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Measurements of neutron fluxes with energies from thermal to several MeV in near-Earth space: SINP results

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Abstract

Neutron measurement results obtained at SINP MSU since 1970 are presented. These measurements were made using techniques based on neutron moderation and subsequent detection in a $Li^6I(Eu)$ crystal or a He^3 coronal counter. The measurements were mainly carried out in orbits with inclination of 52° and altitudes of 200–450 km. The spatial and angular distributions of the measured neutron fluxes were studied. The albedo neutron flux was estimated according to the count rate difference for opposite detector orientations towards Earth and away from it. This flux is comparable to the local neutron flux outside the Brazil anomaly region, where local neutrons dominate. Neutron fluxes, generated by solar protons, were detected during a solar flare on June 6, 1991 for the first time. Their spectrum was estimated as a power law with $\alpha > 2$.

1. Introduction

Recent investigations have shown that radiation dose onboard orbital space station "Mir" under shielding of some tens of g/cm^2 is mostly defined by neutron fluxes (Dudkin et al., 1996; Lyagushin et al., 1998). These results are summarized in Table 1. It is likely that a similar ratio of radiation doses will also exist onboard International Space Station (ISS). Neutron flux study in near-Earth orbits is also highly important for the background condition determination in solar neutron measurements. Study of spectral and spatial distributions of high-energy neutrons enables a correction in the intensity of the proton source in the Earth radiation belt at energies of tens–hundreds of MeV. Because of neutron decay, only solar neutrons with energy more than 10–20 MeV make it to Earth's orbit. Thus, for the study of background conditions for registration of these particles (as far as for estimation of the intensity of the radiation belt proton source), neutron measurements in the energy range above 10 MeV are necessary. On the other hand, input in equivalent dose of neutrons with energies 10–1000 MeV and of neutrons with energies 0.1–10 MeV is approximately equal (see Table 1). In the present work we will make an attempt to generalize the results of experimental studies of neutron fluxes and spectra in near-Earth space, which were obtained by SINP, MSU since 1970 up to recent times.

2. Measurement techniques

Two techniques were used at SINP MSU to detect neutrons with energies up to several MeV. In both cases the neutrons are moderated in a hydrogenous layer. In the first technique, neutrons are moderated in polyethylene, and detected by a LiI(Eu) crystal using the reaction

$$^6\mathrm{Li}(n,\alpha)^3\mathrm{H} + 4.78\ \mathrm{MeV}.$$

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Table 1
Equivalent doses from different investigators

Parameter	Daily equivalent dose (μSv/d) under different shield depths		Reference
	20 g/cm^2	30 g/cm^2	
Ionizing radiation dose in the solar activity maximum	143	92	Dudkin et al. (1996)
Neutron equivalent dose near the solar activity maximum	76	115	Lyagushin et al. (1998)
0.1–10 MeV neutron dose	38	58	Lyagushin et al. (1998)
10–1000 MeV neutron dose	37	56	Lyagushin et al. (1998)

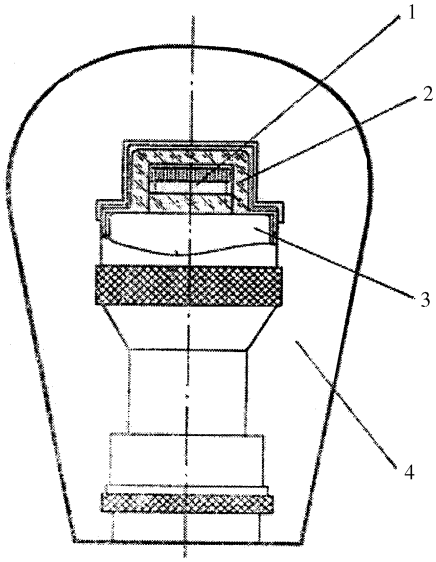

Fig. 1. Neutron detector based on ^{6}LiI scintillator: (1) LiI crystal; (2) anticoincident plastic scintillator; (3) PMT; (4) moderator of a polyethylene.

