Observation of anomalously high flux densities of low-energy heavy nuclei on the Salyut-6, Salyut-7, and Mir orbital stations

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Significant flux densities of Ca–Fe nuclei with energies below 50–100 MeV/nucleon have been detected by a track detector at an altitude ~300–350 km. The flux densities increase with decreasing energy. The uniquely high flux densities of nuclei in the energy range 140–5 MeV/nucleon in 1988–1990—greater than those in previous exposures by one to four orders of magnitude—are correlated with intense solar proton flares in August–October 1989.

In an effort to carry out a systematic study of the heavy cosmic-ray nuclei which have received the least study, with charges $z \geqslant 20$ and energies <200 MeV/nucleon, a track detector has been used for three prolonged exposures on orbital stations. The track detector was made of Lavsan (a polyester) and polyethylene terephthalate. The orbit was inclined at ~51.6° with respect to the equatorial plane; the altitude was ~300–350 km. Exposure 1 was from 29 July 1978 to 15 August 1979; exposure 2 was from 8 August 1984 to 4 August 1985, and exposure 3 was from 26 February 1988 to 11 January 1990. Chambers holding a set of Lavsan layers, ranging in thickness from 20 to 180 μm, with a total thickness of 7–9 mm and an area ~300 cm^2 (in exposures 1 and 2) or ~600 cm^2 (in exposure 3), were mounted on the outer surface of the station. They were retrieved in the course of a space walk. They were then returned to earth. The heat shields on the chambers, which maintained the temperature in the detectors at $\leqslant$40–50° C, had thicknesses ~27, ~6, and ~8.5 mg/cm^2 in exposures 1, 2, and 3, respectively. The procedures for processing the detectors and for identifiying the charge of the nuclei have been described elsewhere.[1]

Figure 1 shows preliminary estimates of the integral flux densities of nuclei with $z \geqslant 20$ in the three exposures. Figure 2 shows detailed data on the flux densities of nuclei in the groups Sc–Cr and Fe in the energy range ~70–200 MeV/nucleon in exposure 1. The nuclear flux densities in Fig. 2(a), converted to interplanetary space, were obtained through the use of a geomagnetic transmission function under the condition that the ratio of the charge to the mass number of the nucleus was $z/A \simeq 0.5$, under the assumption that the detector was screened by the earth for 50% of the time, and under the assumption that the flux density was constant in time. The spectra obtained in exposures 1 and 2 can be associated with galactic cosmic rays, for the following reasons. (a) The flux density of iron, converted to interplanetary space, at an energy ~200 MeV/nucleon agrees with the flux density of these particles in 1978–1979 (see the curve in Fig. 2a). (b) The observed relative composition of nuclei with z

