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COSMIC-RAY NEGATRON AND POSITRON SPECTRA BETWEEN 12 AND 220 MeV[*]

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The interplanetary negatron and positron spectra from 12 to 220 MeV have been determined with a balloon-borne magnetic spectrometer. The observed charge ratio $e^+/(e^+ + e^-) \approx 0.3$ indicates that the flux most likely consists of a mixture of "primary" negatrons and interstellar "secondary" negatrons and positrons. We deduce an absolute solar modulation of the interstellar positron flux which decreases with decreasing magnetic rigidity below about 80 MV.

Measurements of the shape and the charge composition of the interplanetary electron[1] spectrum are important to studies of physical phenomena in the interstellar and interplanetary media. At present, two source mechanisms are considered major potential contributors to the equilibrium cosmic-ray electron flux in the galaxy. "Primary" electrons are directly accelerated in "hot" loci in the galaxy, e.g., supernovae, and "secondary" electrons are produced in collisions of high-energy cosmic-ray nuclei with interstellar matter. Positrons in significant numbers are expected only from the collision source, and their spectrum can be calculated.[2,3] Comparison of the calculated spectra with our measured results, which include information on both the energy spectrum and charge composition of the electron flux between 12 and 220 MeV, allows us to determine the relative proportions of interstellar primary and secondary electrons and to impose restrictions on the propagation and solar modulation of the observed cosmic-ray electron fluxes.

Our measurements were performed near the top of the atmosphere with a balloon-borne magnetic spectrometer. The detector system[4] consists of an array of scintillation counters, a 1-kG permanent magnet, wire spark chambers with magnetostrictive readout, and a Čerenkov counter. The instrument has a geometry factor equal to 3.7 cm^2 sr between 25 and 200 MeV/c, decreasing at lower momenta to 1.5 cm^2 sr at 6 MeV/c. The momentum resolution for electrons below 100 MeV/c is limited primarily by scattering and equals about 25% full width at half-maximum, independent of momentum. Above 100 MeV/c, the momentum resolution is a function of the intrinsic angular resolution and is linear with momentum, rising to 50% full width at half-maximum at 200 MeV/c.

The data presented in this paper are derived from three high-altitude ballon flights launched from Fort Churchill, Canada, on 15 July, 20 July, and 28 July 1968. Average float altitudes were 2.45, 2.40, and 2.35 g/cm^2 of residual atmosphere, respectively, with variations of ±0.15 g/cm^2. The data discussed below were measured during the nighttime period when the local geomagnetic cutoff was below our analysis threshold. Since no statistically significant temporal variations in the measured electron flux were observed among the three flights, the data have been combined for increased statistical accuracy.

A large fraction of the low-energy electrons observed at an atmospheric depth of 2.4 g/cm^2 originate in collisions of cosmic-ray nuclei with atmospheric nuclei above. The separation of cosmic-ray electrons from atmospheric secondaries is nontrivial. Our technique is to express the atmospheric depth dependence of the measured positron or negatron flux $J_i^{\pm}(d)$, for an energy interval i, as

$$J_i^{\pm}(d)=a_i^{\pm}s_i^{\pm}(d)+b_i^{\pm}p_i^{\pm}(d),$$

where d is atmospheric depth, $s^{\pm}(d)$ is the depth dependence of the flux of (atmospheric) secondary positrons or negatrons, $p^{\pm}(d)$ is the depth dependence of the flux of primary positrons or negatrons, and $a^{\pm}$ and $b^{\pm}$ are parameters which represent the relative contribution of the secondary and primary components. The parameters $a^{\pm}$ and $b^{\pm}$ were determined by a least-squares fit to seven data points from 2.4 to 42 g/cm^2 atmospheric depth. The depth dependence $s^{\pm}(d)$ of atmospheric secondary electrons used in our analysis is based upon calculations by one of us.[5] Since $p^{\pm}(d)$ depends upon the unknown primary-electron spectrum at the top of the atmosphere, an iterative process was used. However, the derived spectrum, $b^{\pm}p^{\pm}(0)$, is not strongly dependent on the choice of any reasonable form of $p^{\pm}(0)$, and the process converges quickly.[6] The derived local energy fluxes have been corrected for energy loss in the residual atmosphere above the detector and are given with statistical and estimated systematic errors.

In Fig. 1 our measured differential cosmic-ray electron fluxes (positrons plus negatrons) in 1968 are shown together with recent results[7-11] of other investigators. A striking feature of our 1968 electron spectrum is the low flux of electrons observed in the 60- to 110-MeV region. We believe that this particular feature is genuine, since our analysis clearly excludes any fitting attempts without this minimum in both the positron and negatron spectra. An upper limit only can be given for the flux in this energy interval.

In Fig. 2 we show our measured differential rigidity spectra of positrons and negatrons separately. The prevailing charge ratio between 20 and 220 MV, $e^+/(e^+ + e^-) \approx 0.3$, is inconsistent with the corresponding charge ratio calculated[2,3] for a spectrum of pure collision-produced interstellar secondary electrons, $e^+/(e^+ + e^-) \approx 0.75$-$0.90$.[12] The observed flux therefore most likely represents a mixture of primary negatrons and interstellar secondary negatrons and positrons.

