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Pi's observed in the daylight hemisphere at low latitudes

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Abstract—By comparing recordings made at Pamatai, Tahiti, with those from the magnetometer array operated by the Institute of Geological Sciences, it is observed that Pi's occur at low latitudes on the dayside of the Earth coincidentally with Pi2's recorded (and thought to be generated) near the local midnight sector. The low-latitude daytime Pi's have different spectral components to the corresponding nighttime events and do not show a preferred local time of occurrence. There does not appear to be any large or systematic difference in the arrival of day- and nighttime events. In view of the discrepancies which remain in the understanding of the generation of nighttime Pi2's at mid- and high-latitudes it is not yet possible to place these observations within a context of reasonable interpretation. It is shown that the existence of daytime Pi's in a narrow belt around the equator is an important fact which must be considered in any overall description of the generation and transmission processes resulting from transient phenomena within, or acting upon, the magnetosphere.

INTRODUCTION

Statistical results of a study of the occurrence of Pi2's identified during the nighttime in mid-latitudes at the array of magnetometer stations operated by the Institute of Geological Sciences (I.G.S.) and simultaneous magnetic field response observed at Pamatai Observatory, Tahiti are presented. Pamatai (Geog. co-ords 17.34'S, 210°25'E, Geomag. co-ords 15.3°, 282.7°) is a low latitude station which is in the noon-early afternoon sector when most of the I.G.S. magnetometers are in the local time sector of Pi2 generation. The local time of Pamatai is UT − 10 h. The results presented are rudimentary in that a large carefully selected statistical sample was not available, but are sufficiently clear to justify presentation without more elaborate examination at this stage.

Instrumental differences restrict the degree to which the recordings can be compared. The I.G.S. magnetometers (STUART, 1971; RIDDICK *et al.*, 1975) record magnetic field variations digitally in a band which is flat from 5 s period to d.c., while at Pamatai the pulsation recordings are of the rate of change of the field and are made by a modified bar fluxmeter (SELZER, 1957). The bar fluxmeter has a nonlinear response which is band limited between 10 and 160 s. Magnetic field variation within this period range is recorded on paper charts with a sensitivity of about 0.06 nT per mm at 60 s periods. The chart speed is 6 mm per minute. It is therefore not possible, without a prohibitively large computational load, to make detailed comparisons of waveforms using the two types of records, and only superficial features are considered here.

In the discussion which follows use of the expression 'Pi2' is made with reference to events which occur during local night (approximately 2000–0400 LT). 'Pi' is used more generally to denote relatively isolated packets of geomagnetic oscillation in the period range 20–150 s, in particular those which occur during local daylight hours. The expressions, and the pulsations they represent, conform to the accepted convention (JACOBS *et al.*, 1964) but may be taken to exclude events where a high degree of irregularity is apparent.

For each event which was examined the appropriate values of *AE*, *Dst*, *K* and K_p were noted and tested for systematic relationship to the coincidence or otherwise of day and nighttime events.

ORR and BARSCZUS (1969) discuss Pi2's observed simultaneously at two stations in Africa at a similar latitude to Pamatai separated by 50° in longitude. They show that the local time dependence is very much the same as that usually found at mid-latitudes, i.e. distributed ±3 h about 2300 LT (STUART, 1972). STUART and HUNTER (1975) show examples of mid-latitude Pi2's observed with very little modification near the dip equator on the same longitude. The periods were the same at mid-latitude and equator, and covered the full range of Pi2's (i.e. 40–150 s). Amplitudes in the *H* component were comparable. There is, therefore, evidence that the general nighttime morphology of Pi2 occurrence is the same at mid-latitudes and near the equator.

Both CAMPBELL (1967) and JACOBS (1970) refer to Pi2's being observed around the globe without specific reference to published work. YANAGIHARA and SHIMIZU (1966) found that of 112 Pi2's observed at Fredericksburg during the night, 74 could be identified at Koror and Guam, equatorial stations about 135° to the west (i.e. approximately 9 h later in local time). They showed that when Pi's are observed during the daytime their amplitude near the dip equator is enhanced by a factor of between 2 and 5 relative to Kakioka, on the same longitude but at 26°N. This amplitude enhancement was not evident in local nighttime Pi2's. JAMET *et al.* (1969) investigated the coincidence of Pi2's at Chambon-la-Foret, Pastor (East Africa) and Pamatai. They observed that some nighttime Pi's were observable in the daylight side of the earth, preferentially at low latitudes. Both the above papers acknowledge that Pi2's are generated primarily during nighttime and, without explicit justification, conclude that the transmission process from night- to dayside is in the ionosphere, probably related to enhanced equatorial conductivity.

