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Hungarian Academy of Sciences

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BUDAPEST

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ABSTRACT

The experimental data from Prognoz 4 satellite obtained on a layer of electrons with energies ≤2 MeV in the magnetosheath adjacent to magnetopause at different latitudes are given. At moderate latitudes the data are in favour of the leakage of electrons from the outer radiation belt as a source of the layer considered. At high latitudes these electrons apparently arrive along magnetosheath magnetic field lines trapping the magnetopause.

АННОТАЦИЯ

Проводятся экспериментальные данные со спутника Прогноз-4 относящиеся к слою электронов с Е~2МэВ прилагающему к магнитопаузе внутри переходного слоя на различных широтах. На медленных широтах эти данные сведетелствуют в пользу того, что источником рассматриваемого слоя является утечка электронов из высшего радиационного пояса. На высокие широты эти электроны повидимому поступают вдоль магнитных силовых линий переходного слоя, отволакиваю- щих магнитопаузу.

KIVONAT

A Prognoz 4 mesterséges holdnak a magnetopauza mellett elhelyezkedő magnetosheath-ban lévő, ~2 MeV alatti energiáju elektronokat tartalmazó rétegben mért kisérleti adatait tárgyaljuk. Közepes szélességnél az adatok azt mutatják, hogy az elektronok a külső sugárzási övből kifolynak és ezek szolgáltatják a vizsgált réteg forrását. Magas szélességnél ezek az elektronok a magnetosheath mágneses erővonalai mentén érkeznek és a magnetopauza mentén befogódnak.

INTRODUCTION

Since 1970, when Meng and Anderson [1970] had reported about the permanent existence of an energetic electron layer in the magnetosheath adjacent to the magnetopause based on the measurements of electron fluxes with $E_e \geq 40$ keV made by the IMP 1 and 3 earth satellites and the Explorer 35 lunar satellite more than 20 papers of various groups of experimenters who had observed this event were published. For example, it was reported about the increase of the energetic electron fluxes in the layer just outside the magnetopause from the HEOS 2 data [Page et al., 1973; Domingo et al., 1974, 1977], the PROGNOZ 3 data [Lutcenko et al., 1975; Nikolaeva and Pisarenko, 1979], the IMP 5 data [Meng and Anderson, 1975; Meng et. al.; 1979] the IMP-8 data [Baker and Stone, 1977 a,b; 1978, Bieber and Stone, 1979] , the Vela 5,6 data [Palmer and Hones, 1978] , the ISEE 1, 2 data [Daly et al.; 1979; Williams et. al., 1979] and from the Helios 1, 2 spacecraft [Richter et al., 1979].

Such a large amount of experimental papers dealt with the consideration of physical processes due to which the energetic electron layer is formed presents evidence for the significant interest to this problem. However, there is not now available the generally accepted mechanism for forming the energetic electron layer in the magnetosheath adjacent to the magnetopause. Taking into account the magnetopause dimensions and electron velocities the possible time of their presence on the interplanetary magnetic field lines in the magnetopause vicinity can be estimated: it is not large (≈10 sec) and, therefore, the fact of the layer registration practically at each magnetopause crossing requires a permanent source supplying energetic electrons to the layer [Baker and Stone, 1977 a].

The energetic electron sources proposed by various authors for the layer discussed can be conventionally divided into two groups: the local sources associated with the accelerating mechanisms possibly occurring in the magnetopause vicinity e.g. with reconnection on the dayside and tail magnetopause, with resonance heating of electrons by electromagnetic waves generated in the magnetosheath [Meng and Anderson, 1970; Baker and Stone, 1977, 1978; Daly et al. 1979; Richter et al., 1979] and the sources associated with the energetic electrons originated from the different magnetosphere regions [Baker and Stone, 1978; Palmer and Hones, 1978; Nikolaeva and Pissarenko, 1979; Antonova and Nikolaeva, 1979; Williams et al., 1979].

