"Physics of Auroral Phenomena", Proc. XXXII Annual Seminar, Apatity, pp. 63 - 66, 2009
© Kola Science Centre, Russian Academy of Science, 2009

Polar
Geophysical
Institute

ION ENERGY SPECTRA AT $L \sim 3.6 - 6.7$ DURING DISTURBED GEOMAGNETIC CONDITIONS

T.V. Kozelova[1], L.L. Lazutin[2], B.V. Kozelov[1]

[1]*Polar Geophysical Institute, Kola Science Centre, Russian Academy of Science, Apatity, Russia*
[2]*Space Science Division, Scobeltsyn Institute for Nuclear Physics of Moscow State University, Russia*

Abstract. Differential energy spectra of ions with the energies 0.1-3200 keV has been considered using the CRRES data in the nightside magnetosphere when geomagnetic activity was at levels $AE > 100$ nT. During the events under consideration the CRRES was located near the equatorial plane and crossed the radiation belt and the inner part of the plasma sheet at $L \sim 3.6 - 6.7$. We find that at $L \sim 3.8 - 4.6$ the ion spectra have two peaks. The characteristic energy E_o for low-energy portion of ion spectra increases and the high-energy peak E_P decreases with the increasing L.

At $L \sim$ 5-6.7 the ion spectra have one peak and their shape more often similar to the superposition of Maxwellian and kappa forms. Maxwellian form may represent the ion spectrum in a limited energy range near the knee. Slow stretching of the magnetic field during the substorm growth phase is accompaied by nonadiabatic cooling of the Maxwellian portion of the plasma. The changes of energetic particle flux are nearly adiabatic one.

During the substorm explosive phase at $L \sim 6.2$, the observed changes of ion flux (for all ions > 1 keV) have a non-adiabatic character. The characteristic energy of the Maxwellian portion of the spectrum increases significantly. We compare our results with other observations and discuss the spectrum-preserving and spectrum-altering magnetospheric processes.

1. Introduction

The spectral changes of plasma sheet particles may provide information on the mechanisms of particle energization in the magnetosphere. *Christon et al.* [1989] shown that, at 12-23 R_E, the observed differential energy spectra of quiet-time plasma sheet particles (from 0.030 keV to 1 MeV) are well represented by the kappa distribution function. This distribution has an excess of flux at high energies when compared to the thermal (Maxwellian) distribution. The kappa distribution $J \sim E\,(1+E/\kappa E_o)^{-\kappa-1}$, where J is the observed differential particle intensity, is a function having a Maxwellian form for $E \leq \kappa E_o$ and a power-law form for $E \gg \kappa E_o$. The median value for the characteristic energy E_o is ~ 1.3 keV and for the spectral index κ is ~5.3 during quiet periods.

For disturbed periods ($AE > 100$ nT), *Christon et al* [1991] shown that the ion spectral shapes typically are more complicated and present a superposition of forms. A kappa form is most able to approximate the observed spectral shape at higher energies. The Maxwellian form is most able to describe the shape near knee. The authors [*Christon et al.,* 1991] suggest that the knee spectral characteristics may be explained by acceleration in the current sheet.

The ion spectral shapes may be represented by the kappa distribution function at 11 R_E, as it was shown by *Williams et al* [1990]. At 6-7 R_E, the substorm injection resulted in the replacement of cool preexisting plasma with hot quasi-Maxwellian distributions [*Moore et al.*, 1981].

In this paper, we examine the energy spectra of ions with the energies 0.1-3200 keV at $L \sim 3.6 - 6.7$ using the CRRES data in the nightside magnetosphere during disturbed geomagnetic conditions.

2. Observations

In the present study we show the ion spectral changes in the inner magnetosphere near the equatorial plane associated with the increasing L and with the evolution of the substorm.

