Pi2 pulsation periodicity and variations in magnetotail flows

K. R. Murphy, A. Kale, I. J. Rae, I. R. Mann, and Z. C. Dent

Abstract: Pi2 pulsations are a category of ULF waves with periods between 40–150 seconds frequently observed by ground-based magnetometers predominantly during substorm onset. The origin of these pulsations has been attributed to the coupling of Alfvénic oscillations associated with the generation of the substorm current wedge, and fast-mode compressional waves moving radially inward from the tail, including plasmaspheric cavity modes at low-latitudes. It has recently been suggested that the frequencies of observed night-side auroral zone and low-latitude Pi2 pulsations, or Pi2 waveforms on the flanks, may be due to periodic variations in the sunward plasma flow from the tail such as during multiple bursty bulk flows (BBFs). Using a favourable conjunction of the Geotail satellite with the CARISMA ground-based magnetometers on 23rd December 2000, the relationship between the frequency of Pi2 pulsations observed on the ground and periodicity in Earthward plasma flows has been investigated. Enhanced Earthward flows were seen during periods of substorm activity; however, using time-series analysis a direct link was not observed between the periodicity in the flow-bursts and the periodicity of pulsations within the Pi2 waveband.

Key words: Pi2, Bursty Bulk Flows, Flow Bursts, ULF waves.

1. Introduction

1.1. Pi2 pulsations

Pi2 pulsations are a category of impulsive, irregular Ultra Low Frequency (ULF) pulsations with periods of about 40–150 seconds (6–25 mHz). They often occur during periods of substorm activity, and are associated with impulsive magnetic field dipolarisations. The origin of Pi2s is thought to be disturbances in the near-Earth plasma sheet, including the generation of field-aligned currents in the substorm current wedge.

At higher latitudes, the ground-based magnetic signature of Pi2 pulsations is thought to be dominated by the transient, transverse Alfvén wave carrying the initial field aligned current. If a full substorm onset occurs, then the cross tail current can become diverted through the ionosphere, leading to the formation of the substorm current wedge [9]. If there is an impedance mismatch between the incident wave and the ionosphere, then partial reflection can occur [3, 12]. It is often thought that the Alfvén wave bounces between the plasma sheet and the ionosphere, giving rise to the periodic structure of the Pi2 [3, 12].

The plasmasheet disturbance also causes compressional fast-mode waves to move radially inward towards the Earth. These fast mode waves can couple to transverse waves and excite local field line resonances, or can impact the plasmapause and lead to plasmaspheric cavity mode oscillations. These effects are generally responsible for the dominant signal seen at lower latitudes [12].

The exact mechanism by which the near-Earth plasma sheet is disturbed is not fully understood. Recent work suggests that Earthward high-speed magnetotail plasma flows may rapidly brake as they approach the dipolar inner magnetosphere and may be responsible for the initial plasmasheet disturbance [7].

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1.2. Magnetotail plasma flows

Plasma flows in the central plasma sheet typically have velocities of approximately 30 km s^{-1}; however high-speed Earthward flows with velocities 1 or 2 orders of magnitude higher have been observed at distances as far as $\sim$30 R_E [1]. They are rarely seen closer than 10 R_E, which is thought to be evidence for braking of the flows due to an increased magnetic pressure at the inner magnetosphere. The high-speed flows often exhibit a temporal fine structure—with characteristic timescales of the order of minutes—called flow bursts (FBs). These FBs are often encapsulated in bursty bulk flows (BBFs); envelopes of FB activity with durations of 10's of minutes often occurring within the BBF during which the plasma velocity is greater than $\sim$400 km s^{-1}.

1.3. Pi2 pulsations and flow bursts

Recently it has been suggested that BBFs may provide a mechanism for the generation of Pi2 pulsations, with reported correlations between the periodicity of FBs seen in the magnetotail and the periodicity of the Pi2 pulsations suggesting the possibility of direct driving [6]. It has been suggested that the braking of the flows generates fast-mode waves that directly drive low-latitude Alfvénic field line oscillations on the flanks, and possibly perturbations on the night-side. The braking of flows is also thought to generate a current contribution to the substorm current wedge, with a larger contribution driven by pressure gradients and flow shears [14, 4]. We investigate these hypotheses below.