In the magnetopause vicinity the spectra of energetic electrons up to energies 1-2 MeV were studied only by means of the IMP 8 [Baker and Stone, 1978] and ISEE 1, 2 [Williams et al., 1979] satillites. However the IMP 8 orbit made it possible to measure these electron only close to the tail magnetopause ($-10R_e \geq X_{SE} \geq -40R_e$) and the ISEE 1,2 orbit within the period described in that publication - only on the dayside at latitudes lower than those of Prognoz 4 (ISEE 1, 2 orbit inclination is 30^o). The Prognoz 4 satellite measured spectra of energetic electrons within the 0.3 ÷ 3 MeV range. Its orbit permitted measurements in the dayside magnetopause vicinity at moderate (on the inbound passes) and high (on the outbound passes) solar-magnetic latitudes. The spectral measurements of electrons with the energy of the order of 1 MeV in the magnetopause vicinity have not been ever carried out at such latitudes. Therefore, some Prognoz-4 results on the energetic electron and plasma fluxes given below will provide the additional information which could be useful for proper understanding the source of the layer adjacent to the magnetopause and for the manner of its supplying with energetic electrons.

INSTRUMENTATION

The Prognoz-4 measurements of the energetic electron fluxes were carried out by means of a spectrometer consisting of three semiconductor detectors surrounded by a plastic scintillator which was looked through by a photomultiplier. The spectrometer is located in an aluminium collimator with acceptance angle of 60^o. The anticoincidence screen allows the decrease of the background from the penetrating cosmic radiation and from proton with their paths out of the electron acceptance angle. The electron fluxes were measured within five energy ranges: 0.3 to 0.5; 0.5 to 0.8; 0.8 to 1.2; 1.2 to 2.0; 2.0 to 3.0 MeV. The geometrical factor of the instrument was $\approx 1.8\ cm^2 ster^{-1}$, the calibration was performed with radioactive sources Cs^{137}, Bi^{207}, Ru^{106}. The electron spectrometer was oriented perpendicularly to the Prognoz 4 spin-axis directed towards the Sun with an accuracy of about 10^o. The satellite spin period was ≈2 min. The energetic electron spectrometer has been described in more detail in Mineev et al. [1978].

The low energy ion fluxes within the range 0 to 4400 eV (16 energy intervals) were measured on board the Prognoz 4 satellite with a wide-angle differential modulation-type analyzer (Faraday cup) oriented parallel to the satellite spin-axis. The instrument sensitivity to the unidirectional flux was $\approx 4 \times 10^5\ cm^{-2} sec^{-1}$; ions were recorded within the acceptance angle of 90^o. To measure the total energy spectrum of ions and also the spectrum of energetic electrons $\approx$2 min 44 sec were required. The more detailed description of the ion analyzer can be found in Gringauz et al. [1974].

EXPERIMENTAL RESULTS

The Prognoz 4 orbit (the apogee was $\approx$200000 km; the perigee was $\approx$600 km; the inclination was $\approx 65^{\circ}$, the rotation period was $\approx$4 days) made it possible to study the energetic electron and plasma fluxes in the solar wind, in the magnetosheath and in the magnetosphere. During its active operating period (from the end of December, 1975 up to the middle of March, 1976) the satellite passed through the magnetosphere more than 20 times. The magnetopause crossings during the satellite inbound passes were within $35^{\circ} \leq \varphi_{SM} \lesssim 50^{\circ}$ and $-30^{\circ} \leq \lambda_{SM} \lesssim 30^{\circ}$, and during its outbound passes within $60^{\circ} \leq \varphi_{SM} \lesssim 75^{\circ}$ and $-90^{\circ} \lesssim \lambda_{SM}$ -10°, φ_{SM} and λ_{SM} are the latitude and longitude in the solar-magnetic coordinate system, respectively.

Fig.1 shows three Prognoz 4 orbits on 1-2; 14-15 and 19-20 revolutions in the solar ecliptic coordinate system. In *Fig.1* the dashed curve indicates the magnetopause location and the dot-and-dash curve does the position of the earth bow shock according to plasma measurements on 14-15 revolutions on February, 15-16, 1976. The thick solid line presents the portions of the orbits on which in the magnetosheath the spectrometer recorded electron fluxes more intense than those in the solar wind. The double line marks the satellite position when the enhanced electron fluxes were observed in the magnetosphere and double dashed line does the case when the energetic electron fluxes exceeded the maximum ones recorded by the instrument.

