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Energy spectrum of proton flux near geomagnetic equator at low altitudes

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Abstract

The results of proton energy (tens keV – several MeV) spectrum measurements near geomagnetic equator ($L < 1.15$) at low altitudes (<1000 km) are presented. We used data of experiments onboard ACTIVE, SAMPEX, NOAA TIROS-N satellites and SPRUT-VI (MIR station) and cover a time range of about 30 years (including previous measurements). It was found that the kappa-distribution function fits the experimental spectrum with the best correlation coefficient. A comparison of energy spectra of near-equatorial protons and ring-current protons was made. Using the estimation of the life time of near-equatorial protons we explain the difference in spectral indices of radiation belt and near-equatorial proton formation. We conclude that the ring current is the main source of the near-equatorial protons.

Keywords: Low-energy near-equatorial protons; STEB; Double charge exchange; Ring current

1. Introduction

The near-equatorial ($L < 1.15$) proton (E_p: tens keV – several MeV) flux enhancements at altitudes less ~1000 km were found in the experiment AZUR by Moritz (1972) and confirmed by Hovestadt et al. (1972). Russian experiments onboard the Kosmos-484 satellite (Butenko et al., 1975) and SPRUT-V onboard the MIR station (Biryukov et al., 1996) showed similar results. These results were confirmed later using the ACTIVE satellite data (Grachev et al., 2002), NOAA POES (Sørbø et al., 2006) and SPRUT-VI and SAMPEX data (Grigoryan et al., 2005). The list of experiments where the near-equatorial proton flux was registered at low altitudes is given in Table 1. The repeatability of these results allows us to say that between the inner radiation belt and the upper edge of the atmosphere at altitudes 200–1300 km there is a band of proton flux enhancements.

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2. Observation and discussion

The low-energy proton formation can be observed as a band of proton flux enhancement in the equatorial region. The formation has been seen for a long time, for example, NOAA satellites data shown in Fig. 1 (1978–2005).

The first author who discovered the near-equatorial proton band (Moritz, 1972) proposed the two stage charge-exchange mechanism:

(1) $H^{+*} + H \rightarrow H^{*} + H^{+}$, in the ring current
(2) $H^{*} + O \rightarrow H^{+*} + O^{-}$, in atmosphere near the Earth

Here $*$ marks the energetic particle (atom). H^{+*} – energetic ion in ring current and near-equatorial region. H – neutral hydrogen of exosphere. H^{*} – energetic neutral atom. O – neutral oxygen atom. O^{-} – charged oxygen atom. The role of oxygen at altitudes about 500–800 km is essential, for example the $N_O(500) = 1.4E+07$, $N_O(600) = 2.4E+06$, $N_O(700) = 4.2E+05$, $N_O(800) = 7.8E+04$, $N_H(500) = 1.4E+05$, $N_H(600) = 1.2E+05$, $N_H(700) = 1.1E+05$,

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Table 1
List of experiments where the near-equatorial protons were registered

Space apparatus	Year	Altitude (km)	Inclination	Energy of protons
AZUR	1969	384–3145	103°	$E_p = 0.25$–1.65 MeV
OV1-17	1969	398–468	85.5°	$E_p = 12.4$–180 keV
OV1-19	1969	471–5796	100°	$E_p = 280$–560 keV
Kosmos-378	1970	240–1770	71°	$E_p \sim 1$ MeV
Kosmos-484	1972	202–236	81.3°	$E_p = 70$–500 keV
Esro-4	1972–1973	245–1175	91°	$E_p = 0.2$–1.3 MeV
NOAA TIROS-N	1978	850	98.9°	$E_p = 0.03$–2.5 MeV
S81-1	1982	170–290	85.5°	$E_p > 360$ keV
OHZORA	1984–1987	320–850	73°	$E_p = 0.65$–35 MeV
ACTIVE (Intercosmos-24)	1989–1992	500–2500	81.3°	$E_p = 55$–550 keV
MIR (SPRUT-V)	1991	400	51.6°	$E_p = 0.1$–8.0 MeV
Koronas-I	1994	500	83°	$E_p > 1$ MeV
SAMPEX	1992–1998	520–670	82°	$E_p > 770$ keV
MIR (SPRUT-VI)	1999	350	51.6°	$E_p = 0.3$–5.0 MeV
NOAA POES-17	2005	850	98.9°	$E_p = 0.03$–2.5 MeV
Universitetsky-TATYANA	2005	920–980	83°	$E_p > 2$ MeV