2. Observations: 23rd December 2000

2.1. Instrumentation

To investigate the relationship between the periodic structure of flow bursts seen in the magnetotail and Pi2 periodicity, plasma dynamics, as measured by instruments onboard

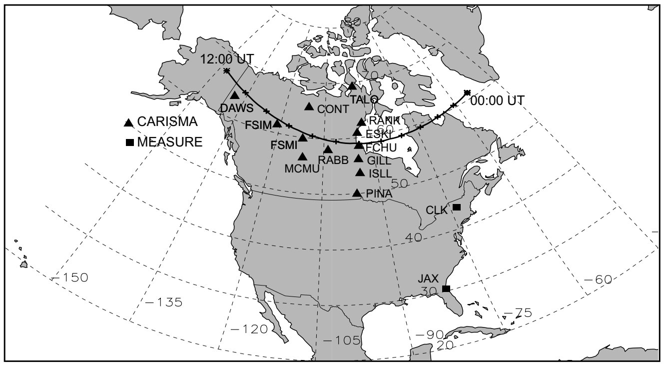

Fig. 1. Ground magnetic field trace (north) of the conjunction between Geotail and the CARISMA magnetometer array for 23rd December 2000, 0000–1200 UT, mapped onto the ground using the Tsyganenko 89c model [15]. The overlaid grid shows contours of geographic latitude and longitude.

the Geotail satellite, were compared to ground-based magnetometer data obtained from the Magnetometers Along the Eastern Atlantic Seaboard for Undergraduate Research and Education (MEASURE)[10] and Canadian Array for Real-time Investigations of Magnetic Activity (CARISMA) arrays (http://www.carisma.ca; formerly known as the CANOPUS (Canadian Auroral Network for the OPEN Program Unified Study) array [13]).

The Geotail satellite carries a suite of instruments to study the structure and dynamics of the tail region of the magnetosphere. The orbit on the 23rd December 2000 was approximately 9 x 30 R_E, with an inclination of -7° to the ecliptic plane. The Low-Energy Particle (LEP) instrument on board measures 3-D ion velocity distributions with energies between 7 eV–42 keV at 12 s resolution, enabling the resolution of structures occurring on Pi2 time-scales [11]. The Comprehensive Plasma Instrument (CPI) data provides information on plasma densities and temperatures in the 50 eV–48 keV range at 64 s resolution, enabling the calculation of plasma parameters characteristic of specific magnetospheric regions discussed below [5]. The Magnetic Field Instrument (MGF) on board Geotail enabled the determination of the 3-D magnetic field vector at 3 s resolution [8].

Plasma flows occurring in the plasma sheet boundary layer (PSBL) are typically field-aligned and are therefore not subject to the braking in the near-Earth region experienced by BBFs in the central plasma sheet (CPS). The CPS represents a more dipolar region than that of the PSBL, and has a characteristic magnetic-field topology defined by [1] which typically satisfies:

$$\frac{B_z}{(B_x^2 + B_y^2)^{1/2}} > 0.5. \tag{1}$$

The CPS has also been defined as the region with an ion plasma-beta (β_i)—the ratio of ion thermal to magnetic pressures—greater than 0.5([1, 2] and references within). Both of these relations are used together to determine whether Geotail resides in the PBSL or CPS.

Site Code	Site	CGM Lat. (°N)	CGM Lon. (°E)	L value
TALO	Taloyoak	78.54	330.01	NA
CONT	Contwoyto	72.97	303.87	11.84
RANK	Rankin Inlet	72.47	335.36	11.20
ESKI	Eskimo Point	70.78	332.51	9.37
FCHU	Fort Churchill	68.57	332.92	7.61
FSMI	Fort Smith	67.45	306.16	6.90
FSIM	Fort Simpson	67.33	293.50	6.84
RABB	Rabbit Lake	67.05	318.42	6.68
GILL	Gillam	66.28	332.46	6.27
DAWS	Dawson	65.92	273.16	6.10
MCMU	Fort Mcmurray	64.31	308.52	5.40
ISLL	Island Lake	63.86	332.80	5.23
PINA	Pinawa	60.19	331.20	4.11
CLK	Clarkson University	55.39	2.14	3.10
JAX	Jacksonville University	41.82	351.41	1.80

Table 1. Ground-based magnetometer stations used during this study. L-shell and CGM position calculated using the NSSDC MODELWeb facility (http://nssdc.gsfc.nasa.gov/space/cgm/cgm.html).