More detailed results on the energetic electron and plasma fluxes measurements during Prognoz 4 pass through the magnetosheath and the magnetosphere are presented in *Fig.2*. This figure shows the electron fluxes J_e within the energy ranges: 0.5-0.8; 0.8-1.2 and 2-3 MeV and the total flux of ions J_i within the energy range 0-4,400 eV($J_i = 6.7 \times 10^{17} \sum_{K=1}^{16} I_k$, where I_k is the current in the K-energy interval) recorded during the outbound pass (*Fig.2b*). In *Fig.2* the arrows indicate the moments when the satellite traversed the bow shock and the magnetopause determined from the characteristic change of ion spectrum (thermalization and drop of plasma bulk velocity) and from the considerable drop of ion flux, respectively. *Fig.2a* shows that when the satellite crosses the dayside magnetopause at medium latitudes ($\varphi_{SM} \approx 45^{\circ}$, $\lambda_{SM} \approx -10^{\circ}$) the flux of 0.5 to 0.8 and 0.8 to 1.2 MeV electron starts to increase in the magnetosheath. The electron fluxes with these energies do not change significantly on the magnetopause and continuing to increase as Prognoz 4 deepens into the magnetosphere they reach the values higher than those maximally recorded by the instrument apparently in the stable trapping region of the outer radiation belt.

Electron flux variations at higher latitudes on the dawn side of the magnetosphere ($\varphi_{SM}=66^{O}$, $\lambda_{SM}=-68^{O}$) have an essentially different character. In the magnetosheath near the magnetopause the energetic electron layer is also recorded (see electron fluxes with 0.5 to 0.8 and 0.8 to 1.2 MeV). However, in the part of the magnetosphere adjacent to the magnetopause the fluxes are essentially smaller and remain at that level up to the stable trapping region deep in the magnetosphere where the flux values also exceed the maximum ones for the electron spectrometer. In addition to the layer of energetic electrons in the magnetosheath Prognoz 4 often recorded the shorttime energetic electron bursts at considerable distance from the magnetopause in the magnetosheath and sometimes in the solar wind.

Shown in *Fig.3* energetic electron fluxes variations during Prognoz 4 crossings of the magnetosheath and the magnetospere are rather typical and repeat mainly from pass to pass. The energetic electron layer in the magnetosheath adjacent to the magnetopause and the electron bursts observed on the outbound passes are recorded by the spectrometer in all energy intervals including 0.3 to 0.5 and 1.2 to 2.0 MeV. However, if the electron fluxes with 0.3 to 0.5; 0.5 to 0.8 and 0.8 to 1.2 MeV increase in the layer by one order and higher as compared to those in the solar wind, then the electron fluxes with 1.2 to 2.0 MeV increase less than by a half order and the fluxes with 2 to 3 MeV do not sufficiently change in the magnetosheath and in crossing the magnetopause (*Fig.2*).

Fig.3 presents the differential energetic electron spectra 1 to 8 measured on February, 15-16, 1976 during the times marked by the appropriate numbers in *Fig.2*. A power law energy spectral index γ ($dJ_e/dE_e \simeq E_e^{-\gamma}$) is also given near each spectrum.

As seen from *Figures 3* and *2* in the solar wind in the magnetosheath the spectral index $\gamma \simeq 1.6$ to 1.7 (spectra 1, 2), but is much higher and equals $3 \div 4$ for the energetic electron layer adjacent to the magnetopause (spectra 3, 7) for electron bursts in the magnetosheath (spectrum 8) and for the stable trapping ragion in the magnetosphere (spectra 4, 5).

DISCUSSION

As it was mentioned above the Prognoz 4 experiment discussed in this paper is the only one which measured the spectra of electrons with the energy of about 1 MeV in the magnetopause vicinity at medium and high solar-magnetic latitudes. The measurements showed an essentially different behaviour of electron fluxes in various magnetopause regions i.e. their increase at medium latitudes on the dayside and decrease at high latitudes on the dawn side with increasing distance from the magnetopause deep into the magnetosphere (*Fig.2*). To our mind this unambiguously suggests that the magnetosheath energetic electron layer just outside the magnetopause is formed by the leakage of electrons from within the magnetosphere near the dayside midlatitude magnetopause. Then these electrons spread over the magnetopause along the drapping it magnetic field lines frozen in the magnetosheath plasma, - and reach higher latitudes. This conclusion is confirmed by close to one another spectral indices γ of energy spectra of electrons in the layer adjacent to the magnetopause (spectra 3,7 in *Fig.3*) and of trapped electrons in the magnetosphere (spectra 4,5) that are much higher than γ in the solar wind and the magnetosheath (spectra 1,2).

