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RELATED INVESTIGATIONS OF Pi 2 MICROPULSATIONS

by

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ABSTRACT

Related investigations of irregular, nighttime, type Pi 2 micropulsations were undertaken with regards to the source and occurrence of these geomagnetic fluctuations. In particular, the local times of Pi 2's recorded by a global network of stations, during 1964, were determined. From this, the Pi 2 daily occurrence maximum was observed near 2230 LMT. For this same year (1964), rapid-run magnetograms from Memambetsu, Japan and Wingst, Germany were analyzed. The initial orientation of the impulsive Pi 2 disturbance vectors was observed to be primarily north-east (north-west) before (after) 2230 LMT. These results suggest that Pi 2 source field lines lie near the 2230 LMT meridian.

Further investigations of the globally observed Pi 2's were made regarding variations in morphology with magnetic activity. The daily occurrence maximum of Pi 2 was found earlier (later) at 2030 (2330) LMT during intervals of high (low) magnetic activity. In this manner, the longitudinal shift of the Pi 2 source is revealed. A statistical study of solar wind protons observed by Explorer 34 satellite was made during the intervals of high, and of low, magnetic activity. This study showed that the Pi 2 source shift may be due to a change in the solar wind flow

direction and/or processes associated with changes in the solar wind proton pressure.

Pi 2's are a train of pulsations having quasi-periods ranging from 40 to 150 seconds and each series lasts about 10 minutes. The periods of Pi 2 micropulsations recorded at Ralston, Canada during 1967 were correlated with simultaneous, Alouette 2 satellite received, VLF radio signals. Some of these VLF emission phenomena, known as 'whistler cutoff' and 'lower hybrid resonance noise band breakup', indicated the location of the magnetospheric plasmapause. Other emissions, known as ELF, were believed to indicate the plasma sheet inner boundary. The variation of the period of the Pi 2's with the indicated magnetospheric subregion locations showed that Pi 2 period varies systematically with positions of the plasma sheet inner boundary during intervals of magnetic quiescence. The results imply a latitudinal (radial) movement of the Pi 2 source in a region near the plasma sheet inner boundary.

Lastly, the rate of Pi 2 occurrence with magnetic activity, during 1964 and 1967, was found to be maximum when the planetary index of magnetic activity, Kp, was 1+ to 2-. The mean Kp index most closely approaches this optimum level during the years of sunspot minimum. Thus, the rate of occurrence result is consistent with the inverse relationship of Pi 2 yearly occurrence with the solar cycle.

In summation, the source studies revealed a 'dynamic' Pi 2 source, in the sense that it varies both latitudinally and longitudinally. An association was shown between Pi 2 and nightside magnetospheric processes and subregions. The occurrence study indicated that processes generating Pi 2's are not clear but approach optimum when the Kp level is between 1+ and 2-.

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CHAPTER I

A BACKGROUND TO INVESTIGATIONS OF Pi 2

a. Introduction

Pi 2 type geomagnetic micropulsations are irregular fluctuations, having a quasi-period between 40 and 150 seconds. They are primarily nighttime phenomena, appearing as a series of impulsive oscillations which usually last 5 to 10 minutes. They are often associated with geomagnetic bay disturbances (Angenheister, 1913; Terada, 1917), fluctuations in auroral luminosity (Fukunishi and Hirasawa, 1970) and intensity fluctuations of charged particles precipitating upon the ionosphere (Milton, McPherron, Anderson and Ward, 1967). The frequency of occurrence of this type of micropulsation is maximum during the years of minimum sunspot activity (Yanagihara, 1956). It is observed that Pi 2 tends to occur with a quasi-period similar to the sunspot rotation period, 26 to 29 days (Saito and Matsushita, 1968).

The interaction of the solar wind and the terrestrial magnetic field can possibly give rise to geomagnetic micropulsations. Much evidence of this interaction has been reported. The magnetopause, or boundary of this solar-terrestrial interaction, has been observed with the aid of satellite experiments (Cahill and Amazeen, 1963; Ness, 1965).

Hydromagnetic interaction between solar wind discontinuities and the terrestrial magnetic field have also been reported (Oglivie and Burgala, 1970). Yet the solar wind stimulates not only geomagnetic activity, such as large scale magnetic storms but also causes variations in the structure of the region inside the magnetopause, viz. the magnetosphere. Carpenter (1970), Hones, Asbridge and Bame (1971) have observed changes in magnetospheric subregions with varying magnetic activity, viz. the extraterrestrial ring current, the plasmapause bulge and the magnetotail plasmasheet, respectively. These observations imply that associations between micropulsations and magnetospheric subregions may also exist. One of the investigations reported in this thesis shows a systematic variation in Pi 2 period with the location of a subregion of the magnetosphere.

The morphology of geomagnetic micropulsations should, in some manner, reflect the nature of the source responsible for these fluctuations of the earth's field. A review of the subject of micropulsations (Jacobs, 1967) reveals that Pi 2 morphology has been considerable well investigated. Yet studies of variations of Pi 2 morphology with magnetic activity have been less consistent. Such studies may provide more information on the source mechanism of Pi 2. In this thesis, a correlated investigation of Pi 2 morphology is reported. Also reported is a morphologic variation study of the change in the most probable time of Pi 2 occurrence, with magnetic activity and with the solar wind. As mentioned, morphologic variation studies have been less consistent and some investigators have reported contradicting observations. To settle some of these contradictions, the variation in the rate of Pi 2 occurrence with the three hour planetary index of magnetic activity, Kp, has been investigated and reported in the last part of this thesis.

The purpose of this thesis is to establish the existence of relationships among Pi 2 micropulsations, the magnetosphere, and the solar wind. This is achieved through the investigations into Pi 2 which were previewed in the above. In some of these studies, correlations were made with satellite observations of VLF radio signals in the magnetosphere and also of protons in the solar wind. The implications of these studies are discussed with regards to the source and generation of Pi 2 micropulsations. However, interpretations of experimental results often differ. For this reason it is necessary to outline the established morphology of Pi 2. In order to understand the implied association of Pi 2 micropulsations with the magnetosphere, a review of the observed dynamics of magnetospheric subregions is also presented. Lastly, various theories suggesting the mechanism of Pi 2 generation are developed.

Some of these theories, based on certain investigational results, require different locations for the Pi 2 source. A discussion of these theories is then useful, to more fully comprehend the generation and source of Pi 2 micropulsations.

b. Pi 2 Morphology

In general, Pi 2 amplitude increases with latitude, reaching maximum near the auroral zones (Saito and Sakurai, 1970). Although a few investigators have found an equatorial enhancement of Pi 2, the maximum amplitude is found at regions higher than 50^{o} geomagnetic latitude (Jacobs and Sinno, 1960). The amplitude of Pi 2 is shown to be maximum near midnight (Saito et al., 1968). Yet, Pi 2's are not sinusoidal continuous oscillations, but rather of an impulsive and irregular nature. Thus a discussion of the occurrence of such micropulsations is more enlightening than discussing amplitude features.

As mentioned, Pi 2's are often associated with geomagnetic bays or baylike phenomena (Saito, 1961). Pi 2 occurrence has also been connected with impulsive geomagnetic H component variations, during magnetic storms (Fukunishi et al., 1970). The local time at which Pi 2 occur most frequently is near 2230 LMT, in low and middle latitudes

(Yanagihara, 1957a; Rostoker, 1967a). This occurrence frequency maximum tends to shift from midnight towards dusk longitudes as the Kp index increases (Yanagihara, 1960), though this variation is not well established (Kannangara and Fernando, 1969). Also, some investigations have found the rate of Pi 2 occurrence to increase linearly with the Kp index (Kannangara et al., 1969; Channon and Orr, 1970). Observations by Yanagihara (1956) show that the yearly occurrence frequency of 'night pulsations' is inversely proportional to the solar activity. Reports by Afanasieva (1961) and Saito et al. (1968) suggest that the peak time of Pi 2 occurrence is found near midnight (2300 to 0100) during sunspot maximum and at earlier times (2000 to 2300) during sunspot minimum. As shown in Chapter II, these occurrence observations imply apparent contradictions.

Saito et al. (1970) gave two examples showing that Pi 2 period is common from middle latitudes through polar regions. On a random noise type background, Fukunishi et al. (1970) observed an 80 second, Pi 2 spectral peak at the auroral zone. This peak was also observed at low and middle latitudes. The evidence suggests that the period of Pi 2 micropulsations does not change with latitude, presumably even up to the latitudes which divide the magnetotail from the region of closed magnetic lines of force. A diurnal variation of Pi 2 period has been shown, with the period increasing towards midnight and decreasing towards noon (Hirasawa and Nagata, 1966; Troitskaya, 1967). Saito et al. (1968) showed that the period of Pi 2 associated with geomagnetic bays, is dependent upon the bay intensity. However Fukunishi et al. (1970) showed the Pi 2 spectral peak decreases in period with magnetic storm development. Troitskaya (1967) showed that Pi 2 period decreases with increasing Kp index. Yet, Rostoker (1967b) observed that two or more prominent Pi 2 spectral peaks may appear, especially for those events occurring during higher Kp values. The relationships among bay intensity, storm development and Kp are not clearly understood. This combined with the above facts, suggests that there is not always a direct association of Pi 2 with geomagnetic bays and/or with the Kp index, although such associations are often observed.

At low and middle latitudes, the first pulse of a Pi 2 series on the north-south geomagnetic component is always northward (Billuad, 1953; Grenet, Kato, Ossaka and Okuda, 1954; Saito, 1961). The movement of the Pi 2 disturbance vector is usually north-east (north-west) prior to (after) midnight (Kato, Ossaka, Watanabe, Okuda and Tamao, 1956; Yanagihara, 1960; Saito et al., 1968). This initial disturbance vector has been shown to converge to the northern auroral zone on the midnight meridian (Saito et al., 1968). In middle latitudes, the polarization of the Pi 2 magnetic disturbance field tends to be counter-clockwise (clockwise) in the northern (southern) hemisphere (Christoffel and Linford, 1966; Sakurai, 1970). Sakurai also observed that at College, located at a lower auroral zone latitude, Pi 2 polarization was counterclockwise in the pre-midnight hours and clockwise in the post-midnight hours. Yet at Point Barrow, located at a higher auroral zone latitude, Pi 2 polarization was either clockwise or indeterminate. As shown in Chapter III of this thesis, polarization morphology can yield information about the origin of Pi 2 micropulsations.

c. Subregions of the Magnetosphere

The magnetospheric plasmapause is a boundary which marks an abrupt change in plasma density at an average equatorial radius of about 4 Re, where 1 Re is a length equal to the radius of the earth. At the plasma-pause, the equatorial electron density changes by a factor of 10 to 100 (or from approximately $100/cm^3$ to $1/cm^3$) within a distance of about 0.15 Re (Angerami and Carpenter, 1966). The plasmapause is asymmetric and has an outward bulge near the dusk meridian. The bulge region has been associated with an interaction between the plasma moving towards the sun from the magnetotail and the flow due to the earth's rotation (Brice, 1967). The plasma in this region is characterized by a R^{-4} density profile. For this reason, Chappell, Harris and Sharp (1970) suggested that the bulge is slowly filled by particles from the ionosphere. During times of low magnetic activity, the plasmapause bulge may be located at distances out to 9 Re and near local midnight. However, when a large surge of substorm activity occurs the bulge moves inward to distances of about 4 Re and to an earlier local time near dusk. The radial speed of this nightside plasmapause motion is of the order of 0.3 Re/hour (Carpenter and Stone, 1967). Thus the bulge region is lost during the main phase of a magnetic storm. Yet the dayside plasmasphere appears shielded from storms, as there is very seldom any radial movement reported there (Carpenter, 1970). During the recovery phase, the bulge begins to be filled again. The plasmasphere bulge is in an everchanging state towards dynamic equilibrium, constantly undergoing a supply and loss process by the modulating tail plasma flow. One possible mechanism suggested by Carpenter (1970) attributes the loss process to the westward convection drifts of the plasmasphere bulge by the increasing tail field. The described motion and asymmetry of the plasmapause is of particular importance to certain Pi 2 theories.

The equatorial magnetic field at a distance of 6.6 Re was observed with the ATS 1 satellite. During magnetic substorms, the field at ATS 1 was observed to be depressed in the dusk to midnight quadrant. Partial ring currents, formed by the inward convection of charged particles near the midnight meridian, was believed responsible for the observed depression (Cummings, 1966). Computations by Schield (1969) showed that an extra-terrestrial ring current weakens (enhances) the geomagnetic field inside (outside) the current site. During magnetic storms, an asymmetric enhancement of the increasing ring current proton intensities occurs. The increases were observed to be greatest in the dusk to midnight quadrant (Frank, 1967 and 1970). At the same time, no increases were observed near local noon. The incessant ring current of protons, usually found at values of L (an equatorial distance in units of earth radii) greater than, or about 6, penetrates to smaller L values during magnetic storms (Frank and Owens, 1970). The intense asymmetric part of the storm time ring currents decays much more rapidly than the symmetric part (Cummings, 1966). The ring current has been considered asymmetric from the ssc to the main phase minimum of a storm, and symmetric during the recovery phase (Hoffman and Cahill, 1968). In conjunction with the rapid asymmetric ring current decay, sudden recoveries of the field at ATS 1 have been attributed to abrupt disruptions of the partial ring currents (Cummings, Barfield, and Coleman, 1968). This thesis will show that the unique features of this magnetospheric subregion provide information relating to Pi 2 micropulsations.

