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KAPPA DISTRIBUTIONS AND FEATURES OF MAGNETOSPHERIC DYNAMICS

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Abstract. Electron and ion distribution functions in the magnetosphere of the Earth in many cases can be described by kappa distributions. Such distributions have a Maxwellian core and a power law spectrum at high energies. Kappa distributions are formed due to relaxation of nonequilibrium distribution functions to the Maxwellian distributions in the conditions of collisionless magnetospheric plasma. Analysis of parameters of kappa distribution is very interesting for the solution of such problems as plasma heating and particle acceleration. Examples of approximations of observed ion distribution functions by kappa distributions during magnetically quite conditions and bi-kappa distributions in the case when plasma populations from two sources are mixed are obtained. Changes of kappa parameters along the trajectories of the flights of THEMIS mission satellites are analyzed. It is shown, that the analysis of the parameters of kappa approximations is the effective method of the magnetospheric dynamics study.

1. Introduction

Magnetosphere of the Earth is the collisionless plasma system. Long-range interactions determine the main features of magnetospheric dynamics, which produce its very complicated and poorly predicted character. However, in many cases distribution functions in the magnetosphere in a wide energy range can be described by kappa distribution, which means the action of comparatively quick relaxation processes and the transform of very anisotropic distributions with multiple gradients in phase space (for example, particle beams) in comparatively smooth near to isotropic distributions. Such process is especially important in the high latitude magnetosphere, where plasma pressure is near isotropic and where the distribution of plasma pressure determines the magnetospheric dynamics.

Kappa distribution has the form

$$f(E)=\frac{n_0}{\pi^{3/2}}\frac{1}{E_0^{3/2}k^{3/2}}\frac{\Gamma(k+1)}{\Gamma(k-1/2)}\left[1+\frac{E}{kE_0}\right]^{-k-1}, \qquad (1)$$

where n_0 is the particle density, m is the mass of a particle, E is the characteristic energy of the particles (related to the thermal speed of the distribution), E_0 is the core energy, Γ is the Euler gamma function [*Livadiotis*, 2017]. Kappa distributions arise from Tsallis statistics as a generalization of Boltzmann-Gibbs statistics for systems that are in a stationary state but out of thermal equilibrium [*Tsallis*, 1988]. For $k\to\infty$ (1) tends to the Maxwellian distribution:

$$f(E)=\frac{n_0}{E_0^{3/2}\pi^{3/2}}\exp\left\{-\frac{E}{E_0}\right\}. \qquad (2)$$

Measurements of particle fluxes in a wide energy range and intercalibration of different measurements are required to obtain the parameters of kappa distribution. That is why very limited information have been obtained till now (see [*Stepanova and Antonova*, 2015*; Kirpichev et al.*, 2017] and references in these papers). In this paper we shall analyze ion spectra obtained during realization of THEMIS mission. Ion spectra were obtained by the electrostatic analyzer (ESA) [*McFadden et al.*, 2008] and the solid-state telescope (SST) aboard the satellites of this mission [*Angelopoulos*, 2008]. The ESA and SST instruments do not allow the determination of the ion composition and it is assumed that protons make the main contribution to the ion flux. The magnetic field measurements (with a time resolution of 3 s) were obtained by the fluxgate magnetometer (FGM) [*Auster et al.*, 2008]. Parameters of the solar wind were obtained using the Wind satellite data (*http://cdaweb.gsfc.nasa.gov/*), and the corresponding time shift due to propagation of the solar wind from the satellite location to the magnetopause was obtained using solar wind velocity data. Data products of the THEMIS satellite mission are available online (*http://themis.ssl.berkeley.edu/, http://cdaweb.gsfc.nasa.gov/*) [*Angelopoulos*, 2008; *Sibeck and Angelopoulos*, 2008]. High energy channels of SST device can be affected by cosmic rays and showed, as a rule, low statistics. That is why energy channels greater than

300 keV was not used in the analysis. Low energy channels of ESA also were not used due to the contamination from the spacecraft potential and photoelectrons.

