). Alternatively, additional independent particle identification through devices such as transition radiation detectors (Prince, 1979; Tang, 1984; Müller and Tang, 1987), magnet spectrometers (Buffington et al, 1975; Golden et al 1984; Golden et al, 1994), or both (Barwick et al, 1995; Golden et al, 1996) has proven to be successful.

In the following, we shall describe recent results that were obtained with the HEAT instrument (Barwick et al, 1997a). A more detailed description of this work has been submitted for publication in ApJ. (DuVernois et al, 2000). We then compare our data with those of other investigators and discuss which conclusions might be drawn. The HEAT instrument, shown in figure 1, encompasses a combination of shower detector, magnetic spectrometer and transition radiation detector. It was designed to measure the intensities of positrons and electrons separately, and exhibits a proton rejection power of nearly 10^5, at an average electron acceptance (after all data cuts) of about 30%. Figure 2 shows the electron spectrum obtained with this instrument in two balloon flights from Fort Sumner, NM, in 1994 and Lynn Lake, Manitoba, in 1995. The energy range of this measurement did not exceed 100 GeV, and the asymptotic power law index of the spectrum above 20 GeV is $\gamma = 3.44 \pm 0.05$. The drop-off below ~8 GeV is mainly due to solar modulation. Figure 2 also includes data from two other recent measurements, and indicates good agreement, although the data of Torii (1999) would support a slightly lower spectral index at high energy.

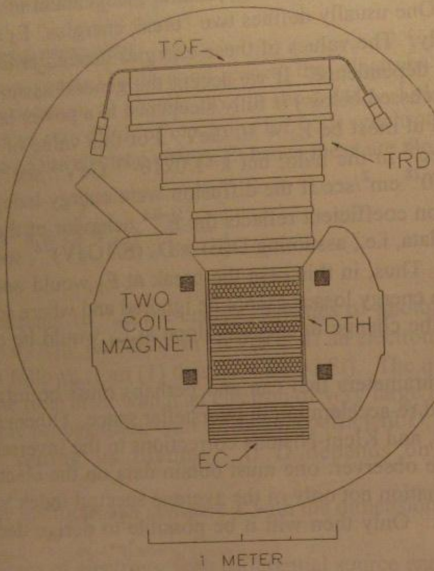

Fig. 1. Cross section of the HEAT instrument. The detector includes time-of-flight counters (TOF on top, and EC on bottom), a transition radiation detector (TRD), a superconducting magnet spectrometer including a drift-tube hodoscope (DTH), and an electromagnetic calorimeter (EC).

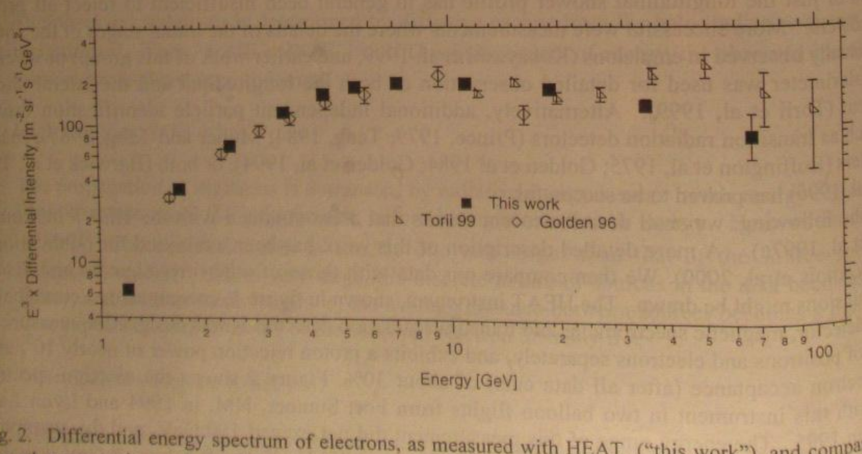

Fig. 2. Differential energy spectrum of electrons, as measured with HEAT ("this work"), and compared with two other recent observations. The intensity scale is multiplied with E^3.