The plasma sheet is a region of magnetic field reversal, or neutral sheet, between the northern and southern halves of the magnetotail. In this equatorial sheet, a low intensity magnetic field having a non-zero vertical component, is observed. Since a pressure balance must be maintained, a decrease in the field pressure is balanced by an increase in particle pressure in the plasma sheet. An enhanced particle energy density is one of the sharp boundaries existing between the plasma sheet and the higher latitude magnetotail region. Comparisons of the average particle energy, density and energy density have been made (Bame, 1967). The greater energy of the plasma sheet resides in the protons. During the main phase of a negative bay, a decrease in the electron average energy density occurs in the plasma sheet (Hones et al., 1971). This was shown to be due to a decrease in the thickness of the plasma sheet by a net loss of tail particles. An increase in the tail current is also observed during this phase of the bay (Coleman and Cummings, 1971). As the bay recovers, the sheet thickens again and the tail current decreases. The inner boundary of the plasma sheet (characterized by an exponential decrease of electron energy density with decreasing radial distance) was reported at positions out to 11.2 Re equatorial distance at times of low magnetic activity (Vasyliunas, 1968). During the main phase decrease of a storm, this inner boundary moves close to 6 Re distance. The plasma sheet inner boundary returns to it's quiet time position immediately following the main phase minimum of a storm (Coleman et al., 1971). One of the investigations of this thesis correlates the period of Pi 2's with the observed position of the plasma sheet inner boundary.

The trapping boundary of energetic electrons (for E greater than 40 kev) was found to be located within the proton ring current, near it's outward edge (Frank, 1971). This trapping boundary was either coincident with the plasma sheet inner boundary or in the plasma sheet itself. The plasma sheet inner boundary was found coincident with the plasmapause in the post midnight quadrant, and 1 to 3 Re beyond the plasmapause in the pre-midnight quadrant. A low energy density electron trough lies between. The ring current was observed to penetrate 0.5 to 1 Re distance into the plasmasphere. The plasma sheet inner boundary and electron trough are within the proton ring current. During the main phase of a storm, the trough disappears and the entire structure moves inward, towards the earth. The inner edge of the symmetric part of the storm time ring current continues to move inward into the plasmasphere, during the recovery phase of a storm (Coleman et al., 1971). With the abrupt disruption of the partial ring currents during storm recovery, the plasma sheet and ring currents disconnect. The ring currents likely move inward and the plasma sheet retires outward. The close and complicated interaction of the magnetospheric subregions makes it difficult to ascertain the location of the Pi 2 source.

d. Theories of Pi 2

The initial kick of either component of a Pi 2 event often has the same sign as the corresponding component of an accompanying bay. Jacobs et al. (1960) suggested this kick may be represented by an equivalent overhead current system in the dynamo region of the ionosphere. Such a current system suggests a nightside auroral zone source for Pi 2. Jacobs (1970) stated that solar wind-geomagnetic field interaction in the tail region gives rise to a broadband hydromagnetic (abbreviated hereafter with hm) impulse which travels to the auroral zones. The impulse contains periods ranging from Pi to bay. Near the auroral zone source, all frequencies arrive at the same time and the leading edge of the bay is very steep. The ionosphere disperses the waves travelling to lower latitudes. This ionospheric dispersion causes high frequencies to propagate faster than lower frequencies and consequently, the leading edge of the bay is less steep at low and middle latitudes than at the auroral zone. Thus Jacobs regarded the bay and initial Pi 2 pulse as a result of modification by the ionosphere, of solar plasma generated hm disturbances. An objection to the idea of Pi 2's as fluctuations of an ionospheric current system was voiced by Saito et al. (1968) who noted the latitudinal variation of bay magnitude is not always the same as that of the amplitude of concurrent Pi 2. Furthermore, observations of occassional clockwise polarization in the northern hemisphere led Jacobs (1970) to believe that Pi 2 could not be described by a single current system. He then suggested that Pi 2 may be caused by a disturbance propagating in the ionospheric E-region. The close relationship between auroral luminosity fluctuations and micropulsations (Campbell and Rees, 1961) and observed Pi 2 phase shifts between two separate stations (Herron, 1966) were cited by Jacobs as further evidence of ionospheric propagation effects. Rostoker (1967a) suggested that Pi 2's originate as eigen-oscillations of auroral field lines which then propagate through the ionospheric E-region. Thus, the polarization of the field would be effected by ionospheric screening, dependent on the location of the station relative to the Pi 2 source.

There are certain reported dissimilarities between

Pi 2's observed in the auroral zone and those observed at low latitudes (Fukunishi et al., 1970). Observed auroral latitude Pi 2 is more irregular in waveform than the damped, mid-latitude Pi 2. Likely, this is because the effect of injected, energetic particles is more prevalent in the auroral zone. As mentioned already, the power spectrum of auroral latitude Pi 2 during a magnetospheric substorm was found to have a background random noise type of dependence with frequency. This random noise is less prevalent at lower latitudes and this might imply that auroral latitude Pi 2's may be generated by a mechanism different from that for low and middle latitude Pi 2's. Also, as the Kp index increased, the fundamental mode of the auroral latitude Pi 2 became obscured and the amplitude of the higher frequency Pi 1 riders increased. A fundamental mode of period greater than 40 seconds was not clearly observable for Kp greater than 3. Yet the fundamental mode was shown to decrease in period as Kp increased for middle latitude Pi 2. According to Hirasawa et al. (1966), the similar diurnal variations of Pi 2 period and Pc 4 period (a continuous micropulsation of period from 45 to 150 seconds) imply a similar generating mechanism at low and middle latitudes. Hirasawa et al. had attributed Pc 4 to hm oscillations at the plasmapause. Fukunishi et al. (1970) calculated the Kp dependence of Pi 2 period from formulae expressing the latitude variation in the eigen-period of hm oscillations (Obayashi and Jacobs, 1958) and the Kp variation of the plasmapause (latitude) position (Binsack, 1967). The Kp versus Pi 2 period relation obtained by them agrees well with the Kp-Pi 2 period observations of Troitskaya (1967). They also observed a decrease in Pi 2 period corresponding to the suggested inward motion of the plasmapause, from 4.6 to 4.2 Re, during the expansive phase of a magnetospheric substorm. Fukunishi et al. (1970) thus concluded that lower latitude Pi 2 is a transient surface oscillation on the plasmapause, excited by hm disturbances. The auroral latitude Pi 2's are considered to be fluctuations of ionospheric current produced by the influx of energetic particles to the upper atmosphere. Yet it may be that only Pi fluctuations of period less than 40 seconds, or Pi 1, are caused by ionospheric current disturbances. Heacock, Mullen and Hessler (1971) showed that when a strong Pi (Pi 1 and 2) occurs at College, in the auroral zone, a faint Pi also occurs at Anchorage, a lower latitude station. However, at Anchorage, Pi 1 at a period about 2.5 seconds was enhanced compared to other periods. This implies that Pi 1 may propagate as hm waves in the ionospheric horizontal waveguide. Also, the variation in Pi 2 period with the suggested plasmapause position does not prove that Pi 2 occur there. As previously mentioned, other magnetospheric subregions, such as the ring currents and the plasma sheet inner boundary, also vary with magnetic activity.

Kato (1971) analyzed geomagnetic micropulsations associated with sudden storm commencements (abbreviated hereafter with ssc) by dividing the signal into several frequency channels. He showed that the initial predominant Pi 2 had periods of about 200 seconds. These 200 second fluctuations clearly exhibited a damped type of oscillation and were of a global scale. Periods of about 100 seconds were shown to be of a more impulsive or resonant nature, occurring on a semi-global scale. Kato showed the filtered waveforms recorded simultaneously at College and Onagawa during a ssc are similar. From such a frequency analysis, it was concluded that Pi 2 is first excited by an hm burst. This is due to a solar wind shock front impacting the magnetopause, on the dayside. The damped 200 second fluctuations which are thus excited, travel along field lines to high latitudes and also across field lines to the nightside of the magnetosphere. Yet, if this were the case, these 200 second fluctuations having a finite propagation velocity, would not arrive simultaneously at two stations separated by 50 degrees of longitude and 36 degrees of latitude, as they were observed. Following the burst, Kato suggested Pi 2's are excited in the magnetosphere nightside and occur with the growth of the substorm. At this time, the particle flow pressure increases against the magnetic field pressure near the ring current site. The mechanism proposed by Kato (1971) calls for a hm burst impacting the field in the vicinity of the inner boundary of the partial ring current. Such an inward burst requires a sudden disruption of partial ring currents. As will be discussed in Chapter III, a sudden partial ring current disruption gives rise to a plasma implosion. Another theory of Pi 2 generation by an implosion of plasmas in the night-time magnetosphere was proposed by Atkinson (1966). This idea is based on the theory of reconnection of open tail field lines proposed by Dungey (1961, 1962, 1967) and also by Axford, Petschek and Siscoe (1965). Atkinson suggested that intermittent field line reconnection gives rise to the implosion of tail plasmas towards closed magnetic lines of force.

Heacock et al. (1971) reported that 95% of the time when Pi events occur at College or at Sodankyla, the plasmapause is located inside the field line connected to these auroral zone stations. This implies that most Pi 2's occur outside the plasmapause, since Pi 2 amplitude in it's latitudinal variation becomes maximum in the auroral zones. Evidence has been offered by Saito et al. (1970) to show that Pi 2 micropulsations associated with a small substorm are due to oscillations of the field lines through the plasma sheet inner boundary. The field lines connected to the maximum amplitude Pi 2 latitudes, in two examples, were shown to pass through the equatorial plane of the nightside magnetosphere at distances of 9.5 and 6.5 Re, respectively. These distances were near the predicted plasma sheet inner boundary. Wasyliunas (1968) found that the plasma sheet inner boundary on the nightside moves inward, towards the earth, as the Kp index increases from 0 to 3. Saito et al. (1970) gave an empirical formula for the relation of Kp to the geocentric distance of the plasma sheet inner boundary, Rps,

$$Rps = 15 - 6\sqrt{Kp} . \qquad (1)$$

A formula was given by Rycroft and Thomas (1970) for the relation between Kp and the equatorial distance of the nightside plasmapause, Rpp,

$$Rpp = 5.64 - 0.78\sqrt{Kp} . \qquad (2)$$

From the two formulae, Saito et al. (1970) found that Pi 2 peak amplitude latitudes mapped closer to the 'inferred' plasma sheet inner boundary than to the 'inferred' plasmapause position, for Kp indices less than 4. At the initial stage of a magnetospheric substorm, Pi 2's are observed to have a period common from middle latitudes to polar regions. At auroral latitudes however, this period may be observed overlapping the noise-like background. The prominent spectral peak of this Pi 2 is frequently seen in the spectrum of auroral zenith intensity fluctuations. Saito et al. (1970) felt that if Pi 2 at plasma sheet inner boundary latitudes (auroral zone) were due to the auroral electrojet fluctuations, then the usual coincident set of Pi 2 patterns at conjugate stations would not be observed. They consider auroral electrojet fluctuations to be a secondary phenomenon produced by a possible Alfven wave modulation of the precipitation of auroral particles. Pi 2 are considered to be primarily due to a transient torsional oscillation of the field lines through the inner boundary of the plasma sheet.

CHAPTER II

RELATED INVESTIGATIONS OF Pi 2 MICROPULSATIONS

a. VLF Emissions and Pi 2 Period

This research is aimed at locating the region of generation of Pi 2 micropulsations. Previous investigators have reported the variation of the plasmapause (Rycroft et al., 1970) and the plasma sheet inner boundary (Saito et al., 1970) positions with the three hour planetary K index. The period of Pi 2 has been observed to decrease with increasing Kp (Troitskaya, 1967). Hence it is reasonable to assume the dependence of Pi 2 period upon the nightside position of a magnetospheric subregion. However, there is a considerable degree of uncertainty as to which subregion generates Pi 2. Some authors (Saito et al., 1970) indicate the plasma sheet inner boundary while others (Hirasawa et al., 1966) suggest the plasmapause as the generating subregion. The hypothesis of Saito and Sakurai is based on a result of their analysis, showing that the latitude of maximum Pi 2 amplitude maps along the field line to the equatorial plane, near the predicted plasma sheet inner boundary. Hirasawa and Nagata's hypothesis is founded on the comparison of their observations of the diurnal variation of the equatorial distance of the plasmapause position (Carpenter, 1966) with the diurnal variation of Pi 2 period. Furthermore, Fukunishi et al. (1970) calculated the Kp variation of Pi 2 period from formulae expressing the latitude variation in the eigen-period of hm oscillations (Obayashi et al., 1958) and the Kp variation of the plasmapause position (Binsack, 1967). The Kp versus Pi 2 period relation obtained by them agrees reasonably well with observations by Troitskaya (1967).