Previous research points to the location of the source of Pi2's being in the midnight sector (see, for example, RASPOPOV, 1968; STUART, 1972, OLSON and ROSTOKER, 1977; KUWASHIMA, 1978,

remain considerable uncertainties about which processes apply in fact. The spatial variation of Pi2 waveform is complex and an extensive observational study is still necessary to permit unambiguous interpretation to be made of the latitudinal and longitudinal variations which are observed.

At high latitudes Pi2's have been shown to have close association with polar magnetic substorms, the formation and sudden brightening of auroral arcs, enhancements of the auroral electrojet and intensification of X-ray and energetic particle precipitation. In quiet magnetic conditions the period of Pi2's is constant over a large area in the midnight sector. In more disturbed conditions, Pi2's recorded at high-latitudes become much greater in amplitude (by an order of magnitude) and more irregular in waveform, containing a greater number of frequency components. The increase in irregularity and spectral complexity occurs at mid-latitudes, but to a markedly lower degree. SAITO (1969) presents an early review of these facts and concludes that no single generation process is sufficient, even in broad principle, to explain the global morphology of Pi2's satisfactorily. He indicates that the primary event which causes Pi2's occurs in the magnetotail region on those field lines which map down to the auroral zone. He summarizes the several hydromagnetic possibilities as "substorm triggered plasma instabilities" and proposes that they are responsible for high-latitude Pi2's, but adds that leakage of ionospheric currents caused by the screening effect of the ionosphere to signals of recording site. However, STUART (1979) shows examples where it is clear that different spectral components of Pi2's recorded at mid-latitudes do not arrive coincidentally at all ground stations. Work in progress at I.G.S. into the spatial structure of Pi2 waveforms brings out clearly the fact that variations in the waveforms of Pi2's at stations separated by less than 500 km are due in part to different arrival time and phase of the individual spectral components.

FUKUNISHI and HIRASAWA (1970) summarise global features of Pi2's and argue that although it seems certain that the primary source of Pi2's is on high-latitude field lines their low-latitude morphology demands additional processes. They suggest that energy is transmitted hydromagnetically to the plasmapause where the sharp radial density gradient of the cold plasma allows it to couple to the field lines there creating surface waves. CHANG and LANZEROTTI (1975) describe a similar process where inward flow of hot plasma which has an unstable velocity distribution results from magnetic field reconnection in the tail and produces magnetoacoustic waves in the cold magnetospheric plasma. They suggest that this may be the primary Pi2 generation process and show that it can result in shear Alfven waves on the last closed field lines of the nightside magnetosphere, by virtue of the plasma gradient at the inner edge of the plasmasheet, or at the plasmapause. Because of the broad bandwidth of the magnetoacoustic disturbance it could stimulate several secondary processes to explain the multiple resonances noted by many authors. The theory of localised field line resonance developed by SOUTHWOOD (1974) and CHEN and HASEGAWA (1974a, b) favours the excitation of Alfven modes, but shows that surface wave eigenmodes may become important in regions where there is a sharp change in density.

OLSON and ROSTOKER (1977) demonstrate very close association, within the zone of auroral activity, between Pi2's and the position of the poleward border of the auroral electrojet. On the basis of spectral structure in relation to latitude they conclude that resonance of auroral zone field lines does not take place in high-latitude Pi2's, and note that a significant proportion of the high-latitude signal must originate in the overhead ionospheric current system (supporting ROSTOKER's earlier view regarding ionospheric transmission). WILHELM *et al.* (1977) concluded that although most Pi2's could be regarded as being due to field line oscillation a substantial number showed spatial variations of coherence near the auroral zone which could best be interpreted as the effect of varying field aligned sheet currents.

KUWASHIMA (1975) concludes that in the auroral zone, Pi2's consist of two parts, an irregular burst which is localised and closely dependent in its character on other related transient phenomena occurring locally, together with a more regular wave which corresponds to the widespread Pi2 observed at mid- and low-latitudes. He considers that the power distribution found in Pi2's cannot be derived from the observed current pattern and argues in favour of forced vibrations or surface waves on auroral field lines being the principal mechanism for Pi2 generation.

