Electron and positron energy spectra: HEAT magnet spectrometer results

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Abstract

Observations of the cosmic ray electron and positron spectra have been carried out with a balloon-based detector, the "High-Energy Antimatter Telescope" (HEAT), flown in May 1994 from Fort Sumner, NM and August 1995 from Lynn Lake, Manitoba. We present a summary of the instrument procedures and data analysis as well as electron and positron measurements. The electron and positron spectra results from the Lynn Lake flight are presented here for the first time and are combined with the previously-reported Fort Sumner data. These measurements have provided new determinations of the energy spectra of electrons from 1–100 GeV and positrons from 1–50 GeV. Within the experimental uncertainties, the intensity of positrons is consistent with a purely secondary origin, due to nuclear interactions in interstellar space.

1 Introduction

Electrons and positrons are a fairly rare component in the cosmic radiation. However, they form a distinct population due to the lack of hadronic interactions in the interstellar medium (ISM) during propagation, and due to their low mass. Measurements of electrons (e^+ and e^-) in the cosmic rays have been previously made from low energies up to nearly 1 TeV (Prince 1979, Nishimura et al. 1980, Golden et al. 1984, Tang 1984). These measurements have shown that the electron intensity is about 1% of the proton intensity at 10 GeV, and decreases more rapidly with energy. The proton differential energy spectrum declines with a power law of about $\mathrm{E}^{-2.7}$ whereas the electron spectrum falls with a power law of about $\mathrm{E}^{-3.1}$ or steeper. Charge-sensitive measurements separating electrons from positrons have shown a positron fraction $(\mathrm{e}^+/(\mathrm{e}^+ + \mathrm{e}^-))$ of a few percent from 1-10 GeV (Fanselow et al. 1969, Buffington et al. 1975, Barwick et al. 1995, Barbiellini et al. 1996, Barwick et al. 1997a). Some measurements found an increase in positron fraction above about 10 GeV (Agrinier et al. 1969, Müller & Tang 1987, Golden et al. 1987) which was unexpected in secondary production models, and which has been variously interpreted (e.g., Dogiel & Sharov 1990, Kamionkowski & Turner 1991, Aharonian & Atoyan 1991). More recent measurements have, however, not seen such an increase (Barwick et al. 1995, Barbiellini et al. 1996, Barwick et al. 1997a) and have been consistent with secondary production in a simple leaky box model.

Electrons in the cosmic rays are thought to consist of two populations: primary electrons most likely accelerated at the same source as the hadronic cosmic rays, and secondary electrons produced in nuclear interactions in the ISM. Positrons would arise only from the latter mechanism, and through the positron fraction reflect the energy-dependent relative fraction of secondary electrons. The secondary electrons and positrons arise from collisions between the hadronic cosmic rays and particles in the ISM (through the $\pi^\pm \rightarrow \mu^\pm \rightarrow \mathrm{e}^\pm$ decay chain). As this yields electrons and positrons in roughly equal quantities, only a few percent of the electrons can be of secondary origin.

The production spectrum of positrons can be calculated from the known intensity of primary nuclei. Positrons are produced continuously throughout the Galactic disk, and in lesser quantities in the Galactic halo, and propagate through the Galaxy. The primary electrons cannot be of extragalactic origin, as inverse Compton scattering off of the 2.7°K background radiation prevents electrons from traversing intergalactic distances.

The differences between the energy spectrum of electrons and that of hadrons are typically understood as a result of radiative energy losses during interstellar propagation. These mechanisms include inverse Compton scattering with microwave background and visible photons, and synchrotron emission from the interstellar magnetic fields. If the electrons are accelerated with the same source energy spectrum as the nuclei ($\sim E^{-2.15}$ experimentally, Müller et al. 1991, Swordy et al. 1993, or $\sim E^{-2}$ theoretically from shock acceleration) the observed spectral shape is consistent with the Galactic confinement time of nuclei of ∼10 Myr at GeV energies in the interstellar medium (Prince 1979, DuVernois 1997). The problems with this naive view are as follows: the energy spectrum of source electrons is unknown, and might be significantly different from that of nuclei; the energy dependence of the confinement time observed for nuclei ($\sim E^{-0.6}$) might be incompatible with the observed spectral shape of the electron flux (Tang 1984); finally, the leaky box model used for these explanations should probably not be applied to electrons as it implies an unphysically large density of electron sources in the Galactic disk (Cowsik & Lee 1979).