2. Single kappa distributions for ions inside the magnetosphere

We selected for the preliminary analysis very quiet period on October 9, 2008 when THEMIS-D satellite crossed the dayside magnetosphere from X=5R_E till near to magnetopause at 10 R_E in GSM. This region is very poorly investigated, as most researches were sure that the auroral oval is mapped to the plasma sheet. However, after selection the surrounding the Earth plasma ring with the same plasma characteristics as in the plasma sheet [*Antonova et al.*, 2013, 2014a], it was shown that the main part of the auroral oval is mapped to this ring. This finding selects the region with X>5R_E as the most interesting for the study.

Fig. 1a shows an example of measured ion spectra by THEMIS-D satellite on October 9, 2008 in the dayside magnetosphere with one minute time averaging from 10:22 to 10:23 UT and pitch-angle averaging in the range of 45°-135° (black line), and obtained kappa approximation (blue line). It is possible to see comparatively good spectra approximation by kappa function. Fig. 1b shows an example of variations of parameters of kappa approximations along the THEMIS-D trajectory. First panel shows three components of interplanetary magnetic field (IMF) and its magnitude, second panel shows the solar wind dynamic pressure, third panel shows the differential ion fluxes measured in the pitch angle interval of 45°-135°. Three next panels show the characteristic energy, *k* and ion number density obtained by fitting the differential ion fluxes with kappa distributions. The bottom panel shows the magnetic field value and its Bz component, which practically coincide (satellite was near the equatorial plane) with that measured by the THEMIS-D. By analyzing Fig. 1b it is possible to see that during selected very quiet period (|Dst|< 3 nT, |AE| <50 nT) spectra slope was very stable (*k* was near to 5) at geocentric distances smaller than 7.5 R_E. The core energy is decreased from 3 to 2 keV. Number density was practically unchanged. At larger geocentric distances, it is possible to observe a small increase in *k* and E_0 and the increase of their scattering. However, n_0 continues to be rather stable. It is possible to observe the regions containing the intrusion of the low energy magnetosheath plasma, in which single kappa approximation is inapplicable.