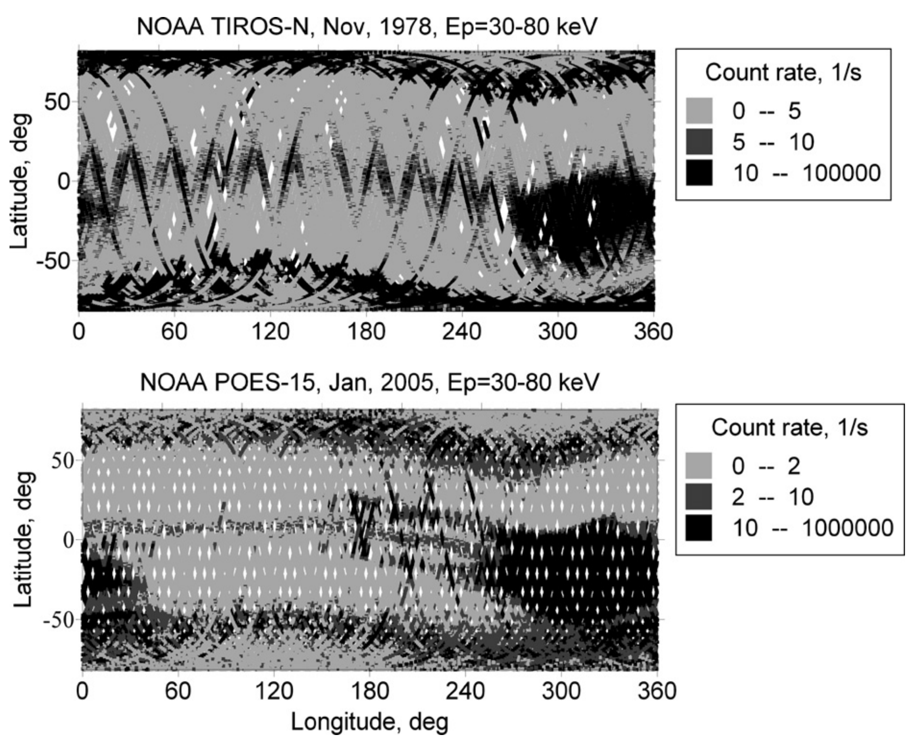

Fig. 1. Geographical maps of 30–80 keV protons at 850 km altitude according to NOAA TIROS-N data in 1978 and NOAA POES data in 2005.

$N_H(800) = 1.0E+05$ (http://modelweb.gsfc.nasa.gov/models/msis.html).

According to most of the experiments these particles are typically observed during geomagnetic disturbances, when the ring current is enhanced, so this formation was called STEB (Storm-Time Equatorial Belt) by Søraas et al. (2003). But there are evidences (e.g. Grachev et al., 2002) that protons with $E > 100$ keV do not feel the geomagnetic activity as well as low-energy protons. Mizera and Blake (1973) presented a spectrum which differs for low and high geomagnetic activity for energies up to 100 keV but from 100 keV to 10 MeV this difference is not essential. There is a minimum in energy spectrum of quiet ring current at energies from 20 to 100 keV (Krimigis et al., 1985). However this minimum is not absolute. There are also protons in the quiet-time ring current!

3. Energy spectrum

The modern radiation belt proton flux model (NASA AP8) does not take into account the existence of near-equatorial protons. To build the model we had to know the differential energy spectrum of near-equatorial protons presented in Fig. 2. The ACTIVE spectrum is an average

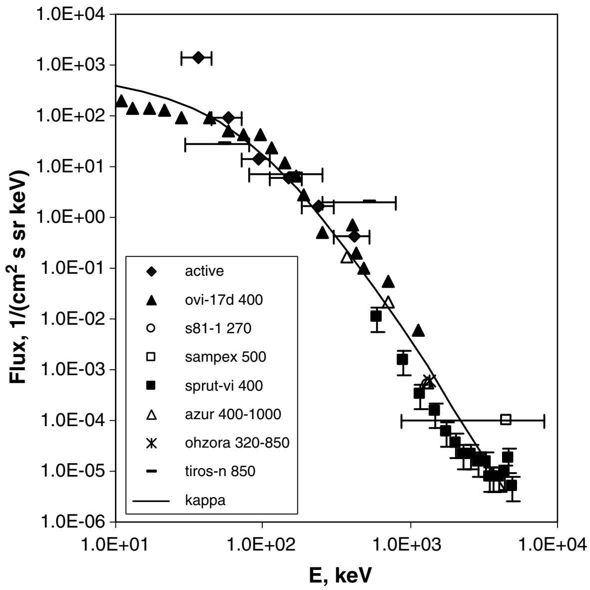

Fig. 2. Differential energy spectrum of near-equatorial protons constructed from several satellite and orbital station data. The approximation of the experimental spectrum is a kappa function.

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.