2 Instrument, balloon flights, and performance

The HEAT detector is described in full detail elsewhere (Barwick et al. 1997b). The HEAT instrument consists of a superconducting magnet and a drift-tube hodoscope combined with a transition-radiation detector (TRD), an electromagnetic calorimeter (EC), and time-of-flight (ToF) scintillators. The instrument has a geometric acceptance of 495±1 cm^2 sr. It was flown on balloons in 1994 and 1995. Although the basic set of detectors used in both flights remained the same, there are a few minor differences which affect overall performance. In the 1995 Lynn Lake flight, one of the six layers of the TRD was non-functional, as were a small number of drift tubes. The resulting slight losses of hadron rejection power were compensated by tightening the electron selection criteria (thereby reducing electron efficiency). Instrument performances for the two flights, after the selections have been applied, are comparable.

The first balloon flight was on 3–5 May 1994 from Fort Sumner, NM. Data were collected at float altitude for about 29 hours. The payload reached a maximum altitude of 36.5 km and descended to a minimum of 33 km at night. This corresponds to a mean atmospheric overburden of 5.7 g cm^{-2}. The payload floated between vertical geomagnetic cutoff rigidities of 4 GV and 4.5 GV and was recovered undamaged near Wellington, Texas.

The second flight was from Lynn Lake, Manitoba on 23–24 August 1995. Data were collected for nearly 26 hours at a mean atmospheric overburden of 4.8 g cm^{-2}. Geomagnetic cutoff was less than 1 GV. This lower geomagnetic cutoff allows cosmic-ray electron data down to $\sim$ 1 GeV to be obtained from the HEAT instrument. The instrument gondola and some internal elements suffered significant damage upon landing in Tadoule Lake, Manitoba (and subsequently being dragged by the wind through a boulder field).

Positron fraction measurements from both flights have been published (Barwick et al. 1995, Barwick et al. 1997a), as have absolute differential energy spectra from the Fort Sumner flight (Barwick et al. 1998). The Lynn Lake absolute spectra and the combined absolute intensity data appear here for the first time. Detector configurations were nearly identical for the flights, so the data sets have been combined to improve statistics.

3 Data analysis

Data taken from the two flights have been analyzed in two distinct manners. The first approach uses tight data selections as described in Barwick et al. 1998 to extract positron and electron spectra. The second selects particles primarily by their charge-sign. Due to the paucity of antiprotons, electrons (e^-) can be selected with high efficiency, but positrons are not distinguished from protons. In both analyses, a GEANT/FLUKA-based Monte Carlo simulation was employed to obtain efficiency-corrected geometrical factors and to model the atmospheric background from interacting protons which is then subtracted from the electron and positron