For charged particle rejection, the LiI(Eu) crystal is surrounded on all sides by a plastic scintillator. Both scintillators are viewed by the same PMT and event separation is based on light pulse shape analysis.

This detector was used for the first time by SINP in 1970 in an experiment onboard the "Molniya-1" satellite (Shavrin et al., 1972). This experiment showed that the chosen method successfully permits the study of fluxes of albedo and local neutrons. In further investigations, the instrument, modified in accordance with the results of the first experiment, was used onboard the satellite "Cosmos-557" and the orbital stations "Salyut", "Salyut-4" and "Salyut-6". A schematic drawing of the latest version of this type of detector is presented in Fig. 1 (Belyaev et al., 1984).

A LiI(Eu) crystal with dimensions 29.4×4 mm^2, enriched by ^{6}Li up to 89%, was used. An anticoincidence plastic scintillator had the dimensions of 60 × 34 mm^2. The mean thickness of the polyethylene moderator was 7 cm onboard "Cosmos-557" and "Salyut" and 2.5 cm onboard "Salyut-4" and "Salyut-6". Neutrons were separated from γ-rays due to the high threshold of event detection in LiI (3.9 MeV). Detector calibrations were made in the metrology laboratory of the D.I. Mendeleev All-Union Research Institute of Metrology. Dependencies of instrument effective area on the inclination angle, on the neutron energy and the probability of neutron event imitation by charged particles and γ-rays were studied. The obtained dependence on the neutron energy for a mean moderator thickness of 7 cm for neutrons, falling along the detector axis, is shown in Fig. 2 (Razumov, 1973).

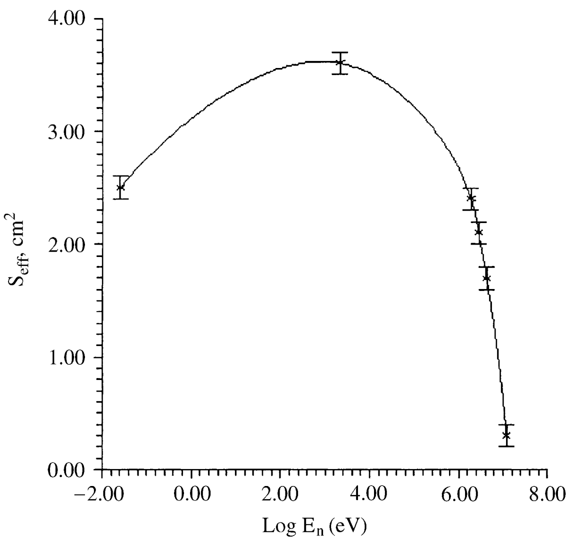

Fig. 2. Dependence of the effective area of the detector shown in Fig. 1 on the neutron energy for mean thickness of polyethylene moderator equal to 7 cm.

The shape of energy and angular dependence of the effective area is determined by the moderator thickness. The effective area maximum shifts to higher energies if thickness increases. For a thickness of 2.5 cm, the effective area dependence on energy is similar to the analogous characteristic of a Bonner sphere of the same thickness (Bramlett et al., 1960); its effective area for mean neutron energy 1.9 MeV (isotope ^{252}Cf) is 1.0 cm^2. Effective area dependence on α (the angle between the detector axis and direction to the neutron source) was found to be

