Ion Cyclotron Whistlers Related to Heavy Minor Ions Observed by the Akebono Satellite and Their Distribution in the Inner Magnetosphere

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Introduction

It is well known that lightning whistler waves are caused by lightning discharge; these waves propagate along geomagnetic field lines as R-mode plasma waves of less than several tens kHz. Ion cyclotron whistler waves, which are electromagnetic ion cyclotron (EMIC) mode waves, have a close relation to lightning whistlers. Propagation characteristics of ion cyclotron whistler strongly depend on ion concentrations in plasma as well as nature of general EMIC waves. *Gurnett et al.*(1965) proposed a generation mechanism for ion cyclotron whistlers along their propagation characteristics. One of the most important features is the lowest frequency of an ion cyclotron whistler that denotes the local crossover frequency ($\omega_{\rm cr}$) of the EMIC mode wave. The asymptotic frequency of a typical ion cyclotron whistler is close to each local ion cyclotron frequency (Ω_i). These facts suggest that we can estimate the ion species and concentrations at a local point or in the propagation path of the waves by analyzing these characteristics of ion cyclotron whistlers.

Observations of ion cyclotron whistlers related to heavy minor ions

Watanabe et al.(1975) reported the first observation of $M/Q = 2$ ion cyclotron whistlers measured by the ISIS-2 satellite. According to their analysis, $M/Q = 2$ ion cyclotron whistlers were observed in the altitude region around 1,360–2,800 km ($L = 1.2$–1.6). *Gurnett et al.*(1970) reported $M/Q = 8$ ion cyclotron whistlers ($M =$ ion mass in amu, $Q =$ ion charge) observed by the Injun 5 satellite in the altitude region around 1,300–2,100 km.

The Akebono satellite was launched in February 1989, into a quasi-polar elliptical orbit with initial apogee and perigee heights of 10,500 and 300 km, respectively. It has been successfully operated to observe the auroral region and the inner magnetosphere for over 25 years. The extremely low frequency (ELF) receiver, which is a sub-system of the very low frequency (VLF) instruments onboard Akebono, measures waveforms either below 50 Hz for one electric field component and three magnetic field components, or below 100 Hz for one component of the electric and magnetic fields [*Kimura et al.*, 1990]. In this paper, we report ion cyclotron whistlers related to $M/Q = 2$ and $M/Q = 8$ ions observed in the highest altitude so far by the Akebono satellite. These events are valuable evidence indicating that certain amount of such heavy ions are present on the propagation paths. We discuss the ion concentration in the inner magnetosphere estimated from crossover frequencies of ion cyclotron whistlers observed by Akebono.

We surveyed the ELF data observed by Akebono in 1989 and 1990. We found that the $M/Q = 2$ ion cyclotron whistler waves were observed in the altitude region around 3,200–10,000 km ($L = 1.5$–3.4), which is a considerably higher altitude than those previously reported. In addition, we discovered ion cyclotron whistlers related to heavier ions. $M/Q = 8$ ion cyclotron whistler waves were observed in the altitude region around 500–4,500 km ($L = 1.2$–3.8).

Discussion and conclusions

Our results suggest that some amount of minor heavy ions such as O^{++}, He^{++} and/or D^+ exist in the high altitude region in the inner magnetosphere. Distribution of $M/Q = 8$ ion cyclotron whistlers is greatly different from that of $M/Q = 2$ ion cyclotron whistlers. This fact suggests that the spatial distributions of $M/Q = 2$ and $M/Q = 8$ ions are different. Furthermore, we examine ion concentrations during the event. We can estimate the concentrations of n species of ions measuring $(n-1)$ crossover frequencies. Even in the case that only $(n-2)$ crossover frequencies can be determined from the data, we can infer the concentrations of n species of ions on the assumption that one ion concentration has a fixed value. For example, we can infer the He^+ and the $M/Q = 8$ ion concentration from two crossover frequencies when we consider only four types of ions (H^+, He^+, O^{++} ($M/Q = 8$), O^+) and assume that the O^+ concentration is a fixed value. So far we have surveyed the ELF data observed by Akebono and observed several hundred similar ion cyclotron whistlers. Recently, it has been revealed that wave-particle interaction is an important process in the control of inner magnetospheric physics. Our studies and results will be useful information for future satellite missions such as ERG[*Miyoshi et al.*, 2013] in the inner magnetosphere, ray tracing, and computer simulations.

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