Some Topics for the Study of the Mechanism of Magnetospheric Substorm by Means of Rocket Observation in the Auroral Zone

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極光帯におけるロケット観測による Magnetospheric Substorm 研究の課題について

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要旨：昭和基地から rocket を打ち上げて substorm の機構を研究する場合，rocket 到達高度が現状程度でも有効で，且つ magnetospheric substorm の本質に係わりがある様な研究課題を，主として geomagnetic pulsation substorm の角度から議論し，提起した．まず substorm 性の地磁気脈動が観測される領域が，極を回って移動していく様子を総合的に示し，この事はあたかも地震と津波の関係の如く，substorm の発生に伴って生じた高 energy 粒子が，内部磁気圏を回って夜側から昼側に drift しながら，粒子あるいは波として次次に極域電離層に降り注ぐためであるとの解釈を与えた．これら脈動の中，Pid 型脈動を rocket 観測すると，Pid そのものの，機構を検証し得ると同時に，"磁気圏津波" の研究に深く関与するはずであり，一方 Ps 6 型脈動を rocket 観測すれば，最近問題になっている multiple field-aligned current の構造及び運動も研究する上に極めて有用であろう．Pid, Ps 6 共に予報時刻まで充分待機し，現象発生と共に rocket を打ち上げる事が出来るという利点がある．

1. Introduction

Recent progress of rocket- and ground-based observations in the arctic and antarctic regions has revealed many problems, one after another concerning the mechanism of the polar substorm. The present author points out in this paper some main problems of the polar substorm to be solved at the present stage by means of small and comparatively low-altitude rockets to be launched from Syowa Station in Antarctica. Since the polar substorm is a consequence of the manifestation of magnetic, auroral, ionospheric, ULF and VLF substorms and so on (AKASOFU, 1968), the problems of the polar substorm are closely related to the problems of any of the manifested substorms. In this paper, some essential problems of the polar substorm are presented mainly from the viewpoint of the ULF substorm or

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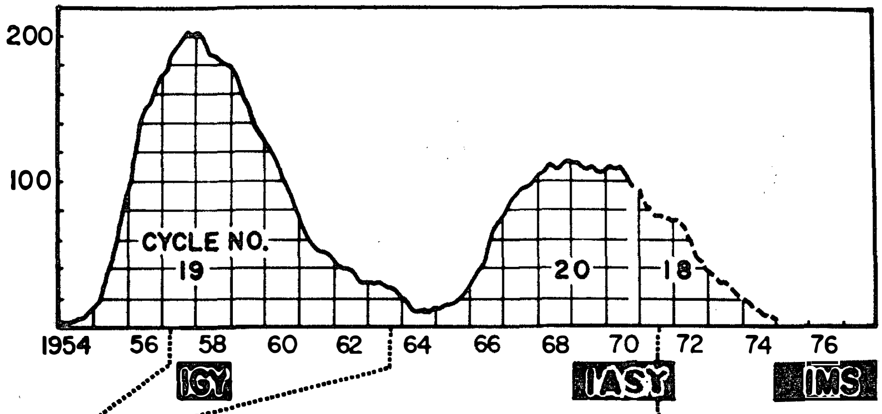
the geomagnetic pulsation substorm.

2. Geomagnetic Pulsation Substorm

In order to point out the problems on the geomagnetic pulsation substorm, it seems better to review briefly the past studies on geomagnetic pulsations associated



Pre-IGY (1957)	Post-IGY (1963)	Post - IASY (1971)			
		Class	Subclass	Other nomenclature	The first paper for each nomenclature
	Pc 1	Continuous pulsations	PP	-- HM emission	Troitskaya, 1961 Tepley, 1961
			CE	3.5-sec band 300 mHz band 4-sec summertime micropulsation Continuous (sub-ELF) emission	Kato-Saito, 1964b Hirasawa-Nagata, 1966 Heacock, 1966 Tepley-Amundsen, 1965
pc	Pc 2		Pc2	Ps	Oguti, 1963
	Pc 3		Pc3		
	Pc 4		Pc4		
	Pc 5		Pc5		
pt	Pi 1	Pulsations associating directly with magne-tospheric substorm (but ex-clude Pc's)	Pi1	spt	Yanagihara, 1959
	Pi 2		Pi2	(primarily pt, namely, associates with substorm!)	
			IPDP	-- Sweeper	Troitskaya-Melnikova, 1959 Duncan, 1961
			Pi(c)	--	Heacock, 1967b
			Pid	Magnetic impulse --	McPherron, et al., 1968 Morioka-Saito, 1970
			Ps6	--	Saito-Morioka, 1971
		Miscella-neous pulsations	Pg	Giant pulsation	Rolf, 1931
			Pac, Psi		Kato-Saito, 1958 Wilson-Sugiura, 1961 Troitskaya, 1961
			Pafe		Kato, Tamao et al., 1959
			Others	Pulsations associating with nuclear detonations " " Meteor showers " " pressure waves " " ocean waves " " earthquakes	cf the review papers by Saito, 1969

Fig. 1. Classes and subclasses of geomagnetic pulsations based on the present knowledge of physical models of occurrence (cf. Table 1). The international classifications proposed at the 1957 Copenhagen meeting and the 1963 Berkeley meeting are compared for reference. As for the first paper for each nomenclature, refer to SAITO *and* KATO *1971.*

Table 1. Probable models for each subclass of Pc and Pi.

