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Energetic Electrons in the Tail and Transition Region of the Magnetosphere

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Abstract—A comparative analysis has been carried out of the parameters of energetic electrons in the tail of the Earth's magnetosphere that belong to three sources, i.e., electrons solar origin, electrons generated in the magnetosphere of Jupiter, and electrons in the Earth's magnetosphere. The differences in the time profile of fluxes and energy spectra of the three electron sources, their relation to fluxes outside the magnetosphere, and periods of the occurrence of electron fluxes of each type are considered.

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1. INTRODUCTION

In the tail and transition layer of the Earth's magnetosphere, electrons are registered from three sources, i.e., the Sun, Jupiter, and the Earth's magnetosphere. Additionally, a slightly changing background of galactic cosmic ray (GCR) electrons and the background count caused in devices by GCR particles are present in all data.

In the majority of cases, electrons of solar cosmic rays (SCRs) are easily determined by their intensity, energy spectra, time behavior, and relation to solar flares and SCR protons. The electrons from minor solar flares and electrons accelerated in the solar wind are also referred as *events of solar origin* [1].

Jovian electrons with energies of a few megaelectron-volts have small fluxes in space regions at 1 a.u., usually < 0.1 (cm^2 s sr MeV)$^{-1}$, and are difficult to observe. As a rule, they are registered during years of low solar activity (SA) when the interplanetary space is not filled with electrons from other sources, solar electrons or accelerated electrons in a disturbed magnetic field.

The electrons with energies ranging from fractions to dozens of megaelectron-volts in quiet periods of SA began to be registered in the beginning of the 1970s (see, e.g., [2]), but it only became clear after the first measurements in the vicinity of Jupiter [3] that a substantial part of these increases corresponds to Jovian electrons. Reports on the identification were published in the proceedings of the Conference on Cosmic Rays in 1975 [4], then in publications [5–7]. The main characteristics of Jovian electrons were described based on the measurements on board the *IMP-7* and *IMP-8* satellites [8–12]. According to the data of *Pioneer 10* and *Pioneer 11,* the similarity of the enhancements in the electron fluxes in the vicinity of Jupiter to increases in quiet periods in the Earth's environment is discussed in [3]. It was found that the enhancements near the Earth have a 13-month periodicity, which supports their Jovian origin (the synodical period of the Earth–Jupiter system is equal to 399 days ≈ 13 months).

Besides the solar and Jovian electrons, electrons of the magnetospheric origin are present within the magnetospheric tail. Most often, these electrons are formed in the process of substorm activity when the fluxes of auroral electrons with energies of a few kileoelectron-volts to a few megaelectron-volts are generated. The time and energy characteristics of auroral electrons have been studied first based on balloon measurements of bremsstrahlung x-ray radiation [13] and then in a large number of publications based on direct satellite measurements. Energetic electrons within a magnetospheric tail are detected during the first years of the direct measurements [14–16].

During the long period when the reconnection in the magnetospheric tail was the main paradigm of a substorm, the registration of energetic electrons in the tail was considered to be a natural result of the beginning of the active phase of a substorm. In the scope of the current substorm model, the auroral electrons are accelerated at closed shells of the quasi-capture region or, in other words, in the auroral magnetosphere. Sometimes, as a result of incomplete magnetic drift, some of the electrons are scattered during magnetopause and brought into the interplanetary environment, while the other part would be transported into the magnetospheric tail and one can expect that that flux would be the maximum on the dawn side within the transition layer.

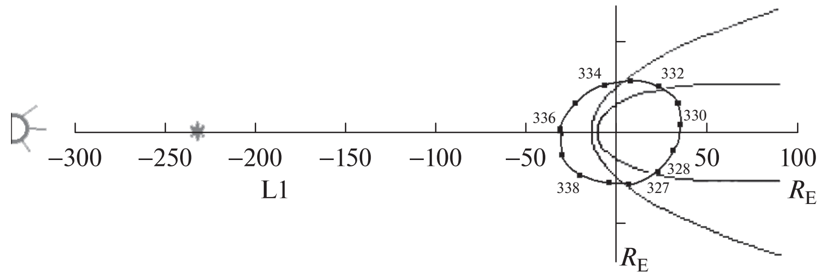

Fig. 1. Example of the *IMP-8* orbit in 1996 (days of 1996 are marked at the orbit) and the libration point L1: location of the *ACE* and *SOHO* spacecrafts.

