The Source, Significance, and Magnetospheric Impact of Periodic Density Structures Within Stream Interaction Regions

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Abstract We present several examples of magnetospheric ultralow frequency pulsations associated with stream interaction regions and demonstrate that the observed magnetospheric pulsations were also present in the solar wind number density. The distance of the solar wind monitor ranged from just upstream of Earth’s bow shock to 261 RE, with a propagation time delay of up to 90 min. The number density oscillations far upstream of Earth are offset from similar oscillations observed within the magnetosphere by the advection timescale, suggesting that the periodic dynamic pressure enhancements were time stationary structures, passively advecting with the ambient solar wind. The density structures are larger than Earth’s magnetosphere and slowly altered the dynamic pressure enveloping Earth, leading to a quasi-static and globally coherent “forced-breathing” of Earth’s dayside magnetospheric cavity. The impact of these periodic solar wind density structures was observed in both magnetospheric magnetic field and energetic particle data. We further show that the structures were initially smaller-amplitude, spatially larger, structures in the upstream slow solar wind and that the higher-speed wind compressed and amplified these preexisting structures leading to a series of quasiperiodic density structures with periods typically near 20 min. Similar periodic density structures have been observed previously at L1 and in remote images, but never in the context of solar wind shocks and discontinuities. The existence of periodic density structures within stream interaction regions may play an important role in magnetospheric particle acceleration, loss, and transport, particularly for outer zone electrons that are highly responsive to ultralow frequency wave activity.

1. Introduction

Global magnetospheric ultralow frequency (ULF) pulsations can arise from a variety of sources internal to the magnetosphere, such as locally stimulated field line resonances and wave-particle interactions (Hasegawa, 1969; Hughes et al., 1978; Southwood et al., 1969). The solar wind is also known to be a source of oscillations, such as through the generation of Kelvin-Helmholtz waves on the magnetopause that couple to field line resonances (FLRs) (Agapitov et al., 2009; Chen & Hasegawa, 1974; Fujita et al., 1996; Southwood, 1974; Walker, 1981) or via ion foreshock generated Pc3 waves (Gary, 1981; Hartinger et al., 2013; Odera, 1986). Sudden increases in the solar wind dynamic pressure, such as those associated with solar wind shocks, are also associated with magnetospheric ULF waves. Generally, any sudden increase in solar wind dynamic pressure can act as a source of broadband compressional power that can couple to magnetospheric eigenmodes. Fast mode oscillations are trapped between gradients in the Alfvén velocity, which can occur at the equatorial ionosphere, the plasmapause, and the magnetopause. Cavity mode oscillations can then couple to FLRs where the FLR eigenfrequency matches the cavity mode frequency (Kivelson & Southwood, 1985, 1986; Walker, 1998). The expected signature of a cavity mode oscillation is a damped magnetic field oscillation, as the cavity oscillations lose energy through FLR coupling, ionospheric dissipation, and leakage through the boundaries. Although the cavity mode has been studied extensively through theory (e.g., Allan, White, and Poultér 1986; Allan, Poultér, and White 1986; Claudepierre et al., 2009; Lee & Lysak, 1989), observations of cavity mode signatures are rare (Goldstein et al., 1999; Hartinger et al., 2012).

The dayside magnetosphere must balance the solar wind dynamic pressure, such that \( B_m^2 - B_{sw} V_{sw}^2 \), and variations in the solar wind dynamic pressure can therefore also produce magnetospheric ULF wave activity (Kessell, 2008; Takahashi & Ukhorskiy, 2007). As the solar wind dynamic pressure varies, the location of the dayside magnetopause, and hence the strength of the dayside magnetospheric field, varies in direct response. While the general control of the dayside magnetospheric field strength and location by the solar wind dynamic pressure is expected on pressure balance arguments, work over the last decade has shown that variations in the upstream solar wind number density are sometimes highly periodic, typically in the Pc5
range ($T=3–10$ min) and longer (Kepko & Spence, 2003; Kepko et al., 2002; Korotova & Sibeck, 1995; Sarafopoulos, 1995; Viall, Kepko, & Spence, 2009). In turn, these periodic dynamic pressure variations drive magnetospheric oscillations at the same period, in what can be termed a quasi-static forced breathing of the magnetosphere. It is important to note that these periodic density structures in the solar wind are not propagating waves. Rather, they are coherent mesoscale structures created very early in the formation of the solar wind, which then advect outward in quasi pressure balance (DeForest et al., 2018; Di Matteo et al., 2019; Kepko et al., 2016; Viall & Vourlidas, 2015; Viall, Spence, & Kasper, 2009; Viall, Spence, Vourlidas, & Howard, 2010).

In a large-scale statistical study comparing discrete frequencies observed in the solar wind number density with those observed in the magnetosphere by GOES, Viall et al. (2009) found that ~50% of the time, discrete magnetospheric oscillations observed by GOES between $f=0.5$ to $5.0$ mHz were driven directly by solar wind periodic density structures and demonstrated a persistent set of observed frequencies, near $f=1.0$, $1.5$, $1.9$, $2.8$, $3.3$, and $4.4$ mHz. In a separate study, Viall et al. (2008) showed that the observations were better organized by the radial length scale of the periodic density structures, rather than apparent frequency (which depends on the velocity of the solar wind). This growing body of work has established that periodic density structures in the solar wind are a significant source of discrete, magnetospheric pulsations, particularly at $f<~4$ mHz (Hartinger et al., 2014) and that these solar wind structures occur more frequently at certain scale sizes (and apparent frequencies) than others. More recently, Viall and Vourlidas (2015) and Viall et al. (2010) used data from the Solar Terrestrial Relations Observatory/Sun-Earth Connection Coronal and Heliospheric Investigation suite to observe periodic density structures leaving the Sun. They demonstrated that the periodic density structures were formed below at least $2.5$ solar radii, the inner edge of the COR2 instrument field of view. These structures had periods of $\sim90$ min ($f=0.2$ mHz), were observed to accelerate through the sonic and Alfvenic transition points up to slow wind speeds, and occurred near coronal streamers.