Subclass	Model
PP	Cyclotron instability of energetic protons trapped near the inner edge of the ring current (1).
CE	Principal resonance of HM waves during their transmission through the lower magnetosphere, and duct propagation to low latitudes (2), (3).
Pc 2 Pc 3	Drift instability of electrons near the inner boundary of the plasma sheet (4). Periodic ionospheric current induced in high latitudes leaks to low latitudes (5).
Pc 4	Hydromagnetic surface waves on the plasmapause (6).
Pc 5	Drift instability of electrons near the inner boundary of the plasma sheet (7).
Pi 1	CE enhanced by plasma instability responsible for magnetospheric substorm (2), (3).
Pi 2	Transient torsional oscillation of field-lines near the inner boundary of the plasma sheet (8); (with increase of geomagnetic activity, transient hydromagnetic surface waves on the plasmapause are mixed (6)).
IPDP	Cyclotron instability of energetic protons drifting westwards in the magnetosphere (9), (10).
Pi(c)	Magnetic effect of irregular auroral electrojet (11).
Pid	Magnetic effect of impulsive ionospheric current due to high energetic electrons drifting from the night-side magnetosphere (12).
Ps 6	Magnetic effect of the fluctuating field-aligned current (13), (14).

Reference

(1)	Cornwall (1965)	(8)	Saito and Sakurai (1970)
(2)	Tepley and Amundsen (1965)	(9)	Troitskaya and Gulelmi (1967)
(3)	Fukunishi and Hirasawa (1968)	(10)	Fukunishi (1969)
(4)	Coroniti and Kennel (1970)	(11)	Saito (1969)
(5)	Kato and Morioka (1970)	(12)	Morioka and Saito (1971)
(6)	Hirasawa and Nagata (1966)	(13)	Saito and Morioka (1971)
(7)	Lanzerotti, Hasegawa *et al.* (1969).	(14)	Saito (1972)

with substorm. The pulsations associated *directly* with magnetospheric substorm are classified into only two subclasses, Pi 1 and Pi 2, in the current international classification which was proposed by IAGA at the Berkeley meeting in 1963. In view of a number of research papers on the substorm-associated pulsations published after the meeting, these should be classified into at least six subclasses by the mechanism as listed in Fig. 1. The main mechanisms of the pulsations may be those as are summarized in Table 1. (As for the further description of the mechanisms, see

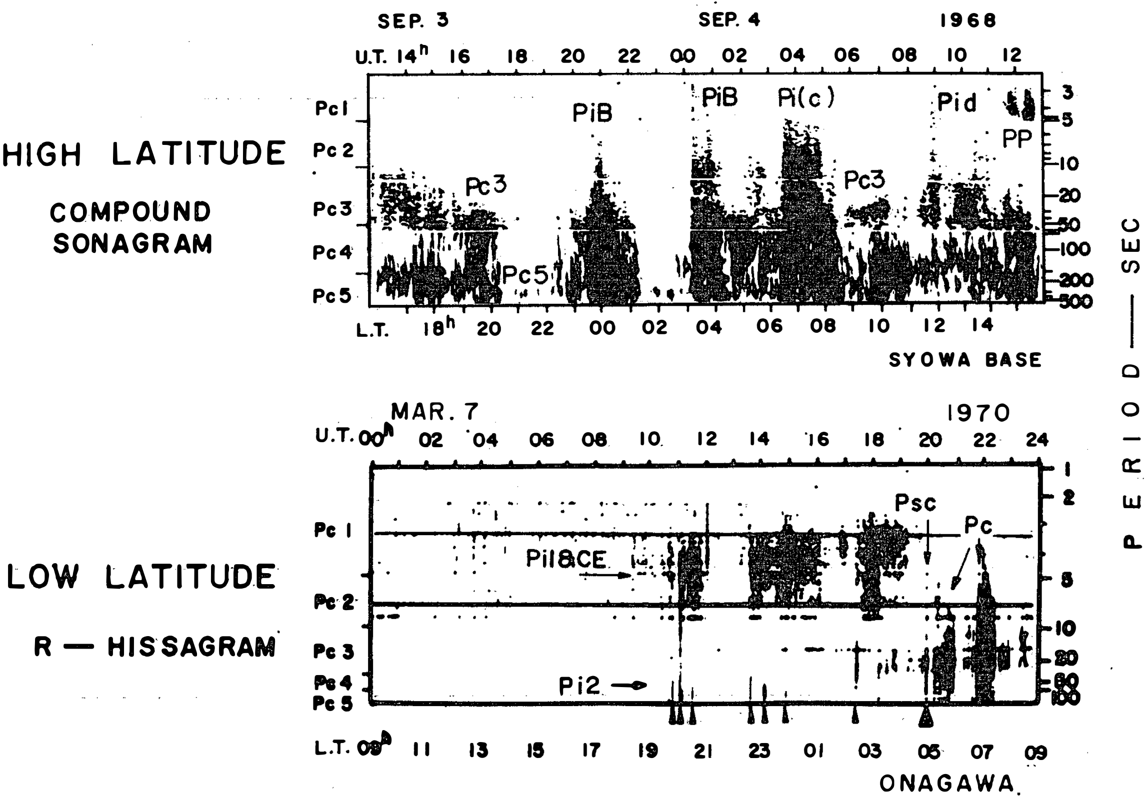


Fig. 2. Example of dynamic spectra of Pi-type geomagnetic pulsations. As for the compound sonagram and the R-hissagram, see SAITO, SAKURAI *et al., 1971 and* SAITO *and* KUWASHIMA, *1971.*

SAITO (1969) or SAITO and KATO (1971)).