$$S(\alpha) = 0.25\, S_0(3 + \cos\alpha).$$

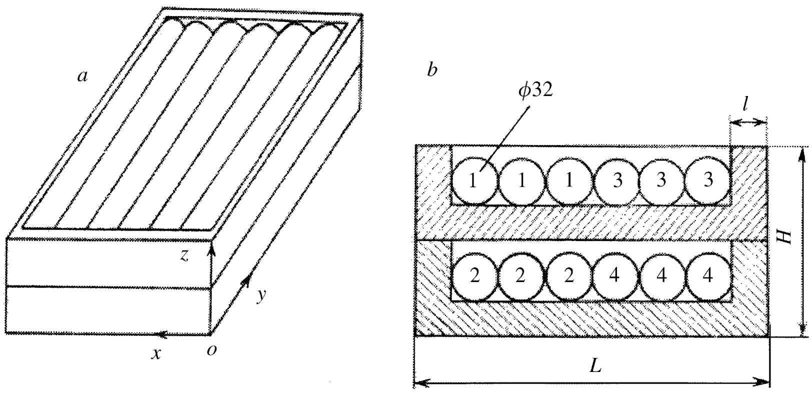

Fig. 3. Neutron detector based on ^{3}He counters.

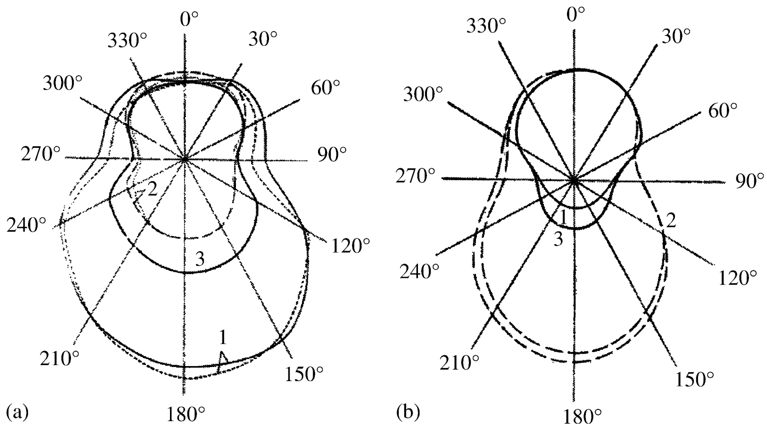

Fig. 4. Measured angle dependencies of helium detector for fast (a) and slow (b) neutrons: (1) open counters (odd triads); (2) shielded counters (even triads); (3) summary dependence of counter on the whole.

In the second technique, neutrons after their moderation are detected by helium coronal counter according to the reaction

$$^3\mathrm{He(n,p)}^3\mathrm{H} + 0.76\ \mathrm{MeV}.$$

A schematic drawing of this detector is presented in Fig. 3 (Bratolyubova-Tsulukidze et al., 1991). The detector consists of 12 helium coronal counters with a diameter of 32 mm and a length of 220 mm. The counters were grouped into triads with the same output and positioned in a plexiglass moderator in such a way that two triads (with numbers 2 and 4) are surrounded by a 15-mm moderator layer from all sides and another two triads are open from one side. In addition, the detector was surrounded by 0.27 g cm^{-2} of Al and 0.2 g cm^{-2} of Fe. An event was interpreted as a neutron detection if the energy release in the helium counter was above 0.25 MeV. For such a threshold, the registration efficiency for thermal neutrons, coming from the direction of the normal to the longitudinal axis of the counter, was $\sim$ 80%, and the efficiency of γ-ray and charged particle registration was small. The detector was used in the experiment onboard module "Kvant-2" of the "Mir" orbital station.

Detectors of the second type, as with the first type ones, were calibrated in the D.I. Mendeleev All-Union Research Institute of Metrology. In the chosen geometry the sensitivity of even and odd triads to fixed energy neutrons is not the same and depends on the angle with the counter axis. For odd triads, opened in the front side, the sensitivity maximum is at angles of $\sim$ 180°, and for even triads the angular dependence is practically symmetric relative to the plane normal to the counter axis and crossing its center. Measured angle dependencies are shown in Fig. 4 (Bratolyubova-Tsulukidze et al., 1991). The difference between similar curves is due to individual counter features and may be used as an accurate estimate of calibration. Such detector geometry permits comparison of neutron fluxes, falling from directions 0° and 180°, and allows us to estimate the ratio of albedo and local neutron fluxes.