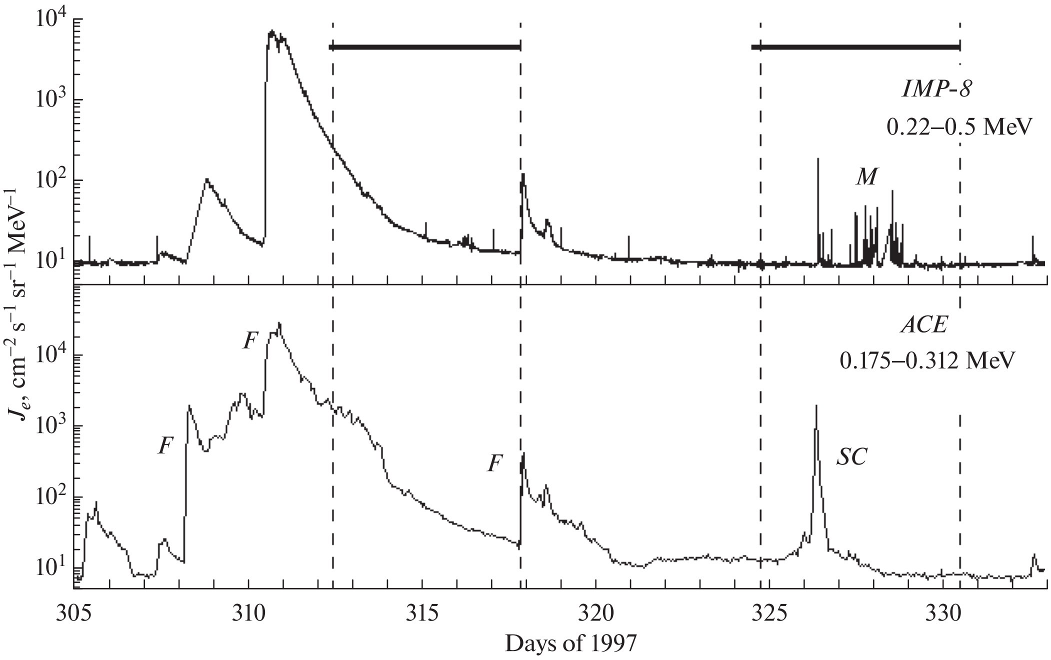

Fig. 2. Measurements of electrons on board the *IMP-8* and *ACE* satellites in November 1997. Solid lines in the top panel show the periods of location of the *IMP-8* satellite within the magnetospheric tail. *M* marks enhancements of electrons generated within the magnetospheric tail.

2. EXPERIMENTAL DATA

The experiments conducted onboard *IMP-8* Earth's satellite with an orbit close to a circular and a the perigee and apogee equal approximately to 30 and 40 R_E (where R_E is the Earth's radius), respectively, and on board the *ACE* and *SOHO* spacecrafts in the solar wind near the libration point L1[1] are considered. A visual representation of the spacecraft's location in the space is given by Fig. 1.

2.1. Magnetospheric Electrons

Figures 2–4 show particular time periods of measurements of electrons with an energy up to fractions of a megaelectron-volt on board the *ACE* spacecraft and the Earth's satellite *IMP-8* with the period of rotation around the Earth of 12.5 days which part of time, about 5 days at each rotation, was located in the magnetospheric tail. Both spacecrafts simultaneously register enhancements in electrons, the flux profiles of which mutually coincide, except for some cases of the location of the *IMP-8* spacecraft in the magnetospheric tail, which manifests the intermagnetospheric origin of the electrons registered by *IMP-8*. The arrival of high-velocity fluxes of solar wind to the Earth, which causes the sudden commencement of a magnetospheric storm (SC), leads to the acceleration of electrons on the shock wave front. These electrons are also registered in the transition layer of the magnetosphere.