Besides the six Pi subclasses, some of the continuous pulsations, Pc's are reported to be associated (indirectly) also with substorm. For example, association of substorm with the PP-type Pc 1 was reported by WILHELM (1968); the CE-type Pc 1 by SAITO, SAKURAI *et al.* (1971); Pc 2 by OGUTI (1963); Pc 3 by MCPHERRON, PARKS *et al.* (1968); Pc 4 by HIRASAWA and NAGATA (1966), and Pc 5 by KUWASHIMA and SAITO (1971). This fact indicates that a polar substorm generates most kinds of geomagnetic pulsations (12 subclasses altogether) in the magnetosphere so that the substorm plays a very important role in exciting most of the geomagnetic pulsations.

Fig. 2 shows a typical compound sonagram (SAITO and KUWASHIMA, 1971) of various types of Pi's and Pc's observed at Syowa Station. These Pi's and Pc's appear with their own characteristic features depending on both local time and substorm time which is defined by the time duration from the onset time of substorm identified by the auroral breakup and geomagnetic Pi 2 pulsation (SAITO and SAKURAI, 1970). Analyzing a lot of dynamic spectra such as shown in Fig. 2, we can draw a progressive behavior of pulsation substorm on magnetic polar co-ordinates. Fig. 3 represents the movement of the area where each subclass of Pi's is observed with respect to the substorm time being compared with the auroral substorm illustrated by AKASOFU (1968). In order to avoid confusion, only Pi's, the pulsations *directly* associated with polar substorm, are illustrated in the figure. It shows that the pulsation substorm could be likened to a "magnetospheric tsunami" traveling around the "inner magnetosphere island" from the epicenter in the night-side cusp of the magnetosphere toward the day-side.

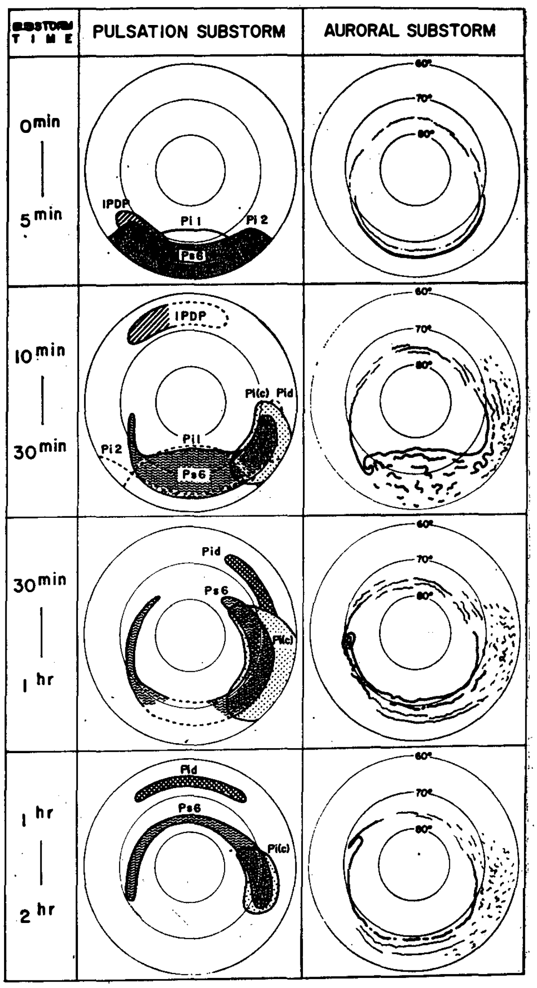


Fig. 3. Progressive movement of the regions where Pi-type pulsations are observed. The broken lines indicate that the pulsations are decaying there. Auroral substorm illustrated by AKASOFU is also shown for comparison.

Among the six subclasses of Pi's, Pid and Ps 6 must be the most suitable pulsations for further study along with the polar rocket observations, for the following reasons:

(1) Both Pid and Ps 6 have been studied little.

(2) Both seem to be related to the most essential and important characteristics of the polar substorm to be studied at the present stage: Pid to the magnetospheric tsunami and Ps6 with the field-aligned current.

(3) We can have enough time to prepare the rocket launching because of the slow circumpolar travel velocities of the Pid and Ps 6 phenomena.

3. Rocket Observation of the Magnetospheric Tsunami Associated with Polar Substorm

Although geomagnetic pulsation Pid is not popular yet, its main features are abstracted from MORIOKA-SAITO's paper (1971) as follows:

(1) The waveform of Pid is expressed by a group of many impulses having the approximate pulse-height with a fraction of gammas, the pulse-width between

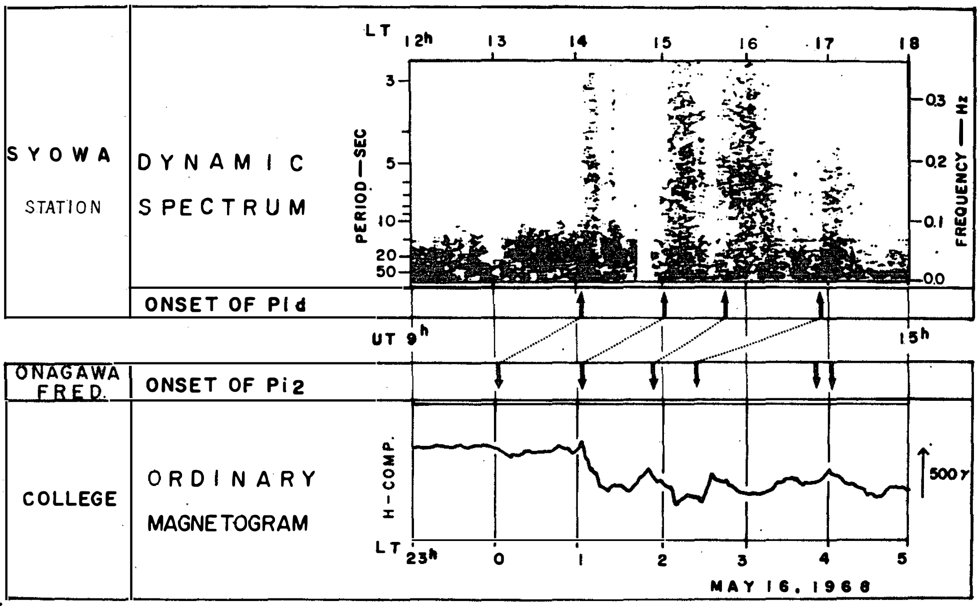


Fig. 4. Systematic time lag of the occurrence of the daytime irregular pulsation, Pid, after the onset time of the nighttime polar substorm.