2.1. The crossing of the radiation belt and the inner part of the plasma sheet. Fig. 1 presents the sequence of ion spectra obtained by the CRRES in 20.5-23 MLT sector for two different events with the $AE \sim 100$-220 nT. On 24 January 1991 the CRRES (Orb 445) crossed the inner plasma sheet from $L \sim 4$ to $L \sim 5.4$ (the panels a-c). On 9 February 1991 the CRRES (Orb 484) moved from $L \sim 3.6$ to $L \sim 5.5$ (the panels d-f). Each frame of Fig. 1 presents the local measured spectra at two time moments for which simultaneously measured Bz component of the magnetic field is shown also. The spectra for the initial (sequential) moments in each frame shown by asterisks (squares). We show also the Maxwellian $M(E_o)$ and kappa $k(\kappa, E_o)$ forms which best approximate the high- or low-energy portions of the observed spectrum.

Two spectral peaks at $L \sim 3.8$-4.6. The overall behavior of the ion spectrum suggests that two different groups of ions have been appeared at this L range, one of them is populated by ions with energy 1-20 keV and another one - by ions with energy above ~70 keV (Fig.1a-1b and Fig.1d-1e). These parts of the spectra (denoted by solid horizontal lines at Fig.1) are well described by the Maxwellian form. At the range of the intermediate energies 20–70 keV the ion intensity abruptly deviates from these Maxwellian forms which are a neighbor both on the left and on the right.

For low-energy portion of ion spectra the characteristic energy E_o increases from 5 keV to 12 keV with increasing L from 4.1 to 5.38. We suppose that the changes in low-energy portion of ion spectra are associated with the protons penetrating into the inner magnetosphere from plasma sheet resulting from a combination of inward large-scale convection, gradient drift, and corotation [*Jaggi and Wolf*, 1973].

For high-energy portion, the peak E_P in the ion spectrum moves to lower energies by increasing the L value as a result of conservation of the adiabatic invariants [*Tverskoy*, 1965]. As the CRRES moves from the Earth, the local measured magnetic field gradually decreased in magnitude with increasing L (Fig.1) and $E_P(L)/B(L) \approx const$ in according with the requirement of Liouville's theorem. However the measured flux changes are adiabatic only in the limited range from E_P to higher energy E^* which changing from 1 MeV to ~500 keV with increasing L.

One spectral peak at L ~5 - 6. In the plasma sheet at L ~ 5-6 the ion spectra have one peak related with the low energy Maxwellian portion of the ion distribution. For the case shown in Fig 1c the high-energy portion of ion spectra (> 120 keV) shows a power law with κ~4. The ion distribution in the energy range 7-120 keV is similar to the Maxwellian form with E_o=12 keV. For the case shown in Fig.1f the final ion distribution has single kappa form.

Thus, the characteristic energy E_o for low-energy portion of ion spectra increases and the high-energy peak E_P decreases with the increasing L at L~3.8-4.6. At L~5-6 the ion spectra have a single kappa form or a kappa form plus Maxwellian form.