In the investigation reported here, the variations of Pi 2 period with changes in equatorial distances of the nightside magnetospheric subregion boundaries, were directly examined. These boundaries, viz. the plasmapause and plasma sheet inner boundary, were determined by observing sudden changes in the characteristics of certain types of VLF radio signals received by the Alouette 2 satellite. The polar orbit of this satellite was almost circular and it scanned a wide latitude range. The VLF receiver on board often observed a sudden change in the characteristics of VLF radio signals. As the satellite moved to higher latitudes, a common type of change observed, most frequently at invariant latitudes of about 60°, is a cutoff in whistler activity. 'Breakups' in the lower hybrid resonance (abbreviated hereafter with LHR) noise band were also observed, often concurrent with a cutoff in whistler activity, LHR 'breakup' involves abrupt frequency and bandwidth changes as well as a transition from a smooth to an irregular appearance on frequency-time records. The whistler cutoff and LHR 'breakup' events take place when the satellite crosses the plasmapause latitude (Carpenter, Walter, Barrington and McEwen, 1968). In addition to these types of events, a sudden change in ELF emission strength was detected by the Alouette 2 receiver. It is tentatively assumed that such a change takes place when the satellite crosses the plasma sheet inner boundary. This assumption will be discussed further in Chapter III.

During 1967, the magnetospheric subregion boundary crossing events were collected with respect to the satellite orbits within ± 2 hours of longitudinal distance from Ottawa. Approximately sixty examples were obtained in total. The geomagnetic micropulsation data were obtained at Ralston, southeast of Calgary, Alberta. In this research, the following conditions were met with regards to the selection of Pi 2.

i) Pi were considered only if they were observed within an interval of ± 2 hours about the time of a satellite 'boundary crossing' event. A shorter interval would yield an insufficient number of Pi 2 events and a longer interval may make a comparison between Pi 2 and subregion boundary positions meaningless.

ii) Selected Pi 2 must have occurred within the local time interval of 1430 to 0530 at Ralston (or approximately 2200 to 1300 UT). Pi 2 is primarily a nighttime phenomena with optimum occurrence being near 2230 LMT. During the daytime, Pi 2 are generally smaller in amplitude and often contaminated with other types of micropulsations (mostly Pc3 and Pc4).

iii) The average Kp index, during a 9 hour interval about the event, must not be greater than 3. During times of greater magnetic activity, the magnetospheric subregions often become coincident in location (Frank, 1971). Thus intervals of magnetic quiescence suit this research purpose and since Pi 2 occur most frequently when 1+ ≤ Kp ≤ 2- (as will be shown in section II.d), few examples are eliminated by this criterion.

The period of each of the selected Pi 2 series was scaled from the north-south component. If more than one series of coherent Pi 2 occurred in the time interval, then the mean value of all the Pi 2 was considered to indicate the period corresponding to the satellite event. The Pi 2 periods were correlated with the boundary crossings. During most crossing events, any possible events due to wide band VLF intensity changes were suppressed with the use of an automatic gain control (abbreviated hereafter with AGC).

It is again pertinent to mention that Pi 2 period does not change with latitude. Saito et al. (1970) gave two examples showing that Pi 2 period is common from middle latitudes through polar regions. On the other hand, Fukunishi et al. (1970) mentioned that the wave forms of auroral zone Pi 2 have a nearly random noise type of power spectrum, whereas the Pi 2 spectrum in low and middle latitudes is characterized by an outstanding peak near 80 seconds. Yet, they showed that auroral zone Pi 2 spectrum has three peaks overlapping the noise-like background. One of the peaks is centered at about 80 seconds as in low and middle latitudes. The other two spectral peaks exist near 20 and 10 seconds. The common peak at about 80 seconds seems to indicate that hm oscillations of that period are of the fundamental mode prevailing in a latitudinal range from low to auroral zone, presumably even up to the latitudes which divide the magnetotail from the region of closed magnetic lines of force.

The periods of the selected Pi 2 series are listed in Table 1. Also listed are the time, nature and equatorial distance (an L value in units of earth radii) of each of the correlated subregion boundary crossings. Based on this table, Figure 1 shows a plot of the Pi 2 period change with the equatorial distance of the plasmapause and/or the plasma sheet inner boundary. An open circle represents a plasmapause event and a solid (dark) circle, a plasma sheet inner boundary event. A triangle represents a coincidence in location of these two subregions.

Table I

Alouette 2 events and the correlated Pi 2 periods at Ralston during 1967.

Date	U.T.	Events	L value	Pi 2 period
Feb. 28	0937	LHR, ELF, AGC	4.88	66 (sec.)
March 4	0837	LHR, ELF, AGC	2.90	48
March 11	0836	ELF	2.86	43
April 7	0602	LHR, ELF, AGC	2.82	65
May 12	0959	LHR, AGC	3.26	55
June 8	0715	ELF, AGC	5.06	80
June 8	0510	ELF, AGC	6.28	76
June 8	0916	ELF, AGC	4.80	59
June 13	0433	LHR, ELF, AGC	4.83	48
July 11	0205	ELF, AGC	8.50	92
July 26	0215	ELF, AGC	4.38	58
Sept. 4	1236	ELF, AGC	5.52	66
Sept. 9	1152	ELF, AGC	3.45	72
Sept. 10	0807	Whsl., ELF, AGC	4.18	69
Sept. 12	1041	Whsl., LHR	4.57	69
Sept. 25	0603	Whsl., ELF	3.99	56
Oct. 5	0849	LHR, ELF, AGC	7.64	95
Nov. 23	0949	LHR, AGC	3.62	47
Nov. 28	0910	LHR, ELF	4.33	72
Dec. 6	0913	ELF, AGC	6.87	81
Dec. 8	1151	ELF, AGC	3.43	61
Dec. 9	1206	LHR, ELF	3.56	67

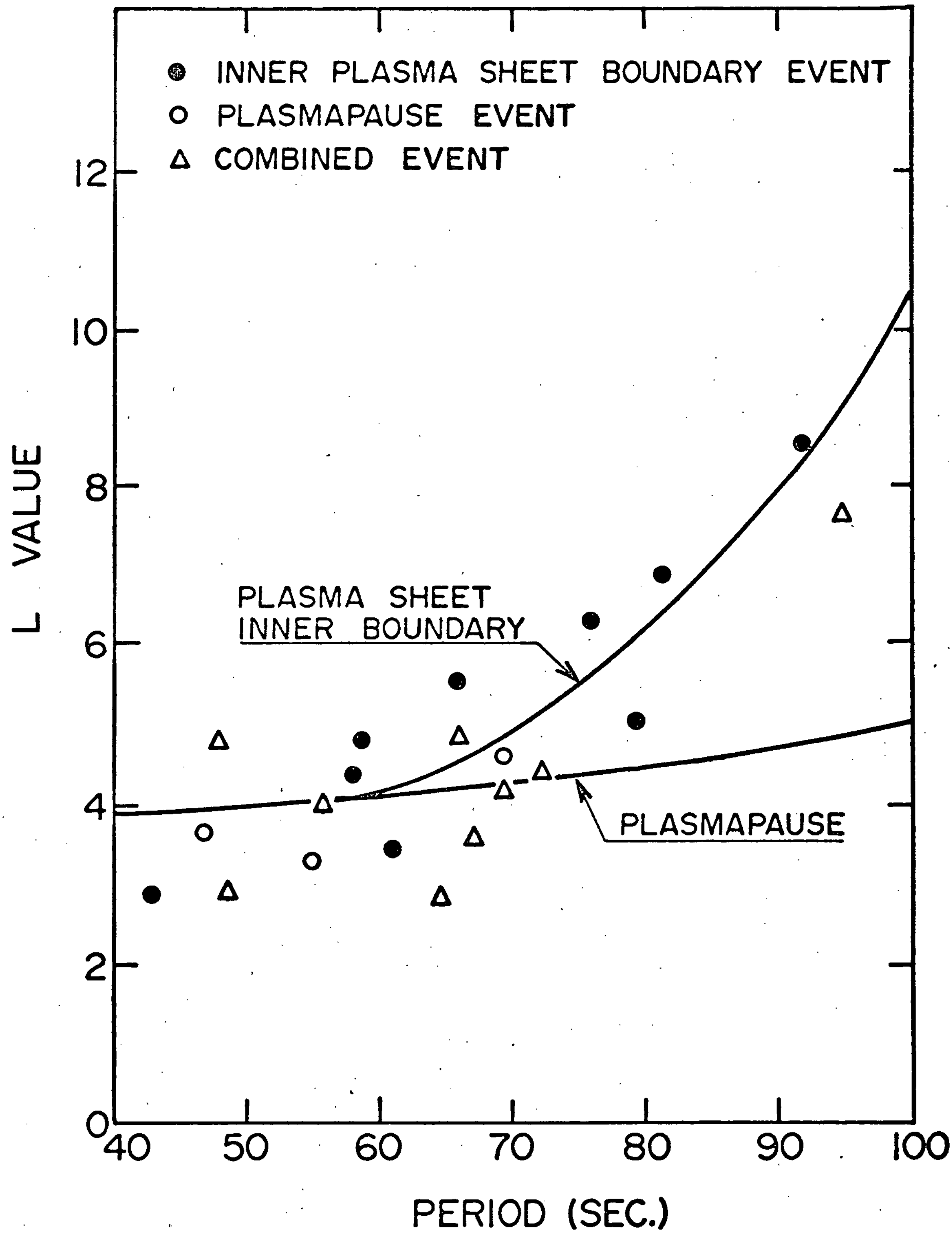

Fig. 1. Magnetospheric subregion L value variations of Pi 2 period

The curve marked with 'plasmapause' is a theoretical one to show how Pi 2 period is expected to change with the location of the plasmapause if Pi 2's are due to plasmapause fluctuations. The curve is based on two empirical formulae. One relates Pi 2 period to Kp index:

$$T = 109 - 14\ Kp \quad (\pm 5),\ (\text{for } Kp \leq 5o) \qquad (1)$$

where T is the Pi 2 period (in seconds). The formula is a least squares fit to a scatter plot showing the Kp variation of Pi 2 period (Troitskaya, 1967, Fig. VII. 8). The other formula represents the Kp variation of the nightside plasmapause position:

$$Rpp = 5.64 - 0.78\sqrt{Kp},\ (\text{for } Kp \leq 5o) \qquad (2)$$

given by Rycroft et al. (1970), where Rpp is the equatorial distance of the plasmapause. The 'plasma sheet inner boundary' curve is also a theoretical one to show how Pi 2 period is expected to change with the location of the inner boundary, if Pi 2 are generated at this subregion boundary. It was obtained by combining (1) and the following empirical relation:

$$Rps = 15 - 6\sqrt{Kp},\ (\text{for } Kp \leq 3o). \qquad (3)$$

This equation relates Kp to Rps, the equatorial distance of the plasma sheet inner boundary in units of earth radii. It was derived by Saito et al. (1970) from six data points about the position of the plasma sheet inner boundary which were obtained by Vasyliunas (1968).

For Pi 2 periods less than 70 seconds, the two curves approach one another. The closeness of these curves is consistent with the observed coincidence of the plasmapause and inner boundary during periods of greater magnetic activity (Frank, 1971). However, the 'plasma sheet inner boundary' curve was derived from data which occurred primarily during times of low Kp. In this range (periods $\geq$ 70 seconds), the curves separate sufficiently to substantiate an agreement between the 'plasma sheet inner boundary' curve and the data from direct observations. The implication of this result is discussed in Chapter III.

b. Pi 2 Diurnal Variations

The purpose of this investigation is to more clearly establish the source field lines of Pi 2 micropulsations. As previously mentioned (Chapter I), the morphology of micropulsations should reflect the nature of the source responsible for these fluctuations. Various characteristics of Pi 2 have been observed. Firstly the maximum amplitude of Pi 2 tends to occur near midnight and at geomagnetic latitudes in the auroral zone (Saito et al., 1970), or at least higher than 50^{o} (Jacobs et al., 1960). Secondly, the direction of the initial movement of the Pi 2 disturbance vector at low and middle latitudes is usually north-east (north-west) prior to (after) midnight (Kato et al., 1956; Yanagihara, 1960). This disturbance vector has been shown to converge to the northern auroral zone on the midnight meridian (Saito, 1961). Thirdly, the local time at which Pi 2 occur most frequently is near 2230 (Yanagihara, 1957a; Rostoker, 1967a). When these three factors are considered, it is reasonable to expect the source of Pi 2 to be found on auroral zone field lines near the midnight meridian. The investigation reported here compares the diurnal variation in the occurrence frequency of initially north-east oriented Pi 2's with that of north-west Pi 2. From these observations, the diurnal variation in the probability of occurrence of north-east Pi 2 is found. This distribution is compared with the diurnal variation in the occurrence frequency of all the observed Pi 2 events.

Pi 2 events occurring from January to May 1964 were selected from the rapid run magnetograms at Wingst, Germany and Memambetsu, Japan. The initial impulsive movements of the horizontal disturbance vector were observed. In particular, the initial north-south component of each

Pi 2 event was compared with the east-west component. As Pi 2's are primarily nightside, dusk to dawn, phenomena, only events occurring from 1400 to 0800 LMT were used. The initial movement of all of these events was usually either north-east or north-west. Examples of these events are shown in Figure 2 and 3. For each of these two groups, the diurnal variation in the number of Pi 2 (occurring in hourly intervals) is plotted in Figure 4. The diurnal variation in the occurrence probability of north-east Pi 2 is compared with the variation in the occurrence frequency of all observed Pi 2 events, in Figure 5.