Previous authors tried to use the power-law approximation of the spectrum. The most accurate power-law spectrum was presented by Gusev et al. (1996) in the form $J_\mathrm{p} = 2{,}4 \cdot E^{-4.4\pm0.2}$ $(\mathrm{cm}^2\ \mathrm{s\ ster\ MeV})^{-1}$. But the low-energy part of the spectrum shows a non-power-law character. We propose the kappa function to approximate the low-energy and the high-energy parts of the experimental spectrum:

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

Parameters of the kappa function are:

$A = 328 \pm 36$

$k = 3.2 \pm 0.5$

$E_0 = 22 \pm 10$ keV

This approximation is better than the Maxwell function approximation

$$f(E) = A\left[\frac{E}{E_0}\right] \exp\left[-\frac{E}{E_0}\right]. \tag{2}$$

power-law

$$f(E) = AE^{-\gamma}, \tag{3}$$

Table 2
Different approximations of the experimental spectrum

	Maxwell	Power	Exponential	Kappa
A	7.4 ± 5.3	$(5.9 \pm 6.7) \cdot 10^6$	49.8 ± 28	328 ± 36
E_0	227 ± 20	–	10 ± 1	22 ± 10
γ	–	3.1 ± 0.2	–	–
k	–	–	–	3.2 ± 0.5
χ^2	16.5	5.08	6.32	4.15
r^2	0.57	0.87	0.82	0.89

or exponential function

$$f(E) = A\exp\left[-\frac{E}{E_0}\right] \tag{4}$$

as it seen from Table 2 where the correlation coefficient r^2 is maximal for the kappa function.

4. Altitude dependence of near-equatorial proton flux

As is shown by Moritz (1972) the flux of near-equatorial protons should not depend on altitude. The source power of these protons is the second stage of the double charge-exchange process. The source and loss rates depend on atmospheric density. Therefore the source for the protons counterbalances the atmospheric density determined losses.

The energy spectra shown in Fig. 3 confirm this assumption.

5. Life time of the near-equatorial protons

The spectral index of ring-current protons is ~4.7 so the near-equatorial proton spectrum is harder $\mathrm{k} \sim 3.2 \pm 0.5$. To explain this difference we had to take into account losses of protons at low altitudes due to a second stage of charge exchange on oxygen. The calculation is the same as in Moritz (1972). The balance equation of protons N_p and neutrals N_H is depends on v (the proton or hydrogen velocity), cross-sections of the generation of protons σ_{01}^0 ($\mathrm{H}^* + \mathrm{O} \rightarrow \mathrm{p}^* + \mathrm{O}^-$) and loss of protons σ_{10}^0 ($\mathrm{p}^* + \mathrm{O} \rightarrow \mathrm{H}^* + \mathrm{O}^+$).

$$\frac{\mathrm{d}N_\mathrm{p}(E)}{\mathrm{d}t} = vn^0\sigma_{01}^0(E)N_\mathrm{H}(E) - vn^0\sigma_{10}^0(E)N_\mathrm{p}(E) = 0$$

The life time $\tau = (v \quad n^0 \quad \sigma_{10}^\mathrm{H})^{-1}$. The $\sigma_{10}^\mathrm{H}(E) = 1.7 \times 10^{-22} \times E^{-5.7}\ \mathrm{cm}^2$ is the cross-section for the charge-exchange process generated the energetic neutrals ($\mathrm{p}^* + \mathrm{H} \rightarrow \mathrm{H}^* + \mathrm{p}$).

In Fig. 4 solid lines show how the life time depends on energy at different altitudes. The dependence of Coulomb scattering life time on energy during quiet and disturbed years of solar activity is shown by two long dashed lines ($\tau = 2.55 \times 10^6 \times E^{3/2}N^{-1}$ where the N is concentration of electrons for min and max solar activity ($N_\mathrm{max} = 1.15 \times 10^5$, $N_\mathrm{min} = 1.61 \times 10^4$) for altitude ~500 km, E – proton energy [keV], τ – life time [s], based on Nakada and Mead (1965) estimations). For comparison, the proton drift time around the Earth (at ~500 km altitude) is given as a dotted line ($\tau = 44/(\mathrm{LE})$ min, where E is in MeV).

