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ABSTRACT

The interplanetary shock, generated during the solar flare of Jan.1, 1978 reached the Earth's orbit on January 3, 21^h UT. Aboard Prognoz-4 satellite the fluxes and spectra of energetic electron /E>30 keV/ and proton /E>500 keV/ fluxes and energy spectra of solar wind ions up to 4.5 keV and magnetic field were measured, with a time resolution ~10 sec. Time variation of these characteristics are given including preshock and postshock frequency spectra of magnetic field fluctuations. Effective acceleration of protons in the oblique shock observed. The mean free path of protons with E<6 MeV was determined by using the time interval of anisotropic particle flux observations as λ~0.2 a.u.

АННОТАЦИЯ

Межпланетная ударная волна возникшая во время солнечной вспышки 1 января 1978 г. достигла Земль 3 января ~21 ч. U.T. На спутнике Прогноз-4 в это время были измерены потоки и энергетические спектры электронов с энергией E>30 кэВ и протонов с E>500 кэВ, потоки и энергетические спектры ионов солнечного ветра /до E~4,5 кэВ/ и магнитное поле, с разрешением по времени ~10 сек. Приведены временные вариации всех этих величин включая частотные спектры флуктуаций магнитного поля до и после фронта ударной волны. Была определена величина среднего свободного пробега протонов с энергиями E<6 МэВ /λ~0.2а.е./ по длительности времени наблюдений анизотропных потоков частиц.

KIVONAT

Az 1978. január elsejei napkitörés által keltett bolygóközi lökéshullám január 3-án 2100 UT-kor érte el a Földet. A Prognoz-4 fedélzetén folyamatosan mértük a mágneses teret, a napszél energiaspektrumát 4.5 keV-ig, valamint az energikus elektronok (>30 keV) és protonok (>500 keV) fluxusát és spektrumát. A mágneses tér fluktuációi és a fent emlitett mennyiségek időbeli változásait vizsgáltuk. Megállapitottuk, hogy a ferde lökéshullám hatékonyan gyorsitott protonokat. A <6 MeV energiáju protonok szabad uthosszát a lökéshullám előtti anizotróp protonfluxus térbeli kiterjedéséből állapitottuk meg.

1. INTRODUCTION

During the last years the direct connection between some energetic particle phenomena such as shock spikes, ESP events, acceleration by IARs/interplanetary active regions/ and the propagation of shock waves, interplanetary sector boundaries and other disturbances became clear. These phenomena were observed from 0.3 AU throughout the solar system /c.f. reviews [1] - [3] and papers [4] - [12]/.

Theoretical description of energetic particle scattering and acceleration in the turbulent solar wind can be found in a series of papers c.f. [3], [13] - [15]. Model calculations were carried out for several types of events: the effects of interplanetary conditions on energetic particle parameters were calculated [3].

Best developed models of charged particle - interplanetary medium interactions are connected with the theory of shock spikes, where the thickness of interaction region is less then 1-2 Larmor radii. In the case of a shock spike the intensity of 0.1 - 1.0 MeV protons suddenly increases for about 10 minutes before and after the passage of a shock wave [3]. Large scale events /ESP, IAR/ are less understood, because in these cases the energetic particle propagation effects - convection, diffusion, adiabatic deceleration can play an important role, too.

In order to construct realistic models of energetic particle modulation and acceleration in the interplanetary medium we must have simultaneous data not only about these energetic particle fluxes, but also about the solar wind plasma and interplanetary magnetic field. Such intercorrelated data analyses were already carried out by Sanderson et al. [16] and Pesses et al. [12].

The Prognoz-6 high apogee satellite carried out simultaneous plasma, magnetic field and energetic particle measurements in a wide energy range. The available time resolution enabled us to study even the small scale energetic particle events. The geometrical configuration made the determination of angular distribution of energetic particles possible in a hemisphere pointing toward the sun. This configuration was especially useful when the magnetic field vector had a large polar angle ($\Theta \gtrsim 30^{o}$). In most of the experiments the pitch angle distribution can be determined only in the ecliptic plane (c.f.[8]). Three dimensional angular distribution was measured only in a few experiments. In particular, three dimensional measurements helped to confirm the theoretical prediction of isotropic angular distribution of 0.02 - 0.4 MeV protons behind shock fronts onboard ISEE-3 [16].

In this paper we present some results of the observations of Prognoz-6 during the energetic particle event of January 3-4, 1978. We have chosen this event because during this period several clearly separated phenomena followed each other each of which can be determined from magnetic field and plasma observations as well. One of the most interesting features of the event was that some of the observed phenomena were connected with an oblique shock. In addition to usually given in such studies medium parameters we used also frequency spectra of magnetic field power fluctuations, calculated according to [24].

We compared our data to hourly averages of energetic particle, plasma and magnetic field data of IMPs 7 and 8 [18], [19] and found a reasonable agreement both in the absolute values of measured values and in the temporal variations. The high resolution data sampling enables us to study the detailed structure of the shock and the following high speed plasma stream as well as their effects on the energetic particles. We can expect even more interesting results from observations, by spatially separated satellites, for instance combining the observations of an earth orbiting satellite with that of the Helios 1,2 space probes.

2. EXPERIMENT

2.1 <u>Trajectory.</u> *Fig.1.* shows position of Prognoz-6 during this period; when the flare occurred it was in the high latitudes magnetosheath near the bow shock, later it crossed the bow shock and entered the free flowing solar wind. In this region the magnetosheath plasma and magnetic field parameters usually are close to that of in the solar wind. One can assume, that the Earth's bow-shock did not distort significantly the observations.

In this case the position of the satellite does not have a strong influence on the observed energetic particle fluxes because the Larmor radius of these particles was higher than the satellite's distance from the bow shock. This can be seen in *Fig.2.* where time intensity profiles of 1.4-5.8 MeV protons observed during three magnetosheath crossings in November 1977 are shown. Arrows represent the motion of the satellite while the solid lines represent the moments of discontinuity intersections. One can see that intersecting the bow shock does not influence the proton intensity.

2.2 <u>Instrumentation</u>. The magnetic field was measured by three-component flux-gate magnetometer with a sensitive interval of 0 - 20 γ and accuracy $\pm$ 1 γ [19]. One axis of the magnetometer was permanently pointing towards the sun, the two other axes were rotating in a plane, perpendicular to this direction, with a time of revolution of ~120 sec. The time resolution was 10.24 sec, so the angular resolution in the rotating plane was $\pm 15^{o}$.