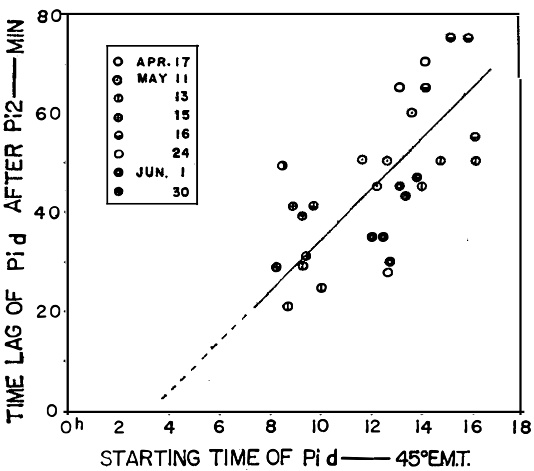


Fig. 5. A linear relation between the starting time of Pid and the substorm time which is represented by the duration after Pi 2.

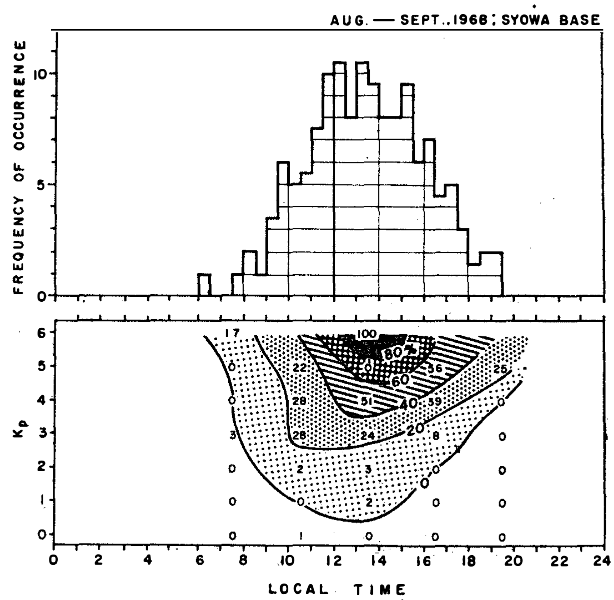


Fig. 6. (Top) Diurnal variation in the frequency of occurrence of Pid. (Bottom) Diurnal variation and Kp dependence of the probability of Pid occurrence.

one and five seconds, and the repetition period between five and twenty seconds.

(2) Pid occurs most frequently in the daytime and tends distinctly to occur on a magnetically disturbed day.

(3) Pid is frequently accompanied by the daytime cosmic noise absorption and X-ray microbursts.

(4) Prior to the onset of Pid on the day-side auroral zone, a magnetic substorm is observed on the night-side (Fig. 4).

(5) The time lag of the onset of Pid behind that of the substorm is proportional to the local time of the onsets of Pid (Fig. 5).

On the basis of these observed results, MORIOKA and SAITO (1971) proposed the following *precipitating-particle hypothesis* for Pid. Part of energized electrons produced during the onset of the magnetospheric substorm drift eastward around the earth along the constant L-shell, and are precipitated into the day-side auroral zone, causing the daytime cosmic noise absorption and the X-ray microbursts. The high-energy electron microbursts contribute to the ionospheric E-layer giving rise to a series of temporal and localized enhancement of the ionospheric current, which induces a group of impulsive magnetic field variations as observed. This hypothesis is in contrast with the *HM-wave hypothesis* that some impulsive HM-waves propagate directly from a source in the magnetosphere toward the earth causing a group of impulsive magnetic field variations, Pid.

These two hypotheses can be examined by means of small rockets penetrating the ionospheric E-layer provided the following observations are carried out.

(1) Magnetic field variation. If the HM-wave hypothesis is right, magnetic impulses with pulse height 10^2-10^3 times larger than that of ground-based Pid should be observable above the E-layer (cf p. 398 of SAITO, 1969).

(2) Particle precipitation. If energies, flux and pitch angle of the precipitating electrons are observed by the rocket, our model calculation on the basis of the precipitating-particle hypothesis can be examined.

Such observation is valuable not only to examine the mechanism of Pid from the viewpoint of geomagnetic pulsations, but also to examine the mechanism of the magnetospheric substorm itself by means of the low-altitude rocket, since the magnetospheric tsunami which is one of the most important phenomena associated with substorm can be forecasted by Pid. Fig. 6 shows that the occurrence of the daytime pulsation Pid can be forecasted with the probabilities of 80-100%, if a sufficient large substorm corresponding to $Kp > 5$ occurred in advance on the night-side.

