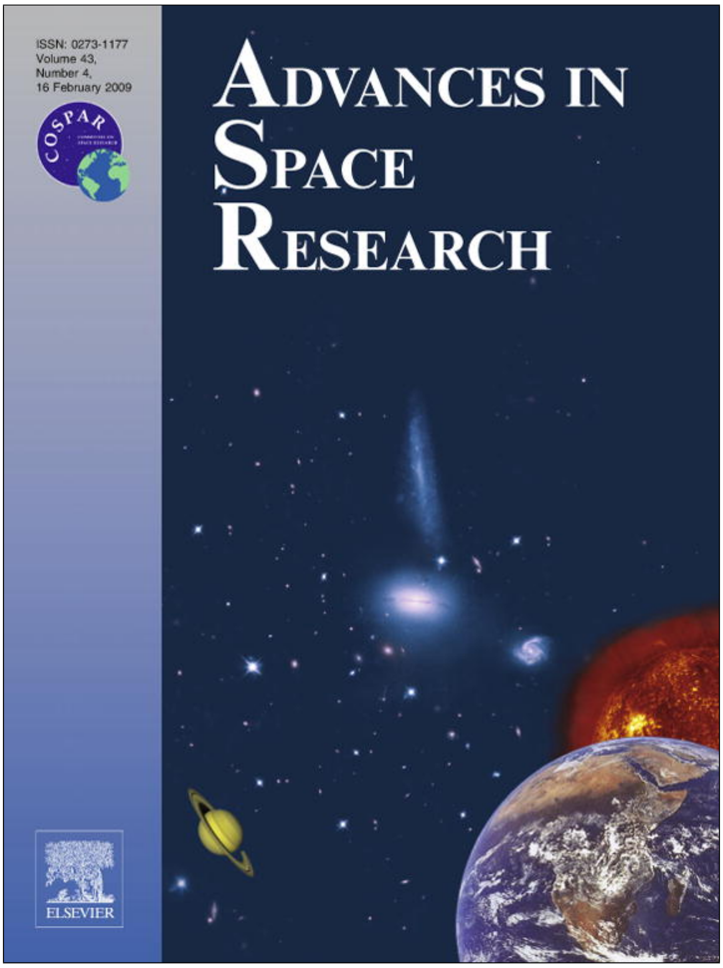
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Creation of model of quasi-trapped proton fluxes below Earth's radiation belt

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Abstract

The object of investigation is the phenomenon of proton (from tens keV to several MeV) flux enhancement in near-equatorial region ($L < 1.15$) at altitude up to ~1300 km (the storm-time equatorial belt). These fluxes are quite small but the problem of their origin is more interesting than the possible damage they can produce. The well known sources of these protons are radiation belt and ring current. The mechanism of transport is the charge-exchange on neutral hydrogen of exosphere and the charge-exchange on oxygen of upper atmosphere. Therefore this belt is something like the ring current projection to low altitudes. Using the large set of satellites data we obtain the average energy spectrum, the approximation of spectrum using kappa-function, the flux dependence on L, B geomagnetic parameters. On the basis of more than 30 years of experimental observations we made the empiric model that extends model of proton fluxes below 100 keV in the region of small L-values ($L < 1.15$). The model was realized as the package of programs integrated into COSRAD system available via Internet. The model can be used for revision of estimation of dose that low-orbital space devices obtain.

Keywords: Quasi-trapped protons; Earth magnetosphere; Geomagnetic storms; Modelling; Storm-time equatorial belt

1. Introduction

In 1969 Moritz discovered the band of low-energy protons precipitation near the geomagnetic equator ($L \lesssim 1.15$) at altitudes below 1000 km using the AZUR satellite data. It was found that enhancements of proton flux with energies from ~10 keV to several MeV are regularly observed in the equatorial region. It was proposed that their existence can be explained by the double charge-exchange mechanism. In that suggestion the ring current and radiation belt protons interacting with neutral atoms (mainly hydrogen) of upper atmosphere on the altitudes 1.5–10.0R_e (R_e – Earth radius) produce the energetic neutrals. These neutrals can reach low altitudes and after the interaction with the Oxygen atoms they can be trapped again. The experimental evidences for the model described above were published by Moritz (1972), Hovestadt et al. (1972), Mizera and Blake (1973). Later Greenspan et al. (1999) studied the long-term variations of proton flux using SAMPEX data on protons >770 keV and found that in the period of solar minimum near 1997 year there is minimum of observed flux. They confirmed also the results of Butenko et al. (1975) where the day–night asymmetry of proton (70–500 keV) flux was reported. Biryukov et al. (1996) using the SPRUT-V device onboard MIR station sorted the events into groups in north and south geographic hemispheres and found that there are two maxima of proton (>100 keV) flux: one at geomagnetic equator directly (in north hemisphere) and the second at $L \sim 1.1$ (in south hemisphere). The results of Grigoryan et al. (2002) and Grachev et al. (2002) showed that L-profile of proton flux has two maxima or more and there is minimum of flux at the equator ($L < 1.04$) directly. The information about the shape of L-distribution and the dependence on the magnetic local time was explained in work of Søraas et al. (2003). Later almost the same author collective Sørbø et al. (2006) found the calculations of Tinsley (1979). This