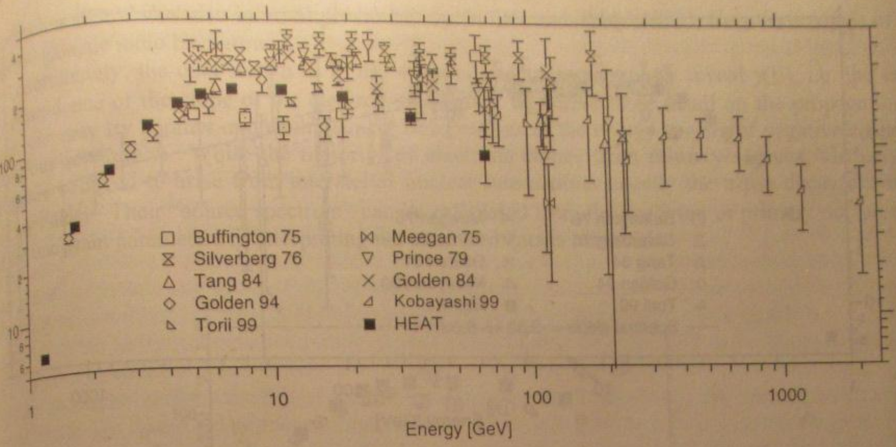

Fig. 3. Compilation of data on the differential energy spectrum of electrons since 1975. The intensity scale is multiplied with E^3.

In figure 3, we show a compilation of all data published since 1975. The measurements extend to energies of about 2000 GeV, but it should be noted that all data above ~ 300 GeV come from a single set of observations (Kobayashi et al, 1999). Obviously, there are significant disagreements in the absolute normalization of different measurements. Even at energies around 10 GeV where the counting statistics are generally quite good, we find intensities varying by about a factor of two. The more recent data tend to favor lower intensities than the earlier results, but still show discrepancies outside their given error limits. Due to these differences, the overall slope of the spectrum cannot be determined with good accuracy. If some of the individual spectra, including the HEAT results, are extrapolated to higher energies, they would tend to significantly undershoot the measurement of Kobayashi et al (1999) which reaches into the TeV range.

The differences among the individual data sets could result from undetected hadron background in those data that report high fluxes, or from uncertainties in the energy scale (which are amplified if the flux values are multiplied with E^3), or from uncertainties in the instrumental acceptance efficiencies used by individual observers. Hadron contamination is not likely to be a problem for those instruments that use two independent techniques for hadron rejection, i.e. the majority of the data in figure 3. Uncertainties in the energy scale of the order of at least 10% can probably not be excluded for most of the measurements. Efficiency corrections are notoriously difficult, but probably more reliable for the more recent data where more powerful computer simulations could be made than in earlier investigations.

Let us assume that the systematic differences between the individual data sets are due to errors which do not depend strongly on energy. In that case, the power-law slope of the spectra would not be affected. We then arbitrarily normalize the entire data set of figure 3 to about the same intensity around 10 GeV. The result is shown in figure 4. While this procedure does not generate perfect convergence of all