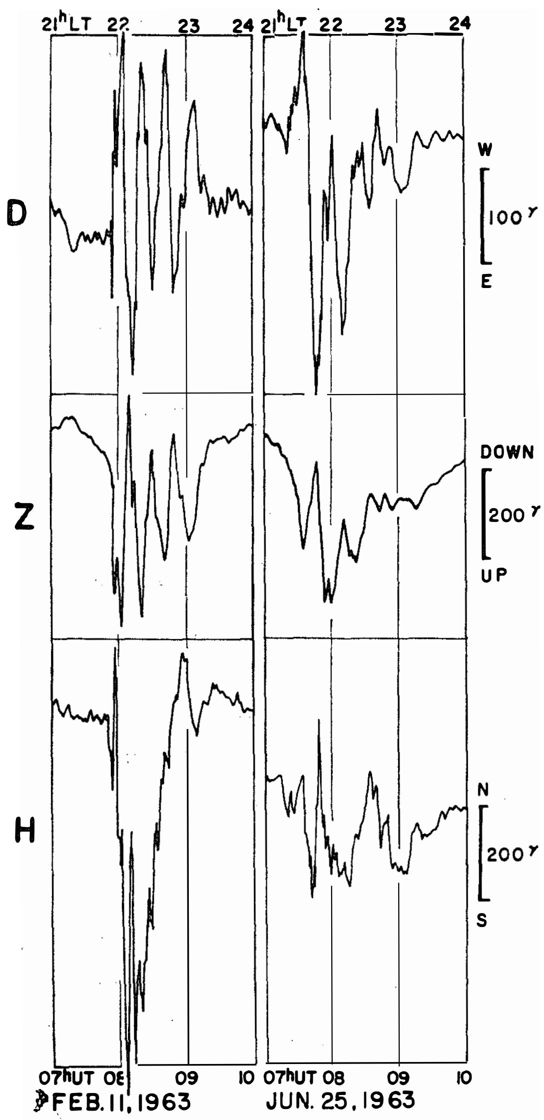


Fig. 7. Example of ordinary magnetograms of two Ps 6 events. Note that Ps6 tends to dominate in the declination component.

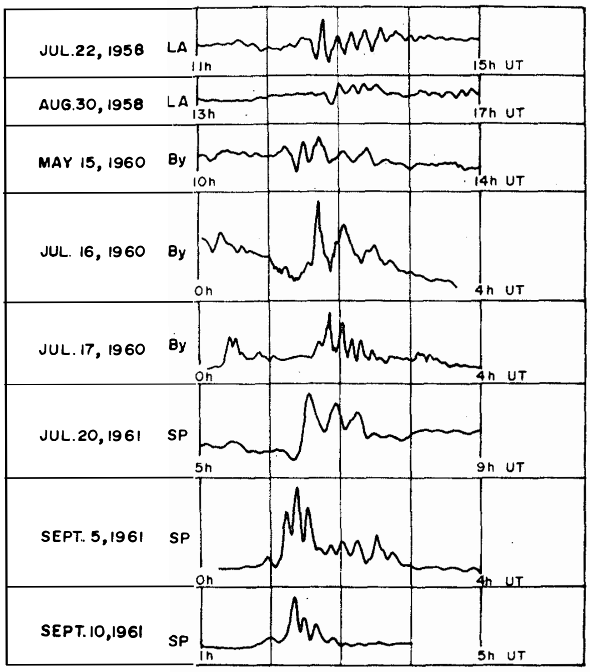


Fig. 8. Ps 6 events (declination) which appeared on limited ordinary magnetograms at Little America (LA), Byrd Station (By) and South Pole (SP).

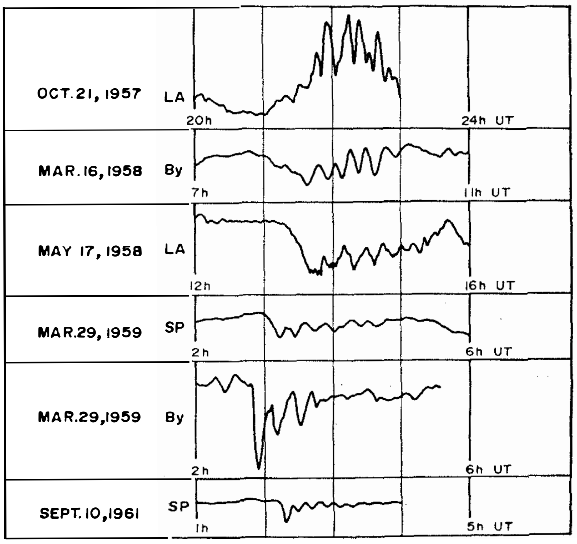


Fig. 9. Ps 6 events (H-component) which appeared on limited ordinary magnetograms at LA, By and SP.

4. Rocket Observation of the Field-Aligned Current during Polar Substorm

As described in the previous section, Pid is a suitable phenomenon to study the magnetospheric tsunami traveling *along a constant L-shell.* On the other hand, geomagnetic pulsation, Ps 6, seems to be closely related to a field-aligned current during the magnetospheric tsunami traveling *along the auroral oval.*

Since Ps 6 was found quite recently (SAITO and MORIOKA, 1971; SAITO, 1971) and is still unpopular, waveforms of typical Ps 6 events are shown in Figs. 7, 8 and 9. Main characteristics of Ps 6 can be summarized as follows:

(1) It shows a damped-type waveform with the period between 10 to 40 minutes and the amplitude of the order of $10\sim 100\ \gamma$ near the auroral oval.

(2) The clearest Ps 6 tends to be observed in the declination component (Fig. 7) just beneath the auroral electrojet. Figs. 10 and 11 show the N-S and the E-W components, respectively, of both magnetic field variations on the ordinary magnetograms and the movements of the auroral bands on the normal and expanded aurorагrams* during a midnight substorm. The figures show clearly that the Ps 6 event occurred when active auroral bands stayed extending from the east, through the zenith, to the west of Fort Yukon.

