ENERGY SPECTRA OF ELECTRONS AND POSITRONS FROM 5 TO 100 GeV

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ABSTRACT

We report and discuss new measurements of the intensities and energy spectra of cosmic-ray electrons and positrons over the energy range 4.5 to 50 GeV, and of the all-electron flux to 100 GeV. These measurements have been obtained with the first balloon flight of the HEAT magnet spectrometer in 1994. The results are consistent with an essentially secondary origin of galactic positrons.

INTRODUCTION

Previous measurements of electrons ($e^+ + e^-$) up to roughly 1000 GeV (Prince 1979, Nishimura et al. 1980, Golden et al. 1984, Tang 1984) have shown that their intensity amounts to about 1% of the flux of protons around 10 GeV, but decreases more rapidly with energy ($\propto E^{-3.1}$) than the proton spectrum ($\propto E^{-2.7}$). Separate measurements of positrons and electrons have only been possible at much lower energies and have indicated a "positron fraction" ($e^+/(e^+ + e^-)$) around 10% in the region 1-50 GeV (Fanselow et al. 1969, Agrinier et al. 1969, Buffington et al. 1975, Müller and Tang 1987, Golden et al. 1987, 1994, and 1996, Barbiellini et al. 1996, Barwick et al. 1995 and 1997a). These observations have led to a number of conclusions, but have also left some key questions unanswered:

1)The predominance of negative electrons requires acceleration in primary sources.

2) The steepness of the observed energy spectrum is usually explained as a consequence of radiative energy losses during propagation through the interstellar medium. However, there are several problems: The energy spectrum of electrons at the source is not known a priori, nor is it known that electrons and nuclei originate at the same acceleration sites; the energy dependence $\propto E^{-0.6}$ of the containment of nuclei may be difficult to reconcile with the observed shape of the electron spectrum (Tang 1984); and the "leaky box" approximation which ~~is usually~~ used, assumes an unreasonably high density of electron sources in the galactic disk (Cowsik and Lee 1979).

3) The small flux of positrons appears to be esentially consistent with a secondary origin. However, a small primary contribution of positrons cannot be excluded with certainty. This question is discussed by Coutu et al. at this conference (paper OG 7.1.3.).

Progress in our understanding of these issues requires measurements of electrons and positrons separately, and over as large an energy range as possible. This was the motivation for the construction of the High-Energy Antimatter Telescope (HEAT) which was flown on balloons in 1994 and 1995. In the following, we shall present and discuss results from the 1994 flight, but by the time of the conference,we hope to also have the analysis of the 1995 flight available.

THE EXPERIMENT

The first balloon flight took place in May 1994, from Fort Sumner, New Mexico, (vertical rigidity cutoff 4.5 GV), with float altitudes between 3.8 and 7.4 g/cm² for about 29 hours. The flight instrument consists of a combination of a superconducting magnet spectrometer (using a drift-tube hodoscope (DTH) tracking chamber), with particle identifiers employing time-of-flight scintillators (TOF), a transition-radiation detector (TRD), and an electromagnetic calorimeter (EC). A detailed description of the instrument is given by Barwick et al. 1997b.

For each event in flight, the following quantities are measured:

(1) magnitude of the particle charge (top TOF scintillator and TRD)
(2) sign of the charge and particle momentum (DTH)
(3) trajectory and direction of traversal (DTH, TOF, TRD)
(4) energy (EC)
(5) electron/hadron characteristics from shower profile (EC)
(6) Lorentz factor for electron/hadron discrimination (TRD)

These measurements provide a high degree of redundancy in particle identification and permit hadron rejection power in excess of 10^5. Specifically, for a particle to be accepted as electron or positron, we require that a well reconstructed downwards trajectory through the instrument be identified, that the particle be singly charged, that the momentum be defined with good precision, and that the momentum be consistent, within experimental resolution, with the energy measured with the EC. In addition, the event must be characterized by a "good" shower profile starting within the first radiation length of the EC, and it must exhibit a saturated transition radiation signal in the TRD. Key to the success of the data analysis procedure is the fact that the response functions of all detector elements are accurately determined from accelerator calibrations, from the flight data themselves, and from Monte Carlo simulations.