The most probable local time of occurrence of initially north-east (north-west) Pi 2 is at 1930 (2330) as is shown in Figure 4. From Figure 5, it can be seen that Pi 2 occurrence is centered about 2205 LMT. This is near 2300 LMT after which the probability of initial north-east orientation becomes less than 50% (also shown in Figure 5). Thus, Pi 2 is found to occur about 2205 LMT, prior to (after) which the initial Pi 2 orientation is primarily north-east (north-west).

c. Pi 2, Solar Wind and Geomagnetic Activity

Studies of morphologic variations in micropulsations may provide information on variations in the source of these

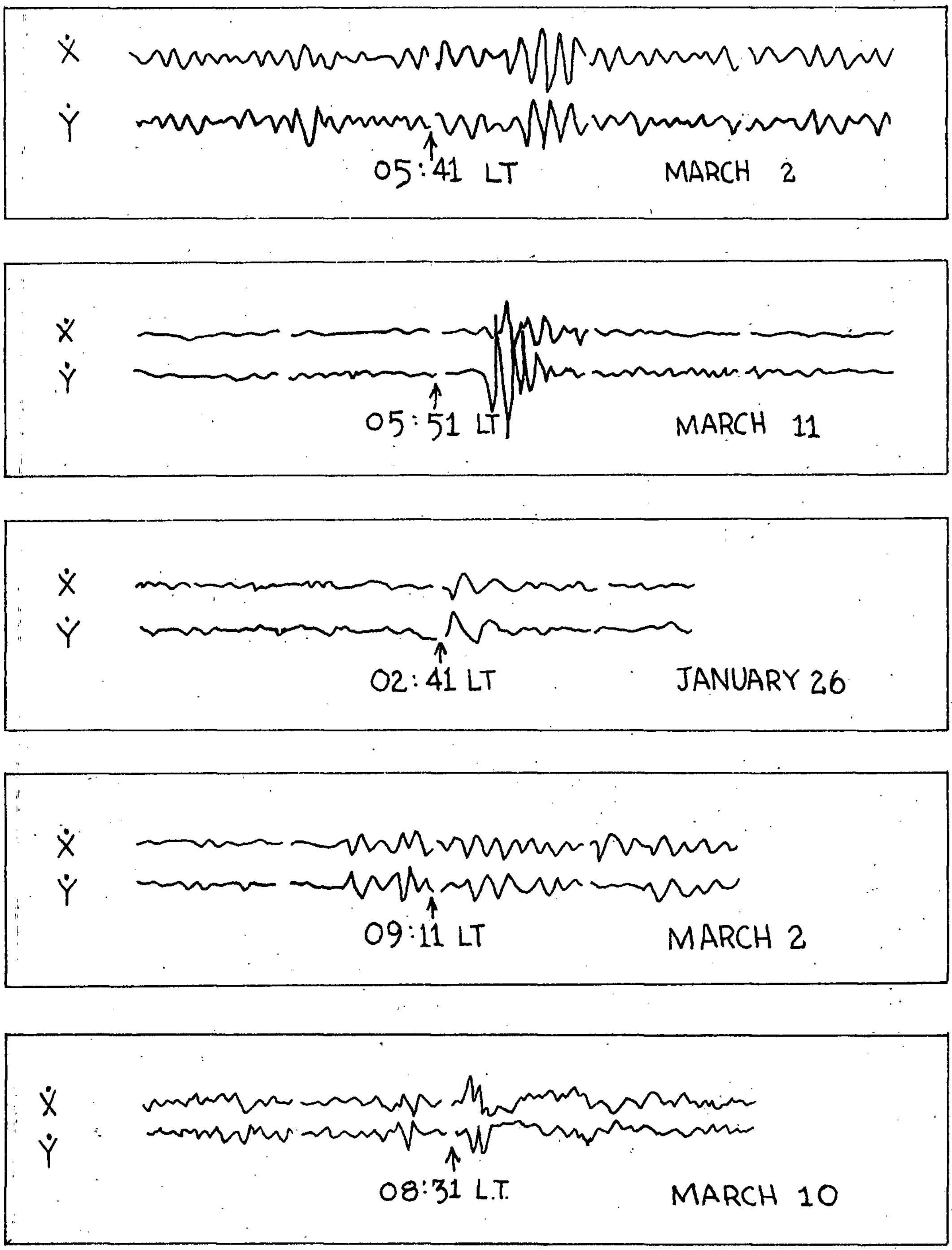

Fig. 2. Magnetograms of initially north-west (Ẋ+, Ẏ-) Pi 2

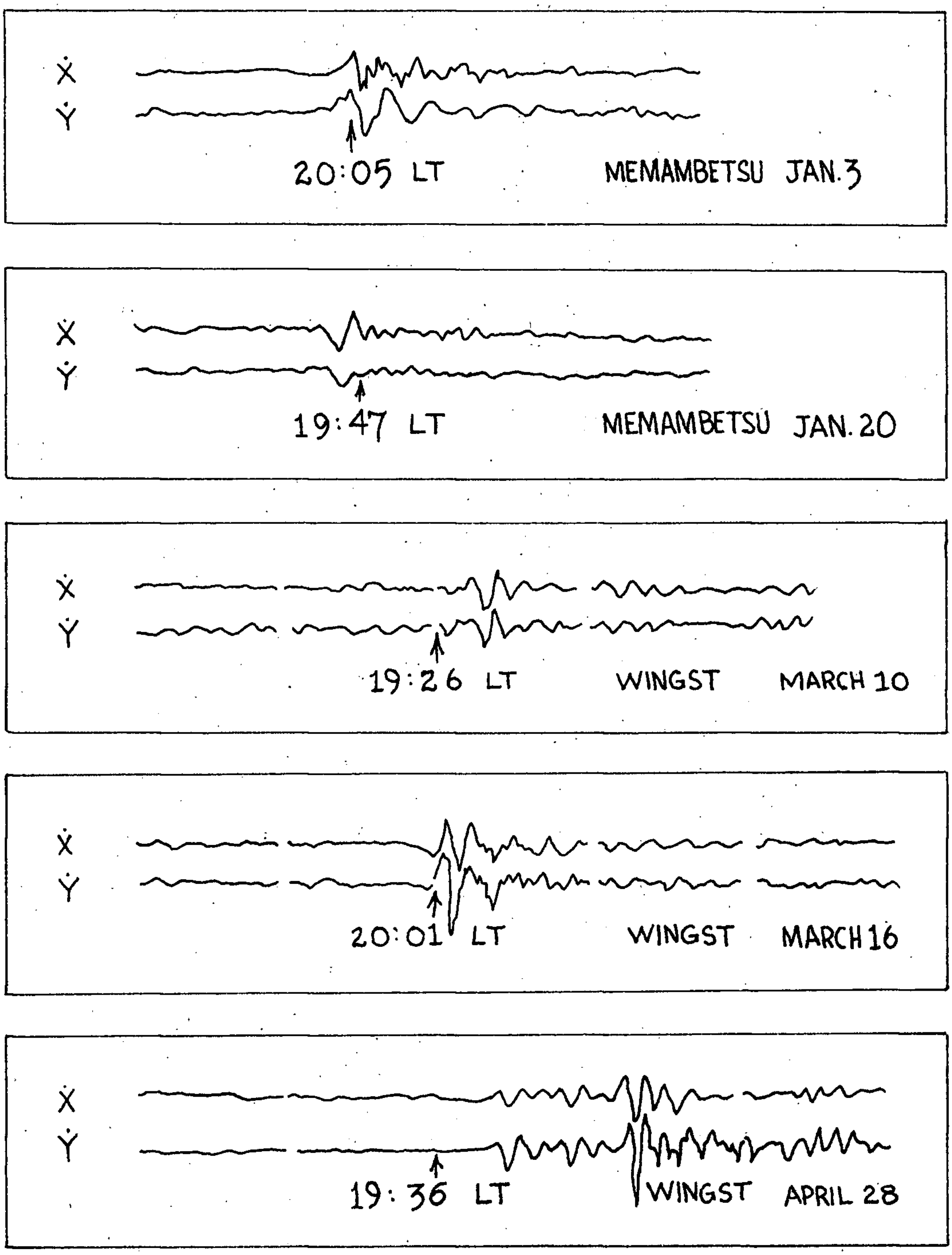

Fig. 3. Magnetograms of initially north-east ($\dot{X}$+, $\dot{Y}$+) Pi 2

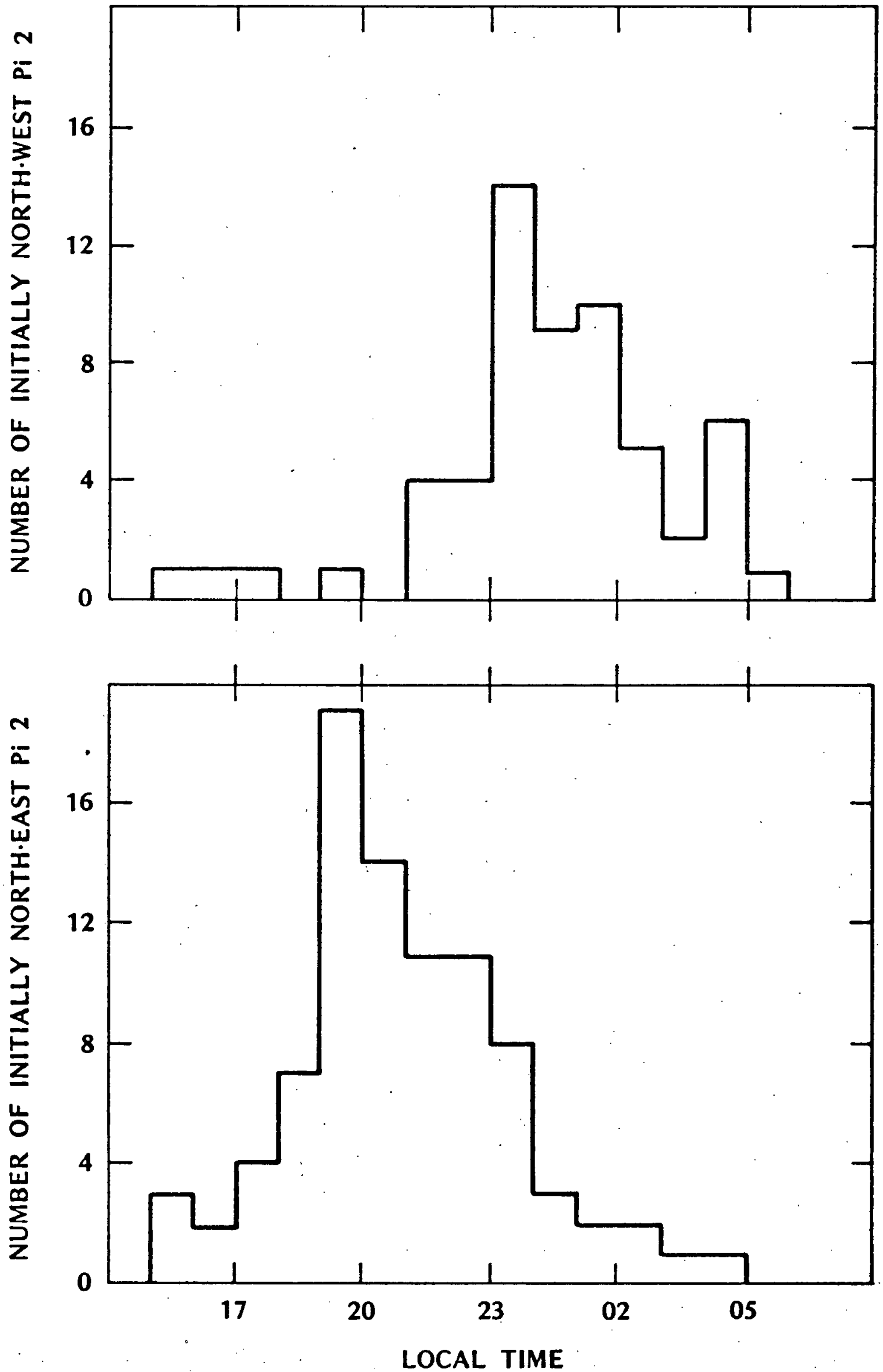

Fig. 4. Diurnal variation of initially north-west and north-east Pi 2 occurrence frequencies