(3) The declination Ps 6 shows frequently the waveform with the pulses deflecting to both east and west with respect to the pre-breakup value (for example, Feb. 11 event in Fig. 7 and the top-three events in Fig. 8).

(4) The waveform of Ps 6 drifts from the midnight auroral zone toward both the dusk- and the dawn-sides with the velocity of about 1–2 km/s along the auroral oval (Figs. 12 and 13) and also toward the pole (Fig. 13). (Note that a clear Ps 6 event occurred even near the local noon at the polar cap station, Little America ($\Phi=-74.7°$), as seen at the top of Fig. 9.)

(5) The large-scale fluctuations of magnetic field with the maximum declination range of 60° observed in the magnetotail by OGO-5 (RUSSELL, MCPHERRON *et al.*, 1971) have waveforms closely similar to general Ps 6, although Ps 6's recorded simultaneously on the ground do not always show perfectly concurrent waveforms (Fig. 14).

* Auroragrams are obtained with a newly-designed high-speed aurora analyzer, "Auroragraph", by the following process:

(1) Project the all-sky-camera data on a semi-transparent screen using a movie projector.

(2) Put a slit along the N-S(or E-W) meridian of the all-sky-camera image on the screen.

(3) Take the picture of the image on a film running continuously toward the direction perpendicular to the slit.

One-hour data of optical aurora or radar aurora can be automatically analyzed by this auroragraph within only five seconds. Further description of this new device will be published elsewhere in the near future.

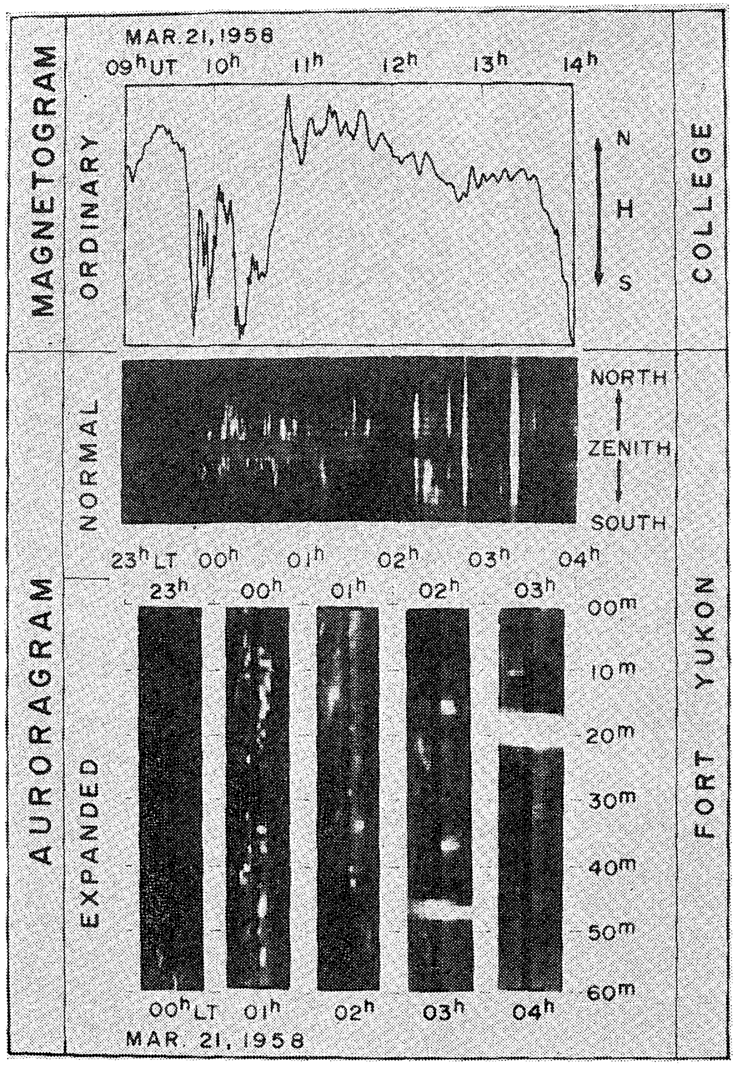


Fig. 10. The N–S component of both ordinary magnetogram and normal/expanded auroragrams for the substorm event on March 21, 1958. Note that the active auroral band stayed near the zenith during the event.

