Statistical studies of fast and slow Z-mode plasma waves in and beyond the equatorial plasmasphere based on long-term Akebono observations

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(Received June 26, 2005; Revised October 5, 2005; Accepted October 5, 2005; Online published March 10, 2006)

In order to investigate spatial and temporal variations of fast and slow Z-mode waves frequently observed in the equatorial plasmasphere, statistical studies have been performed by using plasma wave observation data obtained by the Akebono satellite within a period from 1989 to 1995. It has been clarified that fast and slow Z-mode waves are intensified within $\pm 5^\circ$ of geomagnetic latitudes in an altitude range from 6000 km to the apogee (10500 km) of the satellite without obvious local time dependence. Long-term averaged intensity of fast Z-mode waves has almost the same orders of magnitude as that of slow Z-mode waves. These results indicate that significant part of fast Z-mode waves are not produced by the linear mode conversion process from slow Z-mode waves, but excited by more direct process. Furthermore, the region of intensified fast and slow Z-mode waves has been spread in a wider geomagnetic latitude range of $\pm 10^\circ$ during geomagnetic storms. These evidences suggest that one of the possible free energy sources is ring current particles injected into the equatorial region of the plasmasphere during geomagnetic storms.
Key words: UHR, fast Z-mode, slow Z-mode, magnetic equator, plasmasphere, magnetosphere.

1. Introduction

After the first identification of slow Z-mode (so-called upper-hybrid) waves from the rocket observation with an apogee of 1500 km (Walsh *et al*, 1964), many satellite observations have been reported concerning existence of slow Z-mode waves in the magnetosphere and plasmasphere (Gurnett *et al*, 1979). Olsen *et al*. (1987) have shown that intense slow Z-mode emissions are observed in the geomagnetic equatorial region of the plasmasphere of $L > 3$. In addition, on the basis of the initial data analysis of the plasma waves and sounder (PWS) system on board the Akebono satellite, Oya *et al*. (1990) have found enhancements of intensity slow Z-mode waves including fast Z-mode waves in the inner plasmasphere within an altitude range from 1500–10500 km (the domains of fast and slow Z-mode are defined below). These enhancements of plasma waves tend to occur in a limited region near the magnetic equator in the plasmasphere, and have been called "equatorial enhancement of the plasma wave turbulence (EPWAT)". EPWAT exists in a geomagnetic latitude range of $\pm 20^\circ$ with little dependence on the local time and altitude which have been covered by the Akebono satellite. These facts indicate that the free energy source which excites EPWAT locates in the limited region of the equatorial plasmasphere (Oya *et al*, 1991). They have proposed that one of the possible generation mechanisms of the EPWAT phenomena is azimuthal plasma drift in the magnetic equator of the plasmasphere.

In general, plasma waves are generated by the particles that satisfy different resonant conditions depending on their phase velocities. Detailed statistical studies on spatial and temporal variations of these waves are, then, essential to clarify the generation mechanisms. Oya *et al*. (1991) have discussed wave activity near the upper-hybrid frequency including both fast and slow Z-mode waves in the plasmasphere. In the traditional nomenclature, both fast and slow Z-mode waves are often included as Z-mode (or upper-hybrid) waves. In this paper, as described in the next section, since their phase velocity, polarization and their nature of the generation processes is different, we have separated slow Z-mode waves ($f > f_p$) from fast Z-mode waves ($f < f_p$). The purpose of the present paper is to clarify statistical characters of spatial and temporal variations of fast and slow Z-mode waves in the equatorial plasmasphere.

