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ION CONICS OBSERVED BY AKEBONO SATELLITE

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Abstract: Some characteristics of upflowing ion conics in the polar magnetosphere are reported from AKEBONO charged particle observations. The field aligned bulk shift of upflowing ions is well correlated to an enhancement of electron precipitation even with a small scale, whereas the temperature anisotropy of upflowing ions responds to the electron precipitation in a dull way. The event we reported suggests that the parallel acceleration of ion conics is rather independent of the anisotropic heating and is most probably caused by a parallel electric field. The cone angle of upflowing ion conics decreases more slowly than expected from a simple adiabatic motion in the mirror force field. The temperature defined along the cone increases with altitude. These observation results demonstrate that additional ion energization often takes place widely along the field line.

1. Introduction

Ion energization at up to 1–2 R_e altitude along the auroral field lines has been of interest in the magnetosphere physics (see, for reviews, MOZER *et al.*, 1980; BURCH, 1988). The energized ionospheric ions flow out to the magnetosphere as a result of the direct upward acceleration or the parallel velocity conversion by magnetic mirror force, and are considered to be a significant source of the magnetospheric ions (BURCH, 1988; CHAPPEL, 1988). The upflowing ions are basically divided into two categories: conics including TAI (KLUMPAR, 1979), and beams, based on their characteristic pitch angle distributions. Upward ion beams are usually believed to be accelerated by parallel electric field, whereas wave heating is generally thought to cause ion conics. Various acceleration and heating mechanisms have been proposed, but conclusive results have not yet been reported, in particular on the source of free energy for the perpendicular heating of ion conics (KINTNER and GORNEY, 1984; CHANG *et al.*, 1986; KINTNER *et al.*, 1989).

Low Energy Particle (LEP) instrument on board AKEBONO satellite (MUKAI *et al.*, 1990) has often detected upflowing ion conics in the polar magnetosphere. The instrument is designed to make three distinct types of charged particle observations. One of its functions is the energy per charge (E/Q) analysis for electrons and ions. The instrument consists of two sets of E/Q analyzers separated at the symmetric position with respect to the satellite spin axis. The full energy range is 10 eV–16 keV for electrons and 13 eV–20 keV for ions. The range is divided into 64 equally spaced steps on a logarithmic scale and is usually scanned in 2 s. The E/Q analyzers have ten detectors as a whole for different incidence directions simultaneously and separately for electrons and ions. Pitch angle distribution of charged particles is measured by combining these ten detectors and the satellite spin with the rate of about 7.5 rpm. This setup allows us a high-time resolution study on various events, especially under the assumption of gyrotropic distribution of charged particles. It also means that fine phase space distributions of charged particles can be investigated if the event is rather stable. In this report we first present an evident example of bimodal acceleration and heating of ions through a high time resolution analysis. Then it is also suggested that ions often experience multi-step heating in the interaction region extended largely along the field line.

2. High-time Resolution Analysis

Occasionally ion conics show a distinct variation in the region of quick change in electron precipitation. Figure 1 shows dynamic energy spectra and pitch angle distribution with a time resolution of 4 s. Darker area indicates the higher count rates, and one step of darkness corresponds to half a decade. The top panel of the figure presents low-energy electron precipitation within 30° along the field line. The