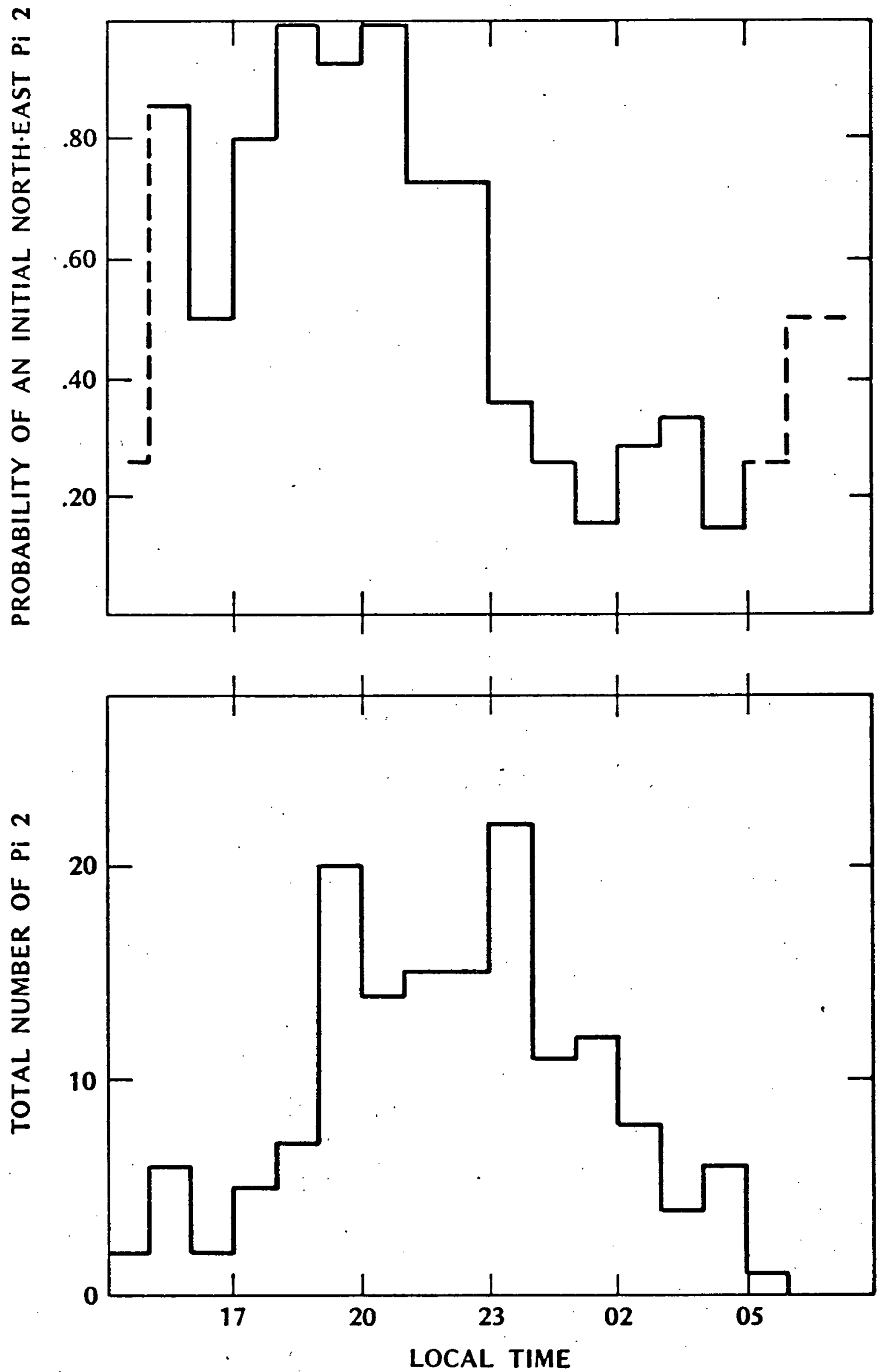

Fig. 5. Diurnal variation of the initially north-east Pi 2 occurrence probability and the total Pi 2 occurrence frequency

fluctuations. Yanagihara (1960) noted a tendency for the most probable time of Pi 2 occurrence to shift from midnight to about 2200 LMT with increasing magnetic activity. In this investigation the tendency is further substantiated by comparing the most probable local time of Pi 2 occurrence during periods of low magnetic activity with the most probable time during high activity. In this manner, the 'dynamic' behaviour of the Pi 2 source is demonstrated. In order to account for this behaviour, the direction and pressure of the solar wind protons is examined during periods of high, magnetic activity.

The local time distribution of Pi 2 events observed by a global network of stations during 1964 (Romaña and Veldkamp, 1968) was determined for periods of magnetic quiescence ($Kp \leq 3+$) and also for periods of high magnetic activity ($Kp \geq 4-$). The diurnal variation in the Pi 2 occurrence was thus determined for each group (one of high Kp, the other low). These variations are shown in Figure 6. Next, a study of the solar wind proton streaming angle and pressure was undertaken, in the belief that the most probable time of Pi 2 occurrence may be conditioned by solar wind. The streaming angle, ϕ, is measured positive eastward from the sun-earth line to the direction of the solar wind flow. Data was obtained, from the World Data Center A, Greenbelt, Md., for the Explorer 34 experiment,

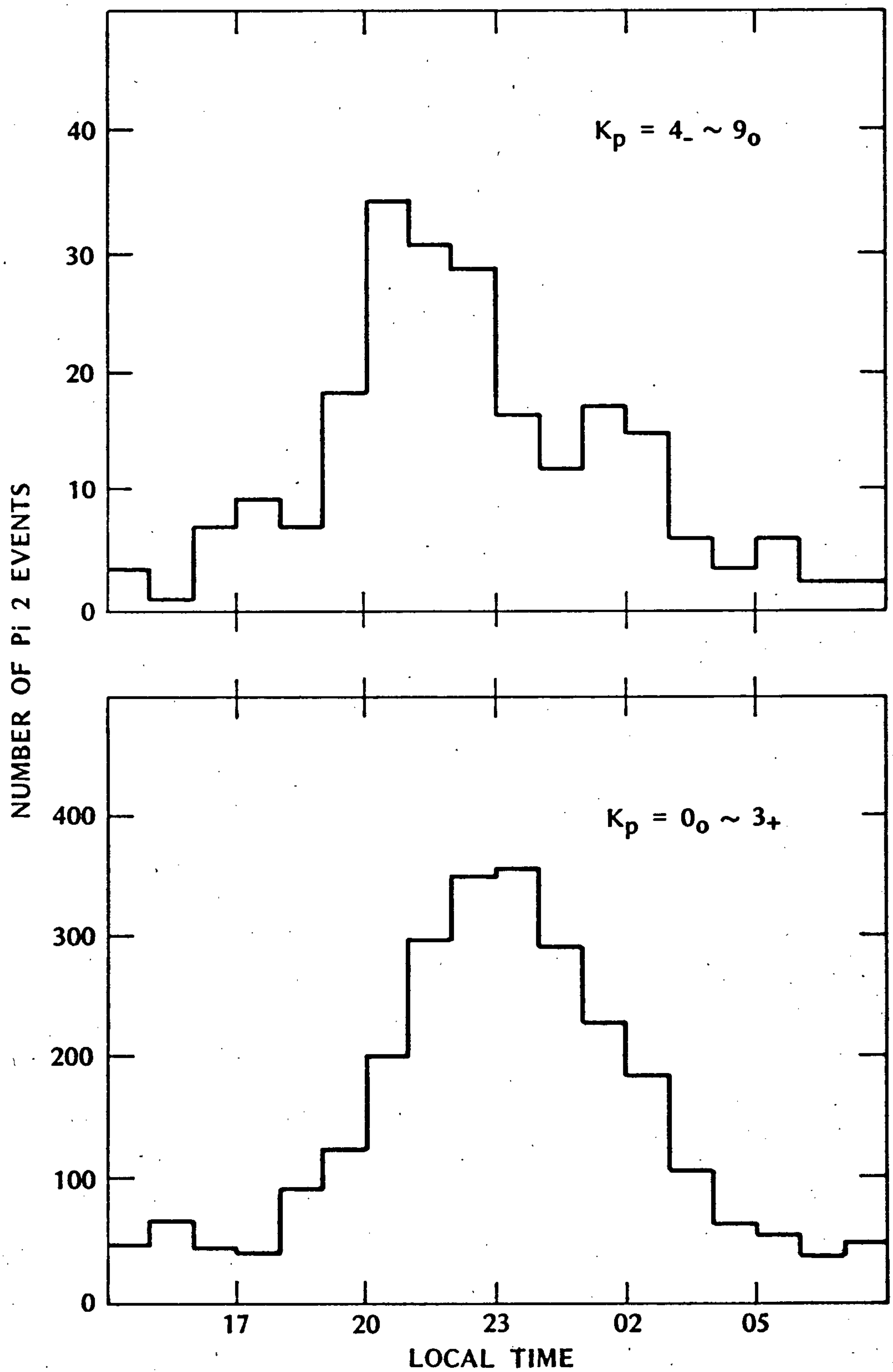

Fig. 6. Diurnal variation of Pi 2 occurrence frequency during high and low magnetic activity

of which technicalities have been described elsewhere (Oglivie, 1968). The proton flow direction, velocity and density data were observed at three minute intervals. Approximately 2,000 such datum points, selected from June to November, 1967 when the satellite was outside the bow shock, were selected during times of high Kp ($\geq$ 4-). The number of points in each flow direction (in a 22.5 degree interval) were recorded and the average proton pressure in each of these directional flow intervals was calculated. This procedure was repeated during times of low Kp ($\leq$ 3+). Thus the probability of occurrence of each directional interval, $P(\phi)$, was found and the product of $P(\phi)$ and the average proton pressure (NmV^2) in that directional interval was calculated. This value, $P(\phi)\cdot(NmV^2)$, represents the 'expected' solar wind proton pressure, in that directional flow interval during the prescribed magnetic activity. The solar wind streaming angle variation of this solar wind proton pressure during times of high and of low Kp is shown in Figure 7.

The combined results (for low plus high Kp) of the Pi 2 occurrence frequencies shown in Figure 6 yield a peak time near 2230. The most probable local time of occurrence of Pi 2 during low (high) Kp is after (prior to) this time. In particular, Pi 2 occurs most frequently at 2030 (2330) LMT during high (low) Kp. This westward shift

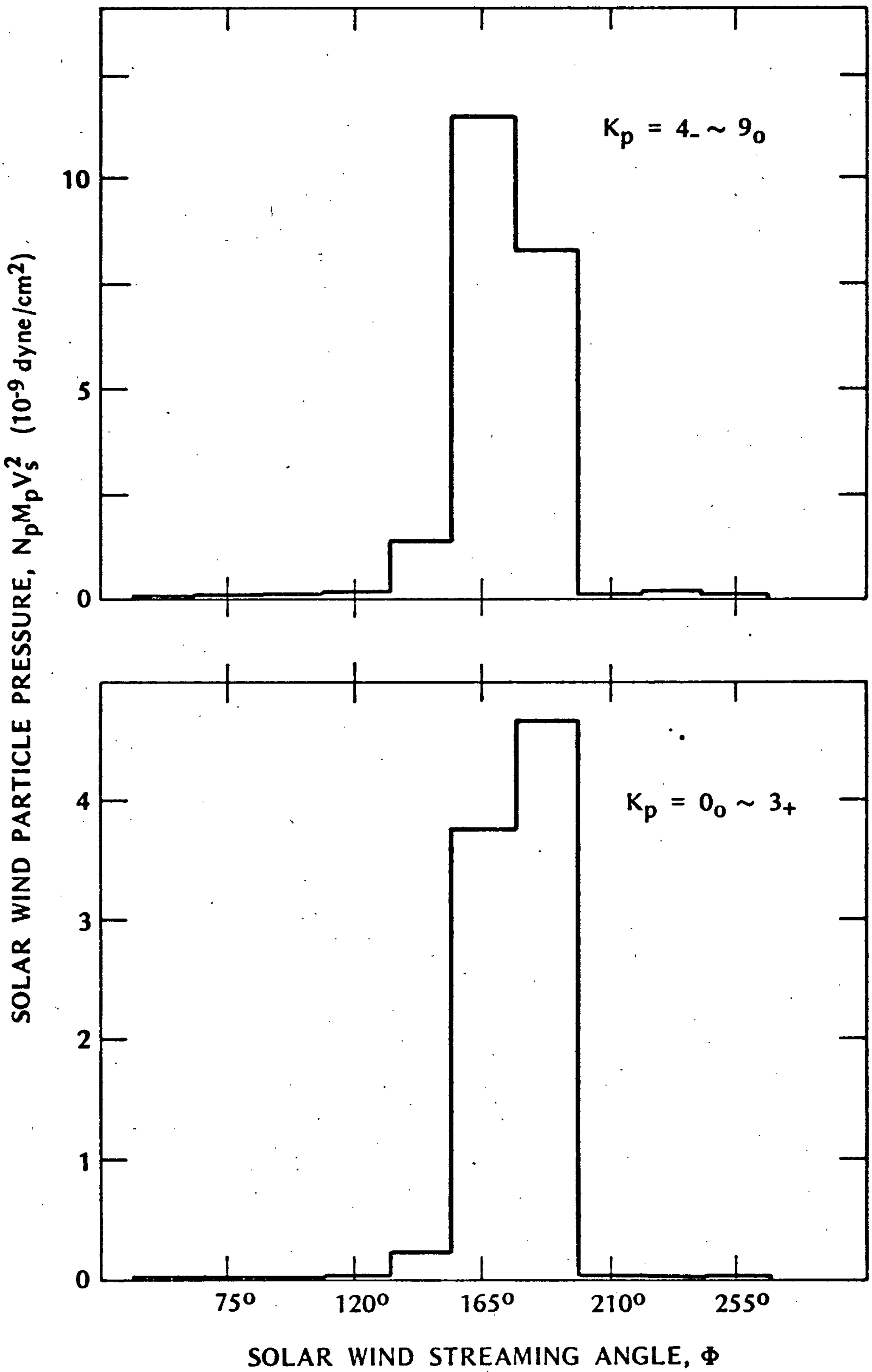

Fig. 7. Solar wind streaming angle variation of particle pressure during high and low magnetic activity

is in agreement with Yanagihara's observation. The streaming angle variation in the solar wind proton pressure has a pressure peak directed at an angle of 188° (165°) during low (high) Kp. Thus, during periods of low magnetic activity, Pi 2's occur most frequently near 2330 LMT, when the solar wind protons at 1 AU are streaming at an angle of 188°. During periods of high magnetic activity, this streaming direction is 165° and Pi 2's occur most frequently at an earlier time of 2030. As expected, the proton streaming pressure is greater during high Kp than during low Kp.

d. Pi 2 Rate of Occurrence

Observations of changes in Pi 2 morphology with magnetic activity and the solar cycle have been less consistent and even appear contradictory at times. As mentioned in section I.b, the rate of Pi 2 occurrence was reported to increase with Kp (Yanagihara 1957b, Kannangara et al., 1969; Channon et al., 1970). This might imply that the occurrence of Pi 2 should increase during sunspot maximum (when the Kp index is higher). Yet, Yanagihara (1956) reported that the yearly occurrence frequency of 'night pulsations' is inversely proportional to the solar activity. In section II.c, the peak time of Pi 2 occurrence was shown to shift westward with increasing magnetic activity.

