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Energy Spectra and Charge States of H, He, and Heavy Ions Observed in the Earth's Magnetosheath and Magnetotail

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H, He, and heavy ions of energies $\geqslant 0.12$ MeV/charge were detected in the magnetotail and in the magnetosheath. It was found that their relative abundances were $\sim 9:1:4\times10^{-2}$, their differential energy spectra were $\sim 1/E^4$, and their atomic electrons were almost completely stripped. These results led us to suggest that they were the low-energy "quiet-time" cosmic rays accelerated within the magnetotail and the magnetosheath to the observed energies.

Pulses of energetic electrons are frequently observed in the magnetotail.[1-6] The observation of energetic protons (10–30 keV) in the tail region was reported only recently by Hones *et al.*[7] In this paper, we report the observation of pulses of ions in the magnetosheath and in the tail with an electrostatic deflection spectrometer on the IMP-7 satellite. We have for the first time identified three species of ions, H, He, and heavier, measured the energy spectra, and inferred the charge states of the ions. From the consideration of the degree of ionization of these particles and the total energy content involved, we suggest that they are low-energy "quiet-time" cosmic rays accelerated locally to the observed energies. The possibility of accelerating electrons and protons in these regions has been suggested previously.[2-7]

The IMP-7 satellite was launched into space on 22 September 1972. The orbit has an apogee of 38 and a perigee 34 earth radii with an inclination of about 15° with respect to the geomagnetic equator. Among all the particle detectors on board the satellite, the electrostatic deflection spectrometer of the University of Maryland is designed for the measurement of low-energy particles. In this instrument, a particle is first selected according to its energy per charge by means of an electrostatic field, and then its energy T and charge Q are determined separately by an additional measurement of the energy deposit of the ion in an Au-Si solid state detector. The details of the system have been published elsewhere.[8] The characteristic of the system (abbreviated as

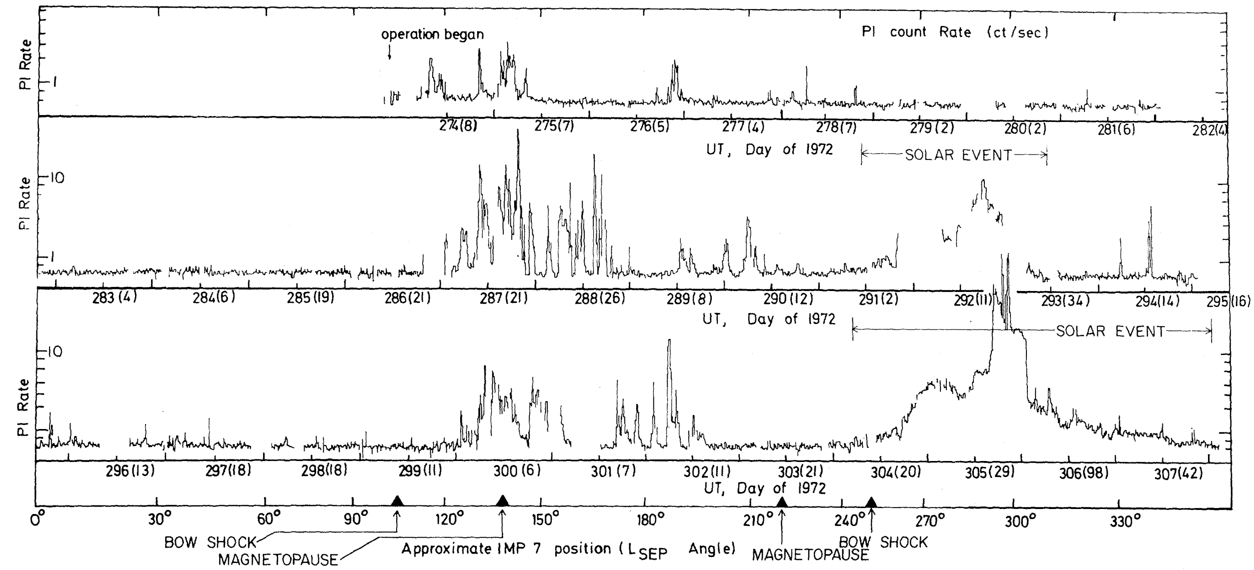

FIG. 1. *PI* count rate (120–160 keV/charge).