The energy E' assigned to electrons and positrons selected by the analysis, is somewhat lower than the energy E at the top of the atmosphere, due to bremsstrahlung losses in the residual atmosphere at balloon height. We therefore correct E' by the factor $f=\alpha^{t/\alpha\ln 2}$ (where t is the residual atmosphere in radiation lengths, and α is the spectral index, taken to be = 3.1) (Schmidt, 1972). Typically, this amounts to a ~ 5% shift in the energy scale. Table 1 shows the raw numbers of electron and positron counts, sorted into energy intervals at the top of the atmosphere. The uncertainties are 16 and 84% Bayesian limits, taking statistical fluctuations and the subtraction of a small proton background into account. For the highest energy interval, the rigidity spectrometer could not differentiate between electrons and positrons

Table 1. Raw numbers of electrons

Energy (GeV)	Electrons ΔN_{e^-}	Positrons ΔN_{e^+}	All-electrons ΔN_e
4.5 - 6.0	1911 ± 45	176 ± 14	2087 ± 47
6.0 - 8.9	1787 ± 43	162 ± 14	1949 ± 45
8.9 - 14.8	921 ± 31	76^{+10}_{-9}	997 ± 33
14.8 - 26.5	344 ± 20	$18.6^{+5.8}_{-3.9}$	363 ± 20
26.5 - 50.0	75^{+10}_{-9}	$6.1^{+3.7}_{-2.1}$	81^{+10}_{-9}
50.0 - 100.0			$19.2^{+5.7}_{-4.0}$

RESULTS

The absolute differential energy spectra are obtained from the counts ΔN of Table 1 as:

$$j_{pri}(\bar{E}) \approx \frac{\Delta N}{\Delta\bar{E}\,\epsilon\Omega\,A\,\Delta t} - j_{atm}(\bar{E})$$

where $\epsilon\Omega A$ is the instrumental acceptance, Δt is the live time, $\bar{E}$ is the weighted average energy, $\Delta\bar{E}$ is the weighted energy interval, and $\alpha \approx 3.1$ is the power-law spectral index. An atmospheric secondary contribution (*atm*) is subtracted to obtain the primary component (*pri*). This contribution is determined from Monte Carlo simulations, as well as growth curves measured for different altitudes during the balloon flight. It is small for electrons but at a level of about 30% for positrons.

The detection efficiency ε is comprised of contributions from all selections made in the acceptance of electrons, including the instrument trigger. To determine ε, a full Monte Carlo simulation of the instrument is made, based on the GEANT software package, and including experimentally determined fluctuations in detector response. The simulation also determines the geometric factor AΩ of the instrument; AΩ = 495 cm^{2}sr. Whenever possible the efficiencies obtained by the simulation are cross-checked with measurements and visual inspection of the raw data. Finally, small corrections to the resulting spectrum are applied which are due to the limited energy resolution of the detector (resulting in "spillover" from one energy bin to the next), and due to the transformation from the measured energy *E′* to energy E at the top of the atmosphere.

Table 2 shows the resulting energy intervals, acceptances, and differential intensities for e$^+$, e$^-$, and (e$^+$ + e$^-$). There are three possible sources of systematic uncertainty: uncertainty in the absolute energy scale by at most 5%, uncertainty in the atmospheric correction which is negligible(~0.5%) for electrons but about 10% for positrons, and uncertainty in ε of at most 10%. Thus, the total systematic error is well below 20%. The error in the lowest energy data point is possibly larger, due to the proximity of the geomagnetic cut-off energy.

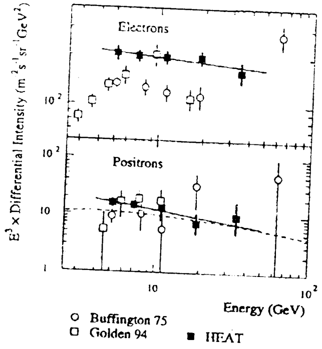
Table 2

$\bar{E}$ (GeV)	$\Delta\bar{E}$ (GeV)	$\epsilon\Omega A$ (cm^2 sr)	$j^-_{pri}(\bar{E})$	$j^+_{pri}(\bar{E})$	$j^\pm_{pri}(\bar{E})$
5.14	1.47	128 ± 13	1.54 ± 0.16	0.118 ± 0.020	1.66 ± 0.18
7.16	2.78	178 ± 15	0.548 ± 0.049	0.0407 ± 0.0065	0.589 ± 0.053
11.1	5.50	175 ± 15	0.145 ± 0.014	$(9.7^{+2.0}_{-1.9}) \times 10^{-3}$	0.155 ± 0.015
18.9	10.7	168 ± 15	0.0291 ± 0.0032	$(1.07^{+0.53}_{-0.38}) \times 10^{-3}$	0.0302 ± 0.0032
34.5	21.1	138 ± 12	$(3.89^{+0.63}_{-0.59}) \times 10^{-3}$	$(2.3^{+2.0}_{-1.2}) \times 10^{-4}$	$(4.12^{+0.65}_{-0.61}) \times 10^{-3}$
66.4	44.0	174 ± 15			$(3.63^{+1.19}_{-0.88}) \times 10^{-4}$