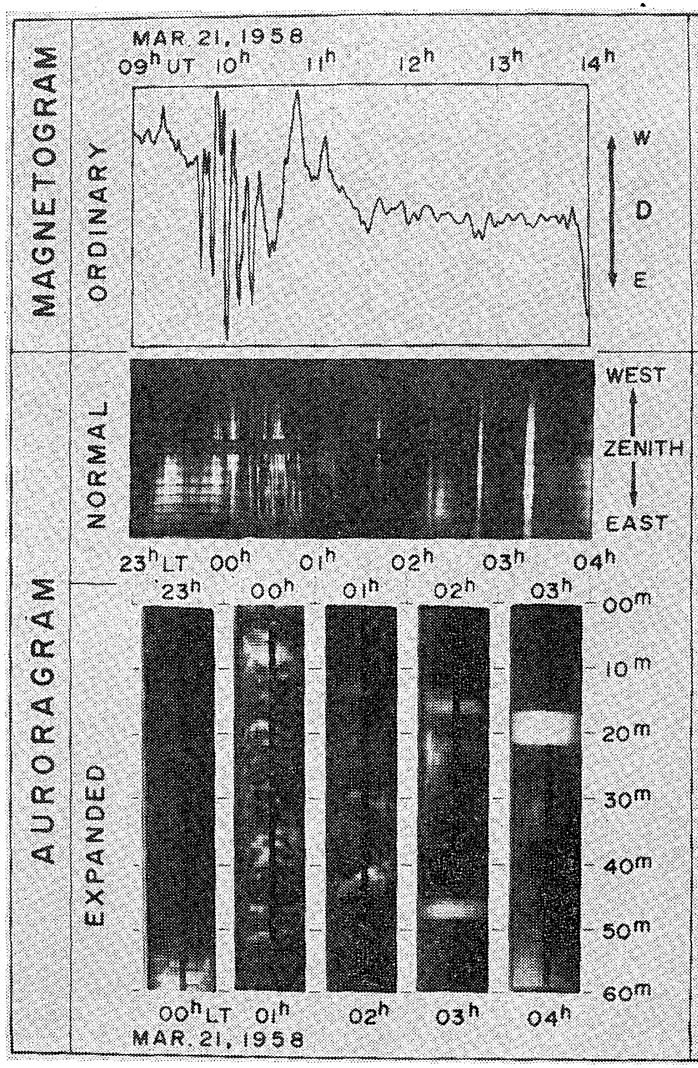


Fig. 11. The E–W component of both ordinary magnetogram and normal/expanded auroragrams for the Ps 6 event near 10 h UT on the same day as that in Fig. 10. Note that the active auroral band extended from the east through the zenith to the west during the event.

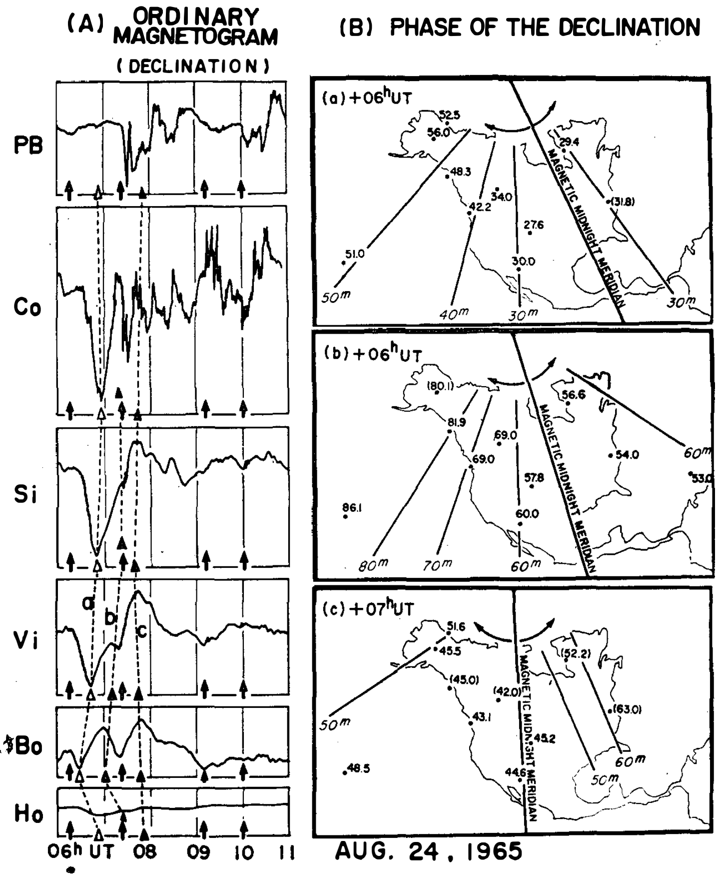


Fig. 12. Traveling phase of the declination Ps 6.

(A) The blank and the solid triangles indicate the phases, a, b and c of the westernmost and the easternmost deflections, respectively. The arrows indicate the onset time of Pid. Note that the Ps 6 is not due to an assemblage of some periodic individual substorms.

(B) The travel of the phase of the declination Ps 6 is shown by the contour lines. The numeral, 69.0 at Victoria in (B) (b) for example, indicates that the easternmost deflection occurred there at 07 h 09.0 m (=69.0 m+06 h).

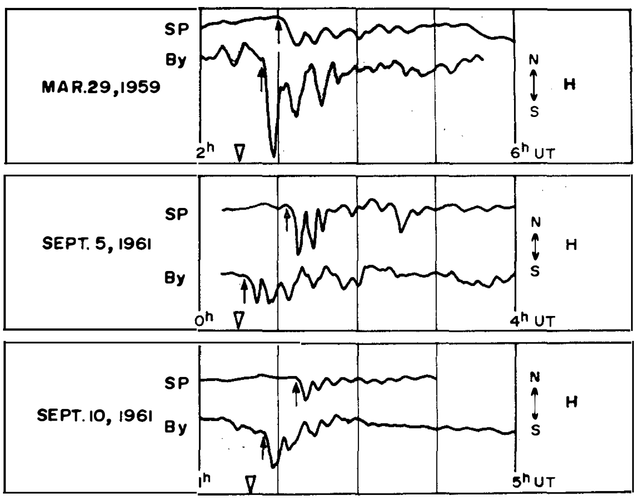


Fig. 13. Three Ps 6 events observed at South Pole (SP) and Byrd Station (By), Antarctica. The time-lag between the world-first onset time (the blank triangle) of the substorm and the arrival time (the arrows) of the Ps 6 at the two stations indicates that Ps 6 travels both in longitudinal and latitudinal directions.

(6) Ps 6 shows a fairly concurrent waveform at a pair of conjugate points.