As has been expected, the readings of both spacecrafts have close time profiles outside the Earth's magnetosphere. All of the enhancements denoted as *F* (flare electrons) and *SC* nearly coincide. Some differ-

[1] <ftp://ulysses.sr.unh.edu/WWW/Simpson/IMPData/hourly_rates/>; <ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/>; <http://sd-www.jhuapl.edu/ACE/EPAM/spec.html>; <http://sohowww.nascom.nasa.gov/about/docs/SOHO_Fact_Sheet.pdf>

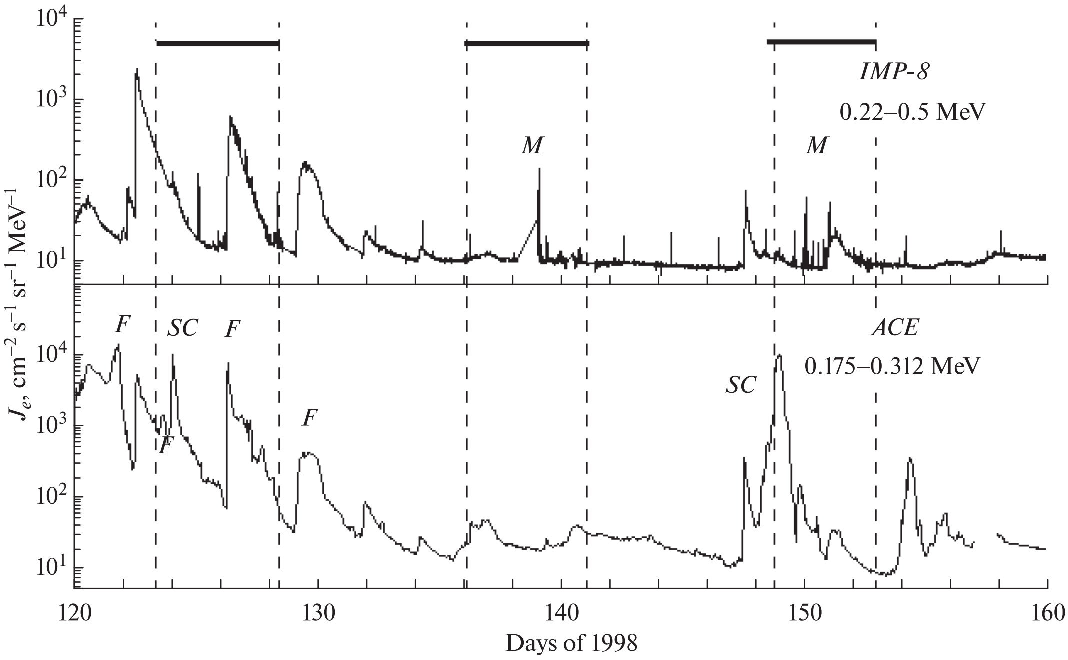

Fig. 3. Same as in Fig. 2 but for May–June 1998.