These mesoscale structures that were injected into the solar wind at the Sun clearly survive to $1$ AU where they impact Earth several days later (Kepko & Spence, 2003; Kepko et al., 2016; Rouillard et al., 2010; Rouillard et al., 2010). Because mesoscale structures are often periodic (Viall et al., 2008; Viall, Kepko, and Spence 2009), the geospace effects go well beyond stochastic buffeting of Earth’s magnetosphere. Instead, periodic solar wind density structures directly drive globally coherent, magnetospheric ULF oscillations. ULF waves are an important driver of magnetospheric particle dynamics, particularly for electrons in the outer radiation belts (Elkington & Sarris, 2016; Mathie & Mann, 2000, 2001; O’Brien et al., 2003; Ukhorskiy et al., 2006). Broadly, ULF waves accelerate, transport, or lead to the loss of these electrons. Acceleration can occur by breaking the third adiabatic invariant through a drift-resonant interaction of the electrons with $Pc5$ ($f=2–7$ mHz) waves (Elkington et al., 1999, 2003). Under a continuum of $Pc5$ wave activity, electrons can undergo stochastic acceleration such that some particles lose energy, while others gain energy, leading to diffusion across drift shells (Elkington et al., 2003; Hudson et al., 2000; Shprits et al., 2008; Tu et al., 2012; Ukhorskiy et al., 2009). Finally, ULF waves can lead to efficient magnetopause shadowing and a commensurate rapid loss of outer belt electrons, particularly within a compressed magnetosphere that would occur with high dynamic pressure (Loto’aniu et al., 2010; Turner et al., 2012, 2013). However, a direct link between ULF waves driven by periodic density structures and magnetospheric particle dynamics has not yet been established.

Stream interaction regions (SIRs) are important drivers of magnetospheric activity (Gosling & Pizzo, 1999; Kilpua et al., 2017; Tsurutani et al., 2006) and in particular can be important for energizing Earth’s radiation belts (Bortnik et al., 2006; Borovsky & Denton, 2006; Miyoshi & Kataoka, 2005; Paulikas & Blake, 1979; Yuan & Zong, 2012). SIRs, formed when a faster solar wind overtakes a slower wind, can sometimes form forward shocks by $1$ AU (Jian et al., 2006; Richardson, 2018), potentially leading to shock-induced ULF wave activity in the magnetosphere. The compression region between the two solar wind streams is also a source of broadband magnetospheric ULF wave power derived from intrinsic solar wind dynamic pressure fluctuations (Kilpua et al., 2013). The effects of SIRs on magnetospheric particle populations are complicated and depend on time, L-shell, and particle energy. Over the full timescale of the interaction (several days), the integral effect of SIR-driven geomagnetic storms is higher fluxes of radiation belt electrons compared to interplanetary coronal mass ejection (ICME)-driven storms, particularly at the higher L-shells ($L>4.5$) (Borovsky & Denton, 2006; Kataoka & Miyoshi, 2006; Kilpua et al., 2015; Turner et al., 2019). Yet on shorter timescales, substructure within the SIR can lead to substantial loss of energetic particles. Kilpua et al. (2015), for
example, found that loss mechanisms dominate over acceleration as solar wind structure within stream interface regions impact Earth, yet the overall interaction of SIRs with the magnetosphere led to higher flux levels than ICME-driven storms. They suggested that the cause of electron loss was magnetopause shadowing, driven by the high solar wind dynamic pressure and high ULF wave activity, which scatters electrons to larger L-shells where they can be lost more effectively (Turner et al., 2012). Analyzing ICME-driven storms, Hietala et al. (2014) found a similar decrease in relativistic electron flux during passage of the ICME sheath and attributed that loss to ULF wave-driven diffusion and magnetopause shadowing, enhanced by solar wind dynamic pressure fluctuations in the ICME sheath.

In this paper we analyze six events demonstrating periodic oscillations in Earth’s magnetosphere following sudden solar wind dynamic pressure increases. All events were associated with SIRs of varying magnitudes, where we defined SIR broadly to include any velocity change that produces an interface region. In all cases, the number density increase at the leading edge of the SIR was followed by quasiperiodic mesoscale number density structures in the solar wind, generally in the 0.5- to 2-mHz (8–30 min) range. After ballistic propagation, ranging from just a few to 90 min, to account for the upstream location of the solar wind monitor, the same oscillations were observed as magnetic field oscillations in the magnetosphere by the GOES spacecraft. For all events, the energetic particle population in the outer radiation belt also responded directly to the solar wind driving. We further show that the periodic density oscillations in the solar wind appear to have been preexisting structures in the upstream slower solar wind that were amplified by the pileup caused by the impact of the higher-speed stream. The discontinuity itself appears to play no direct role in the formation of the density structures, nor in driving the magnetospheric ULF oscillations within this frequency range. We conclude by discussing the potential importance of a quasiperiodic dynamic pressure drivers within SIRs on magnetospheric particles.

2. Events

The events presented here are representative examples visually identified from a number of different data sets and cover solar wind monitors from 14 to 261 RE upstream from Earth’s magnetosphere (Figure 1). They do not represent an exhaustive list of such events. We required each event to exhibit a sharp change in number density, generally a factor of 2 or more, preceded by relatively steady number density, that was then followed by quasiperiodic density variations. We further required that a GOES spacecraft be located in the dayside magnetosphere, where solar wind-driven oscillations are most likely to be observed. Solar wind data are from a variety of solar wind monitors, including Geotail, ACE, Wind, and THEMIS. Variations in solar wind dynamic pressure, \( p_{\text{dyn}} = n m v^2 \), are driven primarily by variations in the solar wind number density, \( n \), and these variations are generally much larger percentage wise than those in velocity. We therefore plot solar wind proton number density rather than dynamic pressure so as to not obscure this fact and plot velocity separately. Events are presented below with increasing distance from Earth of the solar wind monitor. For each solar wind observation we add a constant time shift to the entire time series to
account for ballistic propagation to Earth’s magnetosphere. For one event, the constant time shift assumption is not appropriate, and we discuss the implications of that in the Discussion.