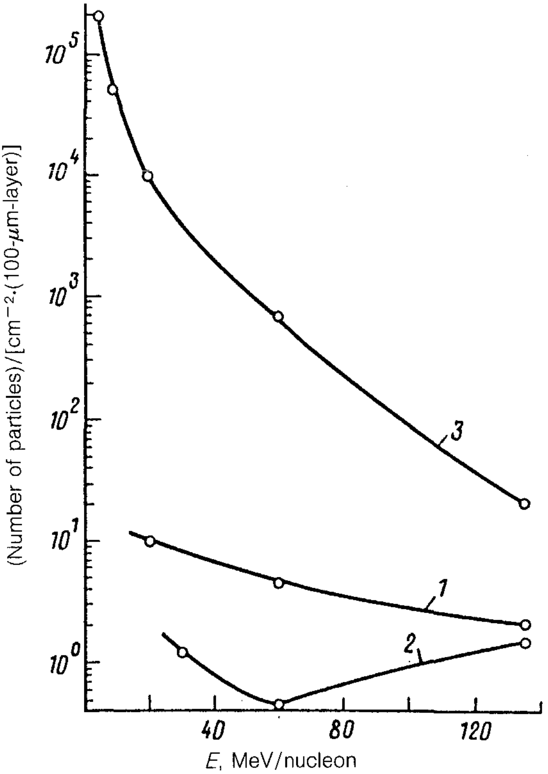

FIG. 1. Energy dependence of the integral flux densities of nuclei with $z \geqslant 20$ in various exposures. 1—Salyut-6, 29 July 1978 to 15 August 1979, 23 September 1978; 2—Salyut-7, 8 August 1994 to 4 August 1985, 24 April 1985; 3—Mir, 26 February 1988 to 11 January 1990, 19–26 October 1989. The underscored dates are the dates of solar proton flares which furnished most (up to 80–95%) of the integral flux densities of protons with energies >25–30 MeV over the entire duration of the corresponding exposure.

between 16 and 28 at energies ~100–200 MeV/nucleon in exposure 1 is identical to the composition of galactic cosmic rays. (c) The flux density of nuclei in exposure 2 (Fig. 1) at a maximum energy ~100–140 MeV/nucleon is smaller than that in exposure 1 by a factor ~1.7. This difference corresponds to the modulation of the low-energy galactic cosmic rays by the solar activity during this period.

Let us attempt to single out an additional component or sum of components of the heavy nuclei in the three exposures above the background of galactic cosmic rays. At energies below ~50 MeV/nucleon, which corresponds to the geomagnetic cutoff threshold for an orbit inclined at ~52° with respect to the equatorial plane, no nuclei of galactic cosmic rays should be detected inside the magnetosphere. In these experiments, in constrast, particles with energies below the threshold were observed in all exposures. Furthermore, the flux densities increase (Fig. 1) with decreasing energy, instead of decreasing, as they do in the case of galactic cosmic rays. In exposure 2, the flux density doubled in the interval between ~60 and ~30 MeV/nucleon (this increase was statistically significant: $\sim 7\sigma$). In exposure 2, it increased by a factor of 5

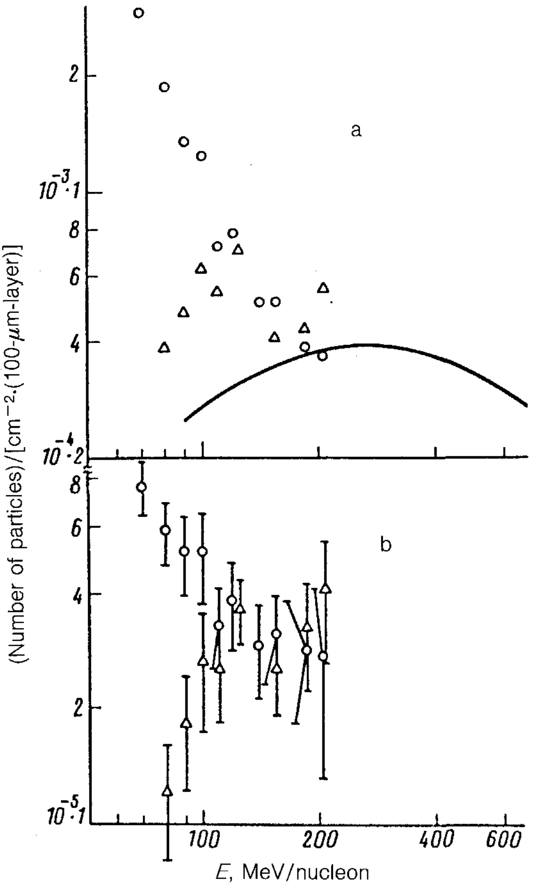

FIG. 2. Energy spectra of nuclei in exposure 1, Δ—The Sc-Cr group; O—Fe. a) Converted to interplanetary space under the condition $z/A = 0.5$; b) in the orbit of the Salyut-6 station. The curve is the spectrum of iron nuclei of galactic cosmic rays in 1978–1979.

between ~140 and ~20 MeV/nucleon. In exposure 3 it increased by a factor of 2×10^3 between ~140 and ~10 MeV/nucleon. It follows from Fig. 2 that in exposure 1 this increase was due primarily to an increase in the flux density of iron nuclei in the interval 120–70 MeV/nucleon. As a result, there was also a sharp decrease (by a factor ~5), from ~1 to ~0.2, in the ratio (Sc–Cr)/Fe in the energy interval 120–80 MeV/nucleon.