The plasma parameters /ion flux, velocity and density/ were determined from the data of a wide angle analyser /Faraday cup/ in 16 energetic intervals up to 4.5 keV. One differential energetic spectrum was obtained in 160 sec. [20].

The detector system registering the energetic particle fluxes was described in [2]. >100, >30 and >9 MeV protons arriving from the antisolar direction were detected by GM counters having a 2.8 cm^2 ster geometrical factor and 324 sec time resolution.

The 1.4 - 5.8 MeV protons were detected by a solid state detector which had a geometrical factor of 1.25 cm^2 ster, an acceptance angle of 90^{o} and time resolution of 10.24 sec. The axis of the detector and the satellite - sun line formed a 45^{o} angle and the detector rotated around the satellite - sun line with a rotation period of about 120 sec.

Protons with energies >0.5 MeV were observed by a GM counter with magnetic filter surrounded by an anticoincidence cup. The geometrical factor was 7 cm^2 ster, the acceptance angle 46^{o} and the orientation was identical with that of described in the previous paragraph.

The differential proton energy spectrum was determined from the data of a semiconductor telescope registering 0.1-10 MeV particles in five channels.

>30 keV electron currents were measured with back scatter method with an effective geometrical factor of 0.1 cm^2 ster from the antisolar direction with a time resolution of 10.24 sec.

The orientation of the individual detectors was known with an accuracy of $\pm 15^{o}$.

3. RESULTS

3.1 General description of the event. In *Figs. 3a, b and c* proton time intensity profiles are shown in various energy intervals together with plasma parameters and magnetic field intensity during January 1-4, 1978. Hourly averages of energetic particle intensities were obtained from Prognoz-6 data while the solar wind and magnetic field parameters represent a combination of Prognoz-6 and IMP-7,8 data [9]. The power spectra of magnetic field fluctuations were determined from Prognoz-6 and the plasma density and temperature were taken from IMP-7 and 8. *Fig. 3.a* shows energetic particle and solar wind velocity data, *Fig. 3.b* plasma parameters and the total power of magnetic field fluctuations, while *Fig.3.c* shows the magnetic field vector components together with the 1.4 - 5.8 MeV proton intensity.

Let us have a look at the time-intensity profiles of energetic particles. Inspection of *Fig. 3.a* shows that the period can be divided into three intervals having different characteristics. These intervals are separated by thin solid lines. The first interval immediately follows the 2N flare at 2150 UT on January 1. Particle intensities during this period show tipical flare originated profiles at least for protons >10 MeV. This interval is investigated in details in an other paper at this symposium [21]. Here we only mention that the particle propagation probably was influenced by coronal and interplanetary diffusion.

The beginning of the second interval coincides with the passage of the generated shock wave which was detected in the form of an SC as well. The intensity decrease of >100 MeV protons is a Forbush effect while the intensity increase in lower energies is an ESP event.

In the third interval the temporal behaviour of >1 MeV fluxes changed sharply. In *Figs. 3.b and 3.c* the same time period is shown for plasma and magnetic field parameters. Plasma parameters changes in *Fig. 3.b* correspond to a piston driven flare generated shock wave system [23]. The beginning of interval "2" corresponds to the passage of the leading edge of the shock while the whole interval to the compressed solar wind region. This compressed region in this case is ~0.01 AU wide. In region "3" the velocity of the flare originated plasma in high while the denstiy is low as one see from the upper part of *Fig. 3.b* where the time dependence of connection longitudes and the flare's site is shown on the solar disc. The connection longitudes were determined by the projection of the observation points along the spiral of interplanetary magnetic field lines taking into consideration the solar wind velocity changes. The shock wave also can be identified by the jump of the magnetic field.

3.2 Shock-spike. *Fig. 4* shows high resolution plasma, magnetic and 1.4 - 5.8 MeV proton data for the passage of the shock front. One can see that the jump of these parameters takes place within about 3-5 minutes, which is on unusually slow increase for this type of interplanetary shock waves. The ratio of magnetic field amplitudes before and other the shock and the change in the magnetic field direction corresponds to the definition of shock waves [8]. The shock normal was determined by the complanarity theorem and has the following components: ($\hat{n}$= 0.99,-0.15, 0.02). The angle between the $\vec{B}$ and $\vec{u}$ vectors is 52°. This indicates that the shock wave is neither perpendicular nor quasiperpendicular. Topology of the shock wave is also shown in *Fig. 4*.

Theoretical works [3], [12] predict that in a case similar to ours the energetic particle fluxes remain practically unaffected. On the other hand when we intersect the shock at 20.50 UT the proton intensity suddenly increases by a factor of 6 - 10. The velocity difference between the ambient solar wind and the shock front was about 100 km/sec consequently the spatial extension of the shock-spike region is about 10^4km. The gyroradius of a 1.5 MeV proton in this compressed magnetic field ($B \sim 40\gamma$) is about $8 \cdot 10^8$ cm, so particle acceleration takes place in a region having a characteristic dimension equal to the gyroradius.

From *Fig.4.* one can see how the angular distribution of protons changes during the transition from undisturbed solar wind to shock-wave. By arrows are indicated moments of time, corresponding to minimum angles between B-vector and the axed of the reception cone of device (20^{o}-30^{o}). In this moments particle fluxes are maximum. Large particle anisotropy is observed due to particle reflection and acceleration at the shock front. Behind the shock-front there is no particle flux modulation due to detector rotation; this corresponds to isotropization of the pitch-distribution of particles. Similar results was obtained from Helios 1,2 spacecraft for ions with energies E 80≥KeV.

Fig.5. proton spectra are given, obtained close to the shock-front in the undisturbed solar wind, and directly at the shock-front. At the shock-front protons are accelerated up to energies ~2 MeV "shock-spike"-effect. The acceleration of protons with energies ≥0.5 MeV is more effective due to the larger time scale of particle-wave interaction. So, we have an acceleration at the oblique shock; the observational results are not in agreement with theoretical predictions for oblique shocks [3].