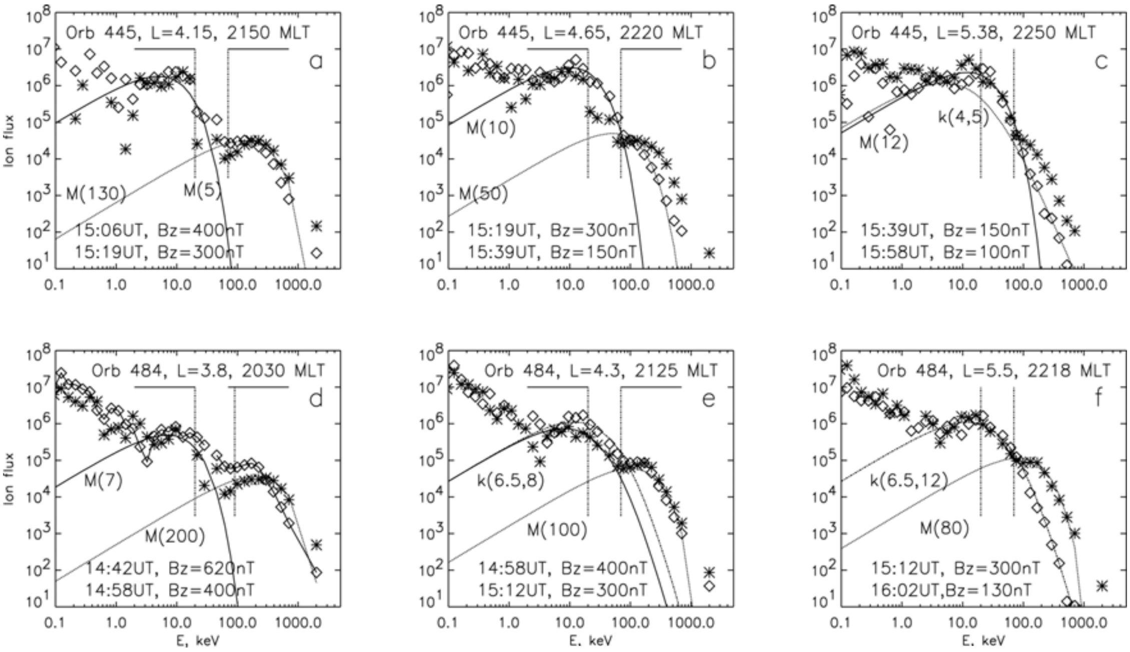

Figure 1. Evolution of ion spectra obtained by CRRES during crossing of the radiation belt. Ion flux in $cm^{-2}s^{-1}sr^{-1}keV^{-1}$.

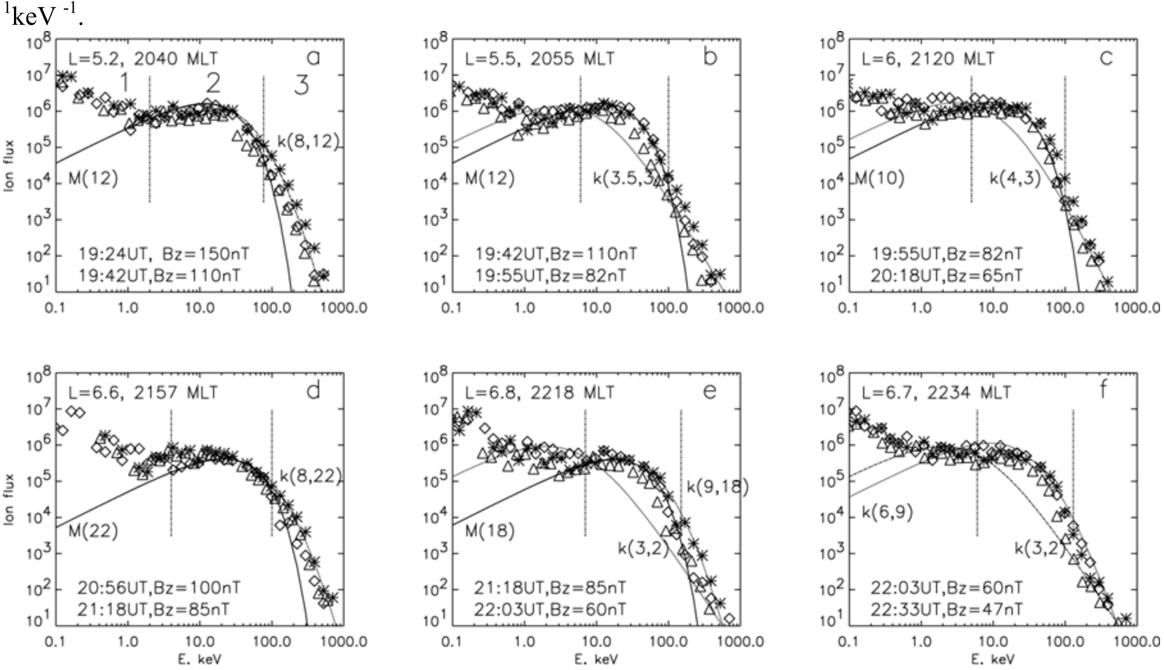

Figure 2. Ion spectra observed by CRRES during substorm growth phase (a-c) and between two substorms (d-f).