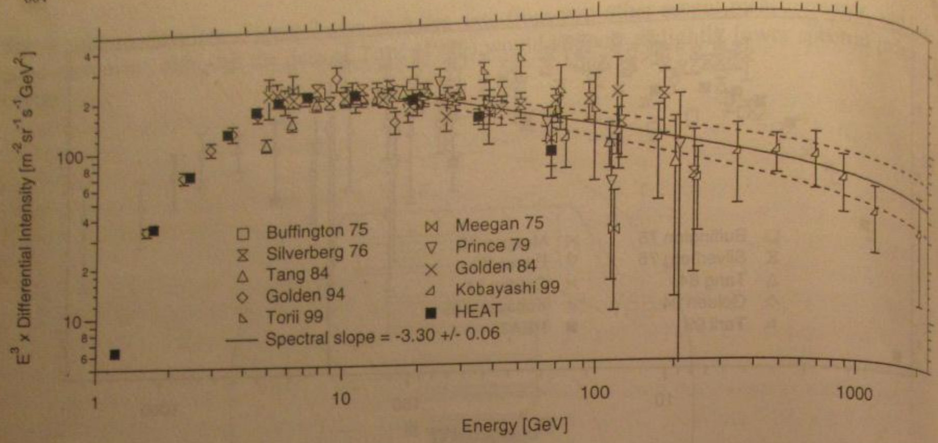

Fig. 4. Same data as figure 3, but arbitrarily normalized for about equal intensity at 10 GeV. The solid line indicates a single power law fit to the data above 20 GeV.

measurements, we use it to determine a single power law fit to the combined data set above 20 GeV. obtain a spectral index $\gamma = 3.30 \pm 0.06$. Clearly, there may exist finer detail, and deviations from a si power law shape cannot be excluded for the true spectrum, but the accuracy of the data is insufficie reveal this. Also, in order to determine the spectrum of *primary* negative electrons, a contributio interstellar secondary electrons would have to be subtracted from the data. This has not been don figures 2, 3, and 4. As the secondary component is only ~10% of the total flux, and the fraction va slowly with energy, the subtraction would not change the slope of the electron spectrum appreciabl this spectral index corresponds to the slope of the fully steepened electron spectrum, the characteris break energy E_2 would be between 10 and 50 GeV. Possible values for the corresponding diffus coefficient have been discussed in section 2. The spectral index at the source would then be $\gamma_o = \gamma - 1 =$ ± 0.06. This is close to the power law index derived for cosmic ray nuclei at their sources, $\gamma \simeq 2.2\pm$ (Müller et al 1991, Swordy et al 1993). Thus, if this interpretation is correct, electrons and nuclei may be generated by the same sources, presumably fairly strong shocks of supernova remnants.

At low energies, below ~ 10 GeV, the observed spectral shape is not representative for interstellar spectrum because of solar modulation effects. In addition, in order to describe the propag from the sources in this region, energy losses due to ionization and bremsstrahlung have to be taken account. An extensive computer simulation, including all these effects, has been provided by Moskale and Strong (1998). These authors conclude that their model can describe the measured data only if source spectrum changes shape, with an index of 2.1 below 10 GeV, steepening to 2.4 above 10 G This model uses either diffusion coefficients that are constant up to rigidities of 3GV, and then vary rigidity as $\propto R^{0.6}$, or diffusion coefficients $\propto R^{0.33}$ for all rigidities but then also including galactic acceleration in the model. These calculations reaffirm a fact that has been previously recognized (T 1984): The change in spectral slope from the demodulated data below 10 GeV to the highest energ too rapid as to be compatible with energy-dependent diffusion and a source spectrum described by a s power law. As energy dependent diffusion is indicated by measurements of the nuclear cosmic ray particular by measurements of the energy dependence of the L/M abundance ratio, a change in the slop the electron source spectrum is probably an inescapable conclusion. A flattening of the electron s spectrum below 2GeV was also inferred previously by Müller and Tang (1983), from an analysis of the non-thermal galactic radio background.

Unfortunately, the data shown in figure 4 are not accurate enough to reveal γ(E), i.e. the exact energy dependence of the slope of the electron spectrum. To derive more detail on the propagation of electrons, one may try another approach, namely observations of the energy spectra of negative electrons and positrons separately. While the majority of electrons comes from primary sources, virtually all positrons are believed to arise from interstellar nuclear interactions (mostly the π-μ-e decay chain) of cosmic ray nuclei. Their "source spectrum" can be calculated from the spectrum of primary nuclei; thus, one of the uncertain parameters in interpreting the measured data is removed.