Together, this shift and the increasing rate of Pi 2 with Kp may imply that the peak time of Pi 2 occurrence should be observed earlier during sunspot maximum. Yet, Afanasieva (1961) and Saito et al. (1968) show that the Pi 2 peak time of occurrence is found near midnight (2300 to 0100) during sunspot maximum and at earlier times (2000 to 2300) during sunspot minimum. In an attempt to explain these two apparent contradictions, an investigation was made of the Kp variation in the rate of Pi 2 occurrence near sunspot minimum (1964) and at a more active year (1967).

The Pi 2 events used in this investigation were those observed by a global network of stations during 1964 (Romaña et al., 1968) and 1967 (Romaña and Van Sabben, 1970). For each of these years the total number of Pi 2 events was found for each three hour Kp level. The rates of occurrence for different Kp levels were obtained by dividing the total number at each level by the total number of times that the particular level occurred during that year. The rates of Pi 2 occurrence, for both 1964 and 1967 were calculated using over 3,000 reported Pi 2 events from each year. The rates, showing a statistical deviation about each point, are plotted in Figure 8.

The Kp variation in the Pi 2 occurrence rate, shown in Figure 8, is similar for both years despite the fact that the average Kp index was higher during 1967. In

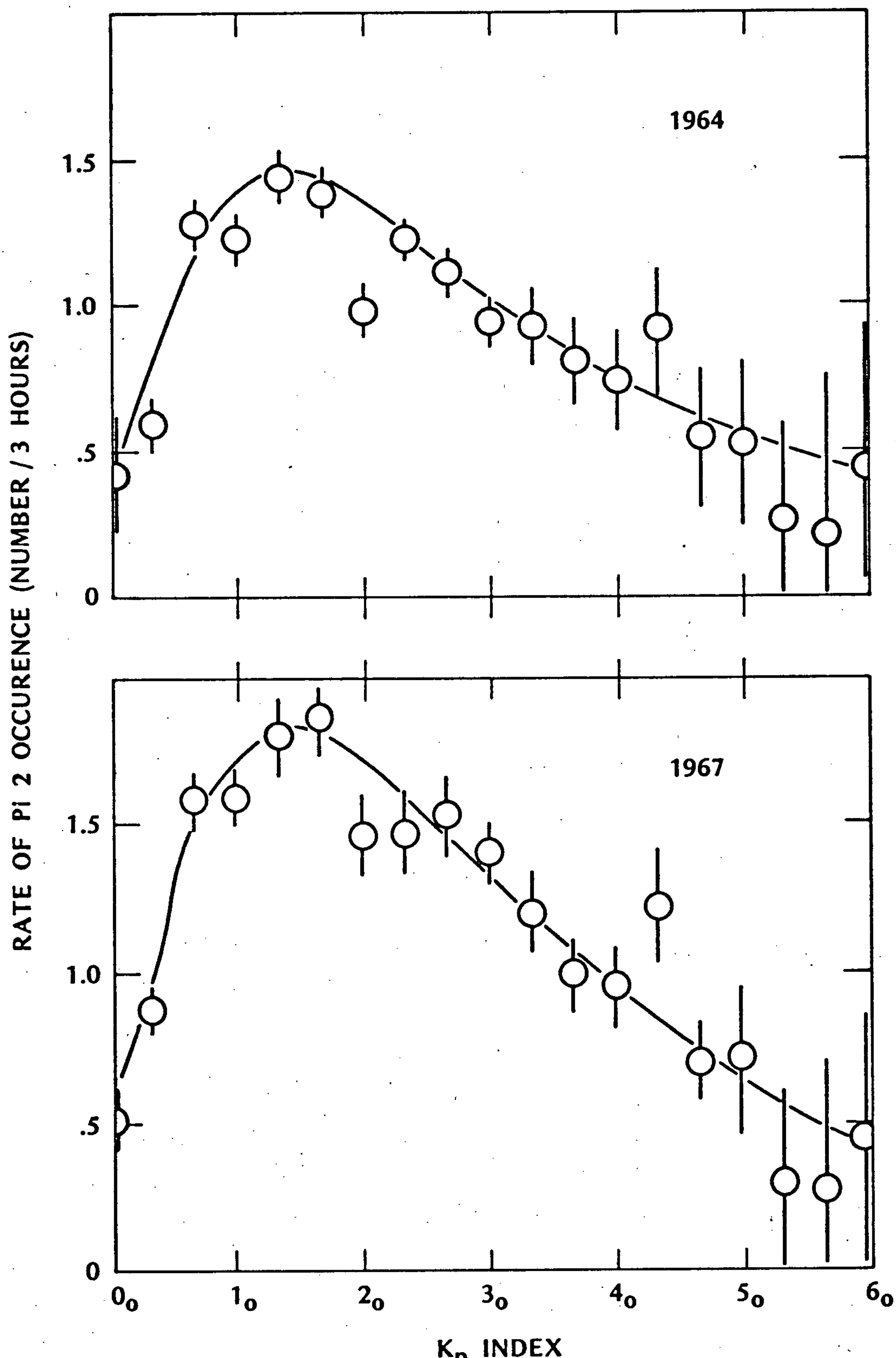

Fig. 8. Kp variation of the Pi 2 occurrence rate during 1964 and 1967

both years, it can be seen that the Pi 2 occurrence rate increases with Kp for Kp values between 0o and 1+. The occurrence rate does not keep increasing beyond Kp = 2o, contrary to results presented by the investigators mentioned earlier. Thus, during years of both sunspot minimum (1964) and of higher magnetic activity (1967), Pi 2 occurs most frequently during intervals when 1+ ≤ Kp ≤ 2-.

CHAPTER III

DISCUSSION OF THE RESULTS

a. Pi 2 and Magnetospheric Subregions

The results of the investigation presented in section II.a and depicted in Figure 1 show an agreement between the 'plasma sheet inner boundary' curve and the data from direct observations. All of the five subregion boundary crossings corresponding to Pi 2 periods longer than about 75 seconds were detected with a sudden cutoff in ELF emission strength and accordingly assumed to identify the plasma sheet inner boundary. In the case corresponding to the Pi 2 period of 95 seconds (December 6th event), a LHR breakup was observed simultaneously. All of these five crossings were identified when the satellite was on the nightside of the earth and at invariant latitudes not lower than 63.6°, viz., $L \geq 5.06$. The local times as well as the larger L values indicate that ELF emissions in these cases may be a type of auroral zone VLF hiss. ELF hiss and chorus, which are often concurrent, take place mostly on the dayside, and at latitudes lower than those at which auroral zone VLF hiss is observed. Although dayside VLF hiss occurs in the polar cusp region, nightside auroral zone VLF hiss is also observed.

VLF hiss was observed at the auroral zone, near and on the poleward side of the 'trapping boundary' for energetic electrons ($E \gtrsim 45$ kev), in latitude range of about 7° (Gurnett and Frank, 1972). Frank (1971) found that the 'trapping boundary' is beyond the outer boundary of the earthward edge of the plasma sheet. In case that the 'trapping boundary' is beyond the outer boundary of the edge, it is within a range of about 1 Re from the outer boundary of the edge. The earthward edge is a 'microscopic' view of the inner boundary of the plasma sheet. Frank found that the plasma sheet inner boundary, or edge, has a finite width, 1 to 2 Re, within which the average energy of electrons in the range 80 ev $\leq E \leq$ 46 kev decreases exponentially with decreasing distance. These pieces of information relate auroral zone VLF hiss, the 'trapping boundary' and the plasma sheet inner boundary to one another. They indicate that the 'trapping boundary' as well as the plasma sheet inner boundary can be approximately located through observation of a sudden cutoff in auroral zone VLF hiss activity on the lower latitude side.

The evidence that Saito et al. (1970) presented to prove their plasma sheet theory was that the latitude of maximum Pi 2 amplitude maps along the field line to the equatorial plane near the plasma sheet inner boundary. The mapping was done based on a certain model of the average magnetic field configuration of the outer magnetosphere

(Fairfield, 1968). The latitude of maximum Pi 2 amplitude was determined from observations at eight stations distributed over a range of geomagnetic latitude from 40.4° to 73.8°. Two Pi 2 events for time intervals having different Kp values were chosen and for each event the latitude of maximum amplitude was determined. It was then mapped to a point on the equatorial plane which was found to be near the position of the plasma sheet inner boundary, inferred from the equation II.a(3). The approach of Saito et al. was indirect, since it depends on the inferred inner boundary location. In this respect, the investigation presented here is a direct observation of the expected Pi 2 variation in period with a magnetospheric subregion, viz., the plasma sheet inner boundary. The results presented in this thesis indirectly suggest that the region of Pi 2 generation, during times of magnetic quiescence, is found near the plasma sheet inner boundary. During times of higher Kp, the Pi 2 period variation with subregion boundaries is less discernable. These ambiguous results are in agreement with the observed coincidence in location of magnetospheric subregions during times of higher magnetic activity (Frank, 1971). One method of establishing a more direct association of Pi 2 with the plasma sheet inner boundary might be to determine the latitude of maximum Pi 2 amplitude while simultaneously observing the location of the inner boundary.

b. Pi 2 Source

From sections II.b and c, it was shown that Pi 2 occur most frequently around 2230 LMT, east (west) of which their initial orientation is primarily north-west (north-east). These results and also those of section II.a imply that the Pi 2 source must lie on auroral zone field lines centered about the 2230 LMT meridian. A theory of night-time plasma implosion may account for the initial movements (Smith and Watanabe, 1972). Two theories of implosion processes have been suggested (Atkinson, 1966; Kato, 1971). Atkinson's theory assumes that intermittent field line reconnection takes place. This gives rise to an implosion of tail plasmas towards the region of closed magnetic lines of force. The implosion should cause the observed initial northward impulse. The initial eastward and westward movements may be aided by the motion of the imploding convecting tail plasmas as they separate to flow about the closed field lines. This convective 'flow separation' has been suggested by superposing the magnetospheric convective and co-rotating potential fields (Axford and Hines, 1961; Nishida, 1966; Brice, 1967). The most effective impact of the imploding plasmas might be at this nightside 'flow separation' point which could explain the diurnal variation in the Pi 2 occurrence frequency.

As mentioned in section I.d, the mechanism proposed by Kato calls for an hm burst impacting the field in the vicinity of the inner boundary of the partial ring currents. Such an inward burst requires a sudden disruption of partial ring currents in the dusk to midnight quadrant, as observed by the abrupt field recovery at ATS 1 (Cummings et al., 1968). The ring current weakens the magnetic field inside the current site and enhances it outside. From a point of hydromagnetics, the ring current carries away some magnetospheric plasmas and frozen-in field lines from the inner region to the outer region across the current site. A sudden partial ring current disruption is expected to let the carried away field lines move back to their normal positions, giving rise to a plasma implosion. These field lines are concentrated about the 2230 LMT meridian. When implosion occurs, the initial movement of the field lines immediately east (west) of this meridian must move inward and veer eastward (westward). This east and west veering is likely determined by Maxwell stress which the implosion exerts upon the field lines, spreading away from 2230 LMT meridian. Field lines far away from the activity centre should move almost radially inward.

c. Pi 2 Source Variations

From the results presented in the Pi 2 source variation study of section II.c, it is seen that the flow direction and pressure of solar wind protons and the most probable local time of Pi 2 occurrence during low magnetic activity are different from those during high activity. It is possible that the local time at which Pi 2 occurs most frequently is dependent upon the solar wind direction. That is, the solar wind streaming direction may determine the direction of the earthward convecting, tail plasma flow which could possibly affect the meridians of peak intensity partial ring currents. Indeed, Cummings (1966) suggested the partial ring currents are formed by the inward convection of charged particles near the midnight meridian. Yet, from low to high magnetic activity, the peak streaming angle changes by only 23°. This corresponds to only about 1 hour thirty minutes while the westward shift in peak Pi 2 occurrence is about 3 hours. Thus the streaming angle change may not fully account for the peak Pi 2 time shift. Processes associated with the increased solar wind streaming pressure during high magnetic activity might give rise to the intense, partial ring currents. This increased plasma density, in the dusk to midnight quadrant, could also account for the westward shift in the peak time of Pi 2 occurrence. Thus, the results of this study display the 'dynamic' behaviour of the Pi 2 source which appears dependent upon the solar wind.