Nikolayeva and Pisarenko [1979] also pointed out the different behaviour of electron fluxed near the high- and low-latitude magnetopause using the data of Prognoz-3 measurements of electron fluxes with lower energies (65 to 85 keV and 125 to 165 keV). This paper discusses the leakage of energetic electrons to the magnetosheath from the magnetosphere at low latitudes as a possible formation mechanism of such electron layer adjacent to the magnetopause, however, the increase of electron fluxes deep into the magnetosphere and the fact that they do not change on the magnetopause at lower latitudes were considered only to present difficulties in identifying the energetic electron layer.

The paper of Williams et al. [1979] discusses in detail the leakage of energetic electrons (and ions) to the magnetosheath via the dayside magnetopause at latitudes lower than those of Prognoz-4. On the basis of measurements of three-dimensional distribution function of energetic charged particles it has been shown that the magnetospheric electrons and protons are trapped up to the distance of about one Larmer radius from the magnetopause. The energetic particles whose cyclotron trajectory impact the magnetopause are lost from the magnetosphere forming the field-aligned flow just outside the magnetopause [Williams et al., 1979]. A similar conclusion on the behaviour of energetic electrons in the energy range $28\text{keV} \leq E_e \leq 214\text{keV}$ near the magnetopause has been made by Palmer and Hones [1978] from Vela 5,6 experiments, the trajectory of which made it possible to study the magnetotail boundary at geocentric distances of $\approx 18 R_e$. Thus the leakage of energetic electrons from the magnetosphere to the layer adjacent to the dayside magnetopause at low [Williams at al., 1979] and medium latitudes seems to be experimentally proved.

Now let us dwell upon the energetic characteristics of electrons recorded by Prognoz 4 in the layer just outside the magnetopause. As it has been mentioned above the electrons spectrometer measures the enhanced electron fluxes up to energies 1.2 - 2.0 MeV in this formation. In the Earth magnetosphere the considerable electron fluxes with such an energy exist only in the trapped radiation belts. This implies that the outer radiation belt is the source of electrons with 1 MeV in the energetic electron layer. For electron with several tens keV the other sources seem possible, for example, accelerated electron of the magnetosphere plasma sheet (Palmer and Hones, 1978).

The origin of energetic electron bursts usually recorded by Prognoz 4 in the high-latitude magnetosheath and (more rare) in the solar wind is also seems clear. The spectral index γ in these bursts is approximately the same as in the energetic electron layer adjacent to the magnetopause. Bieber and Stone [1979] showed that it is the layer that is the source of energetic electron bursts.

In conclusion it should be mentioned that there are two peculiarities in the experimental data which were not satisfactorily explained. 1./ Why does the electron flux with 2.0 to 3.0 MeV not change significantly in the magnetosheath just outside the magnetopause (*Fig.2a,b*)? 2./ Why are the energetic electron spectral indices γ in the solar wind and in the magnetosphere out of the stable trapping region close (compare spectra 1 and 6 in *Fig.3*)? These peculiarities, however, may be associated with the penetrating cosmic radiation which affects the spectrometer and they should be checked by measuring the electron fluxes of higher energies with the instrument better protected from radiation.

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FIGURE CAPTIONS

Fig.1 Prognoz-4 orbits on 1-2 revolutions (December,25-28,1975), on 14-15 revolutions (February,14-17,1976) and on 19-20 revolutions (March 5-8,1976) in the solar-ecliptic coordinate system. The thick solid line represents the magnetosheath portions of orbits on which enhanced energetic electron fluxes were recorded. The double line does the magnetosphere portions of orbits where energetic electrons were observed. And the double dashed line shows the case when energetic electron fluxes exceeded the maximum ones recorded by the spectrometer.

Fig.2 Energetic electron fluxes J_2 in the energy intervals 0.5 ÷ 0. 0.8 ÷ 1.2, 2 ÷ 3 MeV and the total ion flux J_1 in the energy range 0 ÷ 4400 eV as functions of time during an inbound satellite pass (2a) and an outbound pass (2b). The arrows indicate the positions of the earth bow shock (BS) and magnetopause (MP).