By using the data on pre-shock proton angular distribution one can estimate the characteristic time of particle scattering and the mean free-path λ. The anisotropy pitch angle distribution began to be observed two hours before the arrival of the shock (*Fig.4.a*). If one assume that anisotropy is due to the reflected and accelerated particles and takes into acount that the shock speed is 5.10^{7} cm/sec, one can obtain $\lambda=3,5.10^{11}$ cm~2.10^{-2} AU.

3.3 The region of compressed solar wind "2"

This region is observed during ~5 hours. It can be regarded as the region of energetic particle trapping. During acceleration at shock some particles are reflected to region "1", other-penetrate in region "2". The densities of particles in the regions divided by the shock are proportional to the time of existence of particles in each of these regions, or the time of scattering at angle ~$\frac{\Pi}{2}$. The relation of both times depends on the relative power of magnetic field fluctuations at resonance frequency for particles of given energy. Of can be written as

$$\frac{\tau_{S_1}}{\tau_{S_2}} = \left(\frac{B_1}{B_2}\right)^2 \left(\frac{\partial B_1}{\partial B_2}\right)^2 \quad \text{where}$$

τ_s-scattering time, B-magnetic field, ∂B-amplitude of B-fluctuation. The resonance frequency

$$f_{res} \simeq \frac{\Omega_B(V+V_A)}{2\Pi(v+V)} \quad ;$$

Ω_B - the frequency in the field B

V - solar wind velocity

V_A - Alfvén velocity

v - particle velocity

All this values could be determined from the data of described experiment.

On *Fig.6.a* two particle spectra are given - preshock and post-shock ones. For this spectra hourly - averaged data were used. On *Fig.6.b* the magnetic field power spectra are given for the same two time intervals. In the energy - range of 1-10 MeV these spectra have approximately the same steepness, and only the intensity is different. In the compressed solar wind region "2" the power of fluctuations in this energy-range increased by an order of magnitude. Then for the energy-range E_p~1-5 MeV τ_{S_2}/τ_{S_1} is about 6-10. Such a difference of the times of scattering is in accordance with increase of proton intensity, observed in the region "2" (*Fig.3.a*). At the same times high level of magnetic field fluctuations leads to particle isotropization in region "2".

3.4 Region of high-speed stream ("3")

Fig. 3."a" and "b" show that in this region the proton flux with energies E<10 MeV increases and that time dependence of this increase in some degree does repeat the time-dependence of solar wind velocity. Besides a connection between the proton flux and magnetic field direction is obviously absent (*Fig.3.c*). Rather steep boundaries of the increased proton flux do not coincide with boundary surfaces of magnetic field, and a simple geometric interpretation of proton flux growth is impossible. The proton energy spectra in the region "3" are quite different from those in region "2" and will be considered in detail elswhere. Such a comparatively quick variation of particle flux characteristics is relatively rare and may be caused by two possible reasons. First - the change of particle flux and energy spectrum in region "3" with respect to region "2" is caused by the azimuthal movement of the observation point relative to the source. Due to the changes of solar wind speed, the observer becomes connected with the source by means of different magnetic field lines and does observe the azimuthal particle flux distribution at the source. From *Fig.3.b* one can see that proper field line is originated from the flare-region. The second possibility is the statistical particle acceleration during particle interaction with turbulence created in the interaction process of plasma streams with different velocities mechanisms of such an acceleration were considered in the papers [14][15]. We do not have enough experimental data to estimate the influence of each of the effects mentioned, but we believe that the energetic particle fluxes similar to observed in the regions "2" and "3" cannot exist without and acceleration in the interplanetary medium.

4. CONCLUSION

As a result of the preliminary consideration of the event observed January 3-4, 1978, one can conclude:

1. The effective acceleration of protons up to energies about a few MeVs in oblique shocks is possible.
2. In the event observed the level of IMF-power fluctuations increased by an order of magnitude down-stream the shock. Evidently this increase produces variations in the proton fluxes and in their spectra at the shock and in the region of compressed solar wind.
3. The degree of isotropization of energetic protons accelerated and reflected by the shock is evidently depending on the level of magnetic field fluctuations. The mean free path of the protons with energies E<6 MeV was determined by a simple method (by using the time of anisotropic particle fluxes observations).

The authors are planing to continue the study of this event with the use of additional data (in particular of data from other spacecraft).

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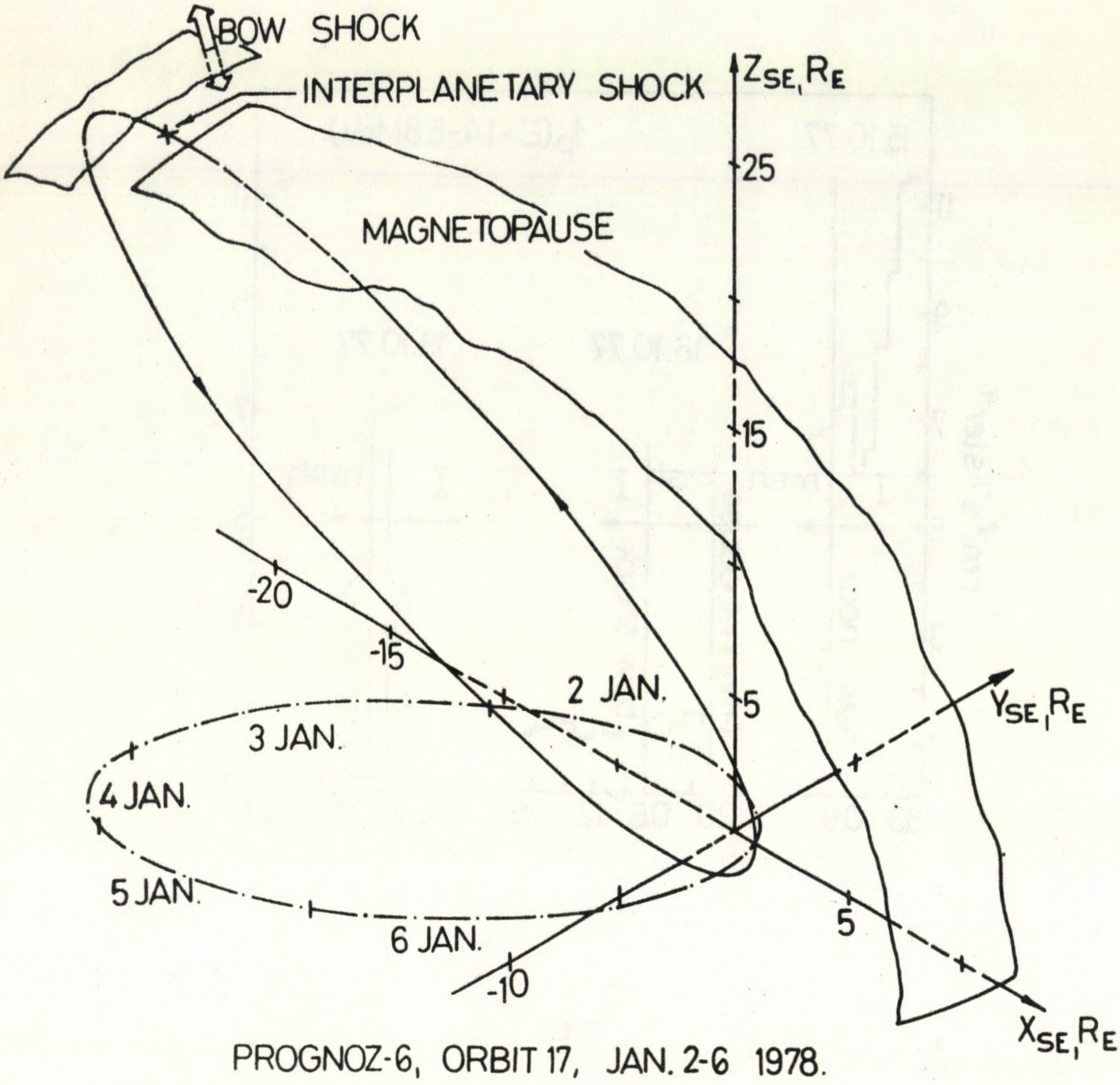