2. Observation and Data Analysis

The Akebono satellite was launched on February 22, 1989 into a quasi-polar orbit with an inclination of 75.1° with an initial perigee and apogee of 274 km and 10500 km, respectively. It continues its observation for more than 15 years, with a relatively shorter orbital period of 3.5 hours. The Akebono/PWS measures two components of electric fields with a time resolution of 2 seconds in a frequency range between 20 kHz and 5.2 MHz. To study the relation to geomagnetic disturbances, SYM-H data have been used. The SYM-H index is essentially the same as the Dst index, although it has a time resolution of 1-minute (Iyemori, 1990). In the present data analysis, plasma wave data in a frequency range of 20–1300 kHz for 7 years are used during a period from March 1989 to December 1995. The total observation time during this period is 22389 hours, which

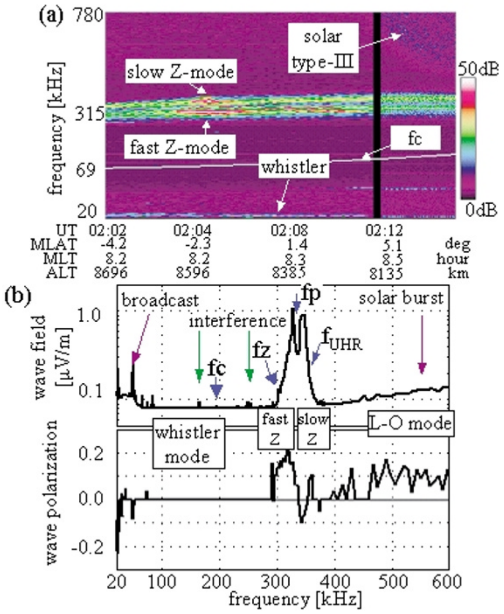

Fig. 1. (a) An example of enhancements of fast and slow Z-mode waves from 2:02 UT to 2:14 UT on Feburary 29, 1992. (b) 1 min averaged wave electric field and polarization from 2:12 UT to 2:13 UT. Identified modes and characteristic frequencies are indicated by arrows.

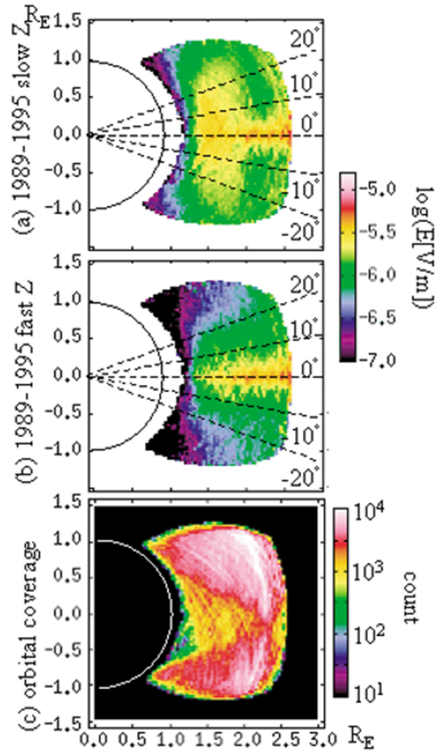

Fig. 2. Distributions of intensity of (a) fast and (b) slow Z-mode waves with respect to the geocentric distance within a period from 1989 to 1995. The panel (c) shows the orbital coverage.

corresponds to 36.5% of 7 years. To avoid an influence of the strong auroral kilometric radiation (AKR), analyzed regions are limited within an invariant latitude range less than 55°.

In order to perform statistical studies of intensity of fast and slow Z-mode waves separately, precise mode identification is essential. In the process of the mode identification, we have checked all of the observed plasma waves on the dynamic spectra to determine characteristic frequencies of plasma waves, such as the electron cyclotron frequency (f_c), the Z-mode cut-off frequency (f_z), the electron plasma frequency (f_p), and the upper-hybrid resonance frequency ($f_{\rm UHR}$). We have employed the following definition to separate fast and slow Z-mode waves in the case where $f_p/f_c > 1$ (Goertz and Strangeway, 1995): A left-handed plasma wave observed in a frequency range of $f_z \le f \le f_p$ is fast Z-mode. A right or almost linearly polarized plasma wave observed in a frequency range of $f_p \le f \le f_{\rm UHR}$ is slow Z-mode. The phase velocity of fast Z-mode waves is larger than the speed of light and are expected to resonate with energetic electrons through cyclotron resonance, while the phase velocity of slow Z-mode waves is smaller than the speed of light and are mainly generated by thermal electrons through Landau-type interaction processes. In general, both modes are called Z-mode waves, but we distinguish these two modes in order to study the origin of these waves.