Figure 2 shows solar wind $|V_x|$ and the total pressure, $P_t = B^2/2\mu_0 + \sum \eta_j kT_j$, for the six events analyzed below, assuming $n_\alpha=0.04n_p$ and $>\alpha=4\alpha_p$. Increases in the total pressure have been shown to be excellent markers of stream interface regions (Jian et al., 2006). The events have been aligned so that epoch time $T=0$ is the time of the number density increase for each event. The 25 November 2008 event (Figure 2f) shows a classic SIR signature, with an increase in total pressure at the forward shock at $T=0$ and a peak in total pressure partway between the slow-speed and high-speed streams, marking the stream interface. Indeed, this event is in the Jian et al. (2006) event list of SIRs. At the other extreme, the second event (Figure 2b), from 29 November 1996, shows only a small change in total pressure and a small jump in solar wind velocity, which has not yet steepened into a forward shock. Yet it very clearly occurs at the
Figure 3. Solar wind and magnetospheric data for the 9 September 2005 event. (a) Wind 3dp $N_p$; Geotail $V_x$; (b) solar wind velocity and (c) solar wind number density measurements. Geotail was located at (14, 27, −0.4) RE geocentric solar magnetospheric. Geotail data in all panels have been time shifted by +5 min to account for propagation. GOES-12 $B_z$ component magnetic field data are plotted in (d), along with the Geotail solar wind number density (blue). The vertical red markers in (c) highlight local increases in $N_p$ observed by Geotail. The GOES-12 >0.6-MeV electron flux ($\times 10^3$) is plotted in (e). The trend toward zero flux after 1800 UT is due to contamination from a solar proton event.
Figure 4. The solar wind velocity (a) and number density (b) data, time shifted by +13.5 min, from the 3dp instrument onboard Wind; (c) The GOES-8 and GOES-10 vertical component of the magnetic field, and running averages (dashed lines) used to detrend the data; (d) The detrended GOES-10 magnetic field data (red) and the Wind density (GOES-8 is not plotted for clarity). The vertical dashed line indicates the appearance of a sudden increase at both GOES and Wind, and tick marks in (d) highlight similarities in the peaks. (e) Comparison of the differential electron flux (#/keV-cm²-ster-sec) from the LANL 1990-095 satellite (red) and the time-shifted Wind number density (black). Vertical lines indicate similar enhancements in both data sets.
boundary between two solar wind streams. The remaining events fall between these two extremes. All data in Figure 2 are from the Wind spacecraft for consistency, whereas below we present data from the closest solar wind monitors available.

2.1. Event 1: 9 September 2005

This event occurred with the closest solar wind monitor, in this case Geotail, located very close to Earth’s magnetosphere, at (14, 27, −0.4) RE. The visually identified time delay between features observed in the Geotail number density data and the geosynchronous magnetic field measured by GOES was 5 min, consistent with the location of Geotail. The Wind spacecraft was located well upstream and far off the Earth-Sun line, at (213, −94, −7) RE, and observed the sharp number density increase just a few minutes prior to Geotail, suggesting a highly inclined shock relative to the Earth-Sun line. The shock normal can be calculated assuming velocity coplanarity, such that \( n = (v_2 - v_1)/(v_2 - v_1) \), where \( v_2 \) and \( v_1 \) are the downstream and upstream velocities (Riley et al., 1996). For both spacecraft, \( v_1 = (-340, 0, 0) \) and \( v_2 = (-460, -100, 40) \), yielding a shock normal of \( n = (-0.8, -0.6, 0.2) \), or 37° in the x-y GSE plane. The velocity, \( v_p \), and proton number density, \( n_p \), measured by Geotail.

Figure 5. Locations of the magnetospheric satellites at 0300 UT on 21 February 2000 (left) and data from the solar wind and magnetospheric spacecraft (right). Note that Polar was well off the equatorial plane, located at (1.5, 3.5, 8) RE. (a) The solar wind \( |v_x| \), (b) dynamic pressure (right) and \( N_p \) (left), shifted in time by +23 min, (c) the vertical component of the magnetic field measured by GOES-10, (d) energetic electron flux from the LANL 1989-046 geosynchronous satellite, (e) energetic electron flux \( (E=50-75 \text{ keV}) \) from LANL-97A, and (f) the Polar HIST front detector electron counts \( (E>375 \text{ keV}) \).
are shown in Figures 3b and 3c, respectively, and the GOES-12 vertical component of the magnetic field, $B_z$, is shown in Figure 3c with the Geotail number density time shifted by +5 min and superimposed. The Geotail $n_p$ shows a large and sudden increase in the number density, followed by a series of 20-min periodic structures, with peak-to-peak amplitude changes of $\sim$10 particles per cubic centimeter, a roughly 20% amplitude variation. GOES-12 also observed 20-min oscillations immediately following the shock, with each oscillation associated with a solar wind density structure (Figure 3c). The amplitude of the periodic changes in both data sets was largest just following the shock and decreased thereafter. The GOES magnetic field data in isolation would suggest a damped compressional oscillation, but comparison with the Geotail number density shows that this apparent damping is a direct result of the decreasing amplitude of the driver. The Wind number density data, obtained 121 RE in Y from Geotail, exhibit some of the same variations observed by Geotail but are clearly different, providing some constraint on the along-shock coherence of these structures. The 1-min resolution $>0.6$-MeV electron flux from GOES-12 is shown in Figure 3d and shows similar periodic behavior that aligns with solar wind driving. Each peak in solar wind density and local magnetic field magnitude corresponded to a decrease in the $>0.6$-MeV electron flux, likely due to compression of the magnetosphere pushing the $>0.6$-MeV particle boundary inside geosynchronous orbit.