The observation of particles with energies below the geomagnetic cutoff threshold might be due to an incomplete ionization of these particles. If so, the particles would have a high rigidity and would be able to penetrate to the orbit at latitudes $<52°$. An incomplete stripping of electrons is characteristic of low-energy heavy ions from solar flares or of the incompletely ionized component of the galactic cosmic rays. Indications that some of the heavy nuclei in the range Ca–Fe in these low-energy particles have an effective charge $q = (0.3\text{–}0.8)z$ or $q = (0.1\text{–}0.2)z$ were found in Refs. 2 and 3. In Ref. 1 we suggested the existence of an additional anomalous component of extra-heliospheric origin for the Sc–Cr and Fe group for energies in the range 80–200 MeV/nucleon. Assuming the previous difference $q_{(\mathrm{Sc–Cr})} < q_{\mathrm{Fe}}$, we can explain the difference between the measured values of the ratio (Sc–Cr)/Fe in the energy range ~30–280

MeV/nucleon (~ 1 inside the magnetosphere[2] and ~ 0.4–0.5 outside it[4]): a pronounced deformation of the iron energy spectrum inside the magnetosphere. On the other hand, there are strong arguments for linking at least some of the detected heavy particles with energies < 100 MeV/nucleon in these three exposures with solar nuclear flares.

Let us explain. We assume that in intense solar proton flares the nuclear component is proportional to the proton component. Exposure 2 is interesting in that the energy spectrum of the galactic cosmic rays was greatly deformed by the solar activity at the preceding maximum. During the exposure, however, there was only a single intense solar proton flare, on 24 April 1985, with a proton flux density $I_p \simeq 150$ $\text{cm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1}$ for protons with energies > 15 MeV/nucleon (Ref. 5). The spectrum of nuclei with energies $\leqslant 60$ MeV/nucleon apparently corresponds to this flare. In exposure 1 there were two intense proton flares,[6] on 23 September 1978 and 16 February 1979. The second had the same number of protons as the flare on 24 April 1985, while the first was considerably more intense, with $I_p \simeq 750$ $\text{cm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1}$. Therefore, the flux density of heavy particles with energies $\leqslant 100$ MeV/nucleon in exposure (1) was probably due to the solar proton flare on 23 September 1978. The uniquely high particle flux densities in exposure 3 should be attributed to several solar proton flares in August–October 1989, the most intense of which was on 19–26 October 1989. According to Ref. 7, over the 12.5 months of exposure 1, the integral flux density of protons with energies > 10 MeV in all solar proton flares with $I_p > 1$ $\text{cm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1}$ was $\sim 1.5 \times 10^9$ cm^{-2}. This figure is comparable to the flux density $\sim 1.2 \times 10^9$ cm^{-2} over the first 18 months of exposure 3. On the other hand, the flux density of protons from the proton flares in August–October 1989 was higher by nearly two orders of magnitude: $\sim 9.6 \times 10^{10}$ cm^{-2}. This ratio corrsponds roughly to the ratio of the flux densities of particles detected in exposures 3 and 1 (Fig. 1). A relationship between the high flux densities of heavy particles and solar proton flares is also implied by the approximate agreement between (a) the index of the nuclear energy spectrum, $\gamma \simeq 2.4$, in exposure 3 inside the magnotosphere and (b) the value $\gamma \simeq 2.7$–3.1 in the solar proton flares in August–October 1989 outside the magnetosphere in the same energy range, ~ 20–60 MeV/nucleon.

Conclusion. Incompletely ionized particles correlated with intense solar proton flares constitute one of the primary sources of the heavy particles detected in an orbit with an inclination $\sim 52°$ and an altitude ~ 300–350 km with energies below 50–100 MeV/nucleon. Exposure 3 actually found the energy spectrum of nuclei for the solar proton flare of 19–26 October 1989, which was the most intense flare over the entire history of observations, dating back to the 1950s.

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