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work explains how the isotropic pitch-angle distribution of protons in radiation belt during the start phases of magnetic storm produce the near-equatorial proton flux distribution that has one maximum near equator and second at magnetic latitude about 30°. But these two additional maxima exist only for short time and we do not take it into account in this paper.

In spite of progress in last years there is necessity for creation of empiric model of these proton fluxes. Such models can be used for calculations of dose adsorbed by surface of space apparatus.

The most common used NASA radiation models AP8/AE8 are based on experimental data of the 60th and do not take into account the near-equatorial proton formation. The proton model AP8 predicts fluxes of protons with energies from 100 keV to 400 MeV at $L > 1.15$. These models take into account the 11-year solar cycle but do not take into account short-term variations of geomagnetic activity. The model requires extension to the region of small energies and small L.

2. Experiments and orbits

The orbit parameters, the type of detector used and energy of registered protons are presented in Table 1. The region of $L < 1.15$ is near equator so we can use only the low-orbit satellites (apogee up to 1000 km). The inclinations of satellites have not essential importance and we can use the whole range of satellites from near-equatorial to polar. We use data on protons with energies from ~10 keV to ~10 MeV. These protons usually registered by gas-discharge counters (Kosmos-484) or semiconductor detectors (most of other satellites). Let us look on the construction of MEPED detector on NOAA POES satellite. To protect the detector from electrons up to ~700 keV the magnetic filter in input collimator used. The sides of detector are protected by high-density metal alloy to prevent the propagation of high-energy protons through the shielding of detector. Two layers of semiconductor detector allow registering the protons up to ~7 MeV only. The only upper detector used to get information about particle energy. The fact of registration of particle in both detectors shows that particle energy exceeds the upper limit.

3. The input data for model: LEP model

Fig. 1 shows the average energy spectrum of near-equatorial protons ($L < 1.15$) with pitch-angles near 90° according data of several space missions. Every point shows the average flux in certain energy channel. Some of data are the average of disturbed flux; some data corresponds to quiet conditions or average of all data so we could not separate all of data precisely. The ACTIVE spectrum is an average of all fluxes at $L < 1.15$ for all of 1990 including quiet and disturbed periods. The TIROS-N, SAMPEX and SPRUT-VI spectra are ~1 month averages in 1978, 1994 and 1999, correspondingly, including quiet and disturbed periods. The points of OVI-17 are taken from Mizera and Blake (1973) for disturbed conditions. AZUR points have been taken from Moritz (1972) for disturbed conditions. OHZORA points have been taken from Gusev et al. (1996) for a quasi-stable component of the low-altitude radiation belt. We have spectra for disturbed (D) and quiet (Q) periods of geomagnetic activity according to OVI-17. According to these data we can make conclusion that amplitude of flux variations is not more than 10

Table 1
Characteristics of space satellites and detectors onboard. SSD is solid state detector.

Space apparatus (device name)	Year	Altitude (km)	Inclination	Detector type	Proton energy	Channels number	Reference
AZUR	1969	384–3145	103°	SSD	0.25–1.65 MeV	6	Moritz (1972)
OV1-17	1969	398–468	85.5°	SSD	12.4–180 keV	4	Kelley and Mozer (1972)
Kosmos-378	1970	240–1770	71°	SSD	~1 MeV	1	Butenko et al. (1975)
Kosmos-484	1972	202–236	81.3°	Gas discharge	70–500 keV	1	Butenko et al. (1975)
TIROS-N and NOAA POES (MEPED)	1979–present days	850	98.8°	SSD, 200 μm	0.03–2.5 MeV	5	Søraas et al. (2003)
S81-1	1982	170–290	85.5°	SSD, mass spectrometer	>45 keV, >100 keV	2	Guzik et al. (1989)
OHZORA	1984–1987	320–850	73°	SSD, telescope	0.65–35 MeV	6	Gusev et al. (1996)
ACTIVE (SPE-1)	1989–1993	500–2500	81.3°	SSD, 100 μm	55–550 keV	5	Grachev et al. (2002)
MIR station (SPRUT-V)	1991	400	51.6°	SSD, 100 μm	0.1–5.0 MeV	8	Biryukov et al. (1996)
SAMPEX (LICA)	1992–1998	520 × 670	82°	SSD, flight-time mass-spectrometer	>770 keV	1	Greenspan et al. (1999)
ISS station (SPRUT-VI)	1999	350	51.6°	SSD, 200 μm	0.3–8.0 MeV	8	Belyaev et al. (2004)

times. We can see that proton flux increases during magnetic storm in comparison to quiet time. But this difference is essential only for energies up to 100 keV. The other feature of this spectrum is power-law shape at energies more than 100 keV and exponent-like shape at energies below 100 keV.