2.2. Event 2: 29 November 1996

The Wind spacecraft was located just upstream of Earth at (53, 10, 5) RE GSE providing solar wind measurements very near the Earth-Sun line. The propagation delay to the GOES location based on visual inspection

Figure 6. The solar wind number density (a) and velocity (b) measured by the ACE spacecraft for the 31 October 2000 event. GOES 10 magnetometer data are shown in (c) and GOES electron flux data ($E>$0.6 MeV) and GOES proton flux data ($>0.6$–4.0 MeV) are shown in (d) and (e), respectively. Vertical lines mark increases in both the time-shifted number density and the GOES magnetic field.

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was +13.5 min. Figure 4c shows the GOES-10 and GOES-8 $B_z$ component of the magnetic field. GOES 10 was located near noon magnetic local time, while GOES 8 was located postnoon, as indicated by the diurnal magnetic field signature. The solar wind number density is shown in Figure 4b, time shifted by +13.5 min. These data show a sharp increase and $\sim$20-min periodicities in the number density near 20 UT (short horizontal ticks). The initial increase is $\sim$60%, leading directly to a $\sim$60% increase in the solar wind dynamic pressure, $\rho v^2$, impacting Earth’s magnetosphere. An additional 10-min embedded oscillation is also apparent, marked with vertical ticks; the GOES-8 and GOES-10 magnetic field data also observed these suboscillations. A comparison between the GOES-10 magnetic field data with the background
variation removed, and the time-shifted solar wind density, shows good agreement for these seemingly damped oscillations (Figure 4d). Rather than being an indication of internally damped oscillations, the GOES oscillations are directly driven by solar wind density oscillations. Electron particle flux data ($E=50$–$225$ keV) from the LANL 1990-095 satellite are shown in Figure 4d. The same 20-min periodicity is observed in the electron flux, suggesting that at these energies the geosynchronous particle population responds promptly to the direct quasiperiodic solar wind driving.

The detrended GOES comparison with Wind in Figure 4c reveals further details. In addition to the sudden increase and oscillations after 20 UT, the preceding 4-hr interval contained oscillations that were observed both in the solar wind number density at in the GOES magnetic field data. Some of the more prominent peaks are marked with vertical ticks in Figure 4c. We note in particular the same period oscillations were observed in the hour prior to this feature (from 19–20 UT), showing that the discontinuity itself is not a

Figure 8. Comparison of solar wind data from Wind, Geotail, and THEMIS with GOES magnetospheric data. (a) Wind 3dp proton density and (b) proton velocity, both shifted in time by +87 min to account for ballistic propagation to Earth. (c) GOES-10 magnetic field and background fit (dashed line) and (d) the residual field from subtracting that fit. (e) solar wind data from Geotail (+8 min), THEMIS-B (−8 min), and Wind (+87 min) compared with the detrended GOES-10 magnetic field. (f) The 1-min resolution 40-keV electron flux from the GOES-13 spacecraft and (g) the same data with the background trend (gray line in f removed). Vertical lines mark increases in solar wind number density observed at all spacecraft and the associated magnetic field perturbations observed by GOES-10.
significant driver of magnetospheric oscillations. Similar oscillations were observed in the LANL 1990-095 data. Finally, there was no clear shock associated with this event. As shown in Figure 2b, this interval occurred slightly after the initial increase in velocity.

2.3. Event 3: 11 February 2000

The projected positions of Polar and the geosynchronous orbiting satellites onto the equatorial plane at 0300 UT on 11 February 2000 are shown in the left panel of Figure 5. Polar was located high latitude (λ∼50°) on the dusk flank and, based on its location, likely mapped to the dusk tail plasma sheet prior to shock arrival. GOES-10 was located at the dusk flank, while the two Los Alamos satellites 1989-046 and 97A were predusk and postdawn, respectively. The Wind satellite was located upstream in the solar wind very near the Earth-Sun line at (127, −0.3, 4.6) Re in geocentric solar magnetospheric (GSM) coordinates.

The solar wind dynamic pressure and proton number density measured by Wind is shown in Figure 5b, time shifted forward by +23 min to account for propagation to the magnetosphere. Dynamic pressure fluctuations (Figure 5b) with a period of 8 min occurred following the shock. The GOES10 measurements of the vertical component of the magnetic field (Bz) exhibit multiple oscillations following the arrival of the shock at 0300 UT. These oscillations are well correlated with increases in the time-shifted solar wind dynamic pressure. Figures 5d–5f show the energetic electron response from three different magnetospheric spacecraft. The Polar spacecraft was located at (1.5, 3.5, 8) Re GSM, near the same local time as LANL 1989-046 and GOES10, but at high latitude, likely very near the open/closed boundary. The front detector electron (E>375 keV) counts (A1) from the Polar HIST instrument observed four impulsive increases in the particle flux, to levels well above the ambient background. The plasma data from Hydra (not shown), which measures the thermal plasma, suggest that Polar entered a boundary layer region with a mix of magnetospheric and magnetosheath plasma at 0300 UT.

The LANL 1989-046 spacecraft was located just sunward of GOES10 and detected four impulsive increases in the electron flux (E=50–150 keV), which also coincided with solar wind dynamic pressure increases (Figure 5d). The enhancements appear to become increasingly dispersive. The timing of the arrival of the higher energy particles (E=105–150 keV) coincides most closely with the increases of Bz observed at GOES10. The LANL-97A spacecraft was located at the dawn flank and while it did not detect a signal in the energetic electron flux (E=50–75 keV) associated with the second impulse, the other increases correspond to dynamic pressure increases. The drift period of a 100-keV equatorially mirroring electron is ∼90 min, so the variations observed here cannot be due to drift echoes. Instead, we may be observing local, prompt, energization of particles, or the movement of particle boundaries as the magnetosphere is driven by the solar wind changes. The globally coherent response of the energetic electrons indicates that the solar wind density structures drove globally coherent magnetospheric dynamics.