BOW SHOCK
INTERPLANETARY SHOCK
MAGNETOPAUSE
Z_{SE}, R_E
25
15
5
Y_{SE}, R_E
-20
-15
2 JAN.
3 JAN.
4 JAN.
5 JAN.
6 JAN.
5
-10
X_{SE}, R_E
PROGNOZ-6, ORBIT 17, JAN. 2-6 1978.

Fig.1

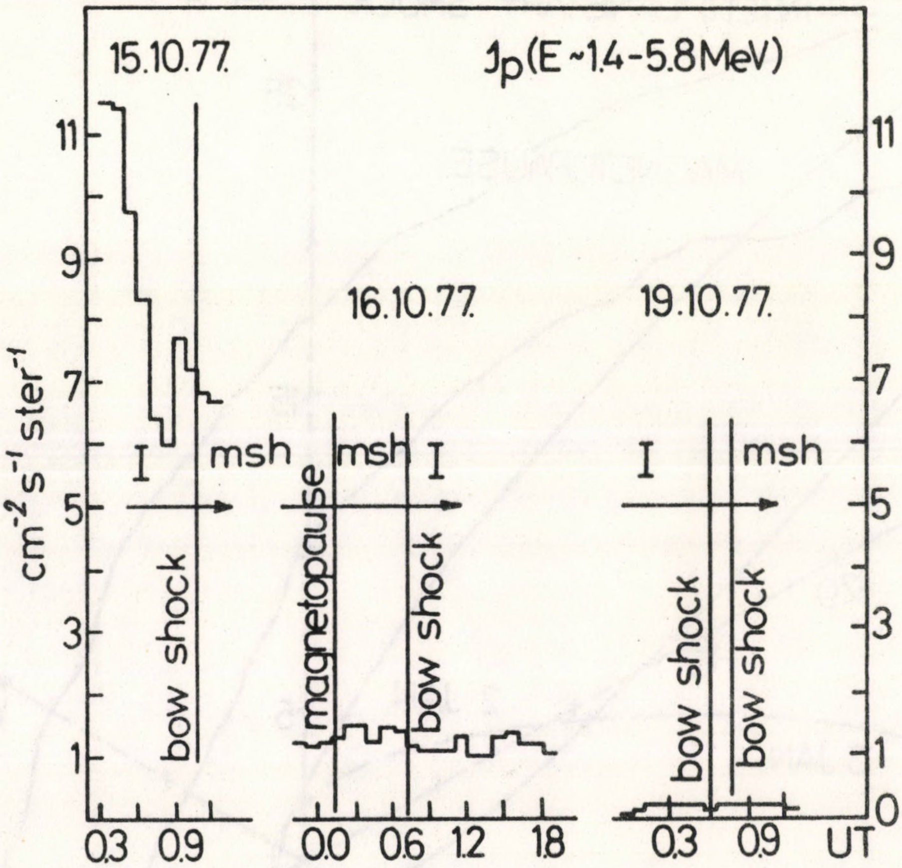

15.10.77.
Jp(E~1.4-5.8MeV)
16.10.77.
19.10.77.
cm-2s-1ster-1
I
msh
bow shock
magnetopause
0.3
0.9
0.0
0.6
1.2
1.8
UT
11
9
7
5
3
1
0