2.2. Ion spectra during slow stretching of the magnetic field lines at L~5.2-6.7. Fig. 2 presents the sequence of ion spectra observed by the CRRES (Orb 560) on March 12, 1991 in 19.5-22.5 MLT sector when *AE*~400-500 nT. These spectra were obtained in the time intervals without the substorm explosive phase. The one substorm onset occur in 2026 UT [*Kozelova et al.*, 2006]. After ~21 UT this substorm began to decay. Another subsequent substorm onset occurred in ~23 UT .

Substorm growth phase. The Fig.2a-2c present the evolution of ion spectra before the first substorm onset. The first energy spectrum on Fig 2a may be described by the single kappa distribution κ(8,12). But later on, this form is transformed to superposition of at least two spectral forms. The subsequent spectral changes are different at different energy ranges denoted by '1-3' in the Fig.2a. Note, that the boundaries (vertical lines in Figure 2) between the ranges are not constant for all spectra. In high-energy region 3, the ion spectra may be described by the kappa function. Sometimes the low-energy portion of the spectrum (region 1) may be described by the same kappa function. At the range of the intermediate energies 7–100 keV (region 2), the ion spectra have the Maxwellian form.

From Fig.2a-2c one can see that the Maxwellian portion of the ion population becomes colder with decrease of the magnetic *Bz* component which means the stretching of the magnetic field lines during the substorm growth phase. In high-energy region of ion spectra the spectral index κ changes from 8 to 4.

Continuation of the Bz component decrease. The Fig.2d-2f present the time evolution of ion spectra between two substorm onsets. One can see that initial spectrum (Fig.2d) and final spectrum (Fig.2f) have similar kappa-like form. However spectral parameters change with the changing *Bz* component. We can use *kT*, the temperature of the entire ion distribution instead of E_0 to characterize the average energy of the observed ion population as in *Christon et al* [1991]. For a single kappa form, E_0 , κ , and *kT* are related as follows, $kT = \kappa E_0/(\kappa\text{-}1.5)$ [*Vasyliunas*, 1968]. Then from 2056 UT to 2233 UT the *kT* temperature decreases from 27 keV to 12 keV.

Thus, the ion population becomes colder during the decreasing of the *Bz* component. This behavior of the spectra suggests a cooling process which, like betatron process, conserves the spectral form. In order to determine the character of the spectral changes, we compare the ion spectra observed in sequential moments of the time with the ion distributions calculated from the initial spectra using the Liouville's theorem (denoted by triangles at Fig.2). From Fig.2 one can see that:

- In the energy region 3, the observed ion flux changes are nearly consistent with the changes required by local betatron deceleration except the Fig.2f.
- In the regions 2 and 1, the the observed ion flux changes are not consistent with the adiabatic changes.

Thus, at *L*~5.2–6.7 the ion spectra may be described by a superposition of the kappa and the Maxwellian distributions. Slow stretching of the magnetic field during the substorm growth phase is accompaied by nonadiabatic cooling of the Maxwellian portion of the plasma. The changes of energetic particle fluxes are nearly adiabatic one.

2.3. Ion spectra during local dipolarization at L~6.2. Fig.3 presents the ion spectra obtained by the CRRES (Orb 445) during the substorm on 24 January. On the whole, from 1650 UT to 1717 UT, the magnetic field increases twice. The Maxwellian portion of the ion population near knee becomes hotter. The high-energy portion of ion spectra follows the power law form with the index weakly changing from 4.5 to 3-4.