The characteristic frequencies have relations of $f_z = -f_c/2 + \sqrt{f_c^2/4 + f_p^2}$, and $f_{\rm UHR} = \sqrt{f_c^2 + f_p^2}$; f_c is obtained from the international geomagnetic reference field (IGRF) 1985 model. The other characteristic frequencies are determined from cut-off frequencies appeared on spectra. When wave polarization is observed, these frequencies are determined by both polarization and cut-off frequencies. From these methods, statistical analysis of intensity of fast and slow Z-mode waves are performed in the next section. Other modes of plasma waves are excluded in the process of the mode identification. In the plasmasphere, whistler mode waves do not contaminate because $f_p/f_c \sim 5$. The free-space electromagnetic waves and electrostatic electron cyclotron harmonic (ESCH) waves can be distinguished by their bandwidths and propagation nature. AKR and kilometric continuum tend to have bandwidths of some 100 kHz and 10–100 kHz, respectively (Hashimoto *et al*, 1999), which have wider bandwidth than Z-mode waves. ESCH waves have discrete spectra with the bandwidth of less than 1.5 kHz (Shinbori *et al*, 2004) and narrower than Z-mode waves.

Figure 1(a) is an example of the dynamic spectrum of plasma waves within a frequency range from 20 kHz to 780 kHz observed in the low latitude plasmasphere. Figure 1(b) is 1 min averaged wave electric field and wave polarization from 2:12 UT to 2:13 UT; the polarization is indicated by the value of $(E_L - E_R)/(E_L + E_R)$, where E_R and E_L are observed right-handed and left-handed electric field intensity. Two continuous narrow band emissions are identified around 315 kHz. The lower band is left-handed polarized and the upper band is almost linearly polarized. Therefore the former and latter are identified as fast and slow Z-mode waves, respectively. A high frequency diffuse emission above 400 kHz is solar type-III bursts, which can be easily excluded in this analysis by their diffusive nature.

In this case, enhancements of fast and slow Z-mode waves are found in the magnetic equatorial region in a magnetic latitude ranges from −2.2° and 3.5°. These emissions are frequently observed in the magnetic equatorial region

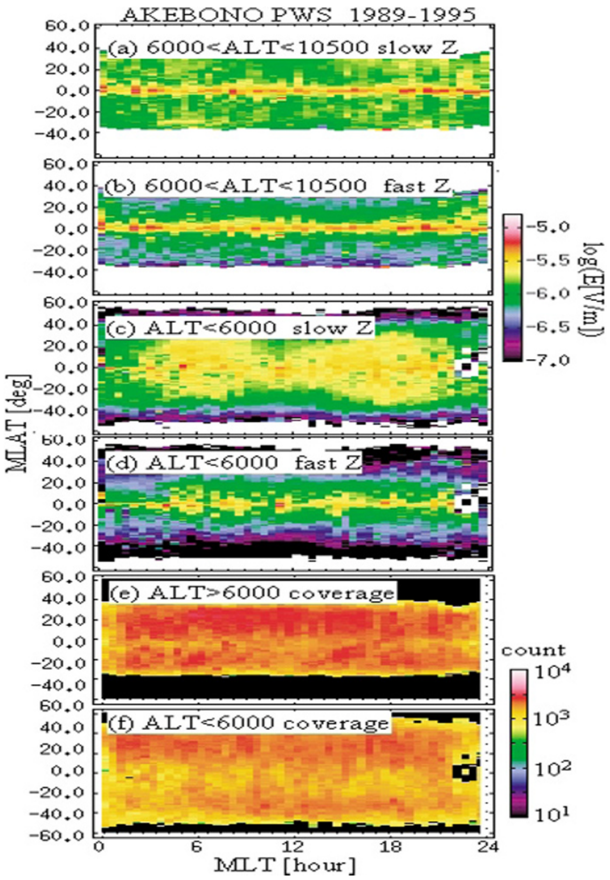

Fig. 3. MLT and MLAT distribution of intensity of fast and slow Z-mode waves within a period from 1989 to 1995. The panels (a) and (b) are the data in the altitude range of 6000–10500 km, and the panels (c) and (d) are those in the altitude less than 6000 km. The panels (a) and (c) are distribution of slow Z-mode waves, and the panels (b) and (d) are those of fast Z-mode waves. The panels (e) and (f) shows the orbital coverage.