2.2. Observations

Favourable night-side conjunctions between the Geotail spacecraft and CARISMA during an interval of substorm activity were sought; one such conjunction occurred during a substorm on 23 December 2000 with Geotail situated in the mid-tail at X_{GSM} -15–17 R_E. The north ground magnetic field trace (obtained assuming Tsyganenko 89c external and IGRF internal geomagnetic fields [15]) can be seen in Figure 1, along with the positions of the ground-based magnetometers (see also Table 1).

Figure 2 shows the unfiltered ground-based H-component magnetograms for the period 0400–1200 UT on 23rd December 2000. The sites cover a wide range of latitudes, from $\sim$30°–$\sim$70° N, with longitudes from $\sim$220°–$\sim$285°. Several substorm bay signatures are seen over this period, from $\sim$0430 UT at all stations, further activity at $\sim$0805 UT being most noticeable at Contwoyto Lake (CONT), and additional activity at $\sim$1012 UT, primarily located near Dawson City (DAWS). The bottom two panels are data from the Geotail LEP instrument, the upper panel being Vx_{GSM}, the lower panel being the earthward component of Vx_{GSM} perpendicular to the field vector, B, and is described below.

During the magnetic conjunction, the magnetic field vector direction measured by Geotail has a large x_{GSM} component, suggesting that Geotail is close to the edge of the CPS in a region of stretched tail-like magnetic field. In this region, a high proportion of the plasma flow is field-aligned and therefore plasma flow velocities perpendicular to the magnetic field direction are considered. To calculate the direction of the measured fields in a coordinate system aligned with the ambient magnetic field, the data was transformed from [X_{GSM}, Y_{GSM}, Z_{GSM}] to [X_{FA}, Y_{FA}, Z_{FA}] where Z_{FA} is field-aligned, X_{FA} lies in a plane defined by Z_{FA} and the geocentric radius vector to the spacecraft and is perpendicular to Z_{FA}, and Y_{FA} completes this right-handed orthogonal set. This orthogonal co-