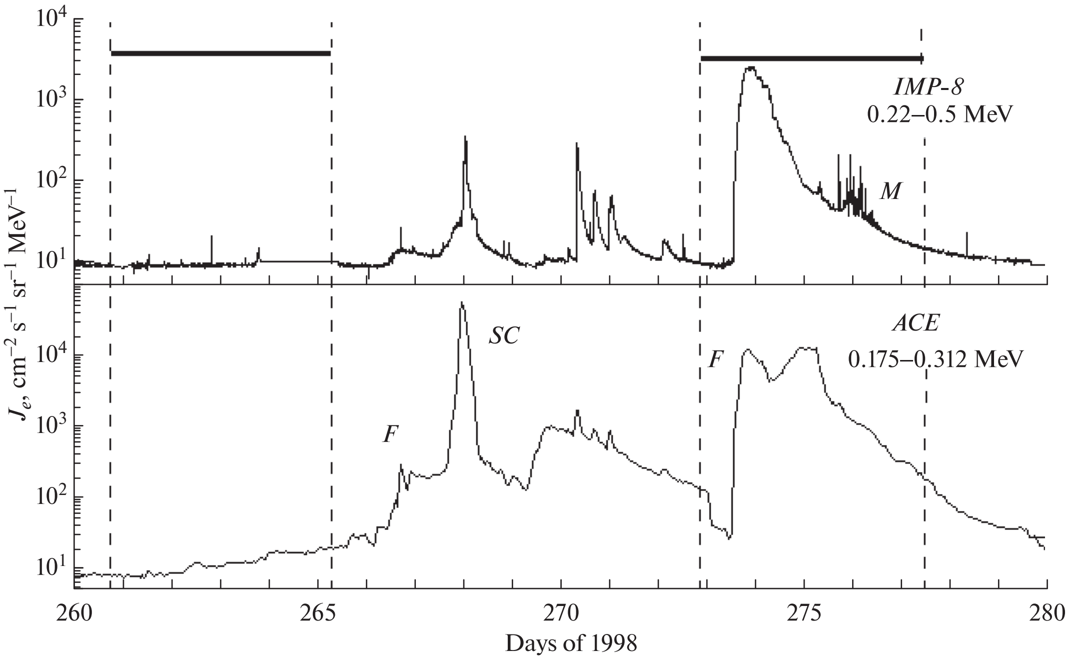

Fig. 4. Same as in Fig. 2 but for September–October 1998.

ences in the electron fluxes are explained by the incomplete coincidence of the observation conditions, i.e., different devices, slightly different energy intervals of the registered electrons, and strong distancing of the observation points (see Fig. 1). Figures 2–4 show that bursts of electron fluxes absent in the L1 point are observed within the magnetospheric tail in all periods shown in the figures.

In the active Sun periods, the magnetosphere is strongly disturbed and almost permanently generates energetic particles, i.e., electrons and protons. It was the case also in 1974, during the first year of the *IMP-8* Earth's satellite flight. The solar activity during that period was going down, but two years were still left until the activity minimum and the disturbance of the magnetosphere was still substantial. Figure 5 shows

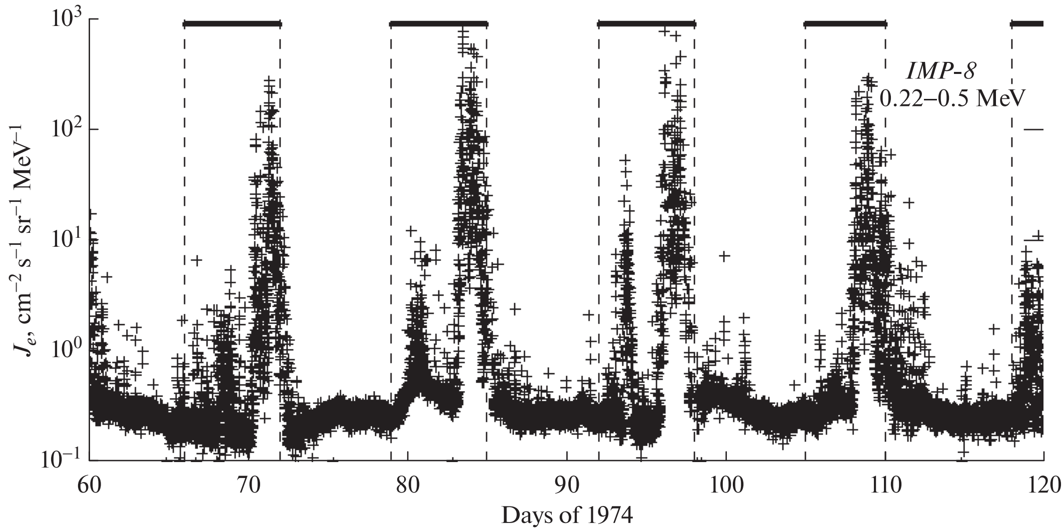

Fig. 5. Electron fluxes with *Ee* = 0.22–0.5 MeV. Dark lines at the top show periods during which the satellite is located within the magnetospheric tail, marked by dotted lines.

electron fluxes with energies of 0.22–0.5 MeV registered by the *IMP-8* satellite in March–April 1974. One can see that in the periods of satellite location within the magnetosphere, to be exact within the magnetospheric tail, substantial bursts of electron fluxes are observed by a factor of almost 1000, which exceeds the electron fluxes outside the bow shock wave formed at the boundary of the magnetosphere and the space free of geomagnetic field.