The total detector area sensitive to thermal neutrons is equal to 108 cm^2 and decreases to 2.3 cm^2 at an energy of ~ 4 MeV. Thus, in comparison with the first type of detector, the second type has significantly more simple and thus more reliable electronics and a significantly higher efficiency of neutron detection. From the outer space direction, the effective detector area may be approximated by the following expressions:

For an unshielded counter

$$S\ (\mathrm{cm}^2) = 0.045E^{-0.5} + 4.0E^{-0.11}\exp(-0.43E),$$

where E is measured in MeV. For a shielded counter

$$S\ (\mathrm{cm}^2) = 5.87E^{-0.104}(1\text{–}2.3\times10^{-4}E^{-0.5})\exp(-0.28E).$$

For a shielded counter from the "Mir" station direction

$$S\ (\mathrm{cm}^2) = 5.87E^{-0.104}\exp(-0.28E).$$

Unfortunately, the available calibrations do not make it possible to define accurately the area of an unshielded counter sensitive to neutrons, generated in the spacecraft. Its effective area is smaller by approximately a factor of 1.5–2, than that of the shielded counter.

3. Albedo neutron measurements

Investigations of neutron fluxes in the energy range < 10 MeV were mainly made for three purposes:

1. Study of the latitude dependence, angular distributions and absolute values of albedo and local neutron fluxes outside the Earth's radiation belts.
2. Study of spatial and angular distributions of local neutrons in the inner radiation belt.
3. Study of neutron fluxes, generated in atmospheric interactions with solar cosmic ray protons (SPAND).

The relation of albedo and local neutron fluxes, and the latitude dependence of these components outside the Earth's radiation belts was studied since the first neutron experiments of SINP, MSU (Shavrin et al., 1972; Razumov et al., 1973). Latitude dependencies of measured neutron fluxes under the Earth's radiation belts are similar to the dependencies of cosmic rays. This fact can be naturally explained by the circumstance that neutrons are born in interactions of cosmic ray protons with the Earth's atmosphere (CRAND), the spacecraft, or the detector itself. The obtained curves in the regions of low and medium latitudes are well approximated by the parameter L^2. For $L = 2$–3, neutron fluxes achieve their maximum values and, for higher L, become practically independent of latitude. According to the data of the experiment onboard the "Cosmos-557" satellite, launched 11.05.1973 in orbit with apogee 250 km, perigee 210 km and inclination 52°, detected neutron fluxes varied from approximately 0.1 cm^{-2} s near the geomagnetic equator to $\approx$ 1.0 cm^{-2} s in the region of high-latitude plateau (Razumov, 1973). The satellite rotated so sometimes the detector was screened from the Earth by the massive satellite body, i.e. screened from albedo neutrons, while at other times it was open to albedo neutron detection. Comparing these two cases, Razumov (1973) showed that the local neutron flux was 0.06 cm^{-2} s near the equator and $\approx$ 0.6 cm^{-2} s at high latitudes. Similar latitude dependence and absolute values of the detected neutron flux were obtained on "Salyut-4" orbital station in 1975 (Lyagushin et al., 1984). The most suitable conditions for measurements of local radiation fluxes were onboard satellite "Molniya-1" (Razumov, 1973). This satellite had a high-elliptical orbit with a perigee of 400 km and an apogee of 39 600 km. At apogee, the detected neutron fluxes were dominated by local neutrons. The apogee flux for the time interval December 1970 to January 1971 was found to be 0.4–0.6 cm^{-2} s. For the same time interval, the albedo neutron flux was determined from the perigee data and was found to be 0.72 ± 0.17 cm^{-2} s.

A more accurate study of neutron flux latitude dependencies was carried out in later experiments. On the high-latitude plateau, the cosmic ray flux depends on solar activity level to the maximum degree. Thus, this region is the most appropriate one to search for the connection between the neutron fluxes measured onboard spacecraft with solar cycle phase.

