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PARTICLE PRECIPITATION ASSOCIATED WITH TRANSVERSE Pc5 PULSATIONS

Masahito NOSÉ[1], Toshihiko IYEMORI[1], Masahisa SUGIURA[2] and James A. SLAVIN[3]

[1]*Geophysical Institute, Faculty of Science, Kyoto University, Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto 606-01*
[2]*Institute of Research and Development, Tokai University, 18-4, Tomigaya 2-chome, Shibuya-ku, Tokyo 151*
[3]*NASA Goddard Space Flight Center, MC 696, Greenbelt, MD 20771, U.S.A.*

Abstract: Interactions between Pc5 pulsations and particles are investigated with the magnetic field data obtained by the DE-1 polar orbiting satellite and the precipitating electron data from the DMSP satellites. We found geomagnetic conjunction events of DE-1 and DMSP in which these satellites respectively observed Pc5 pulsations and particle precipitation approximately on the same geomagnetic field lines. The invariant latitude ranges for the observations of Pc5 and precipitation of 3 keV electrons were almost the same. A statistical study also showed that the region of the central plasma sheet obtained by P.T. NEWELL and C.-I. MENG (J. Geophys. Res., **99**, 273, 1994) falls in the region of the occurrence of transverse Pc5 pulsations. The precipitation of electrons having energies greater than 3 keV was investigated. It is shown that there are differences in the characteristics of 30 keV electron precipitation between the cases in which pulsations were observed and those in which pulsations were not observed. These results suggest that electrons are modulated by transverse Pc5 pulsations.

1. Introduction

Interactions between ULF waves and particles have been reported by many observational studies. There are some theories to explain mechanisms of ULF wave-particle interactions.

Modulations of particle flux, which suggest the effect of drift-bounce resonance, have been investigated by some authors. Flux modulations of energetic electrons and protons associated with the occurrence of transverse Pc5 pulsations were found by KOKUBUN *et al.* (1977) from Ogo-5 observations. They showed that the modulations in protons are larger on the morning side, while the electron modulations are larger on the afternoon side. They concluded that these modulations stem from the drift resonance. CLADIS and LENNARTSSON (1986) explained that the rapid loss of the westward drifting ions observed by ISEE-1 was through a bounce resonance interaction of the ions with the standing Alfvén waves. TAKAHASHI *et al.* (1990) analyzed an ion flux pulsation event associated with a radially polarized transverse Pc5 pulsation. They concluded that the observations can be interpreted as the result of drift-bounce resonance of the ions with the waves.

The events with flux modulations of particles which are consistent with the theoretical predictions by CORONITI and KENNEL (1970) were shown by PAQUETTE *et al.* (1994). They found elevated levels of VLF activity and VLF modulation at pulsation frequency in some events, in which variations of particle precipitation begin several hundred seconds in advance of ULF pulsations. This observation indicates an interaction between particles and equatorial VLF waves whose activity levels are modulated by ULF waves.

A prominent feature of kinetic Alfvén wave, an Alfvén wave with a perpendicular wavelength comparable to the ion gyroradius, is that it has a parallel electric field. HASEGAWA and CHEN (1976) concluded that electrons are heated in the parallel direction because of the parallel component of the wave electric field. HASEGAWA (1976) suggested that electrons that cause the discrete aurora are accelerated by kinetic Alfvén waves to a few keV. Recently, WEI *et al.* (1994) showed from simulation studies that the kinetic Alfvén wave causes field-aligned potential drops of several kiloelectron volts.

In this study we investigate characteristics of electron precipitation associated with transverse Pc5 pulsations, using the magnetic field data from DE-1 and the precipitating electron data from DMSP. We present observational evidence suggesting interactions between ULF waves and electrons.