The satellite enters the magnetospheric tail from the dusk side and exits at the dawn side. Based on this and other examples (graphs for several years were analyzed), one can see that the electron flux is higher at the dawn side. This picture should take place during the acceleration of electrons during substorms because the accelerated electrons drift to the dawn side. However, it should be noted that this regularity is not absolute; sometimes, high fluxes are also observed within the middle of the magnetospheric tail, this fact manifesting existence also of other ways of magnetospheric electron propagation.

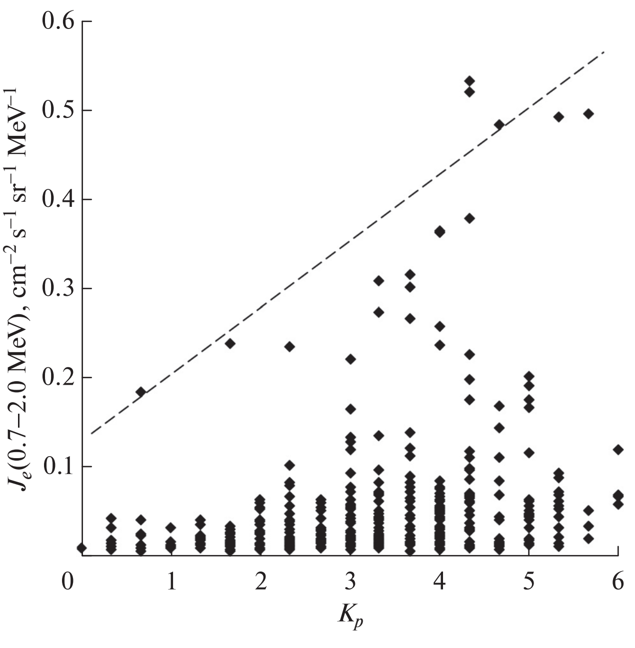

Fig. 6. Dependence of electron bursts within the magnetospheric tail on *Kp*-index level during the first 100 days of 1974.

In order to relate these electron fluxes within the tail of the magnetosphere to its disturbances, Fig. 6 shows a comparison of the amplitude of electron bursts with the *Kp*-index value. It can be seen that the probability of that electron bursts will occur within the magnetospheric tail increases with an increase in disturbances to the magnetic field.

2.2. Jovian Electrons

Electrons with an energy of hundreds of kiloelectron-volts to a few megaelectron-volts are not just observed during solar flares. Currently, it has been reliably found that the Jovian magnetosphere is the main source of the electrons of megaelectron-volt energies observed under a quiet Sun. Figure 7 shows an example of the registration of Jovian electrons by the *SOHO* spacecraft in 2007–2008.

The propagation of electrons from Jupiter to the Earth in the absence of a direct magnetic connection between the Earth and Jupiter when they sometimes have to overcome a substantial azimuthal distance up to 180° is one of the main problems. The electrons come freely to the Earth during the magnetic relation between the Earth and Jupiter which occurs once in 13 months. However, in quiet periods, these electrons are observed then near the Earth during several months undergoing