2.4. Event 4: 31 October 2000

The ACE spacecraft was located in the upstream solar wind at (220, −1, −24) Re in GSM coordinates, very near the Earth-Sun line; Wind was located more than 150 Re in Y, so is not used. A sudden 30% increase in |Vx| and factor of 3–4 increase in N (Figures 6a and 6b) was observed at 1628 UT (unshifted). In the downstream shock region, the number density shows a series of ∼8-min variations, with an amplitude of ∼20%. These variations continued for at least 2 hr. Similar variations were observed in the velocity, albeit at a much lower relative amplitude (∼2%). The magnetic field data from the GOES-10 spacecraft are shown in Figure 6c. The shock arrival at the magnetosphere is indicated at 1713 UT by a sharp jump in the total field strength. The ∼8-min fluctuations observed in the number density by ACE 44 min earlier were also observed by

| Table 1 |
|---|---|---|---|
| Equivalent Length Scales of Periodic Density Structures at the Specified Periods, Assuming a Velocity of 400 km/s |
| min | mHz | Re | km | Mm |
| 2 | 8.3 | 7 | 0.5×10^5 | 50 |
| 5 | 3.3 | 20 | 1.2×10^5 | 120 |
| 20 | 0.8 | 75 | 4.8×10^5 | 480 |
| 60 | 0.3 | 225 | 14×10^5 | 1,400 |

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GOES-10 as magnetic field increases (vertical lines in Figure 6). Figures 6e and 6f show the energetic electron ($E > 0.6$ MeV) and proton flux ($E > 0.6$–4.0 MeV) from GOES-10. Both the electrons and protons show similar variations as the driving density variations, particularly between 18 and 19 UT. The electron and proton variations appear to be in phase with the number density variations.

2.5. Event 5: 27 November 2010

The Wind spacecraft was located far upstream at (220, 7, $-$23) $R_E$, near L1, while THEMIS A, D, and E were near the dayside magnetopause, and THEMIS-B, having now become ARTEMIS, was in the solar wind off the dawn flank orbiting near the Moon (Figure 1). The Wind spacecraft observed a sharp, factor of 3 increase in the number density just prior to 1910 UT (Figure 7b), without a sharp change in velocity (Figure 7a). A series of quasiperiodic, $\sim$5- to 10-min oscillations followed. This solar wind structure reached the magnetosphere almost 1 hr later, where the three THEMIS spacecraft, located in the dayside magnetosheath (note the factor of $\sim$4 increase in density compared to Wind), observed a similar increase in number density followed by similar periodic oscillations. Note the strong similarity between the Wind oscillations observed 1 hr prior and the THEMIS observations, consistent with quasi-stationary structures that have been advected by the solar wind. The decrease in THEMIS A, D, and E density at 2040 UT is due to entry into the magnetosphere. A few minutes later, ARTEMIS observed the solar wind structure near lunar orbit (Figure 7d). Note that the observations between the Wind and THEMIS + ARTEMIS spacecraft were separated in time by 60 min and

Figure 9. An interplanetary coronal mass ejection observed by the Wind spacecraft on 28 June 2013. (a) The components of the solar wind velocity, (b) the proton number density, and (c) the magnetic field in geocentric solar equatorial coordinates. Wind was located at (208, $-$80, $-$6) $R_E$ geocentric solar equatorial. The pink highlighted interval (A) is a region of unperturbed slow solar wind, while the green region (B) is the interplanetary coronal mass ejection sheath.
in the Y direction by \( \sim 50 \) \( R_E \), providing a lower limit on the timescale for evolution and azimuthal spatial coherence of these structures. Figure 7e shows magnetometer data from the GOES-13 spacecraft. For this event GOES-13 was located in the late afternoon sector and compared to the other events where GOES was closer to noon it did not see a strong compressional response. Instead, the periodicities were most clearly observed in the “normal” (N) component, which is azimuthal (Figure 7e). Finally, Figure 7f shows the 1-min energetic electron flux at three different energy levels from the GOES-13 spacecraft. The lower-energy fluxes show a strong similarity to the solar wind periodicities and the GOES magnetic field variations, while the higher-energy fluxes appear to respond more directly to the longer timescale interaction of enhanced density between 2010 and 2040 UT.

The THEMIS A, D, and E spacecraft show some embedded features at timescales shorter than 5 min. For example, both the first and second density structures observed at Wind appear as two peaks on top of a larger background at THEMIS (see 2010–2020 UT in Figure 7d). The THEMIS-B data show hints of this as well. The GOES magnetometer and electron data appear to be responding to this higher-frequency driving, as indicated between 2015 and 2020 UT. We note that at 3–5 min, the driving by the solar wind is no longer quasi-static, complicating the interaction, particularly for the energetic electrons. So although the

**Figure 10.** Zoomed in interval of the sheath interval associated with the interplanetary coronal mass ejection of 28 and 29 June 2013. (a) The solar wind velocity in geocentric solar equatorial coordinates observed by the Wind spacecraft, located at (208, −80, −6) \( R_E \) and (b) the solar wind number density. GOES magnetic field data, time shifted by −50 min to account for propagation of the Wind data from L1, are presented in (c). The solar wind number density in the downstream (green) region is shown in black in (d), while the artificially compressed data are shown in red. The pink and green shaded regions are as in Figure 9.
electrons appear to be responding to the driving, the interaction is not likely to be direct the way it is for lower frequencies.

2.6. Event 6: 25 November 2008

This event was identified as an SIR in the Jian et al. (2006) list and shows the classic features of an SIR. The Wind spacecraft was located well upstream of Earth, and off the Sun-Earth line, at (252, 47, 2) \( R_E \) in GSE coordinates. Wind observed a sharp 20% increase in velocity and a factor of 3 increase in number density (Figures 8a and 8b). This number density increase lasted approximately 5 hr. As shown previously in Figure 2f, the velocity increase at 0500 is the forward shock. The high-speed stream associated with this SIR arrived 12 hr later. Approximately 87 min after the shock was observed by Wind, the density structure impacted Earth’s magnetosphere. Geotail and THEMIS were both located in the near-Earth solar wind and observed the density structure, while GOES was in the afternoon sector moving toward midnight and observed magnetic field fluctuations associated with the dynamic pressure changes.