Measurements onboard the orbital station "Salyut-6", made by the same instrument in the same geometry, showed that in July–August 1978, in April 1979 and in June–August 1980 the neutron fluxes at $L > 3$ were the same to an accuracy of $\pm 10\%$. At the same time, the total fluxes of protons with energy > 50 MeV and electrons with energy > 5 MeV, measured by the same instrument were decreasing significantly (Yushkov, 1988).

The neutron detector in the experiment onboard orbital station "Salyut-6" was positioned on its outer surface. The station's orientation varied. If the instrument axis was directed to zenith, the detector was screened from albedo neutrons by station mass with a mean thickness of ~ 200 g/cm^2, and practically only local neutrons were detected. For the case of the axis orientation to nadir, the detector measured the sum of local and albedo neutron fluxes. Difference in the data from these two orientations can be interpreted as the albedo neutron flux (Lyagushin and Shavrin, 1992). The latitude dependence of neutron fluxes measured onboard "Salyut-6" in 1979–1980 (Yushkov, 1988; Lyagushin and Shavrin, 1992) agrees well with the "OGO-6" results (Lockwood, 1973) and results from theoretical calculation (Lingenfelter, 1963).

Fig. 5 presents the dependence averaged along station orbit of the relative count rates $N(\Theta)/N(0)$ on the zenith angle of detector Θ. Under the assumption that the local neutron count rate is independent of zenith angle and accounting for detector sensitivity measured in laboratory condition before the flight, the albedo neutron angular distributions were

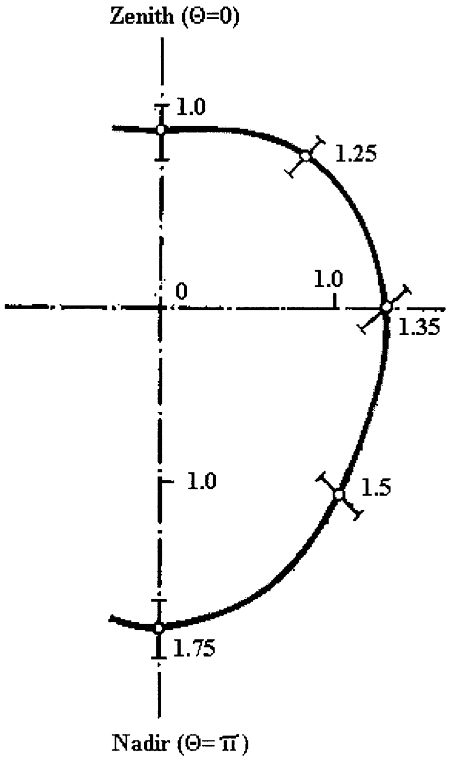

Fig. 5. Angular distribution of the neutron count rate measured onboard "Salyut-6".

estimated as

$$F(\Theta) = 1 + 0.65\cos^4\Theta, \qquad 0 \leqslant \Theta \leqslant 90^\circ.$$

For $\Theta = \pi$, the albedo neutron flux is $\sim$ 75% of the local neutron flux (Lyagushin and Shavrin, 1992).

The neutron spectrum estimation was made using the count rate difference of the shielded and unshielded counters in the whole range from $L = 1$ to 6 onboard the "Mir" station (Dmitriev et al., 1998). Assuming that the neutron spectrum has the shape calculated by Lingenfelter (1963) with cut-off at the energy 2×10^{-7} MeV, the albedo neutron flux can be described by the following equation:

$$\mathrm{d}N/\mathrm{d}E = 0.019L^{1.916}E^{-0.8}\ (\mathrm{cm}^{-2}\ \mathrm{s\ MeV}).$$

Under the assumptions that local neutrons are not yet thermal at the moment they leave the orbital station and that the shape of the spectrum can also be described by the dependence calculated by Lingenfelter (1963), the cut-off in the neutron spectrum will occur at energy $\sim 10^{-3}$ MeV. The local neutron spectrum will have the same shape as the albedo neutron spectrum, but the coefficient in the equation will be 0.029 instead of 0.019.