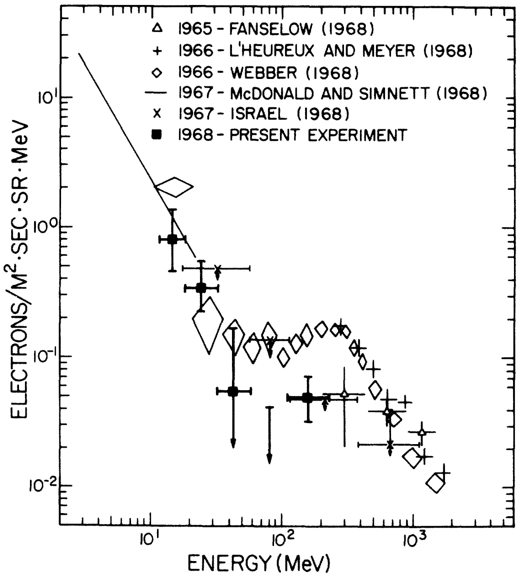

FIG. 1. Differential kinetic-energy spectra of interplanetary cosmic-ray electrons. The year of the measurement is given with the names of the observers.

The absolute solar modulation of positrons in 1968 for our energy interval can be determined (within the uncertainties of the data) by comparing the positron spectrum measured at the Earth with the calculated interstellar positron spectrum of pure collision origin under the assumptions that (1) no other significant sources of positrons at these energies exist, and (2) the calculated positron equilibrium spectrum is sufficiently accurate. Such a comparison with the interstellar positron flux calculated by Ramaty and Lingenfelter[2] (RL) (shown in Fig. 2) indicates that the positron flux between 60 and 110 MeV is modulated most strongly, and that the modulation then decreases rapidly with decreasing energy. The modulation function $F(R)$, which is the ratio of the observed flux and the calculated interstellar flux, is shown in Fig. 2.

This empirically determined modulation func-

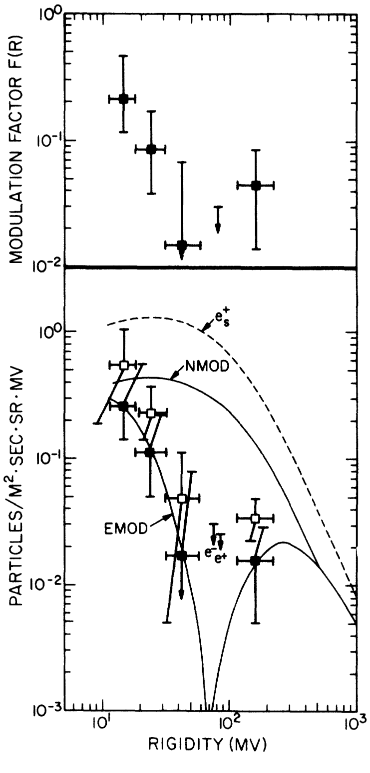

FIG. 2. Differential rigidity spectra of cosmic-ray positrons (closed squares) and negatrons (open squares). Dashed curve $(e_s{}^+)$, interstellar positron spectrum from collision source (Ref. 2). Solid curves, *NMOD* and *EMOD*: result of multiplying $e_s{}^+$ with modulation function $F(R)$ given by Eq. (1) and Eq. (2), respectively, with parameters as given in text.

tion can be compared with theoretical considerations which are based on Parker's diffusion-convection model.[13,14] The predicted modulation function has the form $F(R)=\exp[-\eta/\beta f(R)]$, where βc is the particle velocity, R the magnetic rigidity, and η is a time-dependent parameter that is independent of β and R. There is theoretical and experimental evidence that if the power spectrum of magnetic irregularities in the solar wind has a dependence on frequency ν of the form $\nu^{-\alpha}$, then $f(R)$ is $R^{2-\alpha}$. For cosmic-ray nuclei it is found [14,15] that

$$f(R)=R^{\delta} \text{ for } R>R_0,$$
$$f(R)=R_0 \text{ for } R<R_0, \tag{1}$$

where $\delta\approx 0.5$-1 and $R_0\approx 0.5$-1 GV.

In Fig. 2, the curve *NMOD* was derived by the application of the modulation function $F(R)$ with $\delta=1$, $R_0=0.5$ BV, and $\eta=0.5$ BV, to the interstellar positron spectrum of *RL*. It is clear that neither this choice of parameters nor any other within the range given by nuclei data gives a satisfactory fit to our data. A much better fit to the data is given by the curve *EMOD*, for which $\eta=0.5$ BV and

$$f(R)=R \text{ for } R>R_0=70 \text{ MV},$$
$$f(R)=R_0^2/R \text{ for } R<R_0=70 \text{ MV}. \tag{2}$$

This modulation form, if related to the magnetic power spectrum in the solar wind, would require a ν^{-3} dependence at the relevant frequencies above 10^{-3} Hz. No interplanetary magnetometer data for the time period of our measurements are presently available to check this possibility.