Fig. 2

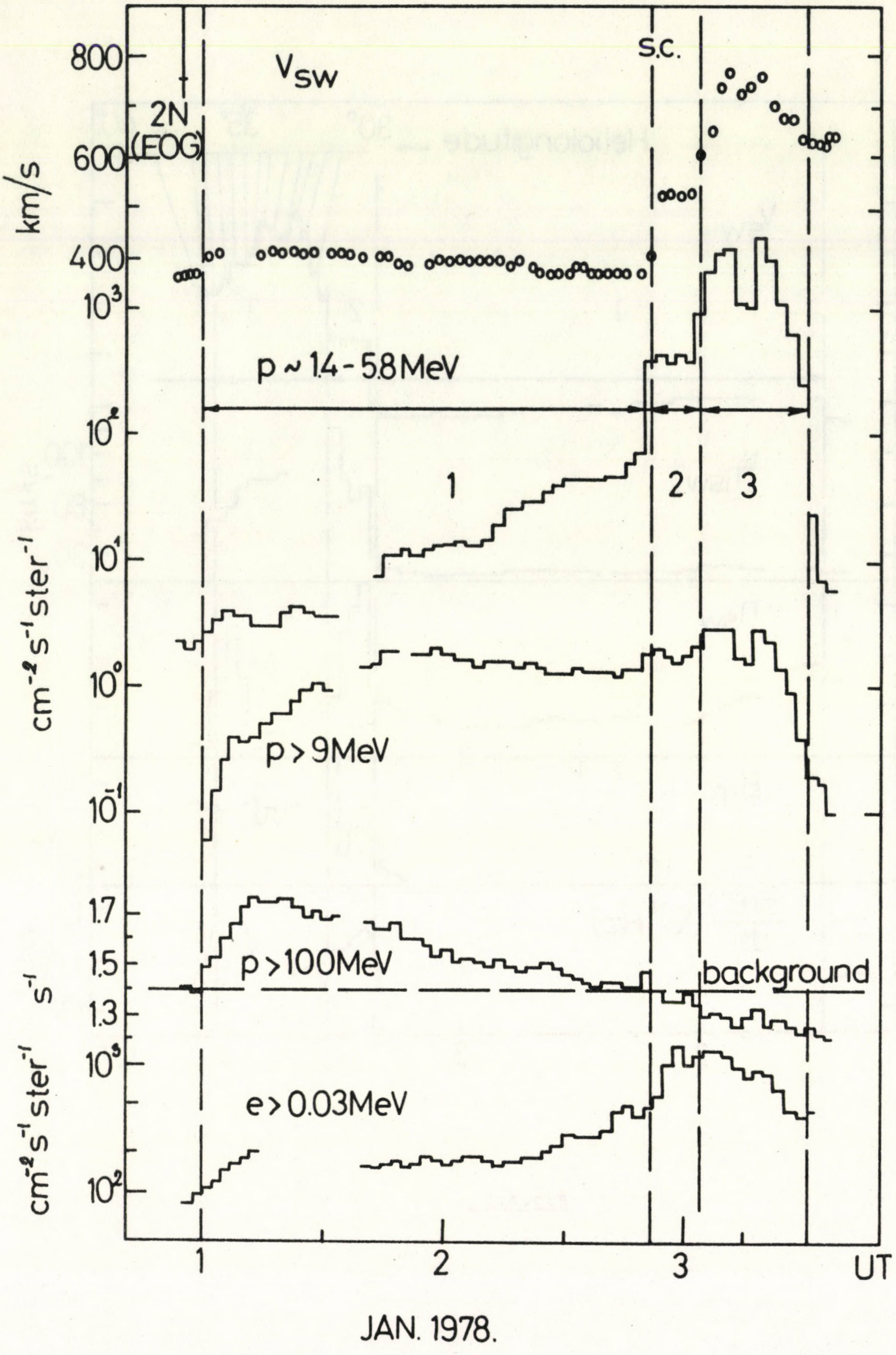

800
600
400
10^3
10^2
10^1
10^0
10^{-1}
km/s
$cm^{-2}s^{-1}ster^{-1}$
2N
(EOG)
V_{SW}
S.C.
p ~ 1.4 - 5.8 MeV
1
2
3
p > 9 MeV
1.7
1.5
1.3
10^3
10^2
s^{-1}
$cm^{-2}s^{-1}ster^{-1}$
p > 100 MeV
background
e > 0.03 MeV
1
2
3
UT
JAN. 1978.