The meridian of Pi 2 generation then, is closely associated with the earthward convecting plasmas in the magnetotail. This meridian has been considered to indicate the 'flow separation' point of the inward convecting tail plasmas and/or the peak intensity of the partial ring currents. In view of this discussion (and the one in section III.b), sketches are presented of the streamline pattern in the equatorial plane of the magnetosphere during low and high magnetic activities. Figures 9 and 10 depict the results of this investigation, showing the solar wind direction and peak Pi 2 occurrence time ('flow separation' point) during low and during high magnetic activities, respectively. The plasmapause behaviour was reported by Carpenter (1970) and Chappell et al. (1970). The partial ring current belts were drawn from the information suggested by Frank (1967) and Coleman et al. (1971).

d. On the Pi 2 Rate of Occurrence

The finding (section II.d) that Pi 2 occur most frequently during intervals when the Kp is between 1+ and

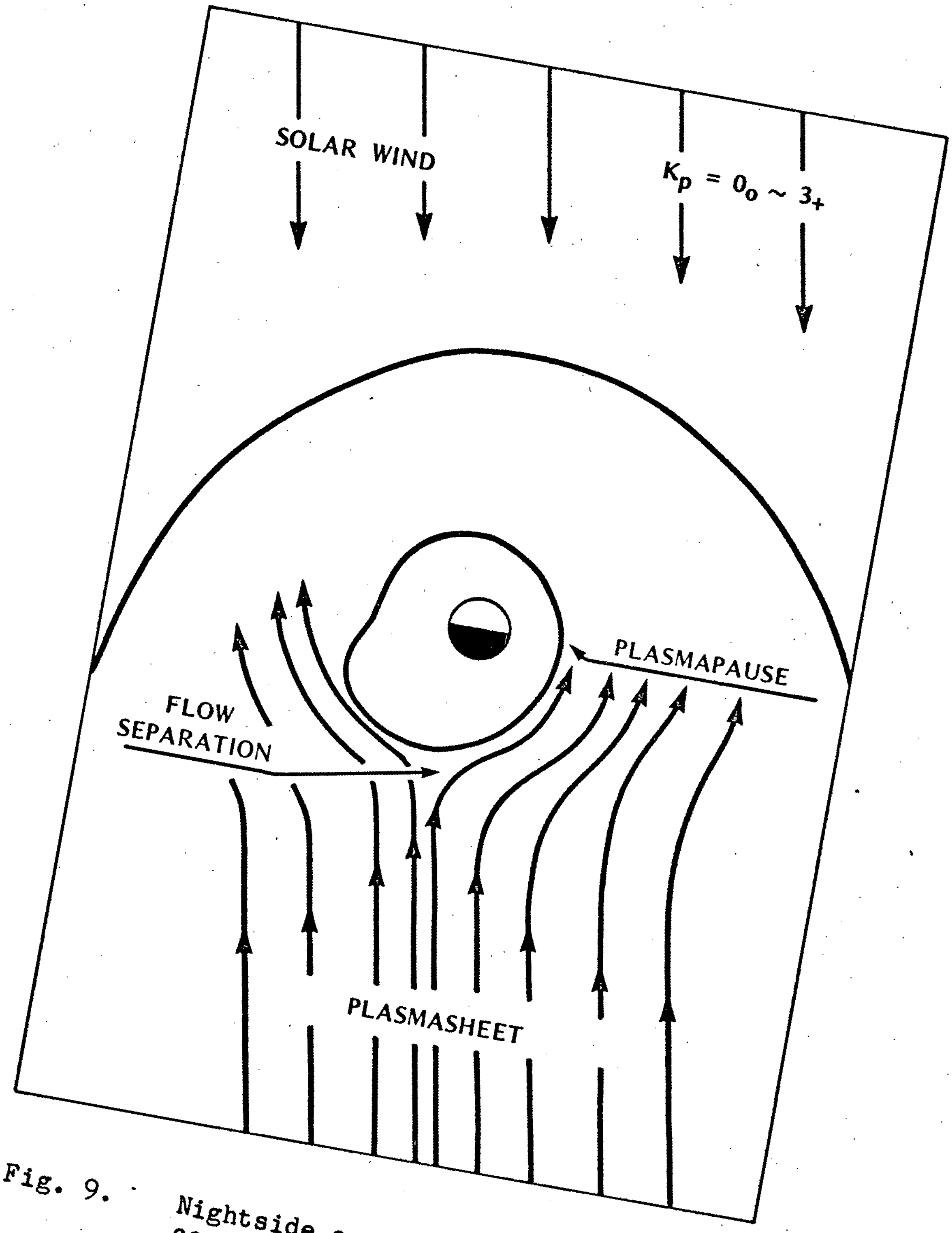

Fig. 9. Nightside equatorial magnetospheric convective system, near the plasmapause, during low magnetic activity

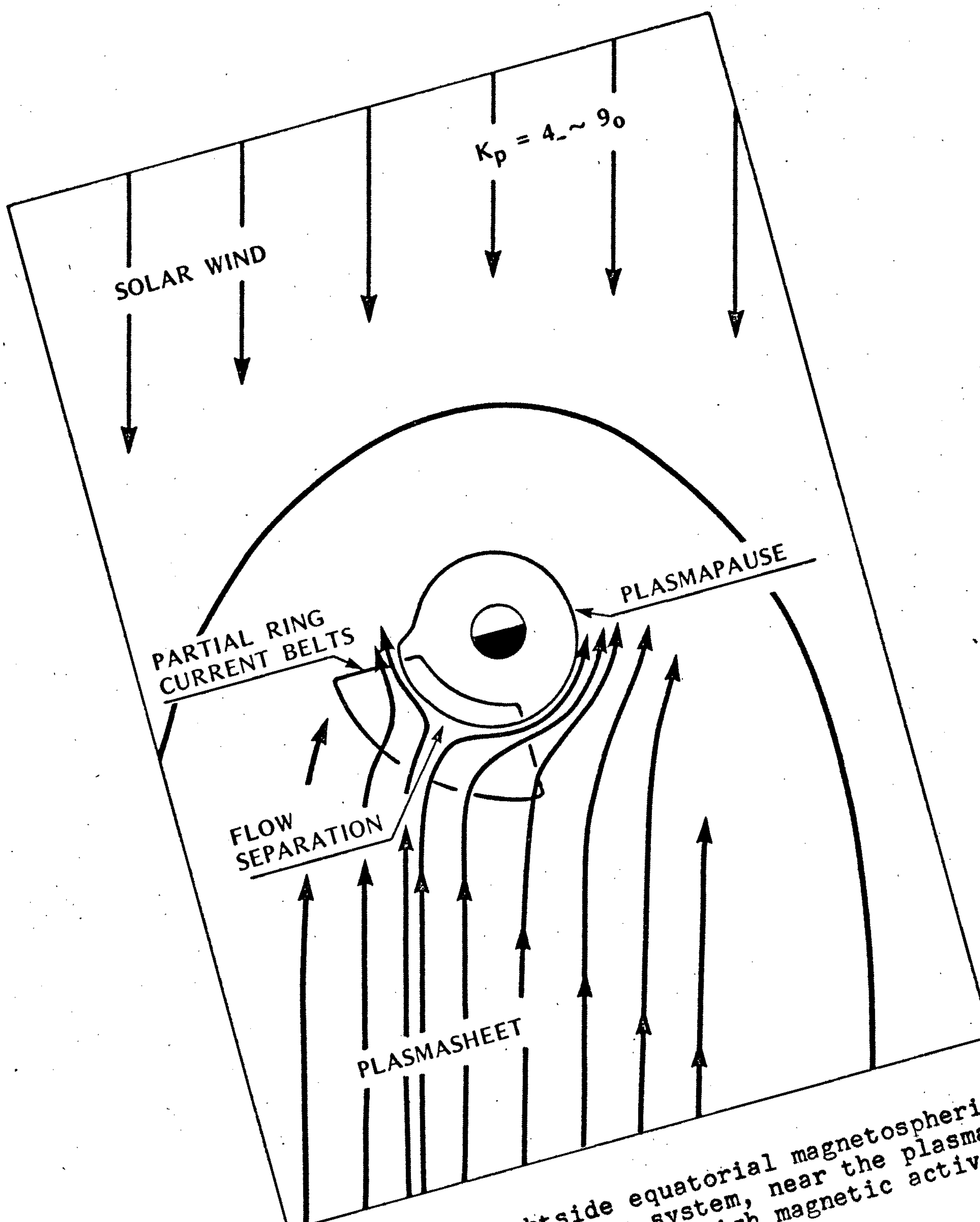

Fig. 10. Nightside equatorial magnetospheric convective system, near the plasma-pause, during high magnetic activity

2-, is unexpected. Although this result contradicts the observations of previous investigators, it is felt to be 'statistically' significant, due to the large amount of data used. A direct consequence of this finding is that the yearly occurrence frequency of Pi 2 should reach maximum when the average Kp index most closely approaches optimum level (1+ ≤ Kp ≤ 2-). This would be during sunspot minimum, in agreement with the observations by Yanagihara (1956). A further consequence of this result is that the peak time of Pi 2 occurrence should not shift during the sunspot cycle. Yet such a shift has been observed (Afanasieva, 1961; Saito et al., 1968). It may be that further investigation is necessary in order to establish whether a systematic change exists (or should be expected) in the Pi 2 peak time of occurrence during the solar cycle.

CHAPTER IV

SUMMARY AND CONCLUDING REMARKS

The investigations presented in this thesis have shown that Pi 2 micropulsations do reflect the nature of their source. This source is in the auroral zone centered near the 2230 LMT meridian, as indicated by Pi 2 occurrence and initial orientation studies. The actual source meridian is 'dynamic' in the sense that it shifts with changes in magnetic activity. Furthermore, the Pi 2 period variation with the location of the plasma sheet inner boundary implies the association of the Pi 2 source with a magnetospheric subregion, and also with the earthward convecting plasmas in the magnetotail. The 'dynamic' source is also dependent upon the solar wind, as evidenced by the correlated studies of solar wind and source variations with magnetic activity. Lastly, as suggested in sections I.b and d regarding period morphology and nonsimilar latitudinal variations of Pi 2 and bay amplitude, Pi 2 are not always directly associated with magnetic activity (Kp) and/or magnetic storms (ssc and bays). The relationship is more complicated, as is seen in the Pi 2 rate of occurrence study. In summation, the Pi 2 phenomenon appears as a complex problem involving the solar wind, magnetospheric subregions and ionospheric conditions. The author feels that this thesis presents some evidence that Pi 2 micropulsations can provide information on the states of the solar wind, magnetosphere and ionosphere.

It was suggested that Pi 2 may be explained by a nightside plasma implosion process near the closed field line boundary and/or the ring current. Two theories regarding implosion have been presented (Atkinson, 1966; Kato, 1971), as to which theory is the more likely, it is difficult to decide. Indeed, it is possible that the two mechanisms each generate Pi 2, and in this sense, they may be regarded as of a complementary nature. Atkinson's theory associated Pi 2 with geomagnetic bay disturbances. Yet many Pi 2's not related to this magnetic activity have been observed (Romaña et al., 1968). These non-related Pi 2's could be due to partial ring current disruptions required by Kato's theory.

The Pi 2 plasma implosion theory and also the theory of Pi 2's as propagating ionospheric disturbances, discussed by Jacobs (1970), each explain much of the observed morphology. An objection to Pi 2 as the effect of a current system was that occassional clockwise rotations are observed when the polarization is usually counter-clockwise. Yet, Pi 2 polarization may be due to inward moving field lines which are veered eastward by the skewed position of the plasmasphere bulge (Smith and Watanabe, 1972). This motion is depicted in Figure 11.

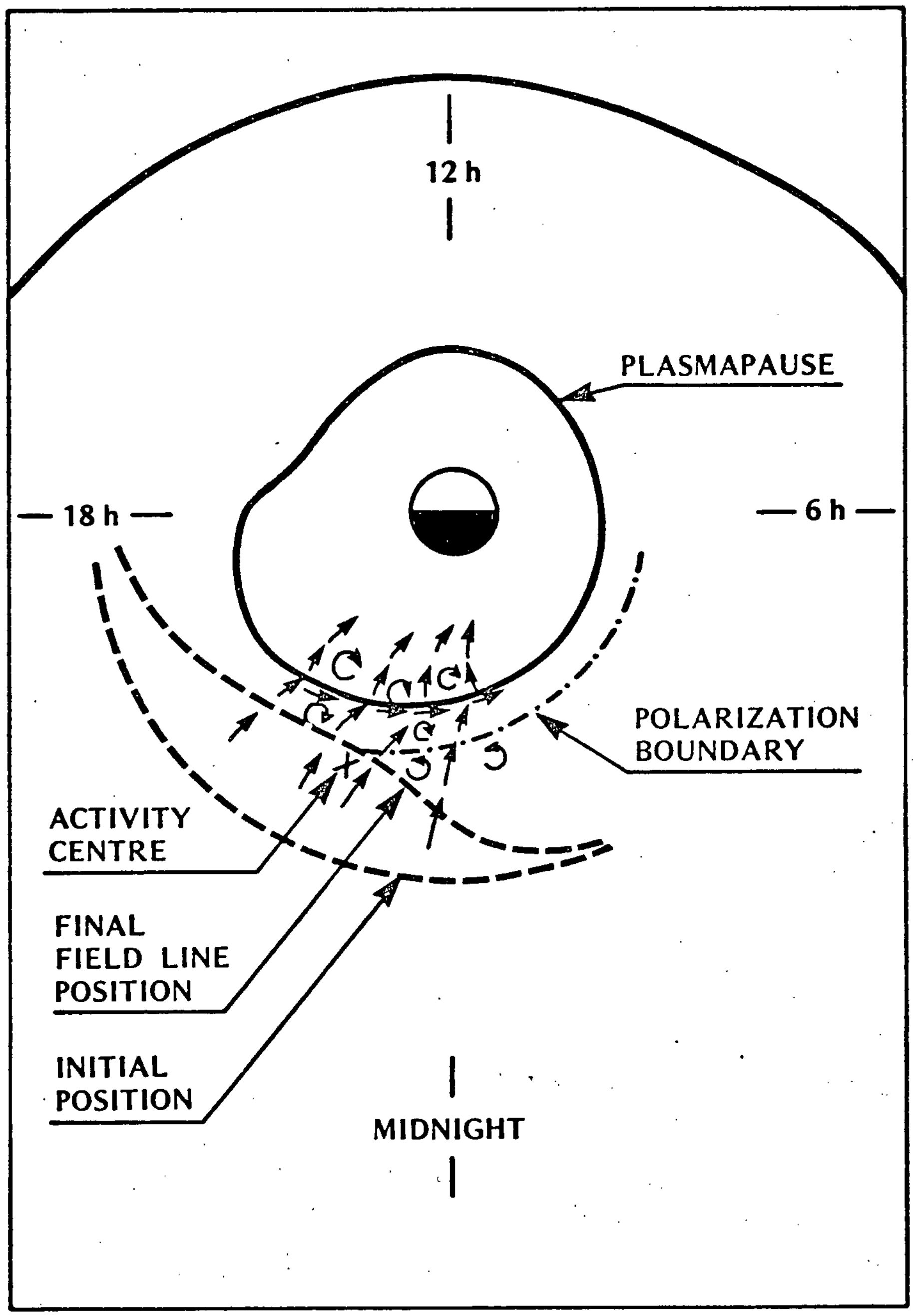

Fig. 11. Motion of magnetospheric plasmas due to an implosion (Smith and Watanabe, 1972)