It is possible that other features of the interplanetary magnetic field could cause the observed modulation effects. The propagation of low-rigidity galactic particles in the solar wind may be related to the "wet-spaghetti" model of intertwined flux tubes[16,17] and recent observations of the filamentary structure of the field.[18] If flux tubes containing a relatively ordered field are indeed a common feature of the interplanetary field and connect to the interstellar fields, particles of low rigidity may penetrate relatively unobstructed into the interplanetary medium. An alternate possibility is the presence of plasma instabilities or irregularities beyond several astronomical units which interact strongly with ~100-MeV positrons.

Additional information can be gained from our data without specifying the nature of the solar modulation process beyond assuming equal modulation for both negatrons and positrons of equal energy.[19] Figure 3 shows the result of using our empirically derived positron modulation function to demodulate the electron spectrum observed at the Earth. The decreasing amount of modulation below about 80 MeV is consistent with the absence of significant long-term variations in the interplanetary electron spectrum below 12 MeV, which has been observed[20] over several years. Similarly, the small modulation makes these electron fluxes consistent with an interstellar knock-on origin.[21,22]

Qualitative information on the spectrum of electrons from primary sources in the galaxy can be obtained by subtracting the calculated interstellar electron spectrum from the demodulated total electron spectrum (see Fig. 3). A comparison of the primary-electron spectrum with an $E^{-2.5}$ power-law extrapolation from higher energies shows that at 50 MeV the interstel-

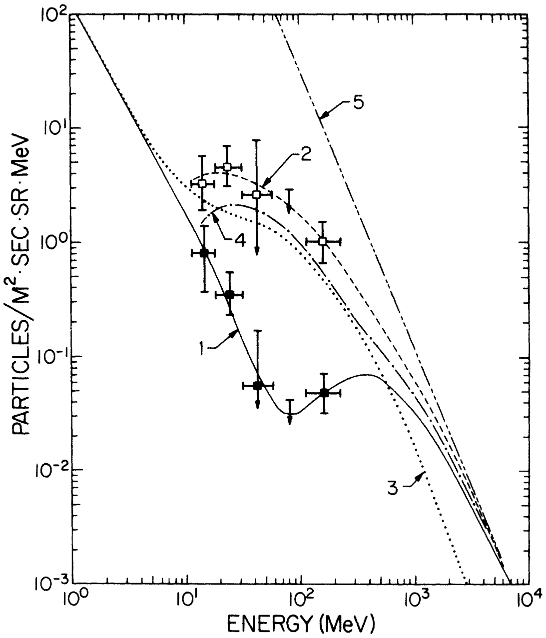

FIG. 3. Differential kinetic-energy spectra of interplanetary and interstellar electrons. Curve 1: composite interplanetary electron spectrum observed near Earth. Closed squares: our measurement. Curve 2: demodulated, galactic electron spectrum, extrapolated smoothly to higher energies, assuming no modulation above 5 GeV. Open squares: our demodulated data points. Curve 3: interstellar secondary-electron spectrum for 4-g/cm^2 matter (Ref. 2) with added contribution of knock-on electrons [T. L. Cline and F. B. McDonald, Can. J. Phys. 46, 761 (1968)]. Curve 4: primary electrons, obtained by subtraction of curve 3 from curve 2. Curve 5: $E^{-2.5}$ power-law extrapolation from higher energies.

lar primary flux is a factor of ~100 smaller. If the deduced primary spectrum is in fact the source spectrum, then the acceleration mechanism for these particles is different from the solar acceleration process, which produces steep power-law spectra at these energies.[23]

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RADIO EMISSION FROM MAGNETIC NEUTRON STARS. A POSSIBLE MODEL FOR PULSARS

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We show that radio emission from a neutron star with a magnetic field of 10^9 G or more can account for the radio emission of pulsars. It is suggested that pulsars also emit two bands, one in the uv or optical, and the other in the infrared in the decamicron wavelength range.

Two types of objects have been considered in theories of pulsars, namely, white dwarfs and neutron stars. However, several arguments now seem to exclude the former hypothesis in favor of the nuetron stars: (1) the lack of optical radiation corresponding to white dwarfs[1]; (2) the existence of pulsar NP 0532 in the Crab Nebula supernova remnant[2] and the likely association of another pulsar with the Vela X remnant[3]; (3) the discovery of class-II pulsation with periods ~10 msec in two pulsars[4]; (4) the systematic increase in the NP 0532 periods[5] which has been interpreted in terms of loss of rotational energy of a neutron star[6,7]; (5) the existence of submillisecond variations in pulse intensity, which implies dimensions of $\lesssim 30$ km[8]; (6) the fact that no white dwarf can rotate or vibrate with the 0.03-sec period of NP 0532[9]; and (7) the detection of optical pulses from pulsars with a pulse shape essentially that of the radio.[10]

Properties of neutron stars without magnetic fields have been extensively investigated.[11,12]