Fig.3.a

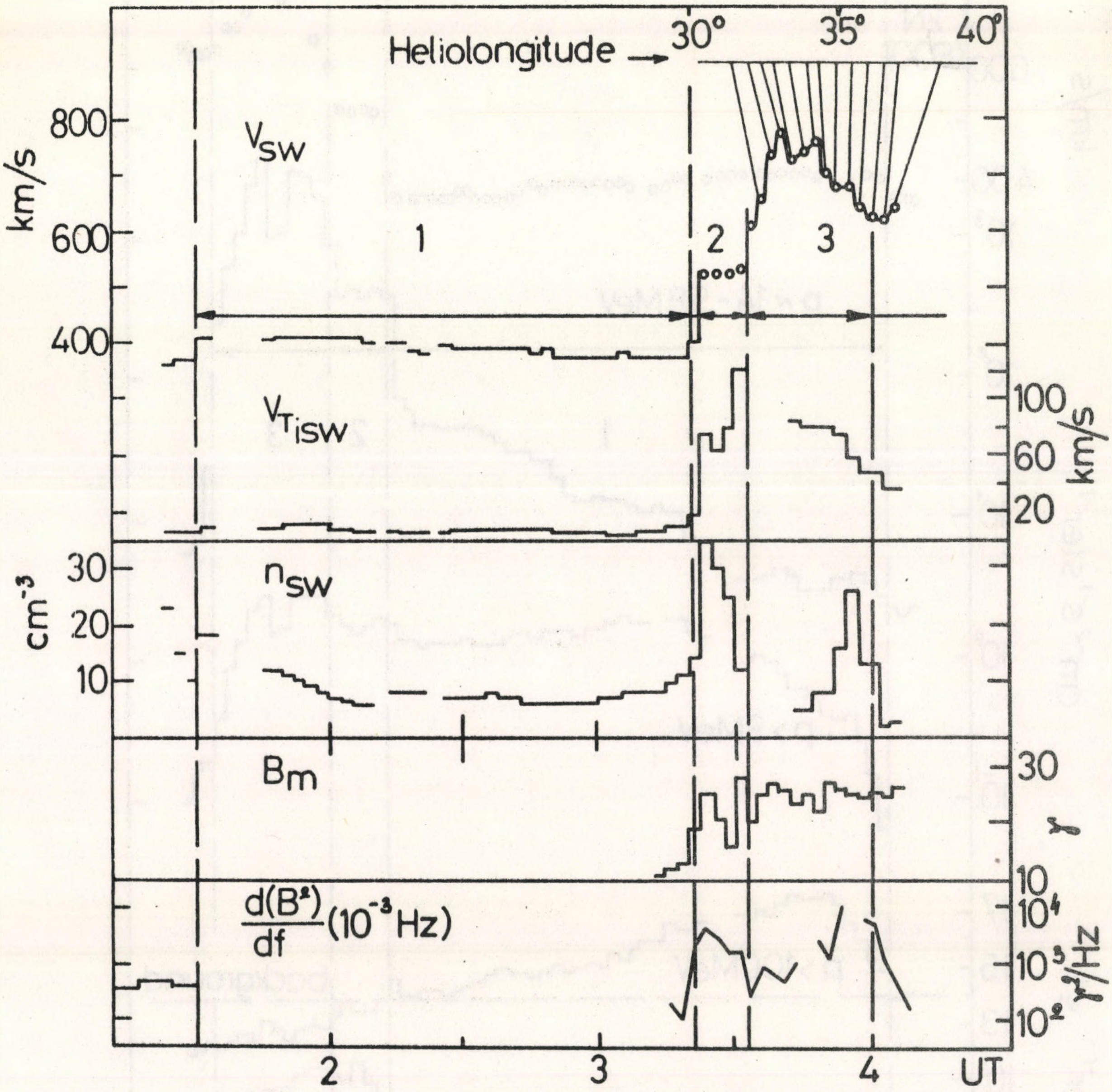

Heliolongitude
30°
35°
40°
km/s
800
600
400
V_{sw}
1
2
3
$V_{T_{isw}}$
100
60
20
km/s
cm^{-3}
30
20
10
n_{sw}
B_m
30
10
γ
$\frac{d(B^2)}{df}$ (10^{-3} Hz)
10^4
10^3
10^2
γ²/Hz
2
3
4
UT

Fig.3.b

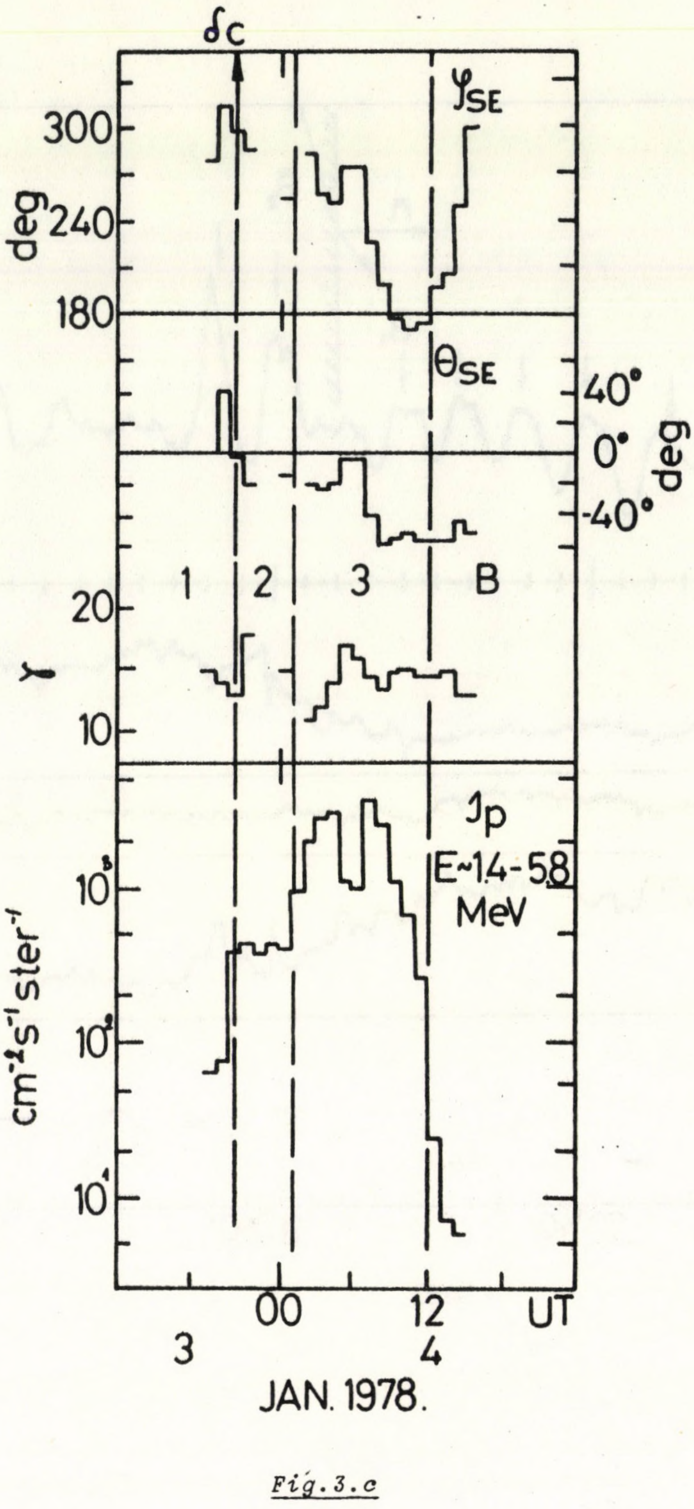

δc
φ_{SE}
300
deg
240
180
θ_{SE}
40°
0°
-40°
deg
1
2
3
B
20
γ
10
J_p
E~14-58
MeV
cm⁻²s⁻¹ster⁻¹
00
12
UT
3
4
JAN. 1978.