Work by Saito and co-workers (e.g. SAITO *et al.*, 1976) on the relationship between low latitude Pi2's and substorms underlines the global aspects of Pi2 occurrence and hints at a single common cause. This cause may be an external trigger action originating in the interplanetary medium, or it may be stepwise relaxation of the magnetosphere from its constantly stressed state of dynamic equilibrium. Clearly the trigger action, if it exists, and the actual processes by which the Pi2 waveform is generated and transmitted within the magnetosphere are far from being identified.

Measurements of propagation of Pi2's relative to the Earth's surface are similarly inconclusive. HERRON (1966) used total field recordings and found that Pi2's propagate away from the midnight sector with an apparent phase velocity of about 50 km s^{-1}. MIER-JEDRZEJOWICZ and SOUTHWOOD (1979) studying hourly sections of data found a predominantly Westward propagation throughout the night with an apparent velocity of 100 km s^{-1} for the frequency band corresponds to Pi2's. Work in progress at I.G.S. using discrete Pi2's (STUART and GREEN, in preparation) finds similar equivalent velocities but demonstrates spatial structure in the direction of motion of the waves. The apparent contradictions are due in part to the methods of data selection and analysis, but mainly to the fact that localising effects dominate the wave generation process. These produce E–W spatial phase patterns which do not represent true wave propagation. The E–W patterns are analogous to the N–S phase variations described by CHEN and HASEGAWA (1974a) and SOUTHWOOD (1974) for field line resonance. Meridional stationary phase patterns have been observed in Pi2 studies at mid-latitude (FUKUNISHI, 1975; BEAMISH *et al.*, 1979; STUART *et al.*, 1979) and have been shown to agree closely with theoretical predictions for shear Alfven mode resonance. Fukunishi presents evidence associating the resonance with the plasmapause while Stuart suggests a more complex situation. All three sets of authors infer that the source energy is propagating Westward.

Thus, although there is now sufficiently close agreement between theory and observation to say that the primary action in Pi2 generation travels from North to South and that it may be predominantly Westward, it is not possible to indicate its real velocity in either direction. Nor has any transmission velocity which might derive from a secondary process of Pi2 generation been identified and verified.

2. OBSERVATIONS

Lists of the dates and times of pulsation events which were either notable or had been used in specific analytical programmes were published in IMS Newsletter (78–3) (ALLEN, 1978) by I.G.S. as part of its contribution to international data exchange. It is from one of these lists that a comparison is made of Pi2 activity observed at the U.K. in the midnight local time sector with similar events identified simultaneously on the dayside of the

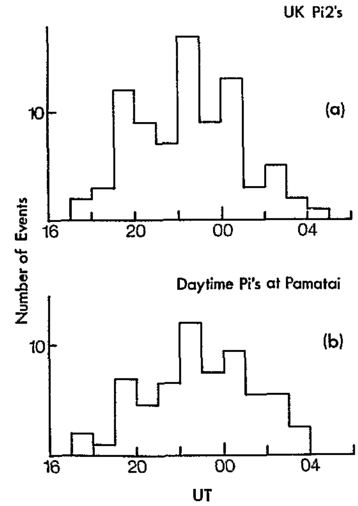


Fig. 1. Distribution of events in UT for the period 22 February 27–April 1976 (a) Pi2's recorded in the U.K. (b) daytime Pi's observable at Pamatai simultaneously with the U.K. events. Events at Pamatai are weighted 1–3 to take quality of response into account.

essentially the same suggesting that no particular

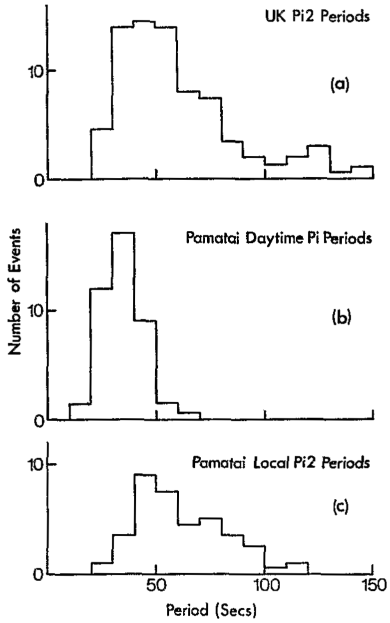


Fig. 2. (a) Spectral distribution of the U.K. Pi2's in Fig. 1. (b) Spectral distribution of simultaneous daytime Pi's at Pamatai in Fig. 1. (c) Spectral distribution of local (nighttime) Pi2's at Pamatai using recordings from March 1978.