We show the GOES magnetic field and a background fit in Figure 8c. We subtract the background fit to highlight the variations in Figure 8d. This introduces an artificial brief negative excursion prior to the oscillations, which we indicate by coloring it gray. Figure 8e shows a comparison of the Geotail (23, 18, -7), THEMIS-B (-7.7, -30, -3.5), and Wind (252, 47, 2) density oscillations, and the related GOES magnetic field oscillations. Each of the solar wind measurements have been shifted in time to align with the GOES magnetic field. For the first 2 hr of the event, particularly between 1 and 2 UT, there is good correlation between the quasi-periodic increases in solar wind number density observed by all three spacecraft, and the GOES magnetic.
field oscillations. The good agreement between the measurements continues for \( \sim 2 \) hr, again placing a lower limit on the timescale of evolution of the solar wind structure.

We show the 1-min resolution 40-keV (black) and 450-keV (red) electron data from the GOES-13 spacecraft in Figures 8f and 8g. We have not plotted the GOES-10 particle data, which was at insufficient resolution (5-min averages) to cleanly observed the driving, and GOES-13 magnetometer data are unavailable. The GOES-13 electron data show a two-part behavior. First is an immediate increase in the particle flux near 0 UT, followed by a slow 2-hr decrease. This is seen in all electron channels of the GOES-13 detector (40–475 keV), although we show only the 40-keV channel for clarity. On top of this overall trend are small oscillations in the particle flux. To pull out more details, we have removed the background trend of both the 40- and 475-keV channels and plotted the residual in Figure 8g. The data show a prompt and coherent response to the solar wind driving, particularly near 0030–0200 UT, with a one-to-one correlation of the particle flux variations and the Geotail solar wind measurements in particular.

3. Discussion

The case studies presented here represent a broad sampling of quasiperiodic density enhancements observed following a sharp increase in solar wind number density, followed by magnetospheric oscillations at the same periodicity. This provides further direct evidence that the solar wind contains periodic density enhancements that drive magnetospheric oscillations, significantly expanding the number of case studies of such events. The observed periods were typically 5–20 min (3.3–0.8 mHz), much lower than the expected magnetospheric cavity mode periods (Hartinger et al., 2013). Since these density structures are frozen into the flow, it is appropriate to think of them as spatial structures, embedded in and carried by the solar wind flow, rather than propagating as waves (Viall et al., 2008). Table 1 provides a conversion of the timescales of the solar wind density structures into equivalent length scales, assuming a nominal solar wind speed of 400 km/s. Note that the shortest-duration (i.e., smallest) density structure at 5 min equates to a 20 \( R_E \) equivalent spatial structure that envelopes the entire dayside magnetosphere. At this period and higher (roughly 3.3 mHz and lower), the interaction of the structure with the magnetosphere is quasi-static and can be considered \( m=0 \) poloidal oscillations. The amplitude of the magnetospheric oscillations is directly related to the amplitude of the solar wind number density oscillations, as governed by \( B_n \sim n^2 \). When propagated to Earth these quasiperiodic enhancements were closely associated with similar quasiperiodic total magnetic field strength oscillations inside the magnetosphere, suggesting a direct driving of the magnetosphere by the quasiperiodic changes in solar wind dynamic pressure. At shorter timescales, less than \( \sim >5 \) min, the structure is smaller than the dayside magnetosphere, and the interaction can no longer be considered quasi-static leading to a more complicated interaction (see, e.g., the 27 November 2010 event).

In this study we focused explicitly on events that contained a sharp increase in the solar wind number density, both because the sharp increase in density is a useful fiducial marker for multispacecraft comparison and also because the sudden impulse of such events on the magnetosphere can have significant particle impacts, either via direct acceleration by the induced electric field of the shock passage (Li et al., 1993; Zong et al., 2009, 2012) or other related effects such as particle transport, loss, and resonant acceleration (see review by Hudson et al., 2008). More specifically, solar wind shock impacts on the magnetosphere are theoretically presumed to initiate global ULF pulsations. We find no evidence for such shock-induced cavity modes at the frequencies (\( f<4 \) mHz) studied here. Instead, low-frequency oscillations observed within the magnetosphere following a shock impact appear to directly driven from periodic density structures in the solar wind. For example, note for the 29 November 1996 event, the sudden appearance at both GOES spacecraft of an apparently damped magnetic field oscillations near 20 UT (Figure 4c). This type of signature—an increase in the compressional component of the magnetic field followed by damped oscillations—is exactly the type of signature predicted to occur in a cavity mode oscillation, yet it was clearly directly driven by the solar wind. We note this is consistent with the recent Hartinger et al. (2013) result that established that cavity modes were limited to \( f=3–20 \) mHz, frequencies higher than observed here.

The association of SIRs with periodic density structures is potentially significant from the standpoint of magnetospheric particle dynamics. High-speed streams are known to be efficient drivers of radiation belt flux enhancements, and SIR-driven storms are more effective at increasing energetic electron fluxes in the outer radiation belts than ICME-driven storms (Dmitriev et al., 2005; Kataoka & Miyoshi, 2006; Miyoshi &
Kataoka, 2005, 2008). There is some evidence that ULF waves, particularly at the frequencies observed here, can play an important role in the energization and transport of radiation belt particles, particularly in the outer zone (Elkington et al., 1999; Mathie & Mann, 2000; O’Brien et al., 2003; Ozeke & Mann, 2008). For all six events we demonstrated a one-to-one correspondence of magnetospheric energetic particles over a range of energies, up to several MeV - standard unit. megaelectron volts, with the periodic solar wind density structures and the magnetospheric ULF waves. All six events demonstrate that these periodic structures can have prompt, coherent, and global impacts on the energetic electron population.