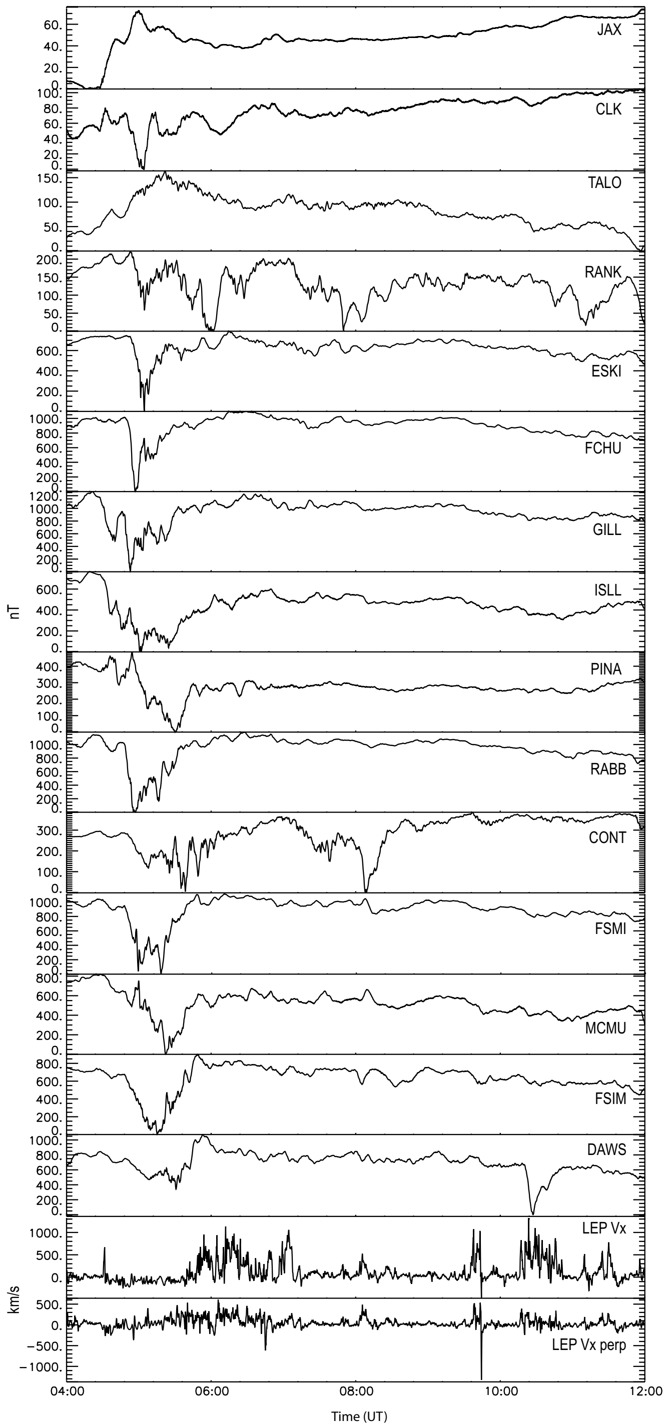

Fig. 2. Stack plot showing (top down) unfiltered H-component magnetometer data for the period 0400–1200 UT on 23rd December 2000from two MEASURE magnetometers and the CARISMA magnetometer array. The Earthward velocity component of the plasma flow as measured by the LEP instrument onboard Geotail is shown as both $\mathrm{Vx}_{\mathrm{GSM}}$ and in terms of field perpendicular velocity, $\mathrm{V}_{\mathrm{perpx}}$ (see text for details).

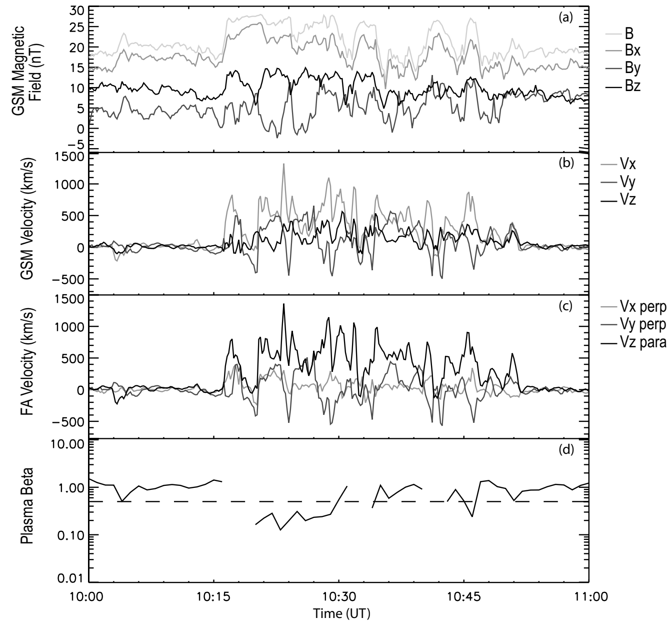

Fig. 3. In-situ measurements recorded by Geotail for the period 1000–1100 UT. The panels show (top down) the magnetic field, the plasma velocity in the GSM coordinate system and the flow in field-aligned coordinate system (FA) measured by LEP, and β_i from the CPI instrument.

ordinate system was derived using a running mean of the ambient magnetic field of 20 minutes duration. In this field-aligned co-ordinate system, $\mathrm{V}_{\mathrm{perpx}}$ represents the $\mathrm{Vx}_{\mathrm{GSM}}$ component perpendicular to the field vector, B.