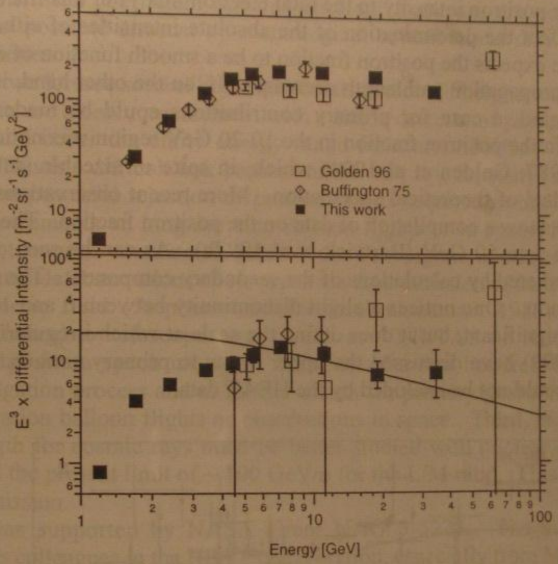

Fig. 5. Differential energy spectra of negative electrons (upper panel) and of positrons (lower panel). The intensity scale is multiplied with E^3. "This work" indicates results from HEAT. The curve in the positron data refers to a model prediction by Moskalenko and Strong (1998).

In figure 5, we show the results on the spectra of charge-separated electrons from the HEAT instrument, compared with those few other observations for which data exist. The agreement between individual data sets is fairly good, but, for positrons, which are of particular interest here, the statistical accuracy of the data does not yet permit strong conclusions. It must be noted, however, that the model of Strong and Moskalenko is in very good agreement with the HEAT positron measurement above the region of solar modulation. Arguably, the positron spectrum seems to decrease towards low energy a little less steeply than the spectrum of negative electrons.

Let us return to the highest energies, around 1000 GeV and beyond. It has been pointed out for a long time by Nishimura and collaborators (e.g., Kobayashi et al, 1999) that most reasonable propagation models predict, for such energies, the electron pathlength to become smaller than the dimensions of the galactic disk. Thus, the spatial distribution of galactic sources becomes important, and a sharp drop-off of the electron intensity is expected when λ becomes smaller than the distance to the nearest source. Kobayashi et al argue that Vela, at a distance of 0.2 to 0.4 kpc, might be the nearest and perhaps only supernova remnant that could generate electrons in the TeV region that we observe near Earth. While the present data cannot prove this suggestion by revealing a drop-off or structure in the energy region beyond 1000 GeV, observations in this region clearly provide a most challenging and promising task for future work.

THE POSITRON FRACTION

Positrons are produced as secondary cosmic rays from collisions of primary nuclei with the interstellar gas. The existence of an additional, primary positron component could have profound astrophysical or particle physics implications as it would indicate the significance of unusual pair production mechanisms, or contributions from dark-matter particle decays. As figure 5 shows, the absolute intensity of positrons is close to that predicted for secondary origin, thus, primary contributions, if they exist, must be small. To investigate this question more accurately, one may determine the "positron fraction", i.e. the ratio of the positron intensity to the total electron flux. For this fraction, many systematic uncertainties cancel that affect the determination of the absolute intensities of either component. If all positrons are secondary, one expects the positron fraction to be a smooth function of energy, falling slowly with energy as the nuclear propagation pathlength decreases. If, on the other hand, irregularities or peaks in this fraction were detected, a case for primary contributions could be made. In fact, in earlier investigations, an increase in the positron fraction in the 10-20 GeV region was noticed (Buffington et al 1975; Müller and Tang, 1987; Golden et al 1994) which, in spite of sizeable statistical uncertainties, became subject to a great deal of theoretical speculation. More recent observations have not confirmed this feature. In figure 6, we show a compilation of data on the positron fraction. These include our HEAT results over the range from 1 to 50 GeV (Barwick et al 1997b). As can be seen, the more recent data follow the general trend predicted by calculations of the secondary component. The lower panel of figure 6 shows just the HEAT results. One notices a slight discontinuity between 6 and 10 GeV. This feature may barely be statistically significant, but it does define the scale at which irregularities could show up, if they exist. Coutu et al (1999) have discussed the upper limits to primary contributions, including dark matter WIMP decays, that could not be excluded by the HEAT data.