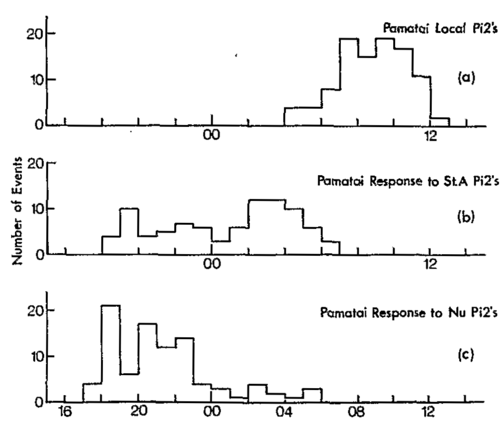
30–40 s, the period typical of Pc3 at this latitude. For comparison Fig. 2c shows the occurrence spectrum of nighttime Pi2's at Pamatai. Because the 1977 data were no longer available from Pamatai, Fig. 2c was constructed for the events which occurred in March 1978. It is similar to the U.K. spectrum and to Pi2 occurrence spectra in general, being asymmetrical with a peak at about 50 s and extending up to periods of 100 s (Stuart, 1972). The similarity of Figs 2a and 2c supports the evidence of Stuart and Hunter (1975) that Pi2's in the midnight sector are transmitted to low latitudes with no significant change in period.

A second analysis of day–night relationships in Pi2's was carried out for March 1978. During this time I.G.S. had magnetometers operating at St Anthony, Newfoundland (Geographic Co-ords 51°24′ N, 55°36′ W, Geomagnetic Co-ords 62.6°, 18.3°) and in Scandinavia. The month was chosen

quarter- and half-way around the Earth from Pamatai respectively. Pi2's in the local midnight sector were identified from the quick-look records for each station and the Pamatai record was scrutinised for coincident response. In addition, Pi2's were identified from the Pamatai recordings for its local midnight sector. Figure 3 summarises this brief survey. Figure 3a shows Pamatai's local Pi2's distributed about 0900 UT (2300 LT). It is very similar to those shown by Orr and Barsczus (1969) for Makerere and M'bour and is essentially the same as that for Pi2's at mid-latitudes (Stuart, 1972). Figures 3b and 3c show the occurrence of daytime Pi's at Pamatai coincident with nighttime Pi2's recorded at St Anthony and Nurmijarvi respectively. Although the statistics are poor, for only one month's recordings, it is clear that sets of daytime Pi's occurred in coincidence with nighttime events at the two quite separate locations.

3. ILLUSTRATIONS

Illustrations of events are taken from the 1976 data set when selected Pi2's recorded in the U.K. were isolated, band pass filtered by digital computation and drawn out on a flat bed plotter. Recordings from Eskdalemuir are taken as representative of the nighttime events in the range of latitudes represented by the U.K. meridional chain (latitude 52° to 60°, L = 2.5 to L = 4.0) over which the main characteristics of Pi2's are constant (Stuart *et al.*



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1979). In the first three illustrations H and D components at Eskdalemuir are plotted on the left hand pair of traces. The right hand pair are H and D traced from Pamatai. Times are synchronised where possible but the time scales are not exactly the same. Amplitude is accurate for the U.K. events but is only estimated for Pamatai.

Figure 4 shows two examples when the daytime Pi were particularly well developed. They occur at 0015 UT on 5 April 1976 and 0333 UT on 20 March respectively. They are characteristic of well developed daytime Pi's. In both cases the event at Pamatai is impulsive, transient in form with a rapid decay in amplitude and is about five times greater in the H component than in D. The events are recorded in Z at about half the H amplitude. However since Pamatai is located on an oceanic island, induced fields (see, for example, KLEIN and LARSEN, 1978) are probably responsible for most of the Z component. Induction also affects the horizontal components so that the H:D amplitude ratio may not be significant. In both cases the dominant period at Pamatai is noticeably shorter than at the nighttime station. However, the longer period event (Fig. 4b) evokes a longer period response at Pamatai and there is an indication that the nighttime dominant period is present in the latter half of both daytime events. It is not possible to comment in more detail on the spectral structure of the events with the data available, except to make the generalised observation that shorter period nighttime Pi2's were more likely to produce a response on the dayside, and that longer period nighttime events tended to produce relatively longer periods in the daytime response.