Fig.3 Energetic electron spectra 1 - 8 measured during the times marked by the same numbers in Fig.2.

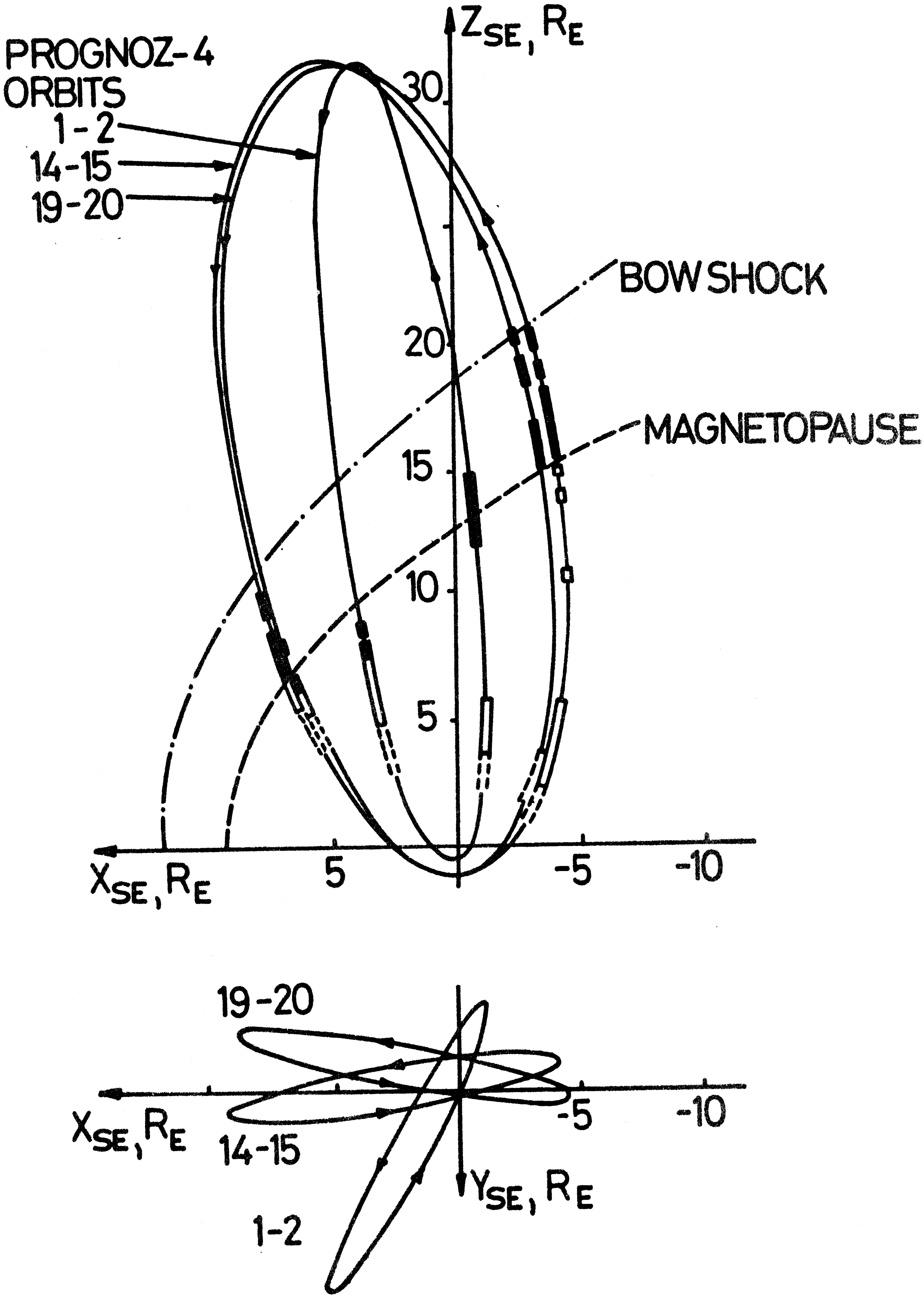
PROGNOZ-4
ORBITS
1-2
14-15
19-20
Z_{SE}, R_E
30
20
15
10
5
BOW SHOCK
MAGNETOPAUSE
X_{SE}, R_E
5
-5
-10
19-20
14-15
1-2
X_{SE}, R_E
-5
-10
Y_{SE}, R_E

Fig.1.