Fig. 3. c

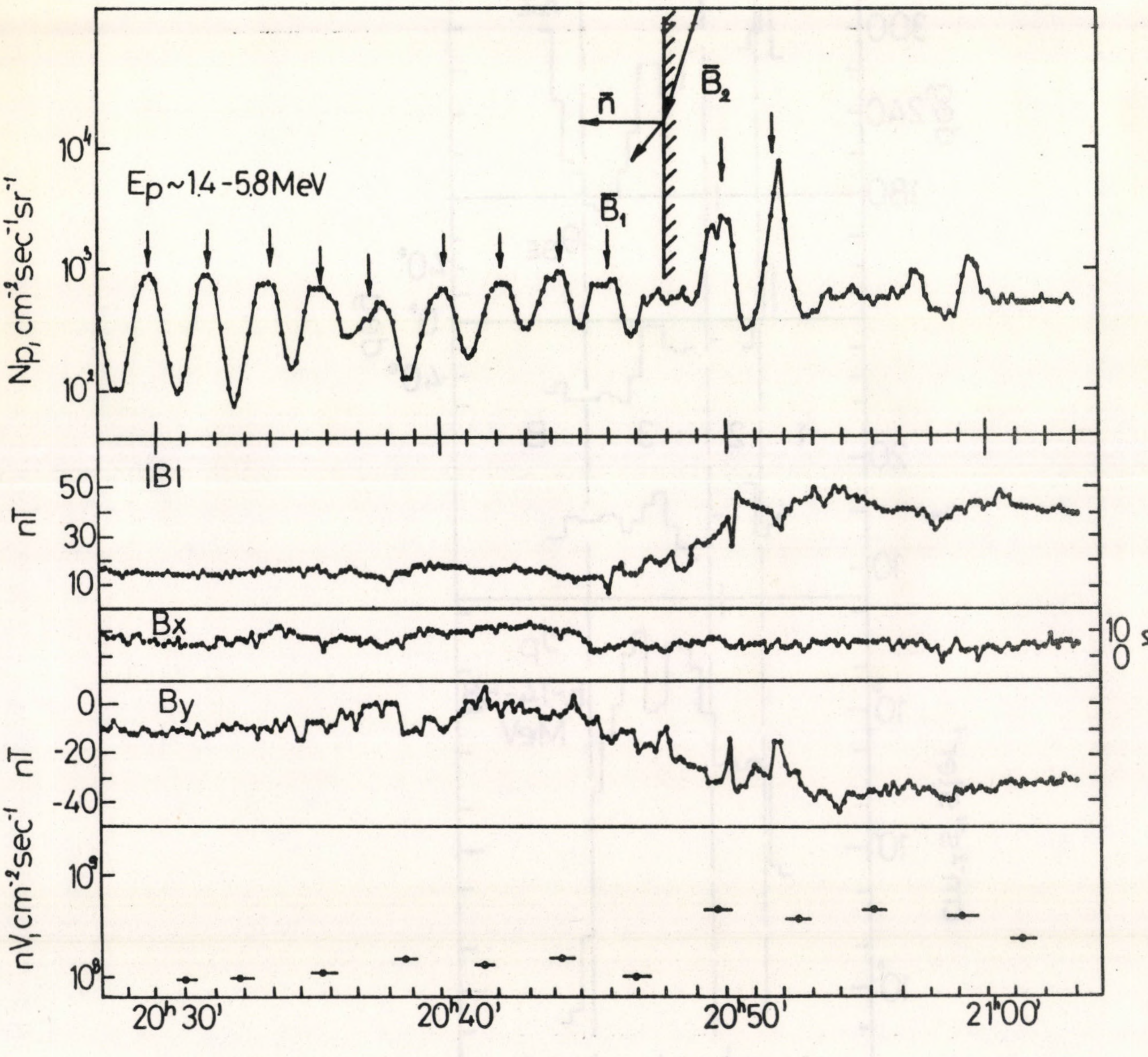

Ep~1.4-5.8MeV
$\bar{n}$
$\bar{B}_2$
B_1
10^4
10^3
10^2
Np, cm⁻²sec⁻¹sr⁻¹
IBI
50
30
10
nT
Bx
10
0
By
0
-20
-40
nT
nV, cm⁻²sec⁻¹
20h30'
20h40'
20h50'
21h00'

Fig. 4

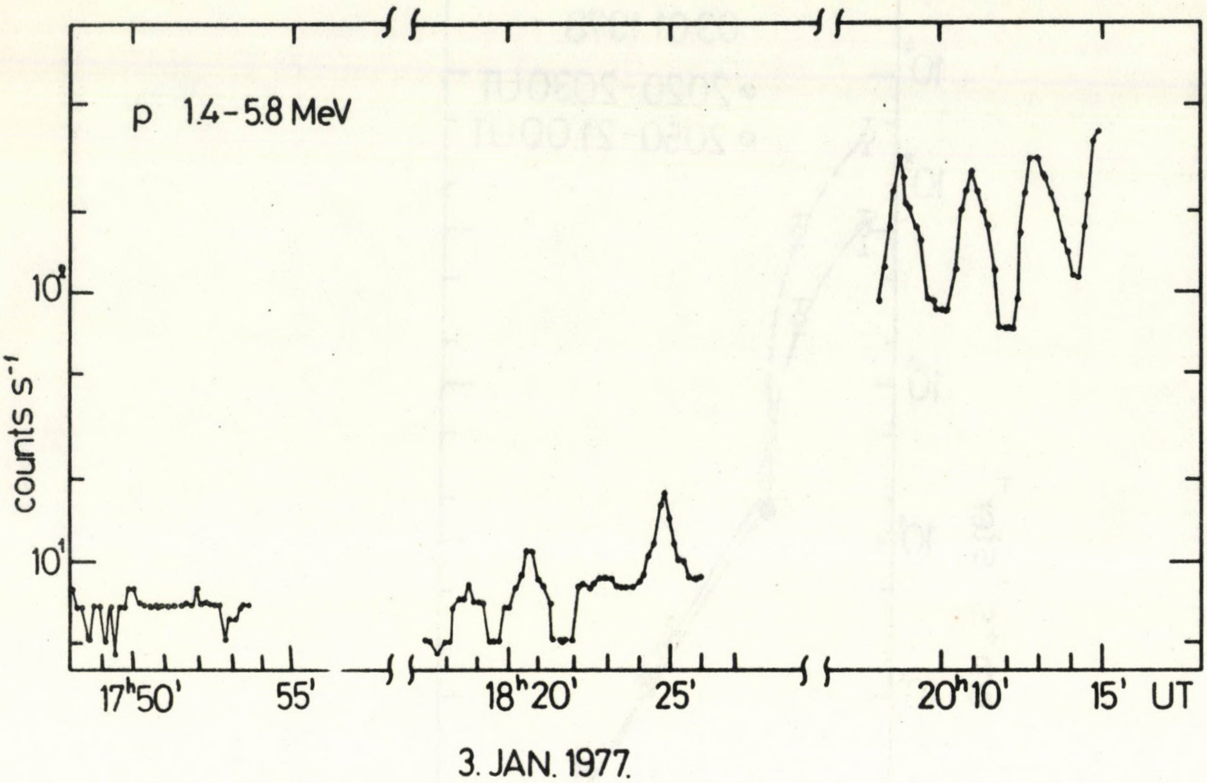
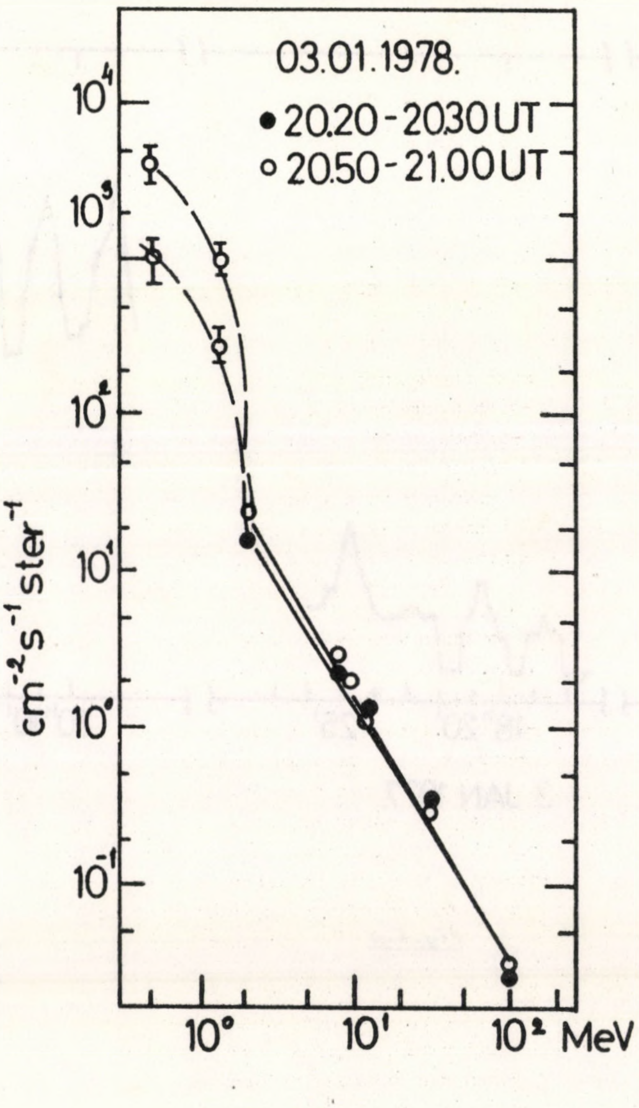