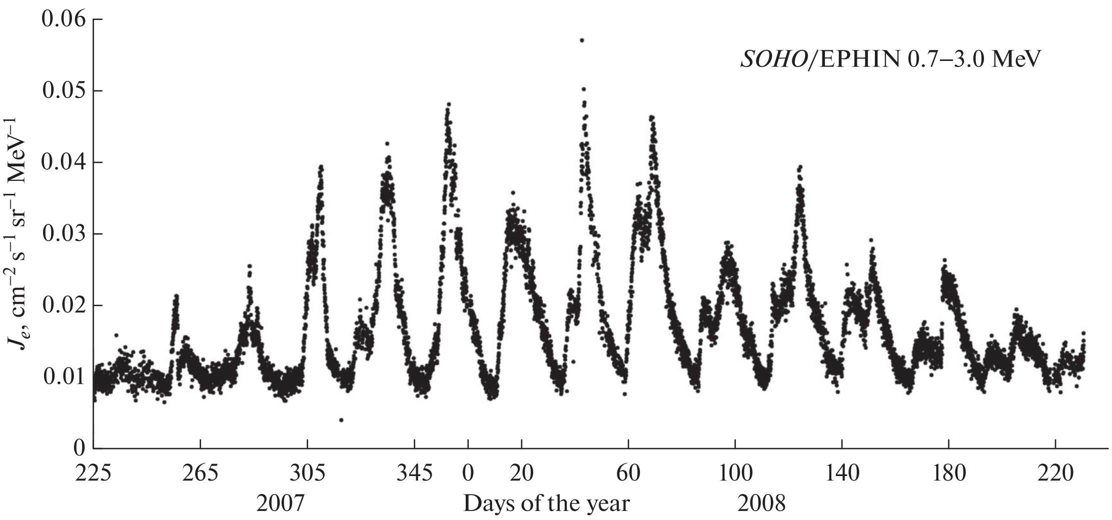

Fig. 7. Time profile of the Jovian electrons in the period of minimum solar activity in 2007–2008.

27-day variations due to the rotation of the Sun. That 27-day modulation can occur due to the formation of corotating interaction regions (*CIR*), the formation and role of which during the propagation of heavy particles was considered in detail in many publications [17]. In [10–11], the *CIR*s are considered to be a barrier for electron propagation. In [18], an alternate hypothesis of magnetic traps existing during several rotations of the Sun was proposed. Passing Jupiter, the trap captures electrons permanently emitted by the Jovial magnetosphere and keeps them for a long time which is sufficient for their registration under the passage of the trap rotating together with the Sun near the Earth. The reliable registration of the Jovial electrons is only possible during quiet periods on the Sun because their fluxes are too low and, as a rule, only exceed the background values of the used detectors by a few times, i.e., mainly in the periods of solar activity minima. An especially long period of these increases was observed during the solar activity minimum in 2007–2008 (14 consequent solar rotations, see Fig. 7).

The period of SA minimum in 1995–1997, when two spacecrafts with highly similar devices that register small electron fluxes (*SOHO*, the *EPHIN* device, *IMP-8*, and the *CRNC* device) but, as has been noted above, are located at substantially different points relative to the Earth's magnetosphere were simultaneously operating in the space, is of special interest. This favorable situation makes it possible to register fluxes of megaelectron-volts for energy electrons separately inside and outside the Earth's magnetosphere. A comparison of the readings of the devices *CRNC* (*IMP-8*) located within the tail of the Earth's magnetosphere and *EPHIN* (*SOHO*) located outside the magnetosphere (see Fig. 8) manifests good agreement between the data on the Jovian electrons at both spacecrafts. Enhancements in the electron fluxes not registered on board *SOHO* are also seen on board the *IMP-8* satellite, which manifests in their magnetospheric origin.

2.3. Energy Spectra of Electrons of Various Sources

The energy spectrum of the fluxes of Jovian electrons under study is an important characteristic. Direct measurements of electrons in the vicinity of Jupiter on board *Pioneer-10* and *Pioneer-11* have shown that the power index of the differential spectrum of the Jovian electrons within the energy range of 0.12–8.0 MeV in a power presentation $J_e \sim E^{-\gamma}$ has a value of γ = 1.5–2 [3], whereas the electrons of the magnetospheric and solar origin have a substantially softer spectrum. As an example, Fig. 9 shows the characteristic integral spectra of electrons for all three sources. For the sake of similarity in the presentation, the data of the *IMP-8* satellite obtained in 1974 were used in the creation of the spectra. The measurements of electrons on board *IMP-8* were conducted by the *CPME* device (the energy channels: E_e = 0.22–2.5, 0.5–2.5, and 0.8–2.5 MeV) and the *CRNC* device (the energy channels: E_e = 0.7–2, 2–12, and 12–50 MeV).

