IPDP Plasma Wave Events Observed in Association with Low Latitude Auroras

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A case study of IPDP (Intervals of Pulsations of Diminishing Period) observed in association with low-latitude auroras is reported. Visible red auroras were detected twice in the time intervals of 11h36m-12h30m UT and 14h10m-14h30m UT on October 21, 1989. Simultaneously there were two rapid northward excursions of the H-component magnetic perturbation with the magnitude of more than 150 nT. The IPDP plasma wave events were observed at Yonezawa during the low-latitude auroras. The energy source of the IPDP plasma wave event is inferred to be the wave-particle interaction involving the asymmetric ring current oxygen ions at the bulge region of the plasmapause during the expansive phase of substorms. The frequency increase is explained in terms of a decrease of energy of the oxygen ion stream while the asymmetric ring current decays.

1. Introduction

It is now generally accepted that IPDP plasma wave events are generated by an ion cyclotron instability in the region where the westward drifting energetic protons encounter the duskside bulge region of the plasmapause (Seraas et al., 1980; Hayakawa et al., 1992; Baishev et al., 1994). Protons from the plasmasheet are injected into the inner magnetosphere at substorm's onset. This injection takes place from the injection boundary in a limited local time area around magnetic midnight. The protons are driven in from the magnetotail by intense cross-tail electric fields. Particles injected along the injection boundary will encounter the duskside bulge of the plasmapause. The protons which can intercept the plasmapause during their westward drift must be located in a limited area. When the protons penetrate into the plasmapause, intense ion cyclotron instability with a strong diffusion process can be generated, if the proton pitch angle anisotropy is greater than the critical value. However, all aspects of the process are not completely understood. It is especially true that the fundamental mechanism responsible for the frequency increase exhibited in the dynamic spectrum remains to be solved. Several models have been proposed to explain the frequency increase of IPDP plasma wave events: (1) Earthward source movement due to $E \times B$ drift causes an increase of the observed frequency in the IPDP plasma wave events (Troitskaya et al., 1968; Gendrin, 1970; Heacock et al., 1976; Kangas et al., 1988). (2) The differential drifting velocity of injected protons leads to an earlier arrival of higher energy protons at the duskside bulge region, which in turn causes the frequency increase of IPDP plasma wave events (Fukunishi, 1969). (3) An increase of frequency is due to the change in the cyclotron frequency produced by the increasing background magnetic field intensity (Roxburgh, 1970). This hypothesis was tested by a comparison of the frequency increase of IPDP plasma wave events observed on the ground and the magnetic field increase in the magnetosphere observed by geostationary satellites. Bössen et al. (1976), however, have disagreed with Roxburgh's hypothesis, because the background magnetic field at the satellites remained constant or even decreased slightly during the IPDP plasma wave events observed on the ground. But, at present, both of them are correct, since the IPDP plasma wave events in the subauroral region take place when the magnetospheric magnetic field at an overhead geostationary satellite increases as Roxburgh observed whereas the IPDP plasma wave events in the auroral region occur when the magnetospheric magnetic field diminishes as Bössen et al. found (Watanabe, 1991) (4) Wave velocity dispersion effects (Knaflich and Kenney, 1967; Lee and Kwok, 1984). (5) Relativistic and parasitic interaction (Thome and Kennel, 1971). (6) Hybrid
model (Pikkarainen, 1983; Koleszar, 1988; Hayashi et al., 1988). The satellite observation of protons involved in the generation of IPDP plasma wave events were reported by Horita et al. (1979). The analyses concluded that the approximate locations of the instability regions at the onset of IPDP plasma wave events were generally near the plasmapause and were at $L$ values between 4.7 and 5.5 with the majority at values between 5.0 and 5.3 in the afternoon–evening sector between 1700 and 2300 LT. Furthermore, they suggested that the frequency increase of the IPDP plasma wave events can be enhanced by the rapid inward movement of the bulge region with increasing $K_p$. (7) A decrease of thermal plasma density at the plasmapause (Lin and Parks, 1976). All the studies mentioned above were concerned with the events...

Fig. 1. $H$-component magnetic perturbation of the fluxgate magnetometer at Moshiri station on Hokkaido Island. The rapid northward excursions (two positive bays) are indicated by the time intervals of 11h36m–12h30m UT and 14h10m–14h30m UT on October 21, 1989. The time variations of auroral luminosity are shown in the middle panel of the figure. The amplitude-time record of the IPDP plasma wave event observed at Yonezawa is shown in the bottom panel of the figure. An arrow in the figure indicates the time of the maximum frequency of the IPDP plasma wave event. Note that the time of the maximum amplitude of the positive bay corresponds to the time of the maximum frequency of the IPDP plasma wave event.
related to auroral substorms at high latitudes. The present paper deals with a preliminary study of physical mechanisms involved in the frequency increase and the generation process of IPDP plasma wave events observed in association with low-latitude aurora.