Two extended BBF events are seen during the conjunction, occurring at times similar to that of the substorms, being approximately 0930–0945 UT, and 1015–1100 UT. There is also smaller flow enhancements at 0755–0812 UT and 0930–0945 UT, though neither fit the criteria of a BBF [1]. Unfortunately, there were periodic data gaps in the Geotail LEP data from 0430–0530 UT, which corresponded with the onset of the largest substorm event measured during the interval, however there is no evidence of strong flows occurring during this substorm onset, hence this event is not studied.

2.3. BBF event between 1000–1100 UT

During this event the Geotail satellite was located at (-17.5, -2.9, -1.9) $\mathrm{R_E}$ in GSM coordinates. During this interval, Geotail was not directly conjugate to any CARISMA magnetometer; rather the spacecraft track was located magnetically between the DAWS and FSIM stations (shown in Figure 1). Therefore in this interval, the DAWS and FSMI are situated closest to local midnight and the onset region, and the Churchill Line meridian is $\sim$3 hours of local time towards the dawn flank. Geotail was located in the CPS as evidenced by $\beta_i > 0.5$, shown in Figure 3d, for the periods preceding and following the flow event. The data gaps in β_i are due to data gaps in the CPI instrument data. During the flow event, β_i decreases below 0.5, due to the increase in the total magnetic field (Figure 3a). Over this period, the CPI-determined ion temperature remains constant, suggesting that Geotail is monitoring the passing of the flow, rather than drifting between the PSBL and CPS.

A small substorm bay occurs around 1012 UT, recorded first at Fort Smith (FSMI). This signature is then recorded at the lower latitude Churchill line magnetometers ($\sim$265 degrees geographic longitude) and westwards at DAWS at 1017 UT—the latter having the largest H-component bay of $\sim$600 nT. As previously mentioned, DAWS and FSIM are close to local midnight, with the Churchill line of magnetometers being closer to the dawn flank. The first large plasma flow occurs at $\sim$1016 UT and continues through successive flow bursts until just after 1050 UT.

A fundamental aspect of the BBF:Pi2 relationship proposed by [6] is that there will be a one-to-one correlation between the FBs and individual oscillations in the waveform of the Pi2 pulsations; both the waveform and the frequency content should therefore be similar between the two data sets. Figure 4 shows ground magnetometer data and Geotail flow burst velocity data (a) band-pass filtered between 40–200 s, and (b) their power spectra in this frequency band. It can be seen from Figure 4(a) that there is no visual temporal correlation evident between the H-component Pi2 signals and the LEP V_{perpx} signals. There are, at times, similar Pi2 periodicities coincident in both data, most notably 1040–1050 UT at ESKI, however it must be noted that even this wavepacket connection appears to be acausal with respect to the BBF, the ground oscillations preceding the initial flow onset. It should also be noted that the Geotail flow velocity measurements have not been time-shifted in the manner of [6] to allow for propagation effects. Figure 4(b), in contrast to the time-series data, shows that, at times, similar frequencies are observed on the ground and in space. For example, there are clear peaks in V_{perpx} in the $\sim$7–8 mHz, $\sim$11–13 mHz and $\sim$15–16 mHz frequency ranges. There is evidence that there are similar frequencies in the H-component magnetometer data in DAWS-FSMI-RABB-PINA-GILL in the $\sim$7–8 mHz frequency band, at JAX-CLK in the $\sim$11–13 mHz, and in MCMU-PINA-FSMI-RABB in the $\sim$15–16 mHz band, though at much lower amplitudes in several cases. It must be noted that FSIM and DAWS show relatively large amplitude waveforms, compared to those of the other stations, since these two stations were closest to the substorm onset region. Both FSIM and DAWS show evidence of a $\sim$7–8 mHz frequnency, however the further peaks in the FSIM and DAWS power spectra appear to be in the troughs of the V_{perpx} power spectra in frequency space.

Whilst it is evident that there were similar frequencies observed in some of the ground and spacecraft measurements, inspection of Figures 4(a) and (b) together reveals that these frequencies are not contemporaneously observed throughout the 1 hour window; neither do the waveforms on the ground and in space show any coherency (i.e., the waveforms are dissimilar at similar times).