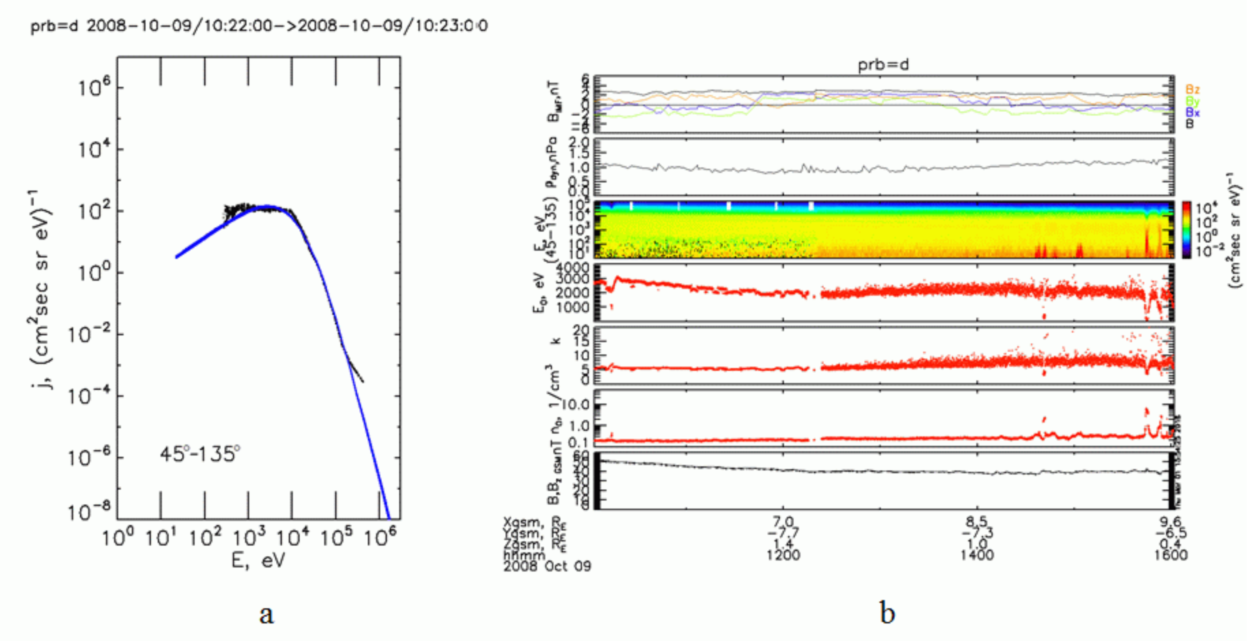

Figure 1. An example (event October 9, 2008) of the measured ion spectra (*black*) in the daytime magnetosphere and its kappa-approximation (*blue*) (***a***) and variation of parameters of kappa approximation along satellite trajectory (***b***).

3. Bi-kappa distribution in the region of plasma mixing

Due to particle penetrations through the magnetopause, magnetosheath plasma appears inside the magnetosphere forming the low latitude boundary layer (LLBL), on the other hand magnetospheric ions penetrate inside the magnetosheath forming the ion leakage. In spite of multiple researches of particle penetration through the magnetopause, the problem continues to be unsolved. It is only clear, that at large magnetic shear at the magnetopause the magnetospheric ions can freely penetrate through magnetopause current sheet when the ion Larmor radii are comparable or larger than the thickness of the magnetopause [*Kirpichev et al.*, 2017].

Fig. 2a,b shows an example of measured ion spectra when THEMIS-D satellite crossed the magnetopause on July 20, 2007 (black lines). Single kappa approximation was used inside the magnetosphere (blue line) and bi-kappa inside the magnetosheath (orange lines). High (red) and low (green) energy components are also shown. Time averaging due to increased particle fluxes at slightly disturbed period (Dst=-22 nT, AE=600 nT) was 35 s and 23 s respectively. It is possible to see the possibility to use single kappa approximation inside the magnetosphere and bi-kappa inside the magnetosheath. The existing of two different plasma populations is especially easy to see inside the magnetosheath, where thermalized solar wind plasma with temperature ~10^2 eV mixed with the hot population penetrating from the magnetosphere. It is possible to see practical coincidence of the slopes of high-energy parts of spectra inside and outside the magnetosphere. However, fluxes of energetic particles are slightly reduced inside the magnetosheath in comparison with the magnetospheric fluxes. Region inside the magnetosphere under the magnetopause is practically the LLBL region containing plasma penetrated from the magnetosheath. Therefore, the approximation by single kappa on Fig. 2a describes only part of spectra with energy larger than 10^3 eV. However, it is difficult to use bi-kappa approximation as was done on Fig. 2b. Therefore, it is possible to conclude that here we see the formation of unified plasma population from two mixed populations.