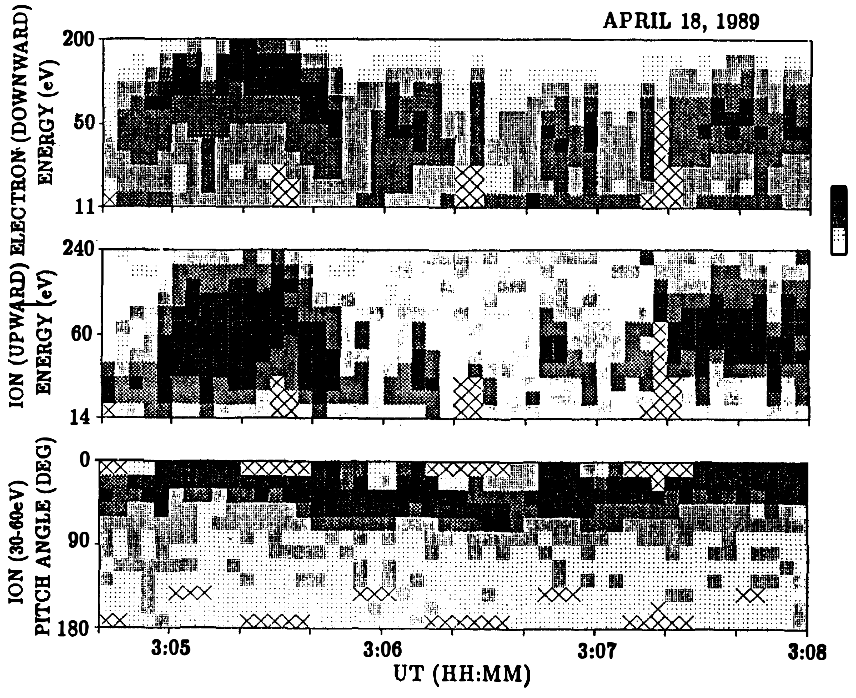

Fig. 1. Dynamic energy spectra of precipitating electrons (top panel) and field aligned component of upwelling ions (middle panel), and dynamic pitch angle distribution of ions with energies of 30–60 eV (bottom panel). Darker area indicates the higher count rates, and one step of darkness represents half a decade. The mark '×' means no data in the bin.

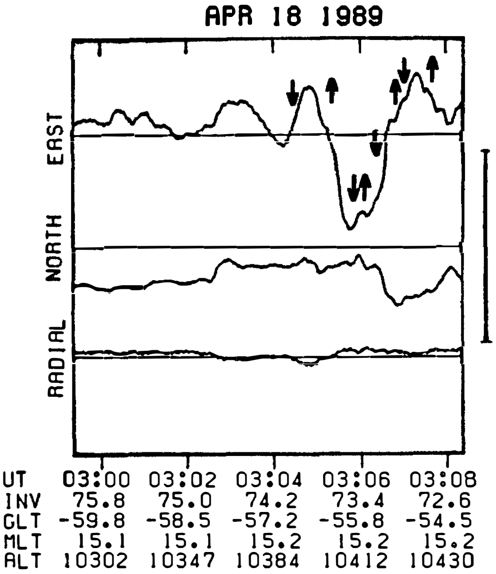

Fig. 2. Magnetic field variations measured by the onboard magnetometer. Residual magnetic fields (observed magnetic field–IGRF model field) are displayed in local geographic coordinates that are aligned eastward, northward and radially outward, respectively.

middle panel reveals upward ion count rates within 30° along the field line. The bottom panel shows pitch angle distributions of ions with energies of 30–60 eV. The upward direction along the field line is taken as 0°, and the downward as 180°. AKEBONO traversed the afternoon auroral region in the southern hemisphere from high to low latitudes (for the orbital information, see Fig. 2).

The energy of precipitating electrons was low during the event as is the case of dayside phenomena, and electrons were never observed above 200 eV. There are four intervals in which electron precipitation was intensified. In the first interval the precipitation seems to form an inverted-V pattern. The observation result of the magnetometer onboard (FUKUNISHI *et al.*, 1990) is presented in Fig. 2. Positive gradient in the east-west component indicates downward field-aligned current, whereas negative gradient stands for upward current. It is found that upward current was detected in these four regions of electron precipitation, and downward current was detected where the electrons were not precipitating. There are also four periods of ion enhancement in the middle panel of Fig. 1, which are well correlated to the intense electron precipitation. On the other hand, the bottom panel shows that ions were upflowing throughout the observation period. These ions apparently had conical pitch angle distributions except for the four intervals of ion enhancement within 30° along the field line. During the four intervals the field aligned component of ions appeared and filled up the bins of 0°–15° or 15°–30° in the bottom panel of Fig. 1.