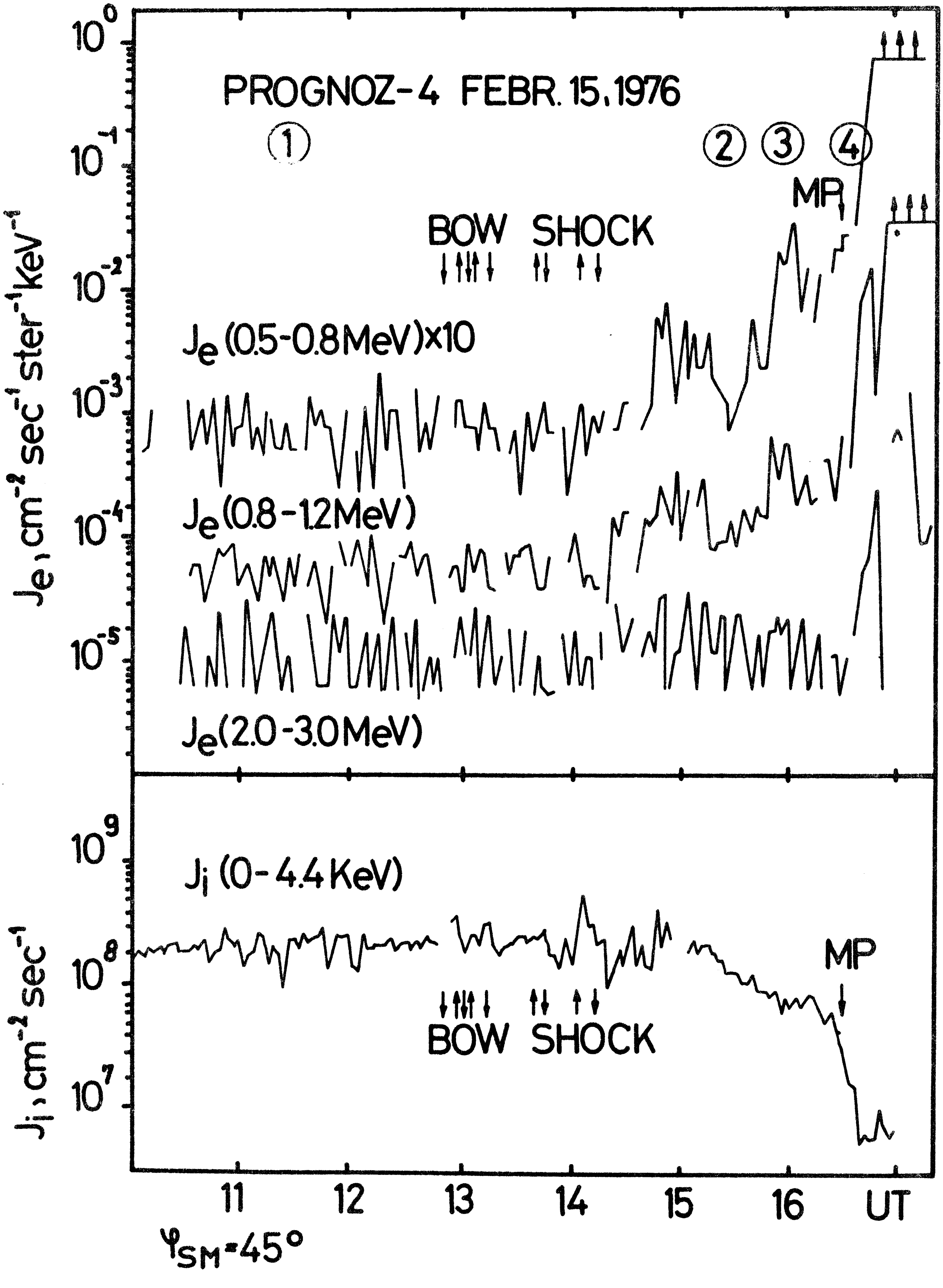
PROGNOZ-4 FEBR. 15, 1976
1
2
3
4
MP
BOW SHOCK
J_e (0.5-0.8 MeV)x10
J_e (0.8-1.2 MeV)
J_e (2.0-3.0 MeV)
J_e, cm^{-2} sec^{-1} ster^{-1} keV^{-1}
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
J_i (0-4.4 KeV)
J_i, cm^{-2} sec^{-1}
10^9
10^8
10^7
MP
BOW SHOCK
11
12
13
14
15
16
UT
φ_{SM}=45°