The dispersion of the ratio of albedo and local neutron fluxes, experimentally obtained by SINP MSU, is not unexpected, because this ratio depends both on the spacecraft type (its mass and geometry) and on the real experiment geometry. In any case, at energy < 10 MeV, local neutron fluxes outside the Earth's radiation belts are somewhat higher, though they do not differ strongly from albedo neutron fluxes.

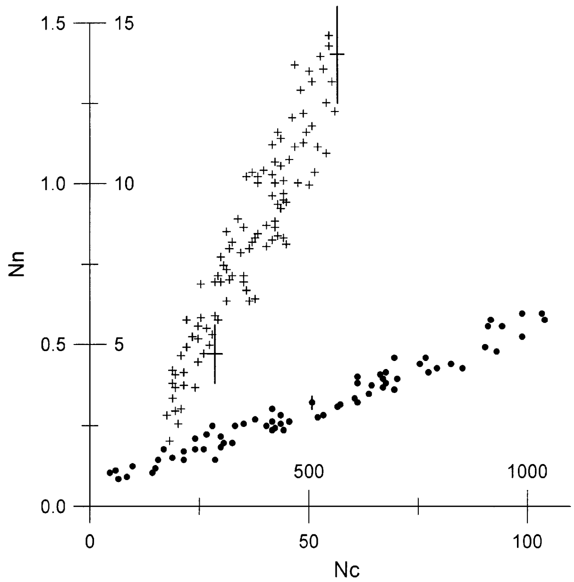

Fig. 6. Neutron count rate (N_n) versus charged particle one (N_c, both rates in s^{-1}) in the SAA region (solid circles, upper and right scales on axes) and outside this region (crosses, lower and left scales on axes).

4. Neutron fluxes in the South Atlantic Anomaly

In measurements in the inner radiation belt, which is crossed by low-orbiting spacecraft in the South Atlantic (Brazil) magnetic anomaly (SAA) region, local neutron flux dominates. The difference in the ratio of local neutron and charged particle fluxes (protons with $E > 50$ MeV and electrons with $E > 5$ MeV) inside the SAA from that outside the SAA is shown in Fig. 6 (Yushkov, 1988). The results come from Salyut-6 measurements made during July–August 1980. Similar results were observed during other periods. The ratio of neutron and charged particle counting rates, defined by the slope of the regression line, is 1:40 outside the SAA and 1:190 inside it. This difference arises from the fact that, in the region of the SAA, the main yield in the charge particle count rate is due to protons with energies 50–100 MeV. These protons have lower local neutron producing efficiency in comparison to cosmic ray protons, that determines the charge particle detector count rate outside the SAA. *On the other hand, the detection efficiency distinction may take place due to distinction of local and albedo neutron spectra.*

The "Salyut-6" experiment results showed that the neutron flux angular distribution in the inner radiation belt is

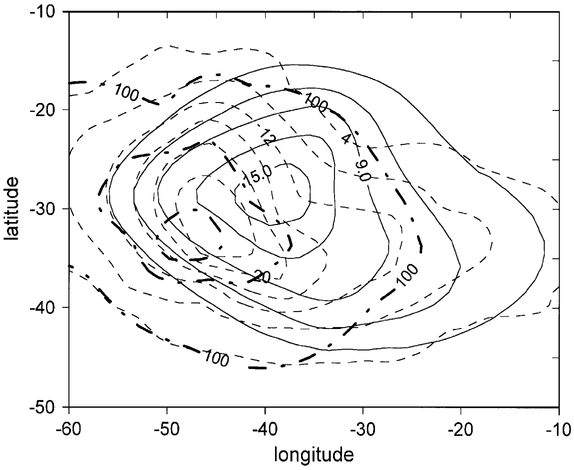

Fig. 7. Particle distributions in the SAA region (in cm^{-2} s^{-1}): (1) neutron flux measured onboard "Salyut-6" in 1979 (solid line, values contain one decimal digit after point); (2) neutron flux measured onboard "Mir" in 1999 (dashed line, values are integer); (3) charged particle count rate (in s^{-1}) onboard "Mir" in 1999 (bold dashed line, maximum level corresponds to 300 s^{-1}).