Usually the substorm dipolarization is not smooth process. A number of localized small scale dipolarizations occurs during the large scale dipolarization of the magnetic field. The Fig.3a-3c show the fine details of the spectral transformations before and during first substorm intensification (1654-1657 UT). The Fig.3d-3f show the spectral changes during more large scale substorm expansion (1704-1712 UT), contained several particle injections. From Fig.3 one can see that:

- In the region 2, the first substorm ion injection may be described by the portion of the Maxwellian form with characteristic energy E_0=20 keV (Fig.3b). The Maxwellian form with E_0= 62 keV may well approximate subsequent injections (Fig.3f). However, while the Maxwellian portion of the ion population becomes hotter during entire dipolarization, the peak flux of the ion spectrum decreases. The decrease of observed peak flux with an increase of *Bz* argues for nonadiabatic heating or enhanced loss processes associated with the dipolarization. The decrease (drop) in the ion flux at lower energies and simultaneous enhancement in the fluxes at the higher energies during dipolarization were noted earlier in [*Lazutin et al.*, 1998].
- In the region 3, the injection of the energetic ions begins still during the explosive growth phase. The observed ion flux changes have a non-adiabatic character. The spectra of the injected energetic ions follow nearly a power law and are displaced nearly in a parallel fashion, the higher intensities corresponding to Maxwellian portion of ion population with the higher mean thermal energy.

3. Discussion

One can see, that the spectral shape and subsequent spectral changes are dependent on the energy range and the substorm phase. In high-energy region 3, the ion spectra may be described by the kappa distribution. The low-energy portion of the spectrum (region 1) sometimes may be considered as a part of the same kappa distribution as in region 3. At the range of the intermediate energies (region 2), the ion spectra have the

Maxwellian form. In the region 3 the ion flux changes are adiabatic during slow growth phase of the substorm and nonadiabatic during explosive growth phase and during dipolarization. In the region 2 the Maxwellian portion of the ion population becomes hotter during dipolarization, however the peak flux of the ion spectrum decreases. The spectral changes with an increase of B_z cannot be completely accounted by local betatron acceleration alone. Other processes (nonlocal betatron acceleration, nonadiabatic heating or enhanced loss processes associated with the dipolarization) must be active. The knee characteristic of the ion spectra may result from magnetotail current sheet acceleration [*Speiser*, 1967] which yields the energy increase from a few to tens of keV range.