This complex spectrum can be described by one function that has exponential slope at low energy and power-law shape at higher energies. The similar shape has the spectrum of protons in radiation belt and ring current (Kovtyukh et al., 1995; Kovtyukh, 2001). One of the good approximations of the spectrum is the kappa-function (1). The k in Eq. (1) is the slope of power spectra at high energies; the E_0 is the temperature of quasi-Maxwellian distribution at low energies:

$$j(E) = A\left[1 + \frac{E}{kE_0}\right]^{-k-1} \tag{1}$$

The whole set of points showed in Fig. 1 was selected for approximation. These results were published before in Petrov et al. (2008). For the quiet geomagnetic conditions $A = 50$, $k = 2.3$, and $E_0 = 30$; and for the disturbed conditions $A = 330$, $k = 3.2$, and $E_0 = 22$.

As it was established before by Moritz (1972) and confirmed by Guzik et al. (1989) the pitch-angle distribution of near-equatorial protons is bell-shaped with the maximum near 90° and can be described as function $j(\alpha) = \sin^n(\alpha)$ with $n = 6$–15 – anisotropy coefficient. We chose the $n = 7$ for the certainty. The flux j outside of geomagnetic equator can be calculated from equatorial flux j_0 and B/B_0 – relation of current magnetic field to the equatorial field using next formula as consequence of Liouville's theorem:

$$j(B) = j_0\left[\frac{B}{B_0}\right]^{-\frac{n}{2}} \tag{2}$$

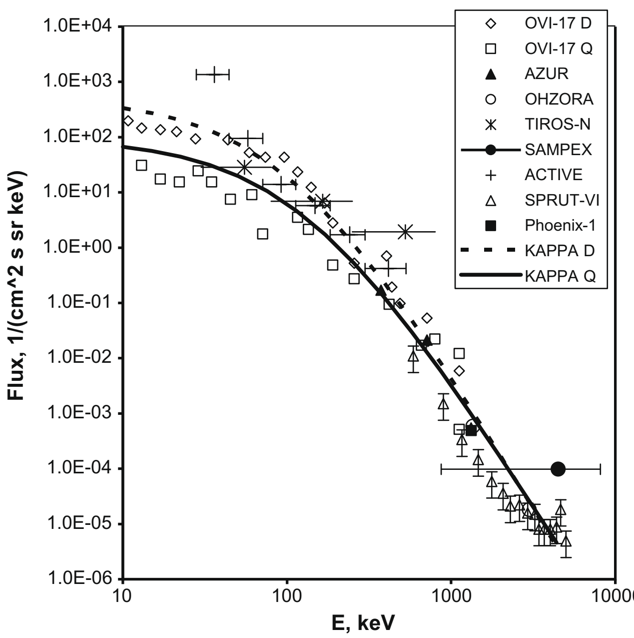

Fig. 1. The average energy spectrum of protons at $L < 1.15$ according data of several experiments. The experimental spectrum was approximated by kappa-function in periods of quiet (Q) and disturbed (D) geomagnetic activity. The fluxes are given for pitch-angles near 90°.

The proton flux at equator (at $B = B_0$) does not depend on altitude (Moritz, 1972; Petrov et al., 2008). The reason of this behavior is the consequence of two factors. The power of secondary protons generation is proportional to atmosphere density. The losses of protons in the atmosphere have the same character.

Using these formulae and assumptions the numerical model LEP (low-energy near-equatorial protons) was constructed. The model flux is defined by product of spectrum and the pitch-angle dependence (3):

$$j = A\left[1 + \frac{E}{kE_0}\right]^{-k-1} \times \left[\frac{B}{B_0}\right]^{-\frac{n}{2}} \tag{3}$$

The model is realized as the package of Perl programs working together on GNU/Linux platform on the SINP MSU web-server. The model is freely available at the moment via Internet in the program complex COSRAD (COSmic RADiation). There is not stand-alone application for desktop computers because we assume that web-based projects are easier to maintain and update than to distribute the new versions to all of the potential users. The address of the main page of LEP model is http://cosrad.sinp.msu.ru/cgi-bin/model/main.pl. Besides the model mentioned above the COSRAD system includes into itself the IGRF model of geomagnetic field (the user can select the year for the calculation of geomagnetic field according the IGRF) and the NASA AP8/AE8 models for calculation of proton and electron fluxes in the region of South Atlantic Anomaly (SAA) and outer radiation belt.