close to isotropic (Lyagushin and Shavrin, 1992). A map of lines with equal neutron detector counting rates in the SAA region was obtained from this experiment data (Lyagushin and Shavrin, 1992). This map is presented in Fig. 7 and supplemented by the "Mir" data. The "Salyut-6" data correspond to levels from 3 up to 15 cm^{-2} s. The drift of the local neutron flux maximum is similar to that of the charged particle flux maximum (Lauriente et al., 1996). The difference in absolute value may be due both to the orbit altitude difference and to the spacecraft mass distribution and its chemical composition in the detector vicinity. The westward drift of the charged particle maximum, measured by GM counter under 2 g cm^{-2} shielding, relative to the neutron maximum may be explained by the electron contribution in the GM count rate.

The neutron flux dependence on the L parameter value in the inner radiation belt for altitudes of about 400 km was obtained in the experiment onboard the "Mir" station (Dmitriev et al., 1998).

5. Solar proton albedo neutrons

Long term observations of neutron fluxes onboard the "Mir" station allowed the detection of Solar Proton Albedo Neutrons–neutrons born in the solar cosmic ray (SCR) proton interactions with the Earth's atmosphere. Besides neutron detector data, proton measurement results from the "Mir" station were used (Bratolyubova-Tsulukidze et al., 1995). The SCR detector was based on a GM counter. It is a spherical detector and detects particles coming from all directions. Minimum shielding corresponds to protons

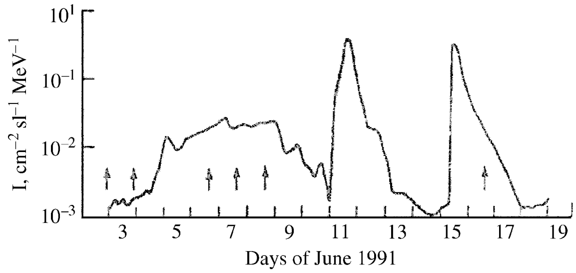

Fig. 8. Proton fluxes in June 1991.

with $E \sim 50$ MeV, and maximum shielding to protons with $E_p \sim 600$ MeV. Due to conditions of SCR shielding by the Earth in various orientations of "Mir" station, the minimum energy of protons detected by the counter may change from 50 to 150 MeV.

Fig. 8 shows the flux of protons with the energy $E_p \sim$ 84–200 MeV obtained onboard the "GOES-7" satellite during the period 3.06.1991–18.06.1991. The arrows indicate times for which the data from the detector onboard the "Mir" station exist. On June 3, the latitude dependence of the neutron flux was very close to that measured during other periods when SCR fluxes were not observed. On June 6–8 and 16, according to the "GOES-7" data, SCR fluxes should be detected in the polar regions. Fig. 9 presents data on the neutron and proton fluxes onboard station "Mir", measured during one orbit on 8.06.1991.

Table 2 presents the SCR proton flux J (proton energy is $E_p > 84$ MeV) measured onboard "GOES-7" for the time when "Mir" station was at high latitudes (June 3, 6–8 and 18). This table also contains neutron count rates measured by two neutron counters (shielded N_1 and unshielded N_2) and the charged particle count rate N_p from "Mir".

If we subtract the data measured on June 3 from the data measured on June 6–8 and 16, the effects connected with SCR may be estimated. To within a factor of 2, the data obtained at high latitudes were the same as the "GOES-7" data. The ratio of the shielded neutron detector's count rate to the open detector's count rate for GCR albedo neutrons is $\sim$ 1.3–1.5. For SCR albedo neutrons this ratio decreases to ~ 0.6. This is connected with the softer spectrum of SCR albedo neutrons.