In such a situation, the polarization at meridians near the abrupt westward edge of this bulge may occassionally be observed as clockwise (in the northern hemisphere). Another objection to Pi 2's due to a current system was that latitudinal variation of bay magnitude is not always the same as that of the amplitude of Pi 2 (Saito et al., 1968). Yet Akasofu, Chapman and Meng (1965) proposed a model current system for an intense polar magnetic storm which showed peak intensities in the midnight to dawn quadrant. Thus, observation of occassional dissimilarities between Pi 2 (occurring near 2230 LMT) and the magnetic bay should be expected on the basis that the activity centres may not be coincident.

BIBLIOGRAPHY

Afanasieva, V. I., Short period oscillations of the geomagnetic field, IAGU Bull., 16C, 48, 1961.

Akasofu, S. -I., S. Chapman and C. -I. Meng, The polar electrojet, J. Atmos. Terr. Phys., 27, 1275, 1965.

Angenheister, G., Ueber die Fortpflanzungs - Geschwindigkeit magnetischer Storungen und Pulsationen. Berecht uber die erdmagnetischen Schnellregistrierungen in Apia (Samoa), Batavia, Cheltenham, und Tsingtau in September 1911. Gottingen Nachr. Ges. Wiss., 565, 1913.

Angerami, J. J. and D. L. Carpenter, Whistler studies of the plasmapause in the magnetosphere, 2, Electron density and total tube electron content near the knee in magnetospheric ionization, J. Geophys. Res., 71, 711, 1966.

Atkinson, G., A theory of polar substorms, J. Geophys. Res., 71, 5157, 1966.

Axford, W. I. and C. O. Hines, A unifying theory of high-latitude geophysical phenomena and geomagnetic storms, Can. J. Phys., 39, 1433, 1961.

Axford, W. I., H. E. Petschek and G. L. Siscoe, Tail of the magnetosphere, J. Geophys. Res., 70, 1231, 1965.

Bame, S., Plasmasheet and adjacent regions, in Earth's Particles and Fields (Ed. B. M. McCormac), p. 373. Reinhold Book Corp., New York, 1968.

Binsack, J. H., Plasmapause observations with the M.I.T. experiment on Imp 2, J. Geophys. Res., 72, 5231, 1967.

Brice, N. M., Bulk motion of the magnetosphere, J. Geophys. Res., 72, 5193, 1967.

Cahill, L. J. and P. G. Amazeen, The boundary of the geomagnetic field, J. Geophys. Res., 68, 1835, 1963.

Campbell, W. H. and Rees, M. H., A study of auroral coruscations, J. Geophys. Res., 66, 41, 1961.

Carpenter, D. L., Whistler studies of the plasmapause in the magnetosphere, 1, Temporal variations in the position of the knee and some evidence on plasma motions near the knee, J. Geophys. Res., 71, 693, 1966.

Carpenter, D. L., Whistler evidence of the dynamic behaviour of the duskside bulge in the plasmapause, J. Geophys. Res., 75, 3837, 1970.

Carpenter, D. L., and K. Stone, Direct detection by a whistler method of the magnetospheric electric field associated with a polar substorm, Planet. Space Sci., 15, 395, 1967.

Carpenter, D. L., F. Walter, R. E. Barrington and D. J. McEwen, Alouette 1 and 2 observations of abrupt changes in whistler rate and of VLF noise variations at the plasmapause; a satellite-ground study, J. Geophys. Res., 73, 2929, 1968.

Channon, M. J. and D. Orr, A study of equatorial geomagnetic micropulsations, Planet. Space Sci., 18, 229, 1970.

Chappell, C. R., K. K. Harris and G. W. Sharp, The morphology of the bulge region of the plasmasphere, J. Geophys. Res., 75, 3848, 1970.

Christoffel, A. D. and J. G. Linford, Diurnal properties of the horizontal geomagnetic micropulsation field in New Zealand, J. Geophys. Res., 71, 891, 1966.

Coleman, P. J. and W. D. Cummings, Stormtime disturbance field at ATS 1, J. Geophys. Res., 76, 51, 1971.

Cummings, W. D., Asymmetric ring currents and the low latitude disturbance daily variation, J. Geophys. Res., 71, 4495, 1966.

Cummings, W. D., J. N. Barfield and P. J. Coleman, Magnetospheric substorms observed at the synchronous orbit, J. Geophys. Res., 73, 6687, 1968.

Dungey, J. H., Interplanetary magnetic field and the auroral zones, Phys. Rev. Letters, 6, 47, 1961.

Dungey, J. W., The interplanetary field and auroral theory, J. Phys. Soc. Japan, 17, Suppl. A2, 15, 1962.

Dungey, J. W., Theory of the quiet magnetosphere, in Solar-Terrestrial Physics (Ed. J. W. King and W. S. Newman), p. 91. Academic Press, New York, 1967.

Frank, L. A., On the extraterrestrial ring current during geomagnetic storms, J. Geophys. Res., 72, 3753, 1967.

Frank, L. A., Direct detection of asymmetric increases of extra-terrestrial ring current proton instabilities in the outer radiation zone, J. Geophys. Res., 75, 1263, 1970.

Frank, L. A., Relationship of the plasma sheet, ring current, trapping boundary and plasmapause near the magnetic equator and local midnight, J. Geophys. Res., 76, 2265, 1971.

Frank, L. A., and H. P. Owens, Omnidirectional intensity contours of low-energy protons (0.5 - E - 50 kev) in the earth's outer radiation zone at the magnetic equator, J. Geophys. Res., 75, 1269, 1970.

Fukunishi, H. and T. Hirasawa, Progressive change in Pi 2 power spectra with the development of magnetospheric substorm, Rep. Ionos. Space Res. Japan, 24, 45, 1970.

Grenet, G., Y. Kato, J. Osaka and M. Okuda, Pulsations in terrestrial magnetic field at the time of bay disturbance, Sci. Rep. Tohoku Univ., Ser. 5, Geophys., 6, 1, 1954.

Gurnett, D. A. and L. A. Frank, VLF hiss and related plasma observations in the polar magnetosphere, J. Geophys. Res., 77, 172, 1972.

Heacock, R. R., A. J. Mullen, V. P. Hessler, C. Sucksdorff, M. Kivinen and E. Kataja, Correlations of OGO-V plasmapause crossing with observations of type Pi micropulsations on the ground, Ann. Geophys., 27, 477, 1971.

Herron, T. J., Phase characteristics of geomagnetic micropulsations, J. Geophys. Res., 71, 871, 1966.

Hirasawa, T. and T. Nagata, Spectral analysis of geomagnetic pulsations from 0.5 to 100 sec. period for the quiet sun condition, Pure and Appl. Geophys., 65, 102, 1966.

Hoffman, R. A. and L. J. Cahill, Ring current particle distributions derived from ring current magnetic field measurements, J. Geophys. Res., 73, 6711, 1968.

Hones, E. W., J. R. Asbridge and S. J. Bame, Time variations of the magnetotail plasmasheet at 18 Re determined from concurrent observations by a pair of Vela satellites, J. Geophys. Res., 76, 4402, 1971.

Jacobs, J. A., Geomagnetic Micropulsations, Springer-Verlag, New York, 1970.

Jacobs, J. A. and K. Sinno, World-wide characteristics of geomagnetic micropulsations. Geophys. J., 3, 333, 1960.

Kannangara, M. L. and P. C. Fernando, Nighttime equatorial Pi 2 micropulsations, J. Geophys. Res., 74, 844, 1969.

Kato, Y., Frequency analysis of geomagnetic micropulsations associated with ssc and Pi 2, Sci. Rep. Tohoku Univ., Ser. 5, Geophys., 21, 37, 1971.

Kato, Y., J. Ossaka, T. Watanabe, M. Okuda and T. Tamao, Investigation on the magnetic disturbance by the induction magnetograph, Pt. V, On the rapid pulsation psc, Sci. Rep. Tohoku Univ., Ser. 5, Geophys., 7, 136, 1956.

Milton, D. W., R. L. McPherron, K. A. Anderson and S. H. Ward, Direct correspondence between x-ray microbursts and impulsive micropulsations, J. Geophys. Res., 72, 414, 1967.

Ness, N. F., The earth's magnetic tail, J. Geophys. Res. 70, 2989, 1965.

Nishida, A., Formation of plasmapause, or magnetospheric plasma knee by combined action of magnetospheric convection and plasma escape from tail, J. Geophys. Res., 71, 5669, 1966.

Obayashi, T. and J. A. Jacobs, Geomagnetic pulsations and the earth's outer atmosphere, Geophys. J., 1, 53, 1958.

Oglivie, K. W. and L. F. Burgala, Hydromagnetic observations in the solar wind, in Particles and Fields in the Magnetosphere, 82, Reidel Publishing Co., Dordrecht, Holland, 1970.

Oglivie, K. W., N. McIlwraith and T. D. Wilkerson, A mass-energy spectrometer for space plasmas, Rev. Sci. Instr., 39, 441, 1968.

Romaña, A. and D. Van Sabben, Geomagnetic data 1967 rapid variations, IAGA Bull., 12v2, 1970.

Romaña, A. and J. Veldkamp, Geomagnetic data 1964 rapid variations, IAGU Bull., 12s2, 1968.

Rostoker, G., The polarization characteristics of Pi 2 micropulsations and their relation to the determination of possible source mechanisms for the production of nighttime impulsive micropulsation activity. Can. J. Phys., 45, 1319, 1967a.

Rostoker, G., The frequency spectrum of Pi 2 micropulsation activity and its relationship to planetary magnetic activity, J. Geophys. Res., 72, 2032, 1967b.

Rycroft, M. J. and J. O. Thomas, The magnetospheric plasmapause and the electron density trough at the Alouette I orbit, Planet. Space Sci., 18, 65, 1970.

Saito, T., Oscillation of geomagnetic field with the progress of pt-type pulsation, Sci. Rep. Tohoku Univ., Ser. 5, Geophys., 13, 53, 1961.

Saito, T. and S. Matsushita, Solar cycle effects on geomagnetic Pi 2 pulsations, J. Geophys. Res., 73, 267, 1968.

Saito, T. and T. Sakurai, Mechanism of geomagnetic Pi 2 pulsations in magnetically quiet condition, Sci. Rep. Tohoku Univ., Ser. 5, Geophys., 13, 53, 1970.

Sakurai, T., Polarization characteristics of geomagnetic Pi 2 micropulsations, Sci. Rep. Tohoku Univ., Ser 5, Geophys., 20, 107, 1970.

Schield, M. A., Pressure balance between solar wind and magnetosphere, J. Geophys. Res., 74, 1275, 1969.

Smith, B.P. and T. Watanabe, On the origin and polarization of nighttime irregular micropulsations, Pi 2, Planet. Space Sci., (submitted for publication), 1972.

Terada, T., On rapid periodic variations of terrestrial magnetism, J. College Sci., Imperial Univ. Tokyo, May 25th, XXV ii, Art. 9, 1917.

Troitskaya, V. A., Micropulsations and the state of the magnetosphere, in Solar Terrestrial Physics (Ed. J. W. King and W. S. Newman), p. 213, Academic Press, New York, 1967.

Yanagihara, K., On the correlation between the frequency of the earth current pulsation and the solar activity, Mem. Kakioka Mag. Obs., 7, 27, 1956.

Yanagihara, K., Earth current pulsations observed at Kakioka, Mem. Kakioka Mag. Obs., 8, 49, 1957a.

Yanagihara, K., Frequency of pulsation and geomagnetic activity, Mem. Kakioka Mag. Obs., 8, 61, 1957b.

Yanagihara, K., Geomagnetic pulsations in middle latitudes - Morphology and its interpretation, Mem. Kakioka Mag. Obs., 9, 15, 1960.

Vasyliunas, V. M., A survey of low-energy electrons in the evening sector of the magnetosphere with OGO1 and OGO 3, J. Geophys. Res., 73, 2839, 1968.