EDS) relevant to the measurement reported in this paper is that it measures the charge states of the particles. This is extremely valuable in studying low-energy particles, since their atomic electrons may not be completely stripped.

The *PI* detector of EDS responds to particles in the energy range from 0.12 to 0.16 MeV/charge, the lowest energy channel of the system. These counts, when plotted against time, yield the intensity profiles of solar and magnetospheric particle events. In Fig. 1, we display 34-day *PI* rates arranged according to the positions of the satellite in sun-earth-probe angles ($L_{\rm sep}$); the daily average *Ap* indices of these days are indicated in brackets next to the respective dates. It is seen from this figure that, aside from two solar events, the detector detected particle pulses in the magnetotail and in the sheath (whose approximate $L_{\rm sep}$ angles are indicated in the figure), the flux intensity rising from and then falling back to its background level in 2–4 h. The structure has a close resemblance with electron islands reported by Anderson, Harris, and Paoli.[2] The frequency of the pulses increases with the geomagnetic activity as seen from the average *Ap* indices.

In order to identify the species of the magnetospheric particles, we plotted the number of events in each of the three energy ranges 0.12–0.16, 0.17–0.28, and 0.38–0.65 MeV/charge, as a function of their energies. After the subtraction of background, which was measured on board by turning off the high voltage of the deflection plates of the instrument, the distribution exhibits three distinct peaks corresponding to particles of charge 1, 2, and a group of heavier ions. Figure 2 shows the distribution in a histogram of the particles in the 0.12–0.16-MeV/charge group recorded on day 287. Combining these with similar results in the energy ranges 0.17–0.28 and 0.38–0.65 MeV/charge, we constructed a three-point spectrum for each species and display them in Fig. 3. The smaller circular dots in the figure were obtained by dividing the particles of a *given species* into finer energy intervals. When expressed in inverse powers, the spectra are $1.0/E^{3.9}$ for H^+, $0.25/E^{3.7}$ for He^{++}, and $0.028/E^{3.7}$ for $Q \geqslant 5$, in units of particles per [cm^2 sec sr (MeV/charge)]. From these spectra and the instrument response, we can fit the distribution by the following relative abundances in the 0.12–0.16-MeV-charge range: H^{+1}:He^{+2}:$C^{+5,+6}$:$O^{+7,+8}$ $= 1.0:1.1\times10^{-1}:3.2\times10^{-3}:1.3\times10^{-3}$. The charge resolution of the instrument is not sufficient to allow us to attach any significance to the abundance of C^{+5} relative to C^{+6} and that of O^{+7} relative to O^{+8}.

The charge states, the fluxes, and the relative abundances are crucial information for understanding the origin of these particles. The fact that they are almost bare nuclei indicates that they are not produced from the earth's plasmasphere and then accelerated to the observed energies; rather, they must have their atomic electrons stripped before the acceleration. Other-

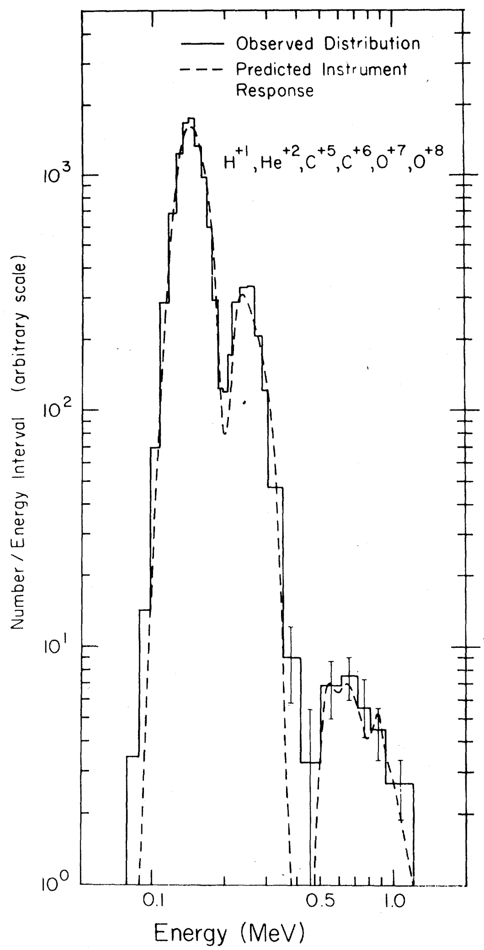

FIG. 2. The distribution of the number of events.