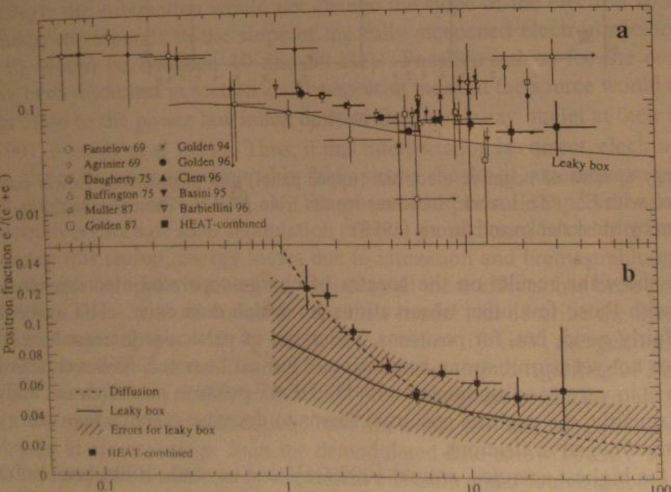

Fig. 6. The positron fraction $e^+/(e^+ + e^-)$ as a fraction of energy. The upper panel shows a compilation of data from several investigations; the lower panel are the results from just the HEAT instrument. The curves "leaky box" and "diffusion" refer to model predictions by Protheroe (1982) and Moskalenko and Strong (1998) respectively. (Figure from Coutu et al, 1999.)

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CONCLUSION

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Thus in summary, the more recent measurements of the positron fraction indicate that interstellar secondary production must be the dominant source of positrons, but the need to increase the statistical accuracy and energy coverage remains.

CONCLUSION

The efforts of many groups over the years have led to a substantial set of data on galactic electrons and positrons. Nevertheless, the interpretation of the data still remains somewhat tenuous. It appears that the source spectrum of electrons has the same shape as that inferred for cosmic-ray nuclei. This would support a common origin of both particle species, most likely in supernova remnants. The source spectrum may not have a continuous power law shape but may become somewhat harder below 10 GeV. The measured data constrain the value of the diffusion coefficient for interstellar propagation, but the energy dependence of the diffusion coefficient remains unclear. Positrons are predominantly of interstellar secondary origin; but possible unusual or cosmological contributions may still be hidden within the experimental uncertainties.

For the future we foresee several key experiments that could help to resolve the remaining puzzles: First, we would like to see a new measurement with a single detector of proven capability to reject proton background, that could cover the entire energy range from around 1GeV to several TeV, with good statistical accuracy. This is a difficult task because of the very low intensity (at most 3 electrons/m^{2}sr day above 1 TeV) and the powerful rejection of protons that is required at high energies. Progress seems possible with new instruments on long-duration balloon flights or in space, for instance, attached to the Space Station. To obtain good counting statistics in the TeV region, non-standard techniques should also be explored. These include observations of electrons via their emission of hard x-ray synchrotron radiation in the earth's magnetic field (Stephens and Balahsubrahmanian, 1983), or perhaps ground-based observations with Cherenkov telescope arrays such as VERITAS or HESS. Second, the accurate measurement of the positron spectrum, up to energies of a few hundred GeV is necessary to better understand the propagation process and to further search for primary positron contributions. Again, this will require long-duration balloon flights or observations in space. Third, the energy dependence of the propagation pathlength for cosmic rays must be better studied with nuclear composition measurements extending far beyond the present limit of ~ 100 GeV/n for the L/M ratio. This is an important task for the proposed ACCESS mission.

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