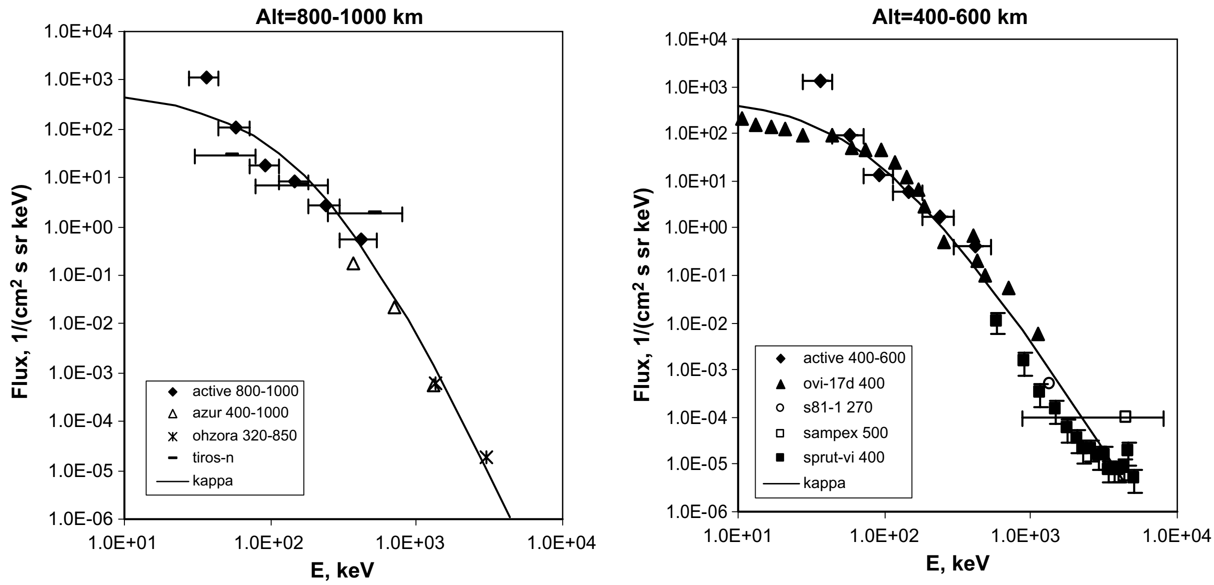

Fig. 3. Energy spectra of near-equatorial ($L < 1.15$) protons at two altitude intervals: 400–600 km and 800–1000 km.

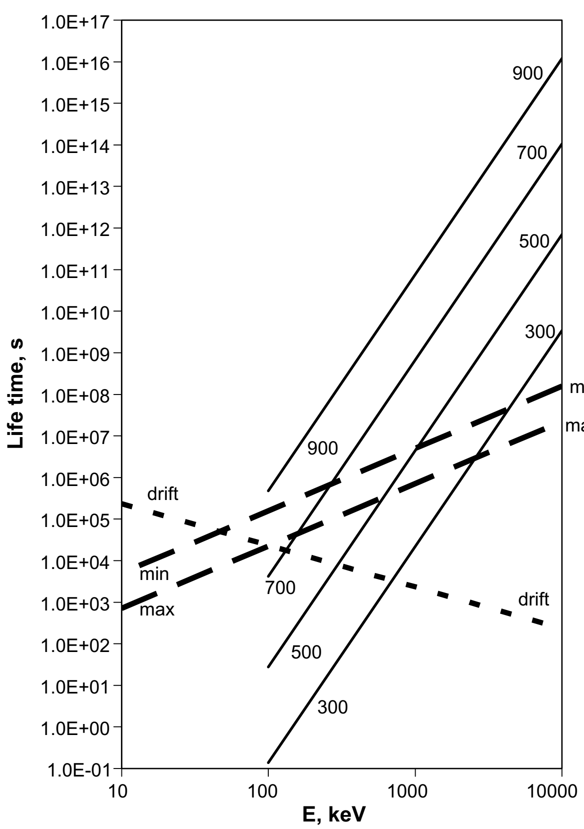

Fig. 4. Life time dependence on energy (due to charge exchange with oxygen in upper atmosphere) of protons at different altitudes (km) is presented using solid lines. Coulomb scattering life time is given using long strokes for periods of max and min solar cycle. For comparison, the drift time of protons at $L = 1.15$ at 500 km altitude is given using short strokes.

The main loss process is charge exchange for $E < 100$ keV and coulomb scattering for $E > 100$ keV.

So the low-energy protons ($E < 100$ keV) cannot persist at low altitudes a long time, and the spectrum becomes harder. In the assumption that all other factors are independent of energy the spectrum of the near-equatorial particles should be harder than the spectrum of the ring-current source.

6. Conclusions

1. The near-equatorial ($L < 1.15$) proton flux enhancements are observed at altitudes up to 1300 km for more than 30 years (from 1969).
2. The energetic spectrum of near-equatorial protons is determined as a kappa-distribution function.
3. The near-equatorial proton flux does not depend on the altitude in the altitude range 500–1000 km.
4. The main losses processes of protons motion are charge exchange with oxygen atoms and coulomb scattering with electrons.

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