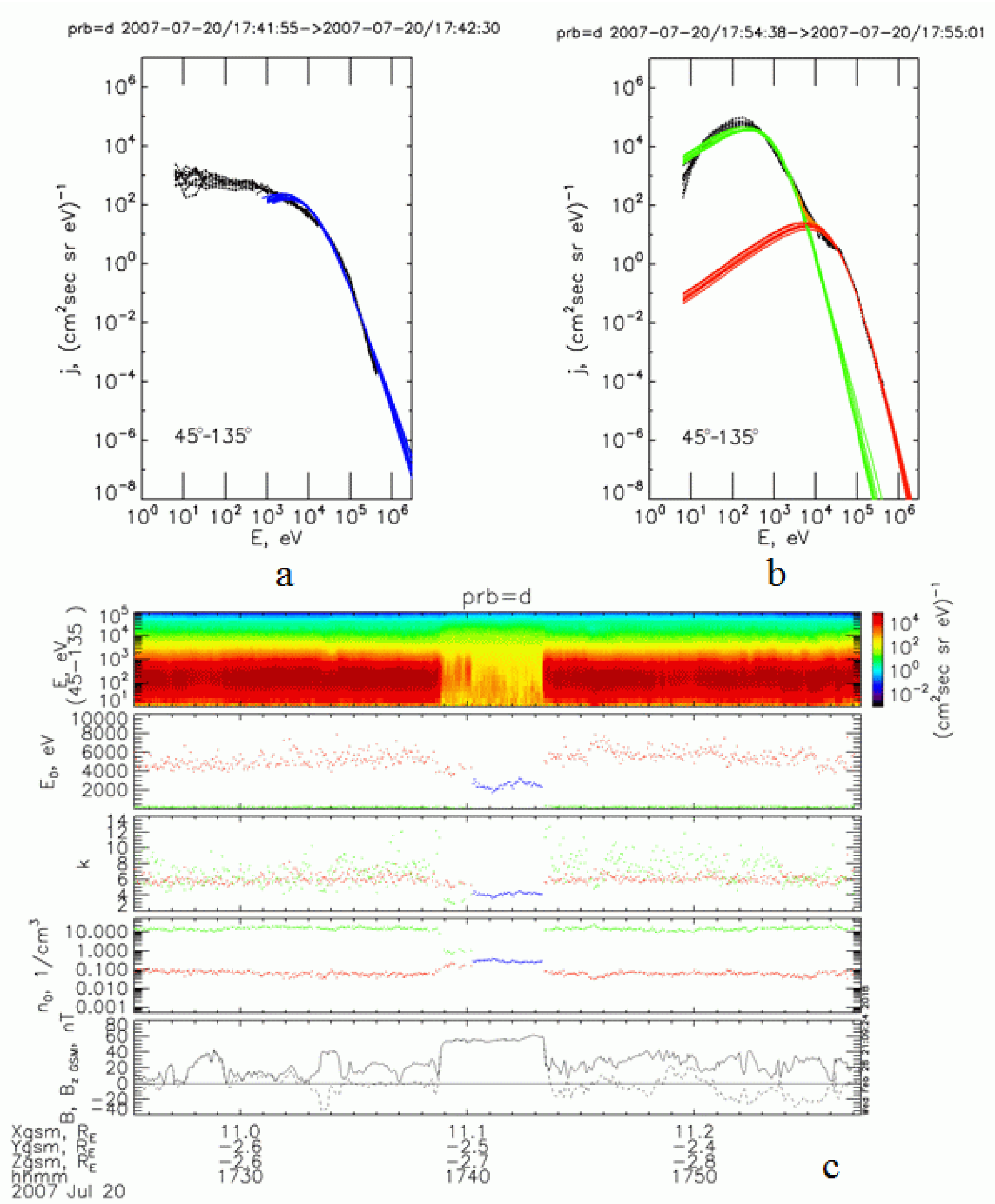

Figure 2. Examples of the measured ion spectra (*black*) in the daytime magnetosphere and its kappa-approximation (*blue*) (***a***) and in the magnetosheath fitted by a bi-kappa distribution (*orange curves*, *green lines* show low energy component, *red lines* show high energy) (***b***), and variations of parameters of kappa approximation along satellite trajectory (***c***).

Fig. 2c shows differential ion fluxes with pitch-angle averaging in the range of 45°-135°, parameters of kappa (blue points) and bi-kappa (green and orange points) approximations, magnetic field and its Bz component correspondingly in GSM. Methods used for obtaining approximations were the same as in [*Kirpichev et al*., 2017]. It is possible to see great magnetic field fluctuations inside the magnetosheath and large scattering of k and E_0. At the same time, we see comparatively stable plasma density for both populations.

4. Conclusions and discussion

We analyzed as an examples two events of spectra measurements along the orbit of THEMIS-D satellite and its approximations by kappa distributions. We think that using of such approximations is very informative for the study of magnetospheric dynamics. Study of MHD parameters such as density, temperature and especially plasma pressure is extremely useful for crude description of the system such as large-scale magnetosheric configuration, system of transverse and field-aligned currents, pressure transport etc. However, it cannot help for investigations of particle acceleration and heating, relaxation of observed particle beams and many other kinetic processes. Determination of kappa approximation parameters, naturally, cannot be used for the analysis of fully kinetic processes. But it can help in the large scale analysis of global processes. In comparison with Maxwellian distribution, which contains only two parameters, kappa function contains three parameters and describes the most typical feature of collisionless plasma systems – the power low tail. It is possible to hope that wide using of kappa approximations will help to solve many actual problems in the physics of magnetosphere.

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