We draw the contour maps of phase space density distribution of ions at selected time intervals for the specific purpose of investigating the energy-pitch angle characteristics of the up-flowing ions (abbreviated hereafter to UFI). Figure 3 shows phase space density distributions of the upflowing ions in eight selected time intervals. Since O^+ is usually a dominant composition of UFI events, the velocity scale is given by assuming that the observed ions are all O^+. If the ions were H^+, the velocity scale values should be multiplied by a factor of 4. Weak conics were observed (0304: 30–0304: 45) till the first upward enhancement of ions occurred. In the first enhance-

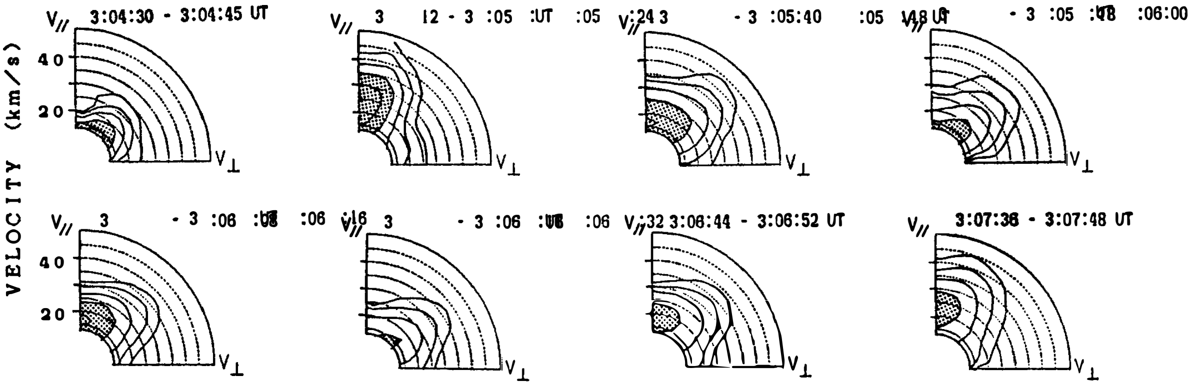

Fig. 3. Phase space density contours at half-decade intervals assuming O^+ ions. The outer contour is at 10^{-9} s^3 m^{-6}. The region above $10^{-7.5}$ s^3 m^{-6} are hatched. The upward half space for the field line is displayed.

ment ion distribution was almost isotropic, but just shifted upward (0305: 12–0305: 24). We could say that this is an upward ion beam, but we also note that there is a signature of heating at lower altitude and subsequent adiabatic upward motion. During the last stage of this upward ion enhancement, the pitch angle distribution revealed an elevated (bimodal) conic in the phase space (0305: 40–0305: 48). Just after the first enhancement of electron precipitation and field-aligned component of upward ions, the phase space distribution approached the usual ion conic signature (0305: 48–0306: 00). Elevated conics were found again in the second and third short enhancements (0306: 08–0306: 16, 0306: 44–0306: 52), and between these times (0306: 16–0306: 32), the usual (non-bimodal) conics were observed. The distribution finally became beam-like, but some weak temperature anisotropy still remained during the last electron precipitation event (0307: 36–0307: 48). These contour maps demonstrate that the field-aligned enhancement of upward ions represents the upward bulk shift of upflowing ions, which are well correlated with electron precipitation. The reduction of ion anisotropy is found only in a large or long-lived region of electron precipitation.

3. Altitude Dependences

Figure 4 shows two examples of phase space density distributions of ion conics and the intersections along the cone of anisotropy. In the upper diagrams the magnetic field direction is taken as upward in the figure. The observations were made in the northern hemisphere, so that the upward direction along the field line is downward of the figure. The ordinate of the lower diagram is the logarithm of phase space density ($\log(f)$). The plot of $\log(f)$ versus energy shows that the "cone temperature" can be defined along the cone of anisotropy. Although ion conics have a high-energy tail and are not considered to be bulk heated at the rocket altitude of the polar ionosphere (YAU *et al.*, 1983), ion conics observed at high-altitude seems to be bulk heated (*e.g.*, KLUMPAR *et al.*, 1984). In this section we deal with the two basic parameters of ion conics: the cone angle and the "cone temperature", and investigate the evolution of ion conics along the field line.