As should have been expected, the magnetospheric electrons have the softest spectrum, then pass the spectrum of solar flare electrons, and the hardest spectrum corresponds to the Jovian electrons. The latter manifests in the form of a strong difference in the nature of magnetospheric electrons of Jupiter and the Earth. It is possible that mainly energetic electrons exit the powerful Jovian magnetosphere, which is why their spectrum is very hard.

3. CONCLUSIONS

Besides the permanent flux in the electron fluxes of the galactic cosmic rays, enhancements in electron

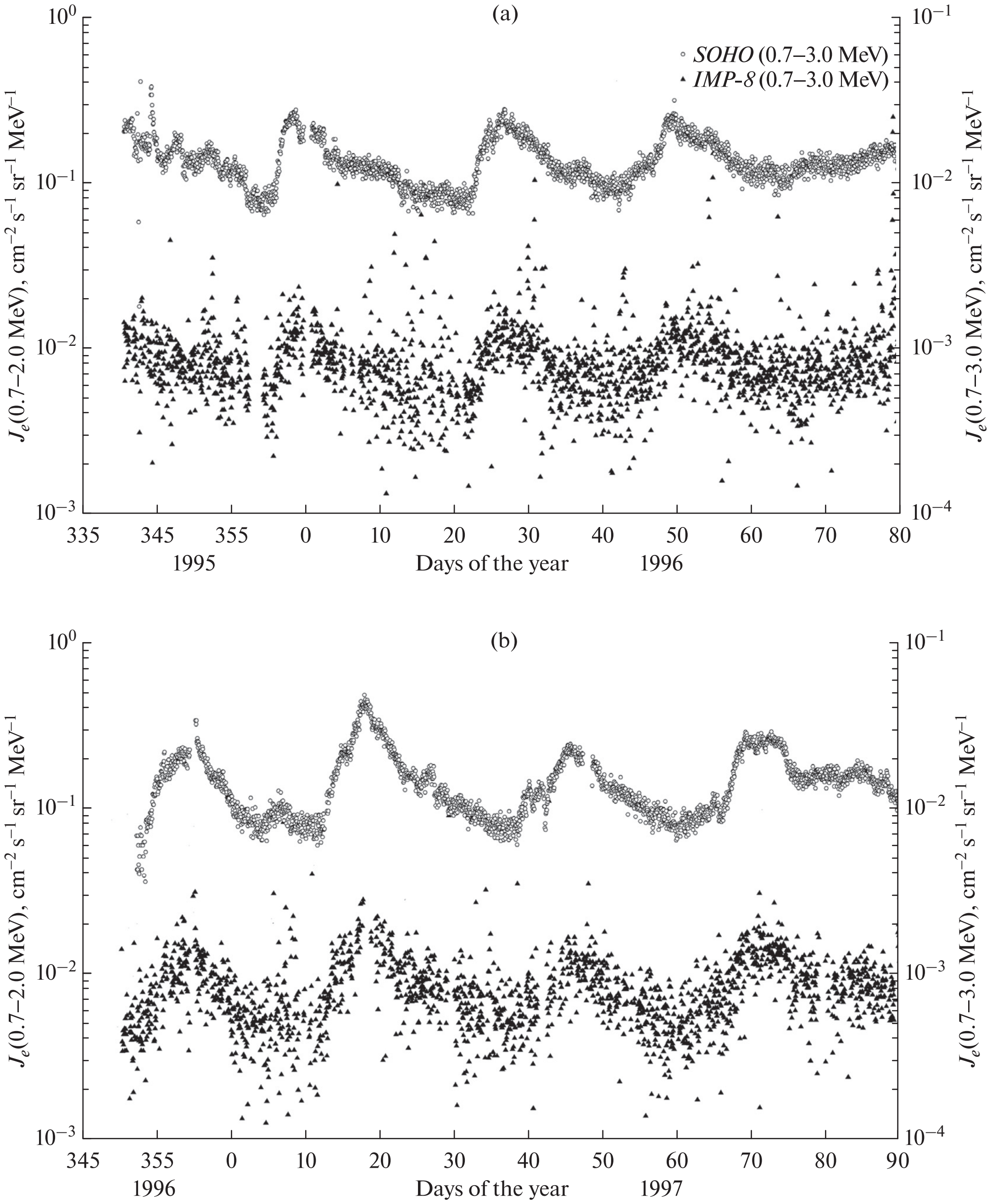

Fig. 8. Fluxes of electrons at *SOHO* (a) in the period of quiet Sun in 1995–1996 and (b) in the end of 1996–beginning of 1997. The 27-day wave corresponds to electrons of the Jovian origin.

fluxes of a different nature, first of all from solar flares accelerated by the turbulent magnetic field in the interplanetary environment and on fronts of bow shock waves of planetary magnetospheres are observed in the interplanetary environment. Moreover, the acceleration of electrons also occurs in the planetary magnetospheres, in particular of the Earth and Jupiter, which is a subject of this study.

The consideration of spatial, time, and energy characteristics of electron flux enhancements made it possible to almost unambiguously identify their sources, i.e., solar, Jovian, and magnetospheric. The Jovian electrons are observed mainly in quiet periods of SA, especially in the years of SA minima due to two causes, i.e., in those periods, the flux of particles of solar and interplanetary origin is small and makes it possible to reveal weak fluxes of the Jovian