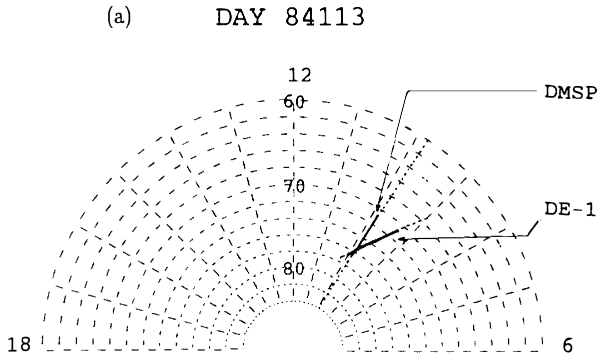
2. Data Set

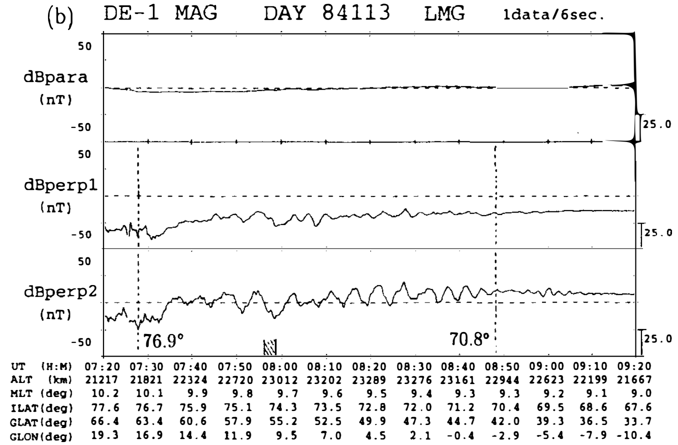
The magnetic field data used here were obtained by the triaxial fluxgate magnetometer (MAGA) on board the DE-1 polar orbiting satellite, which was launched on August 3, 1981 (See FARTHING *et al.* (1981) for the specifics of the magnetometer). The orbit of DE-1 had initial apogee at 4.6 R_E geocentric distance, period of about 7 hours, and inclination of 90° (HOFFMAN and SCHMERLING, 1981). Only the data obtained near apogee (where the magnitude of the main field is less than 1000 nT) were used in this study. Data used are spin-period averages of 1 sample per 6 s.

For precipitating electron data we used those obtained by the SSJ/4 electrostatic analyzer on the Defense Meteorological Satellite Program (DMSP) F6 and F7 satellites (HARDY *et al.*, 1984). The particle precipitation was measured in the energy range from 32 eV to 30 keV in 20 energy channels. One complete 20-point electron spectrum is obtained each second. The DMSP F6 and F7 satellites were launched in December 1982 and November 1983, respectively. Both satellites are sun-synchronous satellites in circular polar orbits with altitudes of about 835 km, periods of about 100 min, and inclinations of 98.7°. The spatial coverages in magnetic local time and magnetic latitude for these satellites are different, that is, DMSP F6 was in the dawn-dusk meridian plane and F7 was in the 1030–2230 local time meridian plane.

3. Analysis and Results

In the period from 1984 to 1986 we found 17 cases of geomagnetic conjunctions of DE-1 and DMSP in which these satellites respectively observed transverse Pc5 pulsations and particle precipitation approximately on the same geomagnetic field lines. The conjunction events were picked up during geomagnetically quiet times ($AE \leq 200$ nT). The following criteria were adopted in the selection of transverse Pc5 pulsations. (1) The perpendicular magnetic field components are dominant in the wave. (2) The maximum





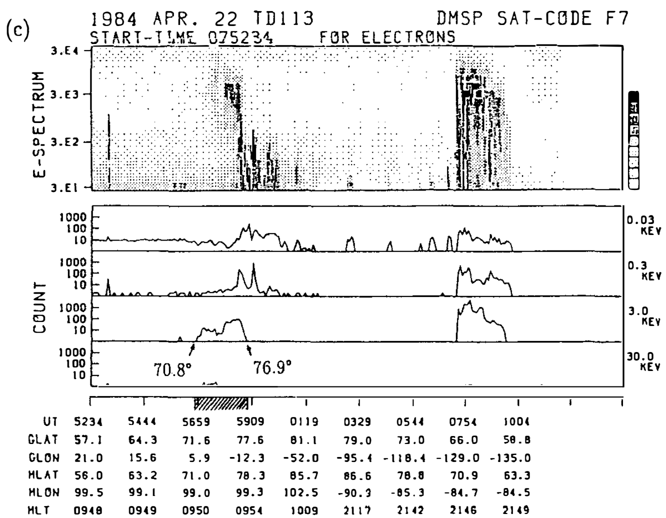


Fig. 1.