2. Observation

The $H$-component magnetic perturbation of the fluxgate magnetometer at Moshiri station is shown in the upper panel of Fig. 1. It is clearly seen that there are two rapid northward excursions which are indicated in the time intervals of 11h36m–12h30m UT and 14h10m–14h30m UT. The time variations of the maximum auroral luminosity in the geomagnetic meridian plane are shown in the middle panel of Fig. 1 for 630.0 nm and 557.7 nm wavelengths (Miyaoka et al., 1990; Kuwashima et al., 1990). The IPDP plasma wave event was observed at Yonezawa during the rapid northward excursion of the $H$-component magnetic perturbation (positive bay). The amplitude-time record is shown in the bottom panel of Fig. 1. It is interesting to note that the time of the maximum amplitude of the positive bay corresponds to the time of the maximum frequency of the IPDP plasma wave event (Higuchi, 1994). An arrow in the figure indicates the time of the maximum amplitude of the IPDP plasma wave event. Figure 2 shows two dynamic spectra of the IPDP plasma wave events during the low-latitude auroras. Satellite observations (DMSP-F9) of precipitating particles during low-latitude aurora have shown the existence of low-energy electrons (30–300 eV) just on the low-latitude side of the ordinary auroral oval defined by an enhancement of precipitating electrons of several keV. A large amount of low-energy secondary electron precipitation becomes effective for the excitation of a 630.0 nm emission line. A sudden brightening occurred at 11h36m UT on Oct. 21, 1989. The 630.0 nm emission was abruptly enhanced and reached the saturation level of the instrument. The maximum intensity was estimated to reach more than 8.8 kR. But, the 557.7 nm emission indicated no significant brightening like the 630.0 nm emissions, except for several ray structures along the geomagnetic field lines, which appeared overlapping the 630.0 nm emissions, with a typical life-time of about 10 to 30 seconds. This indicates that particle precipitation with energy of the order of a keV occurred during the time of the 557.7 nm emission enhancement. The distinctive feature of the low-latitude aurora was an extremely high intensity ratio of 630.0 nm to 557.7 nm emissions. On the other hand, satellite observations (GOES 6 and 7) of the magnetic field during the IPDP plasma wave events in association with low-latitude aurora have indicated the sudden increase of the $H$ and $V$-component magnetic fields at geosynchronous orbits after the gradual decrease of the $H$ and $V$-component magnetic fields. This observation suggests that the transition of the geomagnetic field configuration to dipolar from the more tail-like magnetic field configuration occurred during the IPDP plasma wave event. Observations of energetic oxygen ion fluxes during the main phase of the geomagnetic storm have been reported by several authors (Shelley et al., 1972; Torr et al., 1979). The energetic oxygen ion fluxes lose their energy through charge exchange and momentum transfer collisions with ambient oxygen atoms. The excitation and ionization lead to oxygen emissions and secondary low-energy electrons observed by the satellite during the low-latitude aurora. The IPDP plasma wave event can be generated by the wave-particle interaction involving the asymmetric ring current of energetic oxygen ion fluxes with the anisotropic pitch angle distribution.

3. Interpretation

First, if the frequency increase is solely due to the radial convection of the generation region under the $E \times B$ drift, the inward convection velocity of the generation region becomes $V_a = 1.02 \times 10^{-4} L \text{ m/sec}$ in the time interval of 11h36m–12h30m UT on October 21, 1989. Assuming that the generation region is at $L = 2.5$, the convection electric field can be estimated as $E_1 = 3.22 \text{ mV/m}$. Since the estimated convection electric field becomes large value, because of the unusual source location, we must look for another possibility to interpret the frequency increase of the IPDP plasma wave events in the particular case of the low-latitude aurora. It is possible that the frequency increase can be explained in terms of a decrease of
Fig. 2. Two dynamic spectra of the IPDP plasma wave events during the low-latitude auroras. The power spectrum estimation was carried out by the maximum entropy method in the time intervals of 11h52m–12h07m UT and 14h00m–14h30m UT on October 21, 1989.
energy of the oxygen ion stream while the asymmetric ring current decays. The oxygen ions with higher energy are precipitated in an earlier time, then the oxygen ions with lower energy are precipitated in the later time. This differential kinetic energy of precipitating oxygen ion stream can contribute to the frequency increase of the IPDP plasma wave events in association with the low-latitude aurora. Therefore, consider a possible unstable frequency band of an electromagnetic oxygen ion cyclotron instability and a maximum convective growth rate in the multicomponent asymmetric ring current plasmas. Assuming the particle distribution function to be monoenergetic, the convective growth rate is then expressed by (Higuchi, 1990; Jacks, 1966)

\[
\left( \gamma / \Omega_{O^+} \right) \left( V_g / V_0 \right) = (1/2) \sqrt{\pi N_s} \left( 1 - \omega / \Omega_{O^+} \right) \left( m / 2 \right) \left( 1 - \omega / \Omega_{O^+} \right) - \omega / \Omega_{O^+} \right) G^{-1} \left( \omega, N_{He^+}^+, N_p^+ \right) \times \left[ \left( m + 3 / 2 \right) / \Gamma ((m + 1) / 2) \right] \left( V_0 / V_a \right)^2 - \left( V_g / V_a \right)^2 \right)^{m/2} \left( V_0 / V_a \right)^{-(m+1)},
\]