(Oya *et al*, 1991). In this paper, statistical studies of the spatial and temporal variations of these emissions have been done by analyzing huge amount of data obtained in 7 years.

3. Results

Figure 2(a) and (b) show distribution of averaged intensity of fast and slow Z-mode waves observed from 1989 to 1995. The panel (c) shows the corresponding orbital coverage, which shows numbers of satellite paths when the PWS system is operated in each bin. Almost all bins have more than 500 counts, although the low-altitude equatorial region has less coverage. The first remarkable feature of both intense fast and slow Z-mode waves with intensity greater than 3 μV/m (indicated as yellow and red colors in the figure) distribute in a wide altitude range of 6000–10500 km, but confined in a narrow latitude range less than 10°. The second point is that the enhancement of slow Z-mode waves can be found in a wider latitude range of $\pm 20^\circ$ within the altitude range of 2000–6000 km, that shows different nature from the higher altitude range of more than 6000 km, while fast Z-mode waves are also confined in a latitude range less than 10°. The third point becomes clear when we see the distribution of waves with relatively low threshold level ($\sim$ 1μV/m corresponding to the color code of green) of intensity: Slow Z-mode waves with intensity greater than

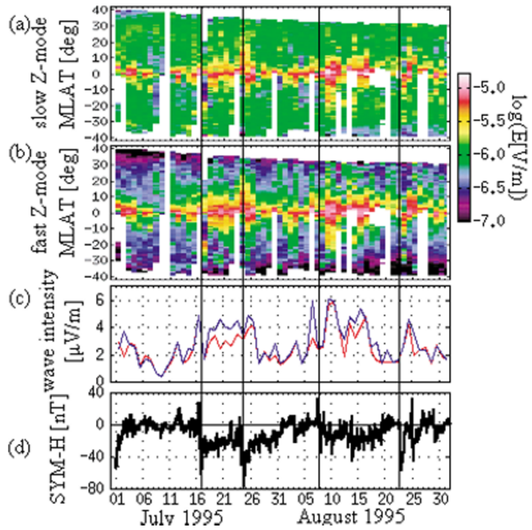

Fig. 4. Temporal variations of one-day averaged intensity of (a) fast and (b) slow Z-mode waves during July and August, 1995. The panel (c) is averaged intensity of fast (red) and slow (blue) Z-mode in the geomagnetic latitude range from -10° and 10°. The panel (d) is the SYM-H index. Four vertical lines are the onset times of the geomagnetic disturbances.

1 μV/m are observed in the whole plasmasphere, while the regions where fast Z-mode waves with intensity greater than 1 μV/m are localized in the latitude range of $\pm 15^\circ$.

Figure 3 shows local time dependence of fast and slow Z-mode waves observed in the same period of Fig. 2. The panels from (a) to (d) indicate distribution of fast and slow Z-mode waves in altitude ranges of 6000–10500 km and less than 6000 km, respectively. The panels (e) and (f) show the corresponding orbital coverage; and almost all bins have more than 500 counts. From the panels (a), (b) and (d), both fast and slow Z-mode waves with intensity greater than 3 μV/m do not show remarkable local time dependence. On the other hand, in the low altitude region below 6000 km, slow Z-mode waves with intensity greater than 3 μV/m tend to appear in a wider latitude range at the dawn and dusk regions. This occurrence feature is not so clear in distribution of the corresponding fast Z-mode waves although there is a faint tendency which follows distribution of slow Z-mode waves. Distribution feature of fast and slow Z-mode waves suggests that the origin of a large part of fast Z-mode waves is different from that of slow Z-mode waves in this region; and fast Z-mode waves are not simply generated from slow Z-mode waves by mode conversion mechanisms.