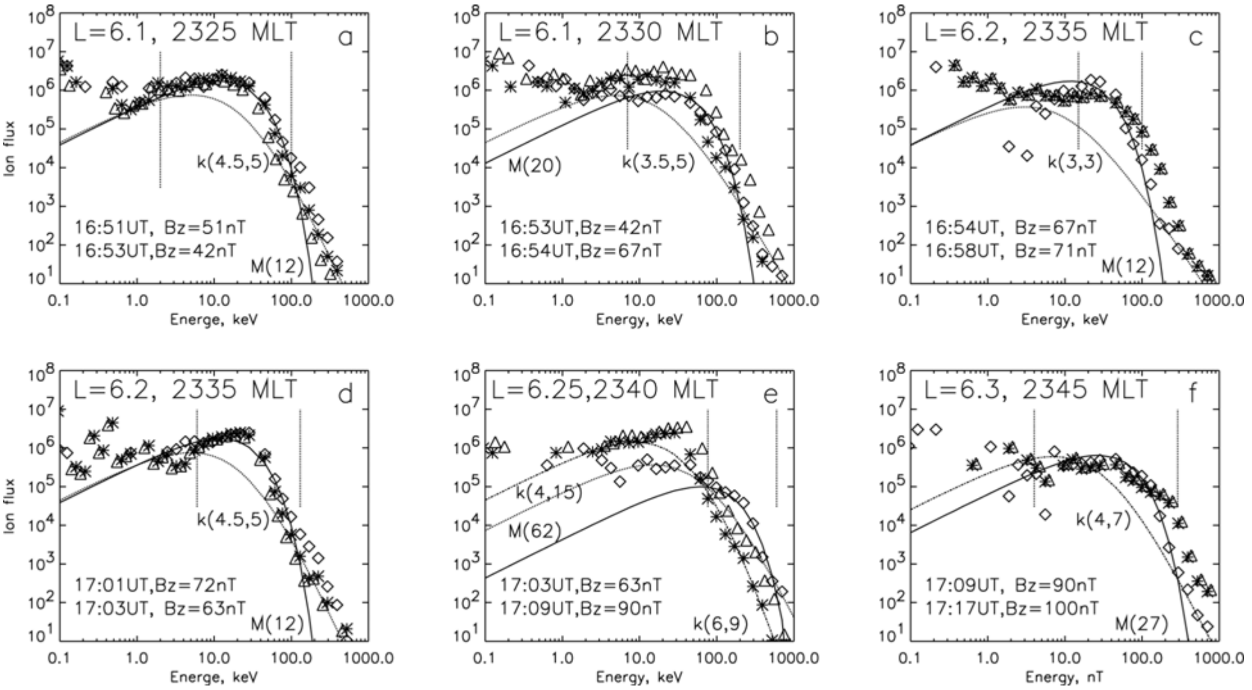

Figure 3. Changes of ion spectra observed by CRRES during the local dipolarizations.

4. Conclusions

We examined the differential energy spectra of ions obtained by the CRRES during the three crossing the inner part of the plasma sheet. Main results are following:

♦ At $L \sim 3.8–4.6$ the ion spectra have two peaks. The characteristic energy E_0 for low-energy portion of ion spectra increases and the high-energy peak E_P decreases with the increasing L. The changes of the high-energy peak are consistent with the conservation of the adiabatic invariants.

♦ At $L \sim 5$-6.7 the ion spectra have one peak and their shape often looks like a superposition of Maxwellian and kappa distributions. Slow stretching of the magnetic field during the substorm growth phase is accompanied by nonadiabatic cooling of the Maxwellian portion of the plasma. The changes of energetic particle fluxes are nearly adiabatic one.

♦During the substorm explosive phase at $L \sim 6.2$, the observed changes of ion flux (for all ions > 1 keV) have non-adiabatic character. The characteristic energy of the Maxwellian portion of the spectrum may vary at several times.

Acknowledgements. The work is performed in frames of the basic research program 16/3 ‘‘Solar activity and space weather’’ of the Presidium of the Russian Academy of Sciences (RAS) and program VI.15 ‘‘Plasma processes in the solar system’’ of the Division of Physical Sciences of RAS.

References

Christon S. P., D. J. Williams, D. G. Mitchell et al., *J. Geophys. Res.*, V. 94, A10, P. 13409-13424, 1989.

Christon S. P., D. J. Williams, D. G. Mitchell et al.,. *J. Geophys. Res.*, V. 96, A1, P. 1-22, 1991.

Jaggi R. K. and Wolf R. A., *J. Geophys. Res.*, 78, 16, 2852-2866, 1973.

Kozelova T. V., L. L. Lazutin, B. V. Kozelov et al., *Ann. Geophys.*, 24, 1957–1968, 2006.

Lazutin L.L., Rasinkangas R., Kozelova T.V. et al., *Ann. Geophys.* V.16, P.775. 1998.

Moore T.E., Arnoldy R.L., Feynman J. et al., *J. Geophys. Res.*, V. 86, A8, P. 6713-6726, 1981.

Тверской Б. А. *Геомагнетизм и аэрономия.* Т.5. N.5.C. 793-808, 1965.

Speiser T.W**.** *J. Geophys. Res.*, V. 72, No 15, P. 3919-3932, 1967.

Vasyliunas V.M., *J. Geophys. Res.*, V. 73, No 9, P. 2839-2884, 1968.

Williams D. J., D.G. Mitchell, C.Y. Huang et al., *Geophys. Res. Lett*, V. 17, No 5, P. 587-590, 1990.