Kilpua et al. (2017) found that the SIR interval itself, the region between the low- and high-speed solar wind, is associated with overall decreases in the radiation belt electron flux and suggested enhanced magnetopause shadowing as the cause. The Kilpua et al. (2017) study examined power in a few millihertz bandwidth (\(f=1.6–5.5\) mHz), rather than testing for discrete periodicities. Quasiperiodic driving by the solar wind is likely to be more impactful than broadband driving, particularly for drift resonance effects and enhancing loss through magnetopause shadowing (e.g., Elkington et al., 1999; Turner et al., 2012). Therefore, the fact that SIRs appear to have inherent periodic density structures that then drive magnetospheric oscillations could contribute to SIR geoeffectiveness in a number of different ways, for example, by enhancing radial diffusion while also periodically altering the location of both the magnetopause and particle trapping boundaries, possibly leading to an increase in shadowing efficiency. The Polar spacecraft observations from the 11 February 2000 event of enhanced particle fluxes at such high latitudes (Figure 5) suggests these structures could also produce loss of magnetospheric particles into Earth’s atmosphere, through enhanced pitch angle scattering. The impact of such solar wind driving on magnetospheric particles is highly energy and location dependent. At the timescales examined here, the observed particle impacts, across a broad range of energies from tens of keV to several MeV megaelectron volts, is likely due to motion of trapped particle boundaries driven by the forced breathing of the periodic density structures. Although not examined in this study, the integrated effect of such driving on overall loss or acceleration of the different particle populations could be important. We believe this to be a fruitful area for further research.

A critical unanswered question is the source of these density periodicities. There has been much previous research on the existence of periodic number density structures in the solar wind, and the period of...
oscillations of the events here falls into the range of these previously discussed oscillations (Kepko & Spence, 2003; Kepko et al., 2002; Viall et al., 2008; Viall, Kepko, and Spence 2009; Viall, Spence, and Kasper 2009). These types of quasiperiodic density structures have been observed in the solar wind away from the types of shock structures examined here and appear to be ubiquitous, especially in the slow wind. Apart from the apparent association with a sharp density increases, which was a deliberate selection criterion, there are no obvious differences between the periodic density structures observed in this study compared to those in previous studies. This leads to the question of whether shock and discontinuity associated oscillations reported here are generated by the shock or whether they are ambient features in the solar wind that are processed by the shock. There is now substantial in situ (Di Matteo et al., 2019; Kepko et al., 2016; Viall, Spence, and Kasper 2009) and remote sensing (DeForest et al., 2018; Viall & Vourlidas, 2015; Viall et al., 2010) evidence that periodic density structures are formed in the solar corona, at the time of solar wind formation. The six events span a large range in amplitude of interacting velocity streams, with velocity jumps ranging from 50–300 km/s, yet all the events otherwise show remarkably similar characteristics in terms of the periodic density structures. We note that the two events that did not exhibit a shock (29 November 1996 and 27 November 2010) appeared qualitatively no different than the four that did. Likewise, the event that was part of a classic SIR (Event 6) appeared qualitatively no different than the other five. It is therefore unlikely that the structures are directly related to the forward shock itself. We explore this a bit further below.

Figure 9 shows a new event that has characteristics of the six events previously presented, including a shock and periodic density structures in the downstream region. Yet, unlike the six events shown above, this was associated with a large ICME, and the periodic density structures were observed in the ICME sheath region, as opposed to a SIR. Physically, however, both types of events represent regions of compressed solar wind at the leading edge of a faster solar wind as it impacts and overtakes a slower solar wind. For this event, the Wind spacecraft was located at (208, −80, −6) RE, well off the Earth-Sun line. The ICME is well defined by the magnetic field signatures and extends from early on 28 June to midday on 29 June (Figure 9c). The shaded interval (B) in Figure 9 highlights the ICME sheath region, while shaded region (A) highlights an unperturbed interval of slower solar wind upstream of the ICME. The sheath contains ~15- to 20-min periodic density structures, and these are shown in Figure 10b. Similar oscillations were observed 50 min later by the GOES spacecraft, which was located in the dayside magnetosphere during most of this interval (Figure 10c). Despite the very large azimuthal separation (80 RE) between Wind and Earth, there is a clear association between the Wind-observed ~15- to 20-min density variations and the GOES magnetic field measurements, particularly between 17 and 18 UT.

The ICME sheath is a region of solar wind magnetic field and plasma that has been plowed into and piled up due to the faster-moving magnetic cloud that was injected into the solar wind earlier. Any existing structures in the slower solar wind ahead of the coronal mass ejection would have been compressed and amplified en route to 1 AU. If the periodic density structures observed in the downstream shock region were preexisting structures in the slower solar wind, then they should be present at a lower amplitude and uncompressed (stretched out) in the unperturbed region (A). To test this hypothesis, we artificially compressed the unperturbed solar wind in interval (A). We first converted the time series to a spatial series, such that \( x_i = V_f (T_f + 1 - T_i) \), then summed the number density over three point windows, in effect compressing the spatial structures by a factor of 3, consistent with the density jump observed at the shock. We then converted the length series back into time, assuming a constant 450-km/s velocity for simplicity. This time series is shown in Figure 10d in red. Note that the 5 hr of compressed data shown in Figure 10d represents 15 hr of observed solar wind data.

We applied the same compression technique to the event of 25 November 2008, which was a strong SIR (see Figure 2f). We show the original solar wind number density data in Figure 11a, and the compressed data (also compressed by a factor of 3) are shown in Figure 11b in red. Four new quasiperiodic enhancements, labeled A–D, appear in the preshock solar wind region and appear similar to the periodic structures that were observed following the shock from about 2230 onward. We have identified the same A–D intervals in the original solar wind data (Figure 11a), where they appear as longer (approximately 1 hr vs. 20 min), smaller-amplitude periodicities. Both of these events strongly support our assertion that the observed periodic density structures downstream of the solar wind shock were not created by the shock, but instead existed in the ambient solar wind, and were amplified and compressed as the faster solar wind ran into it.
Our results indicate that the quasiperiodic mesoscale structures within the SIR were previously structures in the uncompressed slower solar wind ahead and are consistent with the belief that these structures are created at the time of solar wind generation. Evidence for a solar source of periodic density structures includes remote sensing of these structures down to a few solar radii (Viall & Vourlidas, 2015; Viall et al., 2010) and in situ studies using both Helios (Di Matteo et al., 2019) and L1 observations (Kepko et al., 2016; Viall, Spence, and Kasper 2009). Kepko et al. (2016) recently examined a 12-hr interval of solar wind that contained periodic density structures, which previously had been studied as driving magnetospheric pulsations (Kepko & Spence, 2003). The composition and magnetic field changes of that event indicated that the structures were formed by quasiperiodic S-Web magnetic reconnection back at the Sun (Antiochos et al., 2011; Higginson & Lynch, 2018). The observations here are consistent with that picture and provide further evidence for a solar source of periodic density structures.