In Fig. 4(a) and (b), temporal variations of intensity of fast and slow Z-mode waves are plotted in a geomagnetic latitude range of $\pm 40^\circ$ during July and August, 1995. The panel (c) is averaged intensity of fast (red) and slow (blue) Z-mode waves in a geomagnetic latitude range from -10° to 10°, and the panel (d) gives the SYM-H index. Onset times of geomagnetic disturbances are indicated by vertical lines. Comparing these lines and the panel (c), both fast and slow Z-mode waves have a clear tendency to enhance almost simultaneously with the onset of geomagnetic storms. As shown in this figure, fast Z-mode waves are intensified in a wider latitudinal range than slow Z-mode waves and intensity of fast Z-mode waves is greater than that of slow Z-mode waves. This implies that, although we have to consider a propagation effect, it is not likely that these fast Z-mode waves are generated as the result of the mode conversion from slow Z-mode waves (Oya, 1971). On the other hand, both fast and slow Z-mode waves appear in a narrow latitude range of $\pm 3^\circ$ during the geomagnetically quiet periods.

4. Discussion and Conclusion

In the present study, we have investigated spatial distribution of intensity of fast and slow Z-mode waves in the equatorial plasmasphere, and their temporal variations associated with geomagnetic storms. A remarkable feature is that both fast and slow Z-mode waves are localized in a limited latitudinal range of $\pm 5^\circ$ in an altitude range of 2000–10500 km without obvious local time dependence.

The homogeneous feature in the MLT distribution of fast and slow Z-mode waves (see Fig. 3) is unique one compared with other plasma waves observed in the inner magnetosphere, such as the electromagnetic ion cyclotron (EMIC) waves (Anderson *et al.*, 1992), chorus (Tsurutani and Smith, 1977), ESCH (Roeder and Koons, 1989), and kilometric continuum (Hashimoto *et al*, 1999). It is well known that occurrence regions of these waves tend to have clear local time dependence. From this fact, it can be inferred that the origin of these fast and slow Z-mode waves in the plasmasphere are different from other plasma waves in the magnetosphere.

The intensifications and expansions of fast and slow Z-mode waves are well correlated with geomagnetic disturbances, although these waves are also observed in the narrow latitude range during the quiet periods. This fact may indicate that even weak geomagnetic disturbances which occur frequently with about the SYM-H of -40 nT well influence the plasma environments of the inner plasmasphere. One of the possible candidates of the energy source to generate such fast and slow Z-mode waves may be attributed to energetic particles of the ring current or the radiation belt which have been injected deeply into the equatorial region of the inner plasmasphere during the geomagnetic storms. These particles continue to drift around the Earth covering geomagnetically quiet periods and the recovery phase of geomagnetic storms and resulting in the homogeneous MLT distribution of the occurrence of these waves (drift periods around the earth of 10 keV and 100 keV electrons at $L = 2.5$ are 28.8 and 3.1 hours, respectively).

Long-term averaged intensity of enhanced fast Z-mode waves is the same order of magnitude as or greater than that of slow Z-mode waves, and the enhanced region spreads more widely than slow Z-mode waves during disturbed periods. These evidences suggest that some part of fast Z-mode waves are not produced by the mode conversion processes from slow Z-mode waves, but excited by more direct process. By a cyclotron-type wave-particle interaction process, these fast Z-mode waves satisfy a higher-order cyclotron resonance condition. In order this mechanism to work, energetic electrons need to be injected into the inner plasmasphere during geomagnetic storms. Storm-time enhanced convection electric fields, which are larger than a few mV/m (Shinbori *et al*, 2005) may contribute to the injection of energetic particles into the inner plasmasphere and these particles cause a direct generation of fast Z-mode waves through cyclotron-type interactions.

Acknowledgments. The Akebono satellite was established by the Institute of Space and Astronautical Science (ISAS/JAXA). Activities of three authors (T. Ono, M. Iizima, and A. Kumamoto) are supported by the 21st century COE program "Advanced Science and Technology Center for the Dynamic Earth" at Tohoku University. The fourth author (A. Shinbori) is also supported by a grant of Research Fellowship of the Japan Society for the Promotion of Science for Young Scientists.

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