(a) *The passes of the DE-1 and DMSP satellites in MLT-ILAT plane for geomagnetic conjunction event on 22 April 1984. Thick lines represent the passes in which Pc5 pulsation and particle precipitation were observed by DE-1 and DMSP, respectively.*

(b) *Transverse Pc5 pulsation observed by DE-1. The magnetic field data are plotted in the local magnetic coordinate system. The $B_{\parallel}$ component is tangential to the model magnetic field. The $B_{\perp 1}$ component is directed radially outward and the $B_{\perp 2}$ component, eastward.*

(c) *The upper panel shows Energy-Time diagram for electron precipitation observed by DMSP. The lower four panels show the number of counts detected by 4 channels with different energies.*

amplitude of oscillation is greater than 5 nT. (3) The wave lasts for more than 30 min. We defined the events which satisfy the following criteria as geomagnetic conjunction events. (1) The invariant latitude (ILAT) ranges for observations by DE-1 and DMSP are almost the same. (2) The difference between the magnetic local time (MLT) at the location of DE-1 and that of DMSP is less than one hour. (3) The time interval during which DMSP observed particle precipitation is contained in the time interval during which DE-1 observed pulsation. Most of the geomagnetic conjunction events were found in the region around 72° ILAT between 0600 and 1200 MLT.

Figure 1 shows an example of geomagnetic conjunction event observed on 22 April 1984. The passes of the DE-1 and DMSP satellites on which pulsation and particle precipitation were observed, respectively, are indicated by thick lines in Fig. 1a. Figure 1b shows transverse Pc5 pulsation with period of about 5 min observed by DE-1. The data are plotted in the local magnetic coordinate system. Particle precipitation observed by DMSP is shown in Fig. 1c. The period of observation of particle precipitation which is shaded in the bottom of Fig. 1c corresponds to the period shaded in the bottom of Fig. 1b.

The region of fairly smooth, relatively unstructured precipitation of electrons having energies of several keV at low altitudes is assumed to be a projection of the central plasma sheet (CPS) in the magnetosphere (NEWELL *et al.*, 1991). In Fig. 1c the ILAT range for the observation of precipitation of 3 keV electrons is from 70.8° to 76.9°. Judging from the characteristics of precipitation, we interpret these precipitating electrons to be CPS electrons. The broken lines in Fig. 1b correspond to 70.8° and 76.9° ILAT. We assume that DE-1 passed slowly the region in which pulsation existed. Thus we can see that a

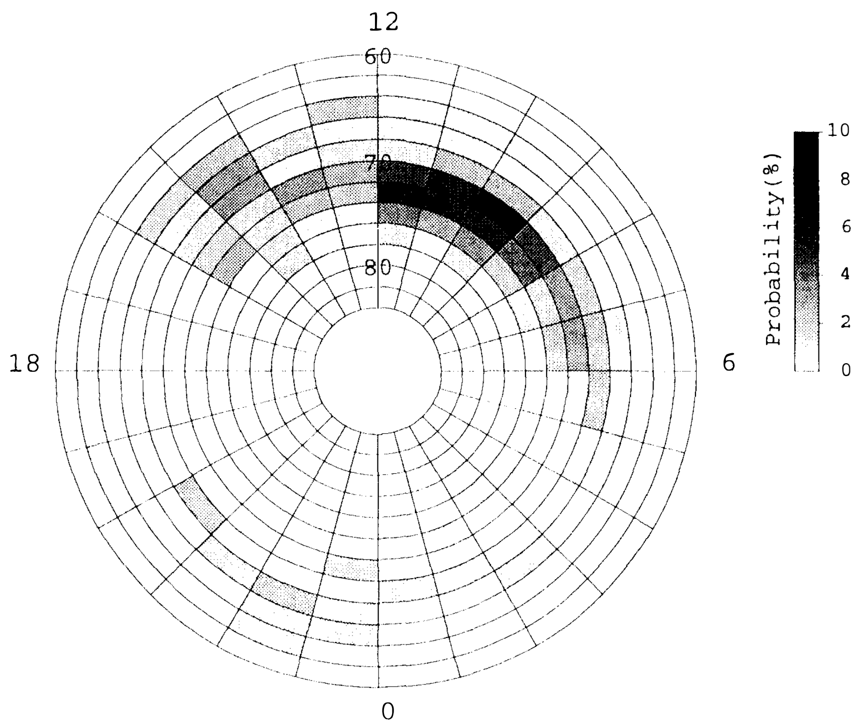
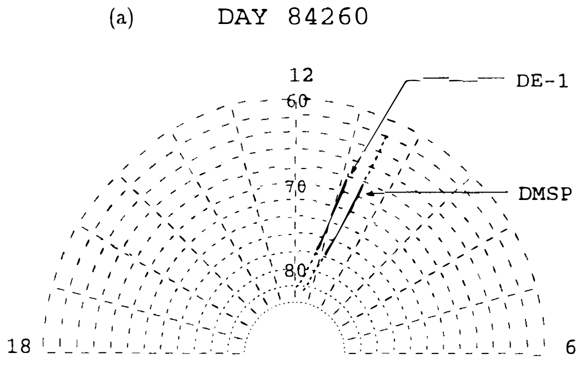