2.4. BBF event between 0600–0730 UT

During this event, Geotail was both magnetically conjugate to the Churchill Line meridian, and located around 24 MLT, in contrast to the event detailed in Section 2.3. Consequently, the conjugacy at this time is was optimal for diagnosing the characteristics of any substorm onsets that occur near local midnight. From Figure 2 it can be seen that there were further FBs and assocuiated Pi2 signatures observed on the ground between 0600–0730 UT. Figure 5 shows the filtered time series

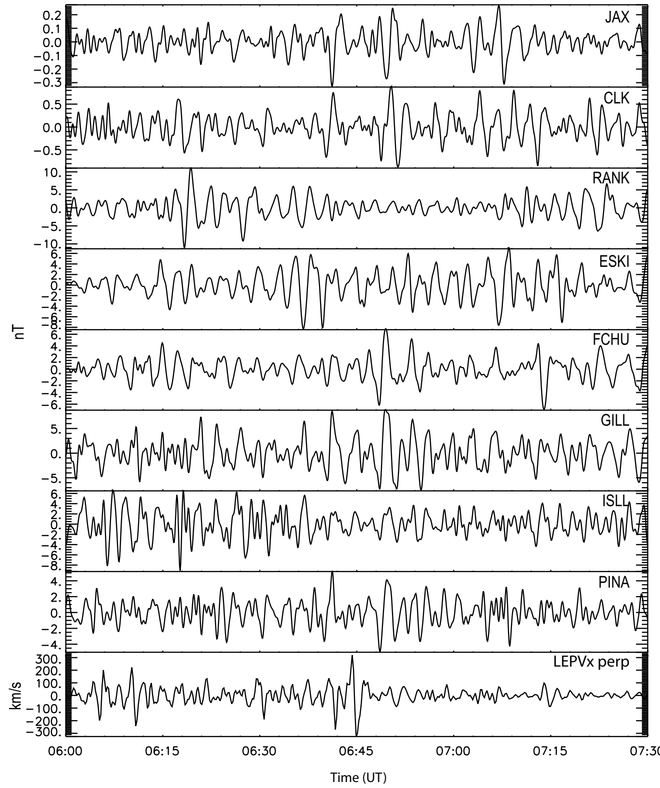

Fig. 5. Stack plot showing the H-component oscillations present in the Pi2 waveband during the BBF event occurring between 0600–0730 UT, from the ground-based magnetometers shown in Table 1 (and analogous to Figure 4(a)).

in the Pi2 frequency range for this interval (and is analagous to Figure 4(a)). Again, there are similar frequencies in the Pi2 band in both magnetic perturbations and V_{perpx} during this interval (for brevity, a power spectra is not shown), but little one-to-one correlation between the waveforms and certainly no coherent wavepacket activity is observed in V_{perpx} concurrent with Pi2 wavepacket observations on the ground.

3. Discussion and Conclusions

In this paper we studied a night-side conjunction between the Geotail spacecraft and the CARISMA and MEASURE ground-based magnetometer arrays in the North American sector and investigate the possible relationship between the periodicity present in flow enhancements comprising a BBF and the frequency content of ground-based magnetometer measurements in the Pi2 wave band, first proposed by Kepko and co-workers [6, 7]. In their model, individual flow bursts drive a transient Pi2 pulsation response via induced currents due to flow braking. At lower-latitudes on the flanks, Pi2 signatures are proposed to be directly-driven by compressional fast-mode pulses associated with periodicity in the braking of Earthward flows. The implications of these statements is that as a result of the proposed Pi2 generation mechanisms, both the frequency content of the flow bursts and the waveform should be similar to frequency content and waveform of the magnetic Pi2 measurements on the ground.