Fig.2a

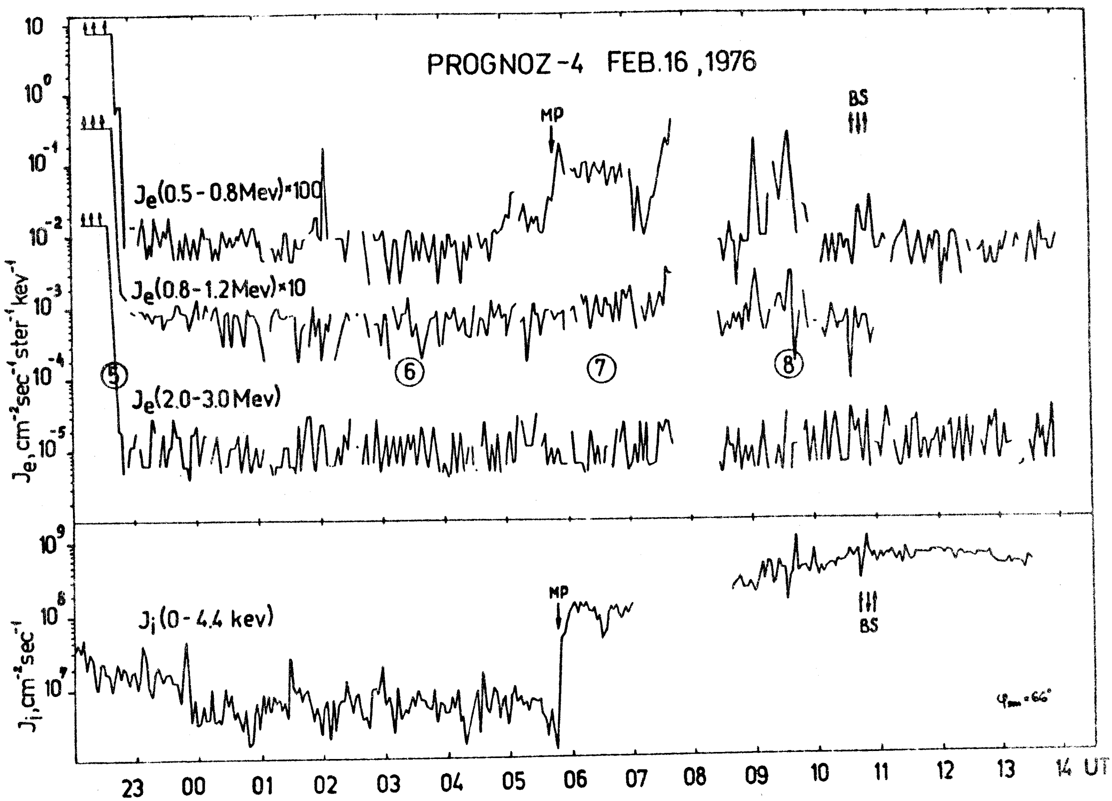
PROGNOZ-4 FEB.16 ,1976
MP
BS
J_e(0.5 - 0.8Mev)×100
J_e(0.8 - 1.2Mev)×10
J_e(2.0-3.0Mev)
5
6
7
8
J_e, cm^{-2}sec^{-1}ster^{-1}kev^{-1}
10
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
J_i(0 - 4.4 kev)
J_i, cm^{-2}sec^{-1}
10^9
10^8
10^7
MP
BS
23 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 UT