Figure 5 shows another good daytime Pi in response to a Pi2 which was recorded at 0246 UT on 5 March 1976. It is included to illustrate the response of Pamatai to the second smaller Pi at 0253 and also the fact that the pair of daytime Pi's appear to trigger low level Pc3 at the daytime station. Before 0246 UT there had been no Pc at Pamatai for several hours, and the 'triggered' Pc continued for several hours. The apparent triggering of Pc3 by Pi's in the daytime was noticeable for many of the events which were identified and occurred over a very wide range of Pi quality. HOLLO and VERÖ (1970) show a significant correlation

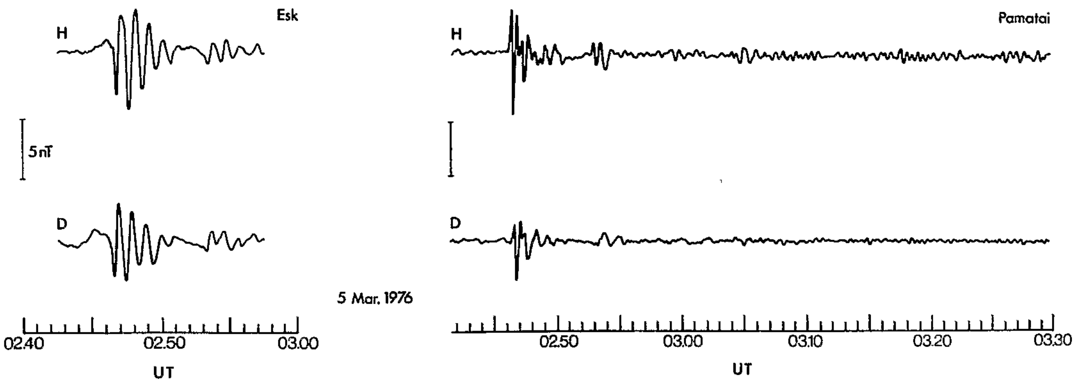

Fig. 5. An example of a well developed daytime Pi which appears to trigger Pc3 on the daylight hemisphere (0246 on 5 March 1976).

between the activity in the morning sector with Pi's occurring pre-midnight, and STUART and BOOTH (1973) analyse a case where a Pi occurring at St Anthony appears to trigger Pc3 in the U.K. Both sets of authors interpret the phenomena as Pi induced Pc3.

Figure 6 illustrates a case where there was little or no daytime response (0037 UT on 23 February 1976) to a well developed Pi2 recorded at night.

In Fig. 7 the Eskdalemuir recordings are set out above those from Pamatai to illustrate the coincident sequence of events which occurred on 14 March 1978. The interesting point of this example is that although the quality of the response is not high (the event at 0135 UT was classed as weight 1 and those at 0148 UT and 0158 UT as weight 2) the train of Pi2's is reproduced in the daytime events with great clarity. It is also interesting to note that in the event Pamatai's Pi begins in coincidence with the first low level oscillation of the right time wave packet and not, as might be expected, with the sudden enhancement in amplitude which occurs at 0138 UT in the nighttime sector. The second and third daytime Pi's begin before oscillation develops fully in the nighttime sector.

4. DISCUSSION

As stated previously, Fig. 1a is typical of the mid-latitude temporal distribution of Pi2's. Interpreted as the latitudinal distribution it illustrates how spatially limited the source region appears to be. On both the Eastern and Western flanks of the distribution comparative studies indicate that the amplitude of Pi2's attenuates rapidly away from the distribution peak. ORR and BARSCZUS note this for equatorial recordings. However, current study of E–W propagation of Pi2's at mid-latitudes at I.G.S. has revealed cases where there is little or no attenuation on the flanks of the distribution.