Figure 5 shows the observed conics distribution against altitude and magnetic

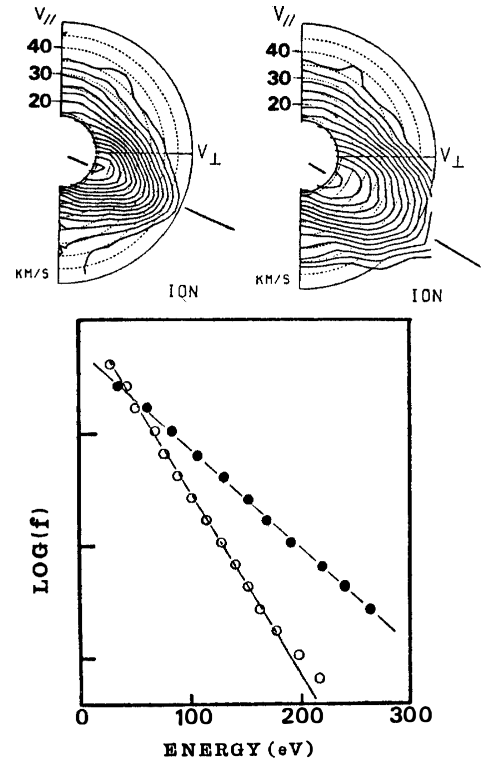

Fig. 4. *Two examples of phase space density distributions of ion conics (upper diagrams) and the logarithm of phase space density plot versus energy along the cone (lower). The velocity scale in the upper diagrams is given by assuming O^+ ions.*

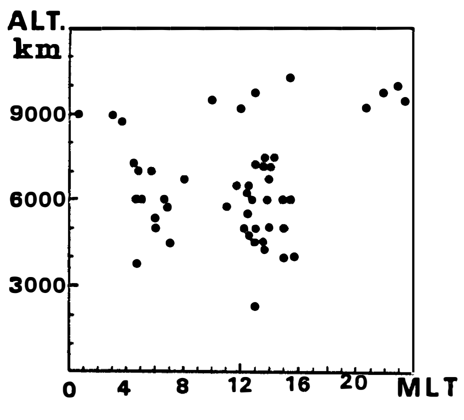

Fig. 5. *Conics distribution against altitude and magnetic local time analyzed in this study.*

local time. The conics events we analyze here were mainly observed on the dayside. This does not immediately mean that ion conics generally occurs on the dayside, but that orbital coverage of the satellite was rather restricted. The altitude distribution is almost uniform in the dayside region. Hence, the results presented here represent the nature of dayside ion conics, and the coupling between altitude and magnetic local time is not indicated in the following figures.

Ion conics were believed to flow upward by means of the magnetic mirror force, so that the cone angle, α, is related to the magnetic field intensity, B, in the relation

$$\frac{\sin\alpha}{\sin\alpha_0}=\sqrt{\frac{B}{B_0}} \tag{1}$$

Figure 6 shows a comparison of the variations of cone angle expected from eq. (1) and

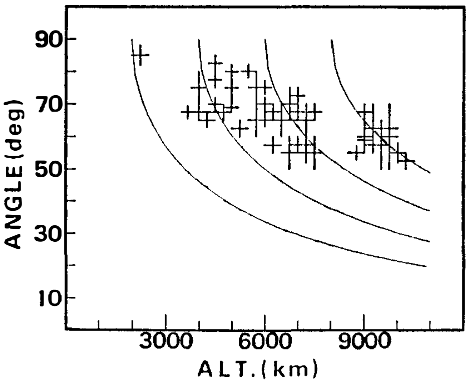

Fig. 6. Altitude dependence of observed cone angle of ion conics. Four curves represent their altitude dependence expectable from the adiabatic motion in the magnetic mirror force field. The vertical and horizontal bars stand for the spread or change during a contuinuous conics event.