electrons. Moreover, with a quiet Sun, new possibilities of the propagation of the Jovian electrons arise and assist in their appearance during the Earth's orbit. Stable structures of the solar wind velocities could form long-lived magnetic traps filled in by electrons each time

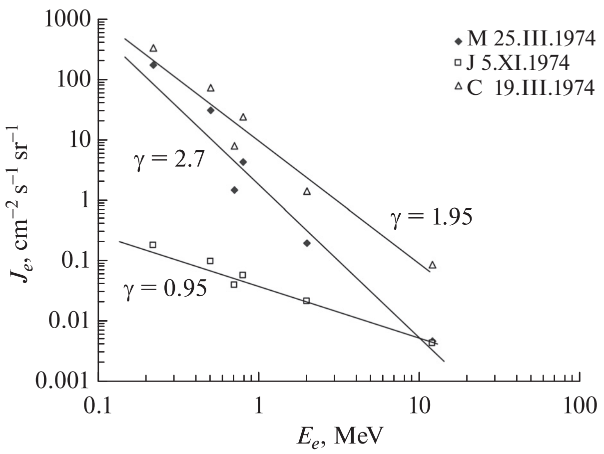

Fig. 9. Electron spectra according to *IMP-8* data for SCR (November 5, 1974), magnetospheric (March 25, 1974), and Jovian (March 19, 1974) electrons.

they pass Jupiter and are registered, then when they pass the Earth. In disturbed years, the solar wind velocity and magnetic field are changing quickly, no long-lasting traps are formed, and the arrival of the Jovian electrons to the Earth becomes difficult.

Within the magnetospheric tail and transitional region, electrons accelerated directly by the disturbed magnetosphere are often registered. Short-term bursts of magnetospheric electrons are the most intense at the dawn side of the tail and within the transitional region. The obtained characteristics make it possible to assume that there is a drift of electrons from the nighttime side of the magnetosphere to the dawn side after their generation during magnetic storms, substorms, and other types of magnetospheric disturbances. As a rule, electrons generated by the bow shock wave do not penetrate into the magnetospheric tail deeper than to the transition region.

Solar-flare electrons penetrate freely into the remote tail of the magnetosphere and have time profiles of fluxes at energies of fractions of megaelectronvolts and higher that are almost identical to those outside the magnetosphere.

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