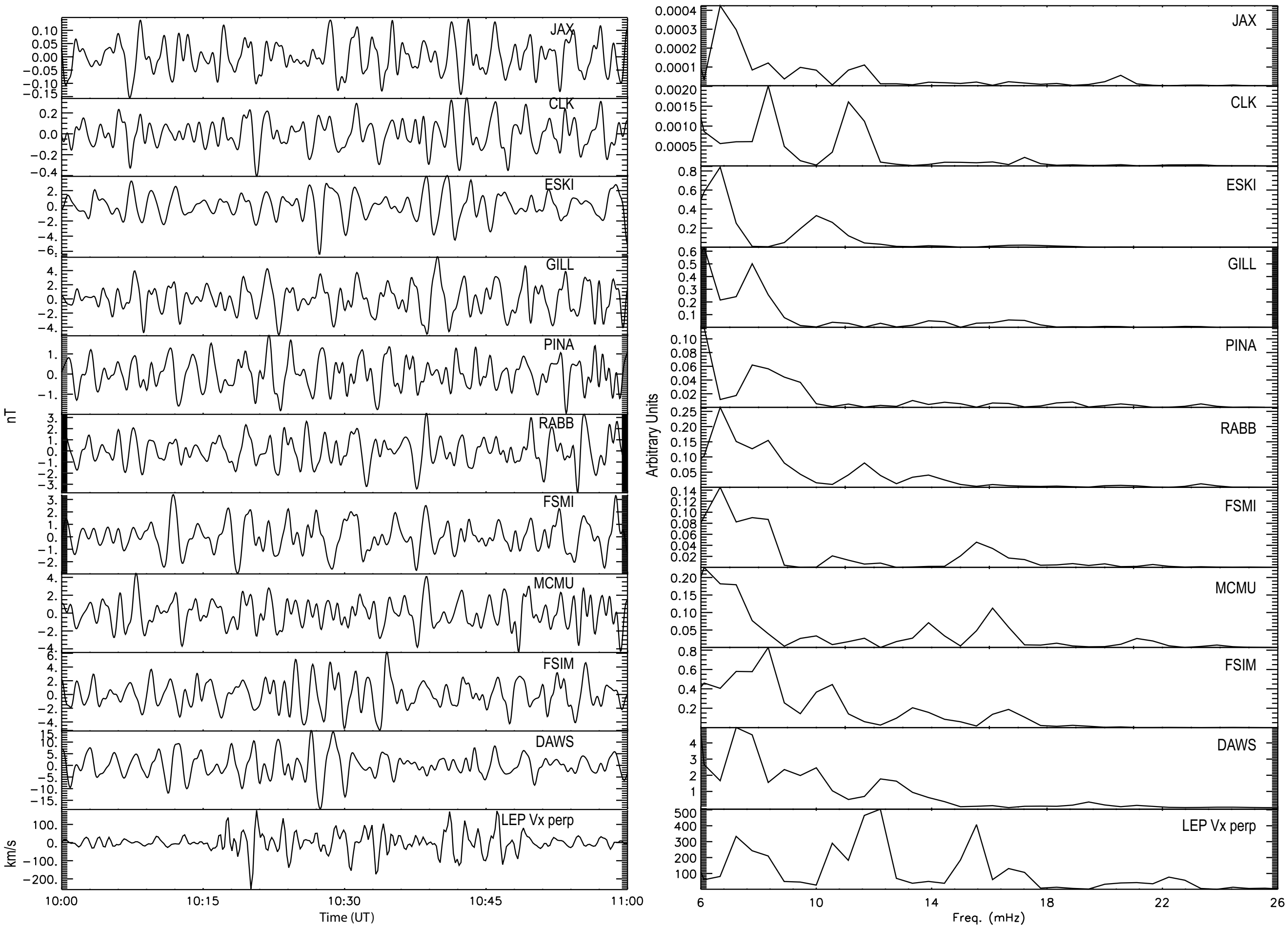

Fig. 4. Stack plots of (a) Band-pass filtered Pi2 (40–200 s) time series between 1000–1100 UT (b) their associated power spectra, filtered in the 5–25 mHz band for the period 1010–1040 UT, for the ground H-component magnetometer data and Geotail V_{perpx} flow data. Power is expressed in arbitrary units. The stations represent several areas of interest noted in [7] namely, stations between midnight and the dawn flank covering a range of latitudes (JAX-CLK-ESKI-GILL-PINA-RABB-FSMI-MCMU) and stations localed radially inward of the magnetotail (DAWS-FSIM).