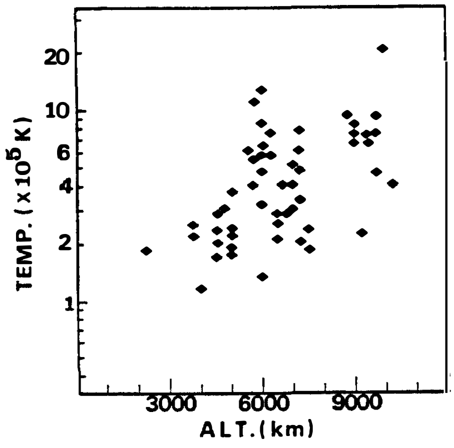

Fig. 7. Altitude dependence of temperature along the cone.

the observation results. We draw four curves of cone angle variations according to the difference in the altitude at which the ions were perpendicularly heated. The vertical and horizontal bars of the observation results indicate the spread or change during a continuous conics event observed while AKEBONO traverses the auroral zone. The observation shows that cone angles tend to be smaller with increasing altitude as is expected, but the reduction rate of cone angle is different from the expected rate. The observed change with increasing altitude is less noticeable than expected. This suggests that the ion conics do not simply upflow in the mirror force field, but the additional perpendicular energization continues as they flow out to higher altitude.

If this is correct, the temperature along the cone should increase with altitude. In Fig. 7 we present the plot of the "cone temperature" against altitude. We plot here the maximum temperature measured during a continuous conics event. Since we analyze only evident conics in the LEP energy range, the lower cutoff of temperature is made artificially by the data selection. The upper envelope of the observed temperatures, however, clearly shows that the more energetic conics are found in the higher altitude.

4. Discussion

A parallel bulk shift of upflowing ions occurs well correlated with the electron precipitation. This is most easily understood in terms of the acceleration by parallel electric field above and below the satellite. We find both the elevated conics and the beam-like distribution in an electron precipitation region (*e.g.*, 0304: 50–0305: 50 UT in Fig. 1). The enhancements of electron precipitation were all associated with upward field aligned current. Upward ion beams are observed only in the upward current region (CATTEL *et al.*, 1980), and the beam-like distributions were also found in the upward current region, so that we might consider the distribution as the ion beam. Although elevated conics can be also produced by the velocity filter (HORWITZ, 1986) and the effect of large heating region (TEMERIN, 1986), the intimate relationship between the elevated conics and beams suggests the acceleration by parallel electric field (KLUMPAR *et al.*, 1984). If the effect of large heating region caused the parallel shift of ions, the parallel shift should be closely correlated with the development of ion perpendicular heating. But our observation indicates that these two energization processes are rather independent.

It was reported that the high-altitude UFI events are more intense and distinct compared with the low-altitude events (YAU *et al.*, 1984). We investigate the altitude dependence by analyzing two basic parameters of ion conics: the cone angle and the "cone temperature". Since we use the data of the E/Q analyzer of LEP in this study, we cannot distinguish between O^+ and H^+ conics. The drastic change of main composition of UFI in this altitude range, however, has not been reported (YAU *et al.*, 1984). Therefore, the altitude dependence reported here is probably not due to the main composition change of ion conics with altitude. The observation result suggests that ion conics do not flow out as a simple adiabatic motion, but additional perpendicular heating often continues. It was proposed that ion acceleration or heating may occur as a two-step process where waves preheat ions at a lower altitude and then they are more efficiently accelerated by some other mechanisms (CHANG *et al.*, 1986). Recent VIKING observations also support a bimodal mechanism for ion beams from the evidence of mass-dependent heating (LUNDIN and HULTQVIST, 1989). Our observation confirms that the ion energization often takes place as a two-step or multi-step process and the energization region is also extended widely along the field lines.

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