where

\[
G(\omega, N_{He^+}^+, N_p^+) = \left( \omega / \Omega_{O^+} \right)^2 \left[ 1 + N_{He^+} \left( 1 - \left( \omega / \Omega_{O^+} \right) \right) \left( 1 - \omega / \Omega_{O^+} \right) \right] + N_p^+ \left( 1 - \left( \omega / \Omega_{O^+} \right) \right) \times \left( 16 - \left( \omega / \Omega_{O^+} \right) \right)^{-1},
\]

and \( m \) is the pitch angle distribution parameter, respectively. Then \( \Gamma(m) \) is a gamma function, and also \( \gamma \) and \( V_g \) are the temporal growth rate and the group velocity of the oxygen ion cyclotron wave, respectively. Then \( N_s \) is the ratio of the number density of the energetic oxygen ion stream to the number density of the cold oxygen ion, and \( V_r \) means the resonance velocity. Numerical results of the unstable frequency band as a function of convective growth rate with parameters of the oxygen ion stream velocity are shown in Fig. 3, where \( N_{He^+}^+ \) and \( N_p^+ \) are the ratios of the number density of the cold proton and helium ion to the number density of the cold oxygen ion, respectively. When the ratio between the velocity of the oxygen ion stream and the resonance velocity is shown in Fig. 3.

Fig. 3. Numerical results of the unstable frequency band as a function of convective growth rate with parameters of the oxygen ion stream velocity. Note that the most unstable frequency increases with decreasing the velocity of oxygen ion stream.
ion stream \( (V_0) \) and the Alfvén velocity \( (V_A) \) is 10.0, the most unstable frequency becomes \( 0.110 \Omega_{O^-} \), where \( \Omega_{O^-} \) is the oxygen gyrofrequency, when the maximum growth rate is 0.029. On the other hand, when the ratio between the velocity of the oxygen ion stream and the Alfvén velocity decreases to be 2.0, the most unstable frequency increases \( 0.34 \Omega_{O^-} \), when the maximum growth rate is 0.0042. The most unstable frequency increases with decreasing the velocity of the oxygen ion stream. This can explain why the frequency of the IPDP plasma wave events in association with low-latitude aurora increases. In addition, there is an optimum ratio of the oxygen ion density to the proton density for the maximum convective growth rate (Higuchi, 1991, 1993). If the number density of the energetic oxygen ion is increased during the main phase of the geomagnetic storm, the unstable frequency bands above the helium gyrofrequency can be suppressed. The lowest unstable frequency band corresponding to the oxygen gyrofrequency remains to be mainly excited (Fraser et al., 1992).

4. Discussion and Conclusions

It was reported that a great solar flare of the largest class 4B/X13 near the central meridian of the sun occurred at 12h29m UT on October 19, 1989. The IMF turned southward two times between 12h50m–13h40m UT and 16h50m–19h00m UT, and the enhanced solar wind velocity was estimated at more than 2000 km/s. Thus, a major geomagnetic storm was triggered with an increase in the horizontal component of the geomagnetic field at 09h17m on October 20, 1989. Magnetopause crossings were observed by GOES 6 and 7 satellites from 17h10m to 19h00m UT on October 20, when both satellites moved outside the magnetopause, showing the strong compression of the magnetosphere in the midst of the main phase of geomagnetic storm. Therefore, the low-latitude auroras were observed twice in the time intervals as mentioned in the abstract. The short time duration (30 minutes) of the northward excursions of the \( H \)-component magnetic field perturbation implies that the asymmetric ring current is incompletely shielded, allowing ionospheric currents and the injection of the asymmetric ring current to unusually low-latitudes (Tinsley, 1986; Rassoul et al., 1992, 1993; Yeh et al., 1994; Yumoto et al., 1994). In addition, it has been shown that the fluxes of oxygen ions in the asymmetric ring current can be comparable or even higher than the fluxes of protons during the main phase of geomagnetic storms (Gloeckler et al., 1985; Krimigis et al., 1985). The number density of oxygen ions was observed to be 10/cm\(^3\) in the narrow L-shell regions centered at \( L = 3 \). Therefore, it is speculated that the fluxes of energetic oxygen ions are the main component of the asymmetric ring current during the time interval of the low-latitude aurora. The IPDP plasma wave event could be generated as a result of the instability of oxygen ion cyclotron waves in association with the large anisotropic pitch angle distribution. Because of the heavier mass of oxygen ions, the characteristic frequency of the generated waves is much lower than that in the case of protons. In conclusion, it is possible that the frequency increase of the IPDP plasma wave events observed in association with low-latitude aurora is explained in terms of the decrease of energy of the oxygen ion stream while the asymmetric ring current decays.

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