The input parameters for the model are L, B/B_0 in the point of calculation. The model works at $0.98 < L < 1.15$, $0.1\text{ Gs} < B < 0.5\text{ Gs}$ for altitudes from 200 to 1300 km. The altitude range is determined by the availability of experimental data. The energy of protons is from 10 keV to 10 MeV.

The scheme of calculations in the COSRAD system is given below:

1. The calculation of the space satellite coordinates based on start coordinates, inclination, apogee and perigee. The other option is the generation of rectangular mesh of coordinates for selected altitude.
2. The calculation of the L, B, B/B_0 in the every point of orbit using IGRF model. The user can select the year for the calculation of geomagnetic field.
3. The calculation of the proton fluxes in the radiation belt and SAA in every L, B/B_0 point using AP8 MIN/MAX model.
4. The calculation of the near-equatorial proton fluxes below radiation belts in every L, B/B_0 point using LEP model. The user of the model can select one of

two levels of geomagnetic activity (high or low) for calculation. The user can select the flux type – integral or differential.

All of these calculations are automatized and user is not obliged to take into account all of interactions inside of program complex but the description of model is full and everyone can now calculate the LEP fluxes by itself.

For the model testing we compared the experimental data with sum of LEP and AP8 model. We used the experimental data on protons with $E = 80–250$ keV registered in MEPED detector onboard NOAA POES-15 satellite. We used the recent data obtained in the first four months of 2008. As the altitude of satellite is about 850 km we calculated L and B according the IGRF model for 2008 at this altitude. After that we calculated the AP8MIN proton flux for $E = 100–250$ keV (AP8 cannot predict protons with $E < 100$ keV) and LEP flux for $E = 80–250$ keV for low level of geomagnetic activity.

The results of calculations and comparison of models with real experimental data are shown in Fig. 2. The flux threshold is the same in both of pictures. There is evident good consistence of calculated data and real experimental data in zones of SAA and near-equatorial region. The fluxes are similar in the order-of-magnitude. There is the difference in the experimental fluxes and AP8 model in the region to the south from SAA and in the region of radiation belts but the reasons of this difference is out of our consideration in this paper.

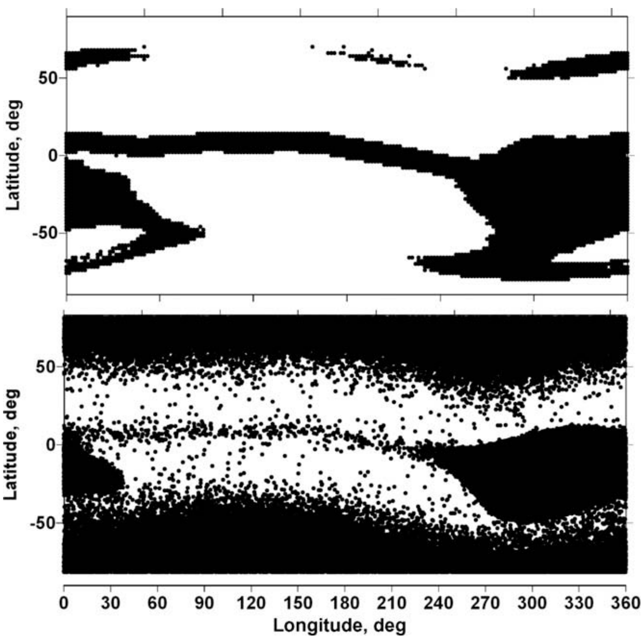

Fig. 2. The upper picture is the sum of the AP8MIN model and LEP model results. The proton fluxes were calculated for $E = 100–250$ keV according AP8MIN model and for $E = 80–250$ keV according LEP model. The model of geomagnetic field corresponds to 2008 year. The lower picture is the data of MEPED detector onboard NOAA POES-15 satellite in the beginning of 2008. The experimental fluxes are given for $E = 80–250$ keV. The flux threshold is 10 particles/(cm^2 s sr keV).

4. Conclusions

1. The scientific information from the dataset including data of several satellites for a period of observation more than 30 years was processed.
2. The properties of near-equatorial proton flux were established.
3. The empiric model of near-equatorial protons was created. The LEP model as the part of COSRAD system is freely available via Internet.

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