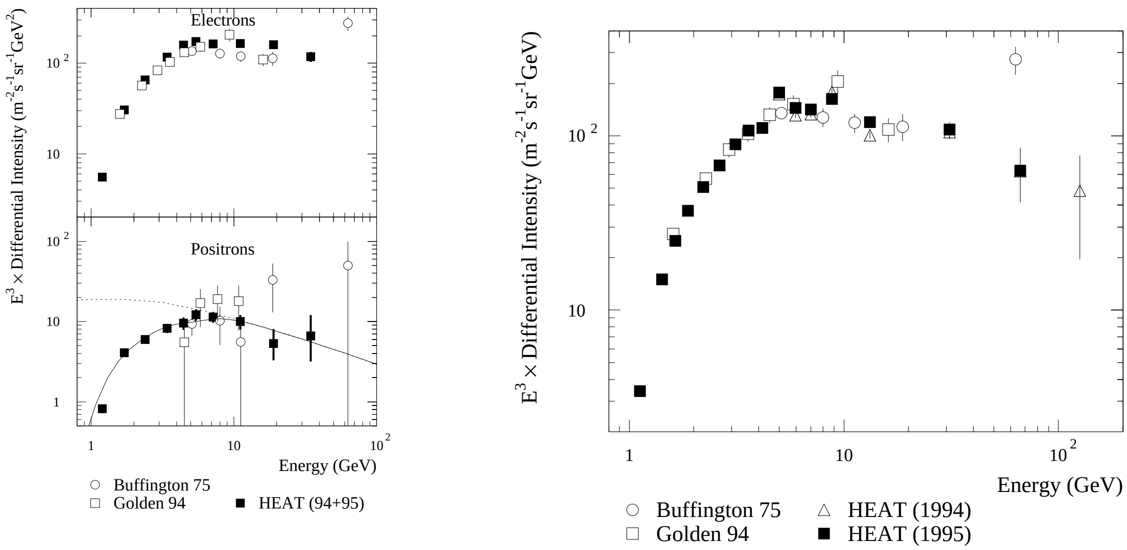

Figure 1: Left: Electron and positron spectra from template fits. Data are the combined set from the 1994 and 1995 flights. The dashed curve is a prediction of Moskalenko & Strong (1998) and the solid curve is a solar modulated version of the same. Right: The electron spectra from each of the two flights independently. These data were derived from a weaker set of selections than used for the positron template fits.

spectra. Energies are corrected to the top of the atmosphere and are spectrum weighted.

The tight/template fit analysis produced the spectra shown in Figure 1 (left panel). The data are plotted with a model calculation of Moskalenko & Strong (1998) for positron secondary production from proton spallation in the Galaxy. The dashed line is without solar modulation while the solid line includes modulation conditions for the two flights. The observed positron energy spectrum is consistent with positrons of secondary origin.

The right panel of Figure 1 shows the electron spectra for the second analysis. The increase in statistics is about 40% across the entire energy range 1–100 GeV over the template fitting. The electron spectra in this method agree, within errors, with the tight fit analysis.

Combining the electron and positron data into an all-electron (e^++e^-) spectrum allows for a comparison between the HEAT-$e^\pm$ experimental results and earlier experiments, not all of which had charge-sign sensitiv-

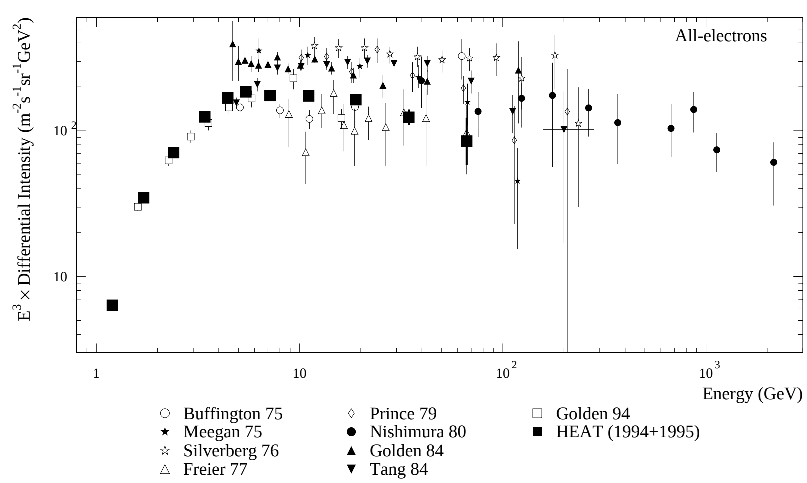

Figure 2: The all-electron (e^++e^-) spectra for the two HEAT flights combined and compared with published data.

ity. The HEAT data from each flight are also combined. Overall the HEAT intensities are lower than those of the older data, but consistent with other shown magnet spectrometer measurements (such as Golden et al. 1994). This comparison of all-electron data sets is shown in Figure 2.

4 Conclusions

These results reflect a pair of flights of the HEAT magnet spectrometer. The high level of hadronic background rejection achieved with this instrument has led to high quality data on the electron and positron spectra from 1–50 GeV. At low energies, these measurements are in substantial agreement with Golden et al. (1994), and at higher energies (near 10 GeV and above) seem to rule out the excess of positrons seen in the past. Overall, the data are consistent with a purely secondary population of positrons produced by proton spallation in the interstellar medium and a primary electron spectrum with power law $E^{-3.1}$ above ∼5–6 GeV. At lower energies, the spectrum is softer, and is not a power law, due, at least in part, to solar modulation.

Acknowledgements
We gratefully acknowledge assistance from D. Bonasera, E. Drag, W. Johnson, P. Koehn, D. Kouba, R. Northrop, and J. Robbins. We also thank the National Scientific Ballooning Facility (NSBF) crews that have supported the balloon flights. This work was supported by NASA grants NAG5-5059, NAG5-5069, NAG5-5070, NAGW-1035, NAGW-1995, NAGW-2000 and NAGW-4737, and by our individual institutions.

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