DISCUSSION

In Figure 1, we compare our results with previous measurements for which absolute intensities have been given for positrons and electrons separately, and in Figure 2, we compare the all-electron energy spectrum (e$^+$ +e$^-$) with previous results, also including measurements which did not employ a magnet spectrometer for charge separation (Meegan & Earl 1975, Silverberg 1976, Freier et al. 1977, Prince 1997, Nishimura et al. 1980, Tang 1984). We find that all results individually exhibit similar spectral slopes over the energy range of concern, but that our overall (e$^+$ + e$^-$) intensity is lower than that of some of the previous investigations by a factor of about 1.5. There are two likely contributors to this systematic discrepancy. First, the absolute energy calibration of individual experiments may be uncertain by up to 10%. Multiplication of the intensities with E^3 (as in Figure 2), accentuates this uncertainty to about 30%. Second, the assessment of the absolute detection efficiency of the instrument is notoriously difficult and does involve some intuitive judgment, although the more recent investigations, such as ours, benefit in this respect from more detailed Monte Carlo simulations than were previously available.

Fig. 1 Differential energy spectra of electrons and positrons



If we fit the spectra to single power laws, we find spectral indices α = 3.4 ± 0.2 and 3.10 ± 0.08 for positrons and electrons, respectively, over the energy range 4.5 to 50 GeV. Thus, the positron spectrum appears to be slightly steeper than that of electrons. If all positrons are of interstellar secondary origin, one expects that radiative energy losses lead to a power-law index at high energy that is larger by unity than that of the production spectrum, i.e., α ≈3.7 for production spectra of the form E$^{-2.7}$. The spectrum of electrons, on the other hand, should steepen less strongly, to an asymptotic slope with α ≈ 3.1 if electrons are mostly produced at the same primary sources as nuclei, and with the same source spectrum characterized by α ≈2.1. However, these asymptotic spectral slopes may not be fully reached below ~ 100 GeV. Thus, it would seem proper to fit our data not to a single power law but rather to a spectral form that reflects a transition from the source spectrum (modified by solar modulation) to a spectrum that is fully steepened due to radiative energy losses. We plan to perform such an analysis once we have improved the statistical quality of our results through the inclusion of data from the second balloon flight of this instrument. Qualitatively, we just conclude that the slightly steeper spectrum of positrons, as compared to that of electrons, is to be expected if positrons are predominantly secondary particles.

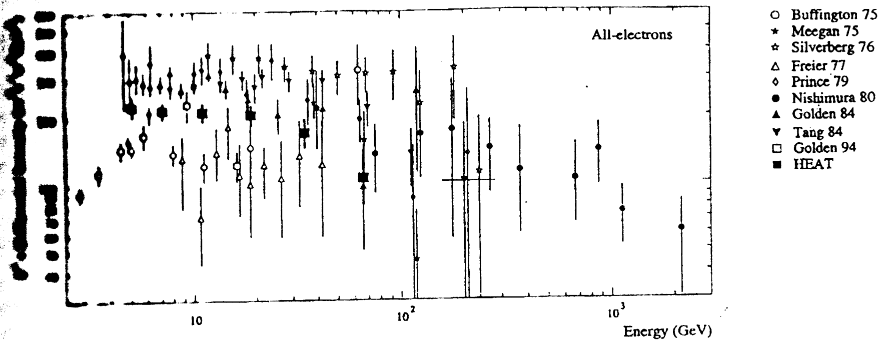


Fig 2 Differential energy spectrum of all-electrons (e$^+$ + e$^-$)

Finally, we observe that a comparison with the calculations of Protheroe (1982) also indicates that the absolute intensity ofpositrons is close to what may be expected if indeed all positrons are generated subsequent to nuclear interactions in the interstellar medium. The expected intensity of positrons according to Protheroe is shown as a dashed line in Figure 1.

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