Fig. 2. MLT-ILAT distribution of occurrence probability of transverse Pc5 pulastion. The same result as Fig. 1b of NOSÉ et al. (1995) except for the format of presentation.



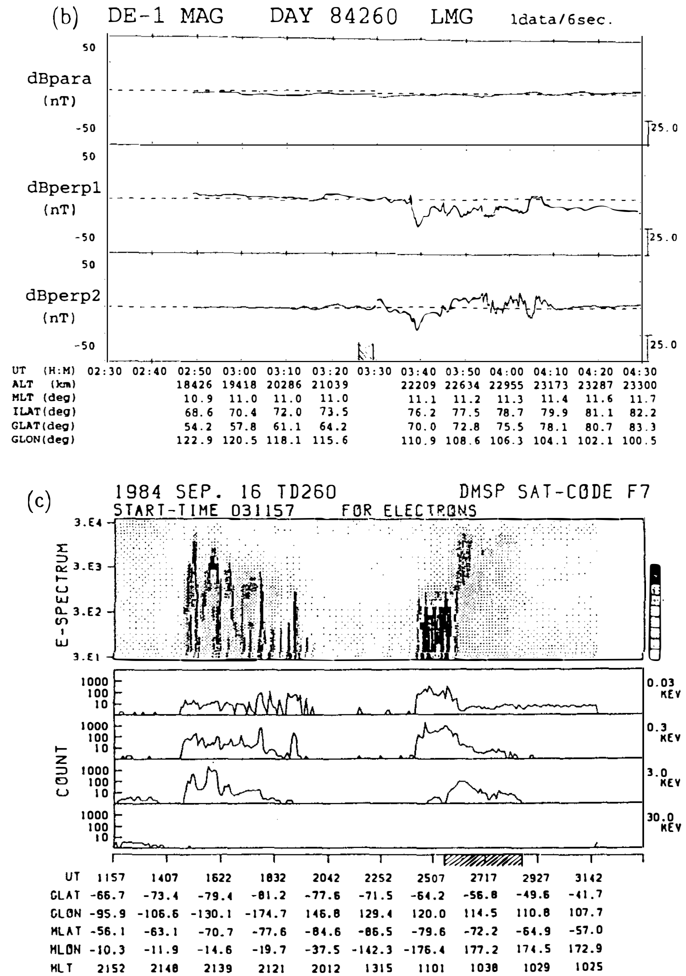


Fig. 3. *(a)-(c) Same as Fig. 1a-c, except for nonexistence of transverse Pc5 pulsation. Observed on 16 September 1984.*

transverse Pc5 pulsation appeared in the ILAT range between the two broken lines which corresponds to the ILAT range for CPS. In a number of other conjunction events, the ILAT range for the observation of the 3 keV electron precipitation, that is, the ILAT range for CPS and that for the observation of Pc5 pulsation were almost the same.

In addition to the case study shown above, a statistical investigation was carried out. NEWELL and MENG (1994) gave projection maps of magnetospheric regions onto the dayside ionosphere, using the particle precipitation data from DMSP. The probability distribution of observing the CPS precipitation was shown in Plate 6a of NEWELL and MENG (1994). Figure 2 shows MLT-ILAT distribution of occurrence probability of transverse Pc5 pulsation investigated by NOSÉ *et al.* (1995). This figure represents the same result as that of Fig. lb of NOSÉ *et al.* (1995) except for the presentation format. From these two figures we can see that: (1) the distribution of the CPS precipitation and the occurrence distribution of pulsations are very similar; (2) the region of the occurrence of transverse Pc5 pulsations falls in the region of the CPS precipitation except that pulsations were not observed on the dusk side.