Fig. 2b

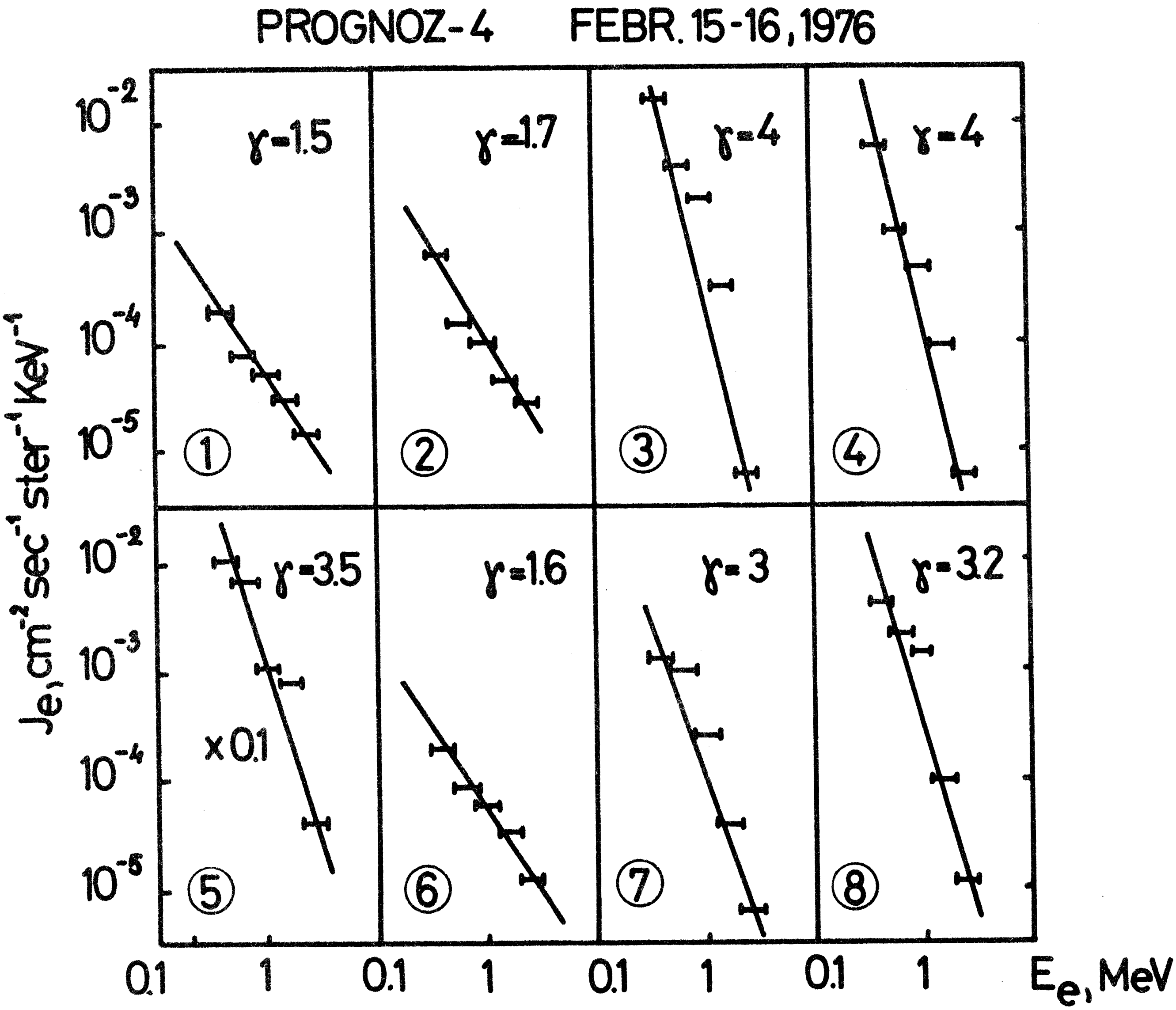
PROGNOZ-4 FEBR. 15-16, 1976
J_e, $cm^{-2} sec^{-1} ster^{-1} KeV^{-1}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
γ=1.5
γ=1.7
γ=4
γ=4
γ=3.5
γ=1.6
γ=3
γ=3.2
x 0.1
1
2
3
4
5
6
7
8
0.1
1
E_e, MeV

Fig. 3

Kiadja a Központi Fizikai Kutató Intézet
Felelős kiadó: Szegő Károly
Szakmai lektor: Gombosi Tamás
Nyelvi lektor: Kecskeméty Károly
Példányszám: 375 Törzsszám: 80-331
Készült a KFKI sokszorosító üzemében
Budapest, 1980. május hó