Taking these observational facts into consideration, Ps 6 seems to be closely related to the field-aligned currents from the magnetosphere to the auroral electrojet along the auroral oval being associated with the magnetospheric tsunami. Recently multiple field-aligned currents related to the Pedersen current across the auroral oval have been observed. Fig. 15 shows an example by ARMSTRONG and ZMUDA (1970) of such multiple field-aligned currents. A set of these field-aligned and Pedersen currents should give rise to the magnetic variations of the declination component both on the ground and in the magnetosphere as observed. The above stated observed facts (3) and (4) mean that the field-aligned currents must change-alternatively their directions and change their location. Since a field-aligned current cannot be detected generally on the ground (FUKUSHIMA, 1969), it must be examined with observations above the E-layer by rockets or satellites. Such complicated field-aligned currents with variable structure and movement, however, cannot be observed by satellites which have an inevitably long revolution period, but are observable by the very rockets in question whose trajectory has a low apex. The time-varying field-aligned currents would be observed when two or more rockets are used a single substorm event with the spacing time of

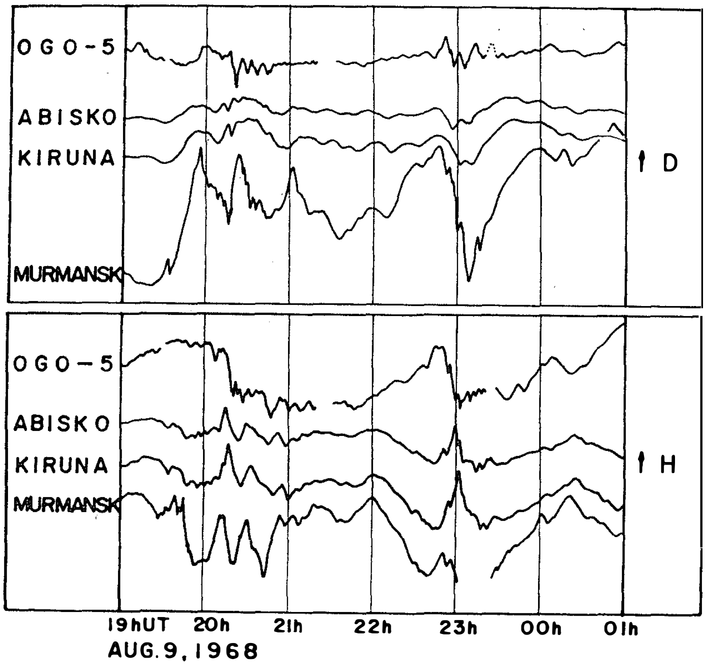


Fig. 14. The magnetic field variations observed simultaneously in the magnetotail by OGO-5 and at the three ground stations. The satellite and the stations were roughly situated around the same magnetic field-line during the observed period. Note the Ps 6-like variations at about 20 h 30 m and 23 h 00 m.

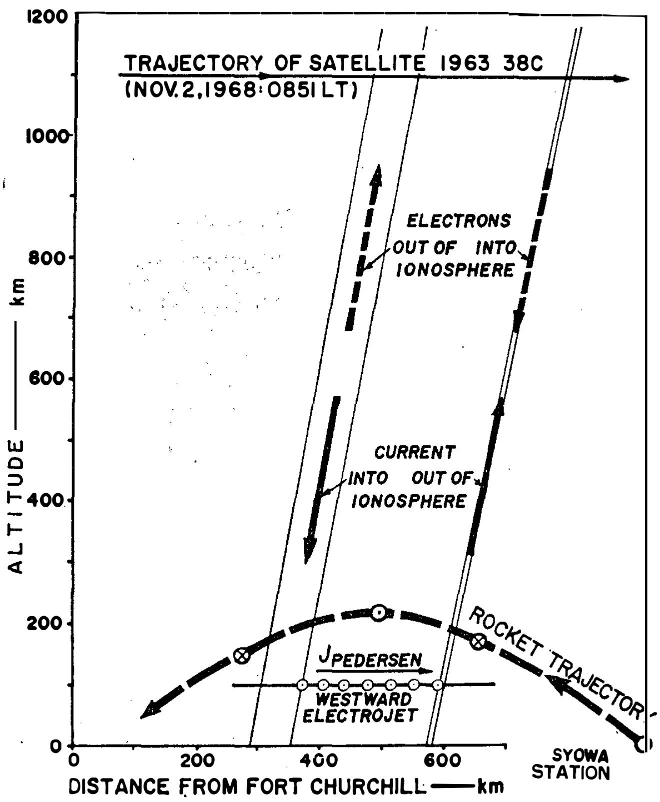


Fig. 15. Multiple field-aligned currents observed by the satellite 1963–38 C (after ARMSTRONG *and* ZMUDA*, 1970). The thick broken curve indicates that if a rocket is launched from Syowa Station along this trajectory, the structure of the multiple field-aligned current can be observed by the alternative magnetic field.*

the order of ten minutes. Magnetic field, kind of the particles responsible for the field-aligned current, flux and pitch angle of the particles must be measured by the rockets to clarify the structure of the field-aligned current. The best chance to launch the rocket can again be forecasted, as we did for Pid, by chasing from station to station the travel of Ps 6 and auroral structure along the auroral oval from the midnight auroral zone to Syowa Station. In order to have enough time for preparing the launching, the dawn- or the dusk-time might be better than the midnight when Ps 6 and substorm break almost smultaneously. In the dawn- or the dusk-time, the auroral oval is generally located polewards to Syowa Station. This location seems to be rather suitable to launch the rockets since these should be obliquely shot to cross the multiple field-aligned currents as illustrated by the broken curve in Fig. 15.

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