Relations between transverse Pc5 pulsations and the precipitation of electrons having energies greater than 3 keV were also studied. In particular, electron precipitation of 30 keV energy was investigated. In Fig. lc, for example, 30 keV electron precipitation was observed in a region around 72° ILAT. This region is contained in the range of appearance of pulsation (Fig. lb). Precipitation of 30 keV electrons was observed in 88.2% of all events (15 of the 17 events). The percentage of the events with more than 10 counts of 30 keV electron precipitation was 29.4% (5 of the 17 events).

We also found 15 cases of geomagnetic conjunctions in which Pc5 pulsations were not observed by DE-1. An example of geomagnetic conjunction events in which pulsations were not observed is shown in Fig. 3. Figures 3a-c are presented in the same format as Figs. la-c, respectively, except for nonexistence of transverse Pc5 pulsation. Of these 15 cases, precipitation of 30 keV electrons was not observed in more than half the cases. Only 2 events with more than 10 counts of 30 keV electron precipitation were found (the rate being 13.3%). Results are summarized in Table 1. It is shown that there are differences in the characteristics of 30 keV electron precipitation between the cases in which pulsations were observed and those in which pulsations were not observed.

Table 1. The rates of events associated with precipitation of 30 keV electrons. The second and third columns represent the cases in which transverse Pc5 pulsations were observed and those in which pulsations were not observed, respectively. The geomagnetic conjunction events were selected with $AE \leq 200$ nT.

	Pc5 (17 events)	No Pc5 (15 events)
30 keV	88.2%	40.0%
30 keV (10 counts)	29.4%	13.3%

4. Summary and Discussion

We investigated geomagnetic conjunction events of DE-1 and DMSP. The following results were obtained.

(1) The ILAT interval of CPS precipitation deduced from DMSP observation and that of the occurrence of Pc5 pulsations observed by DE-1 are almost the same.
(2) The MLT-ILAT distribution of the CPS precipitation obtained by Newell and Meng (1994) and that of Pc5 occurrence are very similar.
(3) The characteristics of 30 keV electron precipitation are different between the cases in which pulsations were observed and those in which pulsations were not observed.

These results strongly suggest the presence of ULF wave-particle interactions. The energy of transverse Pc5 pulsations is supplied by the Kelvin-Helmholtz instability on the magnetopause, and the occurrence distribution of Pc5 pulsations could be controlled by the IMF directions (Nosé *et al.*, 1995). If electrons are modulated by pulsations, the distribution of CPS electron precipitation would become similar to that of Pc5 occurrence. When Pc5 pulsations were detected by DE-1, the precipitation of 30 keV electrons was observed by DMSP at high rates. This fact suggests that electrons are accelerated to more than a few keV by the wave-particle interactions.

CNA pulsations have been studied by many researchers. Sato *et al.* (1985) indicated diurnal variations of occurrence of CNA pulsations. They showed that CNA pulsations with the period 150–600 s had an occurrence peak in the morning (0900–1100 MLT). CNA pulsations accompanying Pc3–5 pulsations investigated by Higuchi *et al.* (1988) have frequent occurrence in the interval of 0500–1300 MLT. Paquette *et al.* (1994) also showed an MLT distribution of correlated riometer and magnetometer pulsation events. The distribution strongly concentrated in the local morning, peaking in the vicinity of 1000 MLT. The riometer is thought to be sensitive to energetic electron precipitation with energy in the range of 15–50 keV (Hargreaves, 1969). These previous results are consistent with our results.

Saka *et al.* (1992) investigated characteristics of toroidal Pc5 pulsations in the morning sector, using ground-based magnetometer and riometer data, electron flux data from geosynchronous satellites, and magnetometer data of Magsat. They gave an interpretation different from ours regarding the causal relationship between particle precipitation and Pc5 waves, namely that Pc5 pulsations were excited by injection of electrons into the morning sector from the nightside of the magnetosphere.

Although it is confirmed in this study that electrons are modulated by transverse Pc5 pulsations, there remains the problem of identifying the interaction mechanism(s). Using DE-1 and -2 data, we are now investigating possible wave-particle interaction mechanisms.

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