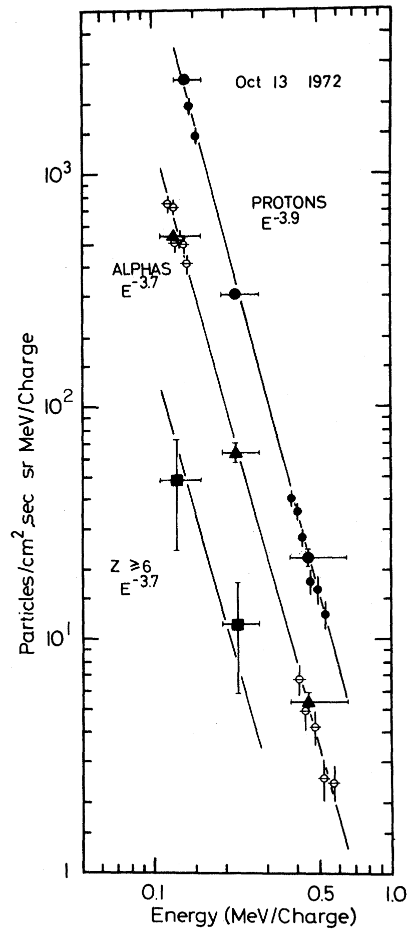

FIG. 3. The differential energy spectra.

wise, the charge states of the oxygen ions of 0.15 MeV/nucleon, for example, would be in the range of 1 to 5 with an average value of 3,[9] but the groups of charges from 3 to 4 were not detected. As to the possibliity that they are particles escaping from the radiation belts, the reported fluxes of *low-energy CNO nuclei*,[10,11] assuming that they were bare nuclei, *could not maintain* a leakage rate with a flux value such as we have observed. Therefore, we must turn to other possibilities.

The first possible source is the solar wind. According to Bame *et al.*[12] and Holzer and Axford,[13] in the solar wind the species fractions of the CNO group for +4, +5, +6, +7, and +8 are 1, 17, 78, 4, and 0%, respectively. However, the acceleration of solar wind particles to the observed energies involves an extremely efficient process. Furthermore the ratio of H/He/CNO in the solar wind is $32:1:7.8\times10^{-2}$ which is different from the value $9.1:1:4.1\times10^{-2}$ that we have observed. Thus we discard this possibility.

Recent experiments showed that there exists a steady component of low-energy cosmic rays in the interplanetary space (maybe of solar origin).[14,15] We suggest that the particles which we observed are the cosmic-ray particles of energies originally below the threshold of our detector, which diffused into the magnetosheath and the tail region, and then were accelerated by hydromagnetic waves to the observed energies.

To see this possibility, we consider the energy spectrum of C and O nuclei of Hovestadt *et al.*[15] The flux of C and O at about 0.3 MeV/n is 10^{-3} $[\mathrm{cm}^2 \text{ sec sr (MeV/nucleon)}]^{-1}$ and the spectrum is still rising towards lower energies with a slope -5. On extrapolation to 0.03 MeV/nucleon, the flux becomes equal to that of the magnetotail CNO at about 0.08 MeV/nucleon (0.16 MeV/charge). Therefore, an energy gain of a factor of 3 would be sufficient to raise the energy of these particles above the threshold of the instrument and thus account for the counting rate increases.

The crucial experimental information needed to support the model proposed in this paper is the existence of a large "quiet-time" cosmic-ray flux of energies greater than about 100 keV/Q. If this turns out to be the case, then we can explore further the acceleration mechanism by measuring the difference in the energy spectra inside and outside of the magnetosheath and the magnetotail. Thus, the region can be regarded as a laboratory for studying the process of particle acceleration in nature, which has been thus far very elusive from detection.

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