We analysed three separate events from the 23rd December 2000 interval, whereby Geotail was in an extended conjunction with the CARISMA and MEASURE magnetometer arrays. Due to brevity, we discuss two of these events in this paper, but concentrate on one in order to present the data in its entirety. For the event occurring between 1000–1100 UT, the power is dominant in the FBs (in the Pi2 frequency band) at ∼7–8 mHz, ∼11–13 mHz and ∼15–16 mHz. Nearly all magnetometer sites show the majority of power, within the Pi2 frequency band of the H-component, to be between 5–7 mHz—lower than that of the dominant frequencies seen in the FBs. At higher frequencies, the features in the FB power spectrum do not reflect those measured on the ground for DAWS and FSMI, the two sites closest to the substorm event. There is power present at a single common frequency for some Churchill line sites, such as RABB (∼11–13 mHz) and FSMI (∼15–16 mHz). These features are isolated and, in general, not common between several magnetometer stations, as might be indicative of a common driver. In summary, between 1000–1100 UT, both the Geotail V_{perpx} and H-component magnetometer data showed some evidence of similar frequency content in predominantly the ∼7–8 mHz and ∼11–13 mHz ranges, though not consistently throughout the magnetometer array. However, comparison of the waveforms reveals that these frequencies are not coherent in the ground and spacecraft measurements, and therefore the waveforms do not show any clear evidence for a directly-driven relationship.

In the results obtained by Kepko et al. [7], the authors show visual correlation between the periodic variation in the V_{perpx} component of the plasma flow velocity and the unfiltered magnetometer data. In the two events studied in this paper, we see no evidence of this behaviour. This could be due to the nature of the incident flow burst being different in this study, than those used by Kepko et al. In their investigations, the flow bursts had a large amplitude and were distinct, with periods of 1–2 minutes. In our study, the dominant frequencies are less monochromatic, with components outside the Pi2 range of frequencies. Also, the time of increased Pi2 activity is less optimal with respect to the inferred substorm onset meridian, with the dominant ground-based activity measured at ∼10 UT (∼4 MLT) and therefore away from local midnight and discussed in Section 2.3, which may also be a contributing factor.

However, the event discussed in Section 2.4 is both magnetically conjugate and the ground-magnetometers and spacraft location are in the local midnight region, and this event shows the same result; there is no evidence of a directly-driven Pi2 signature by the FBs within a BBF.

There is evidence for flow enhancements occurring at times similar to that of substorm onset and therefore increased Pi2 wave activity, for 2 of the 3 events, as seen in Figure 2. However, it does not appear that the flow enhancements always occur prior to the periods of increased Pi2 activity, but seem to be acausal in relation. This is illustrated in the interval 1000 UT–1100 UT by the substorm bay observed at FSMI beginning to form at 1012 UT, prior to the enhanced Earthward flow observed by Geotail, located some -17.5 R_E downtail, at 1016 UT. At DAWS however, the substorm bay begins forming at 1017 UT—after the FB. Similar behaviour is also noted during the 0930–1000 UT BBF event. Therefore it seems apparent that the BBF may not be responsible for the increase Pi2 activity seen in this case.

In summary, there is little evidence for the action of the proposed model outlined [7] in the intervals presented in this paper. Low frequency power ($\sim$7–8 mHz) is seen in both the ground H-component and V_{perpx}, and sporadic evidence for $\sim$11–13 mHz frequencies in some of the ground magnetograms in conjunction with the Geotail V_{perpx}, with the location of the ground magnetometer (at midnight or toward the dawn flank) not affecting this observation. However, there is no evidence for coherent wavepackets in the ground and spacecraft measurements at the same time during the studied interval. Thus, we conclude that during the BBF events between 0400 UT–1200 UT on 23rd December 2000, BBFs occur at times similar to periods of increased Pi2 activity, but there is no evidence supporting a causal directly-driven connection between Pi2s and flow burst waveforms, whereby a burst in flow may be responsible for an individual Pi2 pulsation.

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