p 1.4-5.8 MeV
counts s⁻¹
10²
10¹
17ʰ50'
55'
18ʰ20'
25'
20ʰ10'
15' UT
3. JAN. 1977.

Fig.4.a



03.01.1978.
● 20.20 - 20.30 UT
○ 20.50 - 21.00 UT
10^4
10^3
10^2
10^1
10^0
10^{-1}
$cm^{-2}s^{-1}ster^{-1}$
10^0
10^1
10^2 MeV

Fig. 5

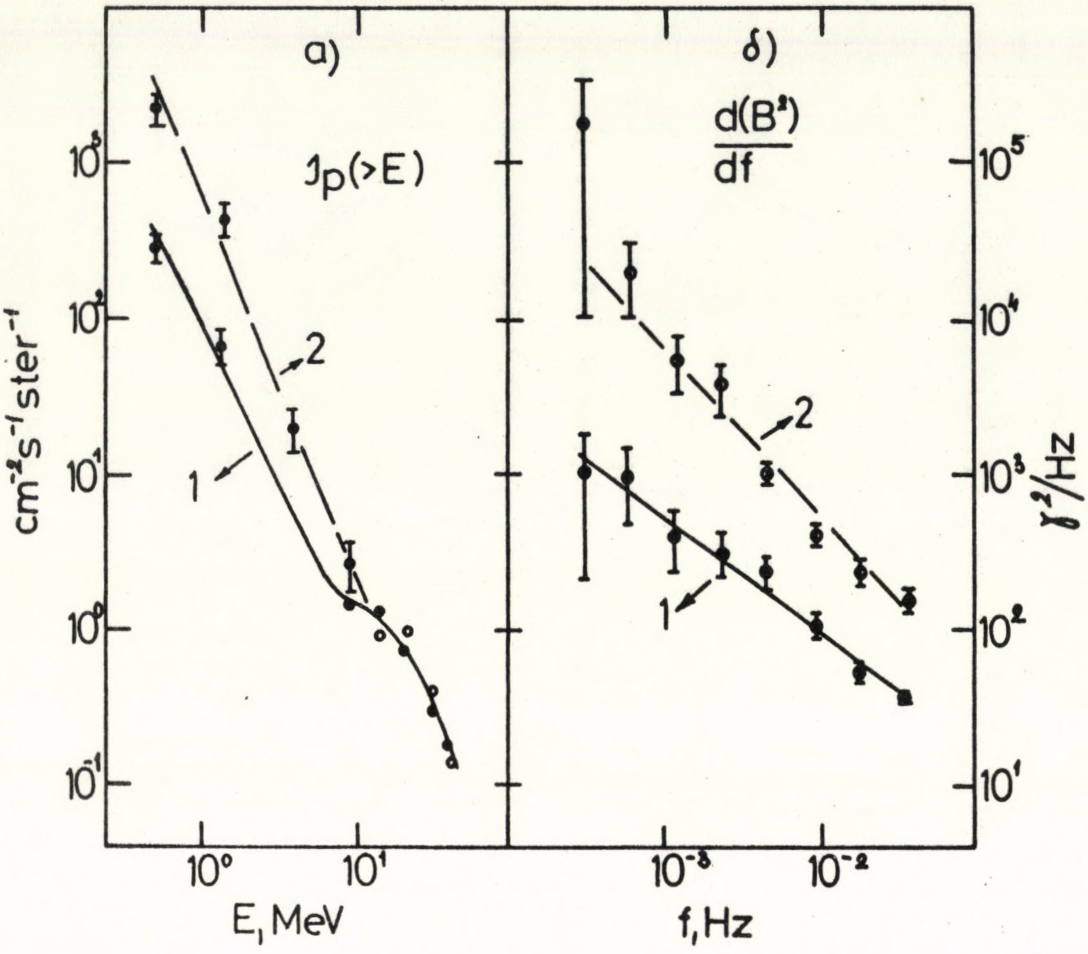

a)
$J_p(>E)$
10^3
10^2
10^1
10^0
10^{-1}
$cm^{-2}s^{-1}ster^{-1}$
1
2
10^0
10^1
E, MeV
δ)
$\frac{d(B^2)}{df}$
10^5
10^4
10^3
10^2
10^1
γ^2/Hz
1
2
10^{-3}
10^{-2}
f, Hz

Fig. 6

63012

Kiadja a Központi Fizikai Kutató Intézet
Felelős kiadó: Szegő Károly
Szakmai lektor: Benkó György
Nyelvi lektor: Varga András
Példányszám: 310 Törzsszám: 80-334
Készült a KFKI sokszorositó üzemében
Budapest, 1980. május hó