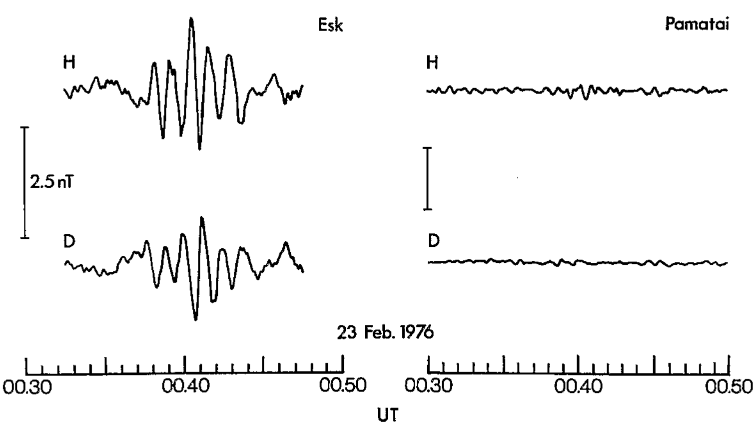

Fig. 6. An example of negligible daytime response to a nighttime Pi2 recorded in the U.K. (0037 on 23 February 1976).

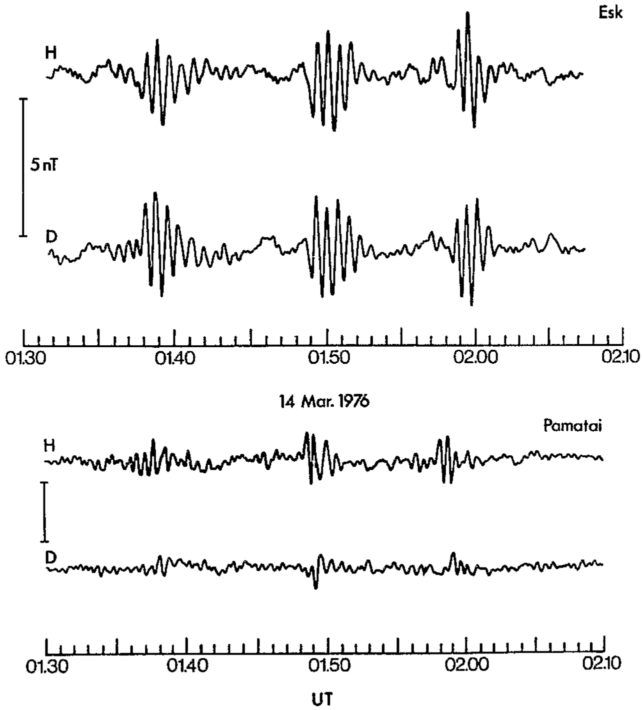

Fig. 7. An example of poor and intermediate daytime Pi's (14 March 1978). The train of nighttime Pi2's is reproduced on the dayside. This example also illustrates possible differences in the arrival times of individual pi's between day and night hemispheres.

In the midnight sector meridional amplitude vari-

decay rapidly in amplitude and in degree of de-recordings (chart speed 30 cm h^{-1}, sensitivity approximately 1nT cm^{-1}) were available. In the hours 0600–1800 only 14 pulsation events which could have been classified as "Pi2 type" were placed in the category because of their isolation or because their form was notably unlike concurrent Pc activity. Their amplitude was always greater than the Pc (up to 10 or 20 nT) and their period was 60–120 s compared with concurrent Pc period of 30–60 s. It seems certain therefore that the appearance of Pi's on the dayside of the Earth is limited to a narrow latitude band around the geomagnetic equator.

Romana and Cardus (1962) show the local time dependence of Pt's reported to IAGA by 70 observatories (Pt was an earlier notation for Pi2). With reservations about the uniformity of reporting, their distribution shows the usual nighttime peak at about 2300 LT but retains a background level, approximately constant throughout the day which is about 10% of the occurrence peak. This early report agrees with the findings here that "daytime Pi's" at Pamatai occur without a preferred nighttime zone. The 10% level of Romana and Cardus agrees remarkably well with the number of very well developed impulsive events noted in the U.K.–Pamatai comparison.