The instruments detect neutrons with $E < 2$–3 MeV. If the shape of the albedo neutron spectrum follows a power-law $N/\mathrm{d}E = kE^{-\alpha}$, the ratio of the data from the two detectors is a function of α. For GCR, we typically obtained $\alpha \leqslant 2$. For SCR albedo neutrons on June 6–8 and 16 we need to accept $\alpha > 2$.

The absolute flux of solar proton albedo neutrons for the 8.06.1991 event was found to be

$$\mathrm{d}N/\mathrm{d}E = 4.3 \times 10^{-5}/E^2 \ (\mathrm{cm}^{-2}\ \mathrm{MeV}^{-1}).$$

In this calculation the energy of detectable neutrons was taken to be > 10 eV.

Table 2
Charged particle and neutron fluxes measured in June 1991

	Day of June	3	6	7	8	18
SCR proton flux	J("GOES-7"), cm^{-2} s sr	0.2	1.9	4	3.1	1.4
Neutron count rate	$N1$, s^{-1}	4.5	55	90	100	100
Neutron count rate	$N2$, s^{-1}	6	30	50	60	45
Charged particle count rate	N_p ("Mir"), s^{-1}	13	22	60	60	50

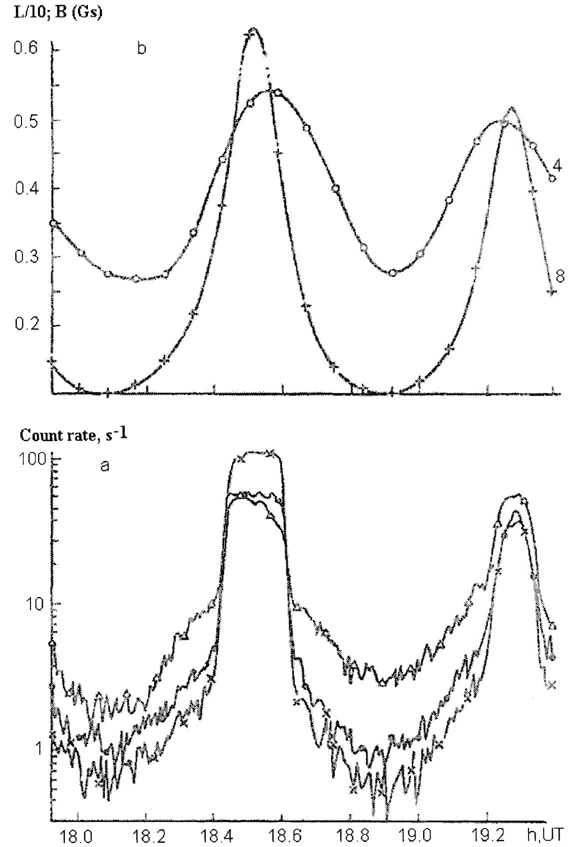

Fig. 9. Geomagnetic coordinates (upper panel) and measured particle count rates during one orbit on 8.06.1991 (lower panel): protons (triangles) and neutrons (shielded counter—solid circles, unshielded one—crosses).

It is important to state that SCR albedo neutrons were also measured on 10.05.1992. In this event, the neutron spectrum was significantly softer than in June 1991.

In these experiments, we measured the fluxes of SCR neutrons onboard station "Mir" for the first time. For energies from 10 eV to 2 MeV, the differential spectrum has a spectral index of $\alpha > 2$. It is necessary to note that the proton spectrum in the 15–84 MeV range, measured by "GOES-7", was at this time $\alpha \sim 1.5$.

6. Conclusions

Long-term studies in near-Earth orbits performed by SINP resulted in the spatial and angle distributions of neutron fluxes. Variations in neutron fluxes with the solar activity phase were not observed. At energies < 10 MeV the local neutron fluxes outside the Earth's radiation belts are somewhat higher, but they do not differ strongly from the albedo fluxes. The neutron detector count rate in the inner radiation belt region is mainly caused by local neutrons.

Fluxes of SCR neutrons were measured onboard station "MIR" for the first time. At energies from 10 eV to 2 MeV, the differential spectrum has spectral index $\alpha > 2$.

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