A more detailed examination of the relationships between daytime Pi's and those recorded by the U.K. array than has been presented, is not justified here because of the limiting difficulty of comparing the *dB*/*dt* trace at Pamatai with the broadband recordings of the I.G.S. magnetometers. However, the principal facts are sufficiently clear, from the evidence and the illustrations provided, to establish the point that Pi's appear in quite highly evolved form on the dayside of the magnetosphere. With the limitations of the recordings in mind it was found that there was no systematic difference in their time of arrival at the U.K. or at Pamatai for the majority of events. In 10 cases the event began at Pamatai about 1 min later than at the U.K. and in 2 cases it appeared to be 1 or 2 min in advance of the U.K. None of the events which exhibited different arrival times at the two locations was particularly high quality and no significant conclusion can be drawn from the observations at this stage. The events in Fig. 7 illustrate the sort of differences in arrival time mentioned, and also the difficulty of making a valued estimate of arrival time differences.

5. CONCLUSION

The results presented link those of Jamet *et al.* (1969) with those of Yanagihara and Shimizu (1966), and extend them sufficiently to justify the following remarks.

(1) Pi's appear in the daylight hemisphere at low latitudes. Their appearance does not exhibit any preferred local time. (The evidence here is for activity at about 0610 and 1200 h LT. Yanagihara and Shimizu show evidence for their appearance between 1200 and 1800 h LT.) The daytime Pi's appear to be a response either to Pi2 generation as recorded at mid-latitudes in the midnight sector or to a common trigger event. In view of the amount of attention which has been given to studies of Pi2 morphology and generation at mid- and high-latitudes, and the brief survey carried out here, it must be concluded that daytime Pi response is exclusively in a band around the geomagnetic equator.

(2) The daytime response varies in quality from very highly developed transient forms (~10%), to barely detectable phase interruptions of existing wave packets or noise in the Pc3 band. The quality of the daytime response (i.e. amplitude, degree of development of wave packet, transient characteristic) does not appear to relate to the quality or amplitude of the nighttime event recorded at mid-latitudes. (c.f. Figs. 4–6).

(3) There are often several spectral components in daytime Pi's. The dominant one is generally at a shorter period than the concurrent nighttime Pi2, and there is no indication of any other systematic relationship.

(4) Daytime Pi's appear to 'trigger' Pc3 activity at the low latitude station.

(5) The existence of daytime Pi's and their properties do not depend on K_p, *Dst* and *K* for the local midnight station. (Note that this analysis refers to relatively quiet background geomagnetic conditions).

(6) Within the accuracy of comparison (±30 s) all but a few daytime Pi's occurred simultaneously with their nighttime counterparts.

Because of the uncertainty in the understanding of the propagation of Pi2's within the midnight sector it would be unrealistic to attempt to specify a mechanism for transmission around the globe, particularly one which operates at low latitude only.

Any magnetospheric process for the transmission of a Pi2, thought to originate at high latitude in the midnight sector, to the dayside involves a relatively large travel time (~100 s or longer). The propagation velocity is limited by the hydromagnetic conditions of the medium. Arrival time differences of this magnitude would have been observable between Eskdalemuir and Pamatai. Their nonexistence argues against propagation from night- to dayside at high altitude and also against triggering by a "transient" in the solar wind which might travel along the magnetopause from dayside to tail. In the latter case, daytime Pi's might be expected to precede those at night by 100–200 s.

Yanagihara and Shimizu refer to simultaneous occurrence and do not discuss difference in arrival time. Likewise Stuart and Hunter do not note any arrival time difference between mid-latitude and the equator in the midnight sector. The short periods of daytime Pi's are in agreement with a selective response of the low latitude field lines to a transient, as described by field line resonance theory. The lack of large and systematic arrival time differences over the globe suggests that a transient change occurs simultaneously all through the magnetosphere, and that the differences in character of the Pi2 pulsations which are associated with it indicate local regions of critical response (probably involving different processes) to the change in magnetospheric condition. The observation that a large number of Pi2's are accompanied by a daytime response and that only 20% of the daytime Pi's had highly developed wave packet structure supports this idea, and argues in favour of a specific magnetospheric (or ionospheric) condition on the dayside whose variability has a critical role in the dayside excitation process. The region where daytime Pi's are observed is a relatively broad band around the geomagnetic equator. Low inclination of the ambient magnetic field and high ionospheric conductivity suggest themselves as agents in the daytime critical condition.

It is interesting to speculate on the fact that at the top of the ionosphere (2000–3000 km) the Alfven speed is about 3000 km s^{-1}. Thus travel times from midnight to noon may be in the range 10–30 s, depending on the path and the propagation mode. At this height a disturbance would excite field lines (on the dayside) whose geomagnetic latitude does not exceed 30°.

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