The observations presented in this paper provide minimums on both the azimuthal coherence and temporal stability of these structures, but we note that it is only the lack of spacecraft measurements beyond L1 halo orbits that preclude a broader investigation. Periodic density structures existed for up to several hours behind the discontinuities. For the 9 September 2005 event, the 20-min periodicities were present for 3 hr following the shock. At 450 km/s, this corresponds to a spatially striated region of solar wind of 5 Gm, containing embedded periodic 540-Mm mesoscale structures. Although the preexisting structures were all formed at the time of solar wind release and acceleration, the newly amplified and compressed structures near the interfaces are “younger” than those further downstream. There is an interplay between forces working to compress and amplify the smaller amplitude and spatially larger preexisting structures at the leading edge of the stream interface and processes such as waves and turbulence that lead to the decay of such structures further downstream from the shock, and this interplay bears further investigation.

The distance between the solar wind monitor and Earth’s magnetosphere for these events was up to 261 >RE (1.6 Gm) with a maximum delay of 87 min between the solar wind observation and the magnetospheric response. For the 25 November 2008, event the azimuthal separation between the Wind and THEMIS-B spacecraft, which both observed similar density structures, was 77 RE, indicating large azimuthal coherence of the structures. For the 9 September 2005 event (Figure 3), Wind and Geotail were separated in azimuth by 121 RE, and while the overall Np structure between the spacecraft was similar, the periodic density structures differed.

The 25 November 2008 event provides further insight into the structuring of the periodic density structures. Figure 12 shows a comparison of just THEMIS-B and the Wind number density measurements. Near the beginning of the event, near 0 UT, the periodic structures between the spacecraft were aligned (Figure 12a). Near the end of the event, near 4 UT, the periodic density structures seen in Wind and THEMIS-B came into agreement again, but at a different time shift, as indicated in Figure 12b, where we have aligned the entire 5-hr density enhancement. The best alignment for the density periodicities at the start of the interval leads to a small gap in time of 6 min between the sharp increase at the leading edge. THEMIS-B and the other near-magnetosphere spacecraft observed a density structure at the leading edge that was not observed by Wind. This difference is also seen in Figure 8e. This alignment of the periodic density structures at the beginning of the event produces an out of phase relationship at the end of the event. If instead we align the leading and trailing edges, the three large density periodicities at the end of the interval line up. Wind and the magnetospheric spacecraft were separated in space by 260 RE in X and 77 RE in Y, and in time by 81 min. Since the overall structure, from 0000–0430 UT, is aligned across the spacecraft, a temporal change explanation is unlikely. Instead, the observations are consistent with flux tubes at the leading edge that are twisted or misaligned with the front edge of the density structure relative to those at the back edge. As this was a very strong SIR, it contained a strong velocity shear in the Y and Z components of 25–50 km/s, which could lead to twisting of the flux tubes within the SIR.

The association of these periodic density structures with SIRs and ICME sheath regions, and the resultant compression of the solar wind plasma by these interactions, suggests a link to planar magnetic structures (Nakagawa et al., 1989). Planar magnetic structures are intervals over which the variations and rotations of the magnetic field occur in a single plane and are thought to be preexisting discontinuities in the solar wind that have been amplified and then aligned by the faster solar wind compressing them (Neugebauer et al., 1993). Whether the periodic density structures behind the forward shocks of SIRs are strictly planar
magnetic structures is not relevant for our study of magnetospheric effects. However, our observations here support the theory that preexisting structures in the solar wind are compressed, aligned, and then amplified by the faster speed wind behind them.

4. Conclusions
We have presented six SIR events that contain quasiperiodic density structures downstream of the leading edge of the interface. After accounting for solar wind propagation, which was up to 90 min, these periodic density structures were then observed to directly drive global magnetospheric oscillations with the same periodicity. For all events, we demonstrated a prompt and coherent energetic particle response to the periodic structures across a range of particle energies. The events ranged from strong SIRs, with a large jump in velocity across the region and a forward shock, to weak SIRs, where the velocity change was minor and no shock had yet developed. Despite the range of velocity change, each event contained periodic density structures with similar characteristics. We further presented evidence that these periodic structures appear to be preexisting structures in the slower solar wind and that these preexisting structures are amplified and compressed as the higher-speed flow pushes into the slower wind. The shock or discontinuity itself appears to have no role in generating these periodic structures nor in generating the <4 mHz magnetospheric oscillations.

A key point is that the structures injected into the solar wind near the Sun and that are swept up and amplified by the higher-speed solar wind are quasiperiodic, rather than random or turbulent. The resultant magnetospheric impact is therefore coherent, and the change in total field strength inside the magnetosphere and changes to the magnetopause location occurs in a quasiperiodic manner. The period of these global, compressional (poloidal) ULF waves, typically 5–20 min, falls within and extends beyond the Pc5 band, which are known to be important for energetic particle acceleration, loss, and transport, particularly in the outer radiation belts. Other papers have observed even lower-frequency driving, although without examining the particle impacts (e.g., Kepko et al., 2002). Since these directly driven pulsations extend beyond the Pc5 band, their magnetospheric impacts are underexplored. Studies examining magnetospheric impacts of low-frequency ULF pulsations should therefore not focus exclusively on the Pc5 bandwidth.

For every event studied here, the periodicity of the solar wind driver was clearly imprinted upon energetic magnetospheric particles. The association of SIRs, which are known to have substantial impacts upon the radiation belts, with periodic density structures likely enhances their effectiveness. While these results show that there is driving of energetic particles by periodic solar wind density structures, the effects are not simple. There are global and local particle responses to the interaction, and the response has time-dependent and quasi-static aspects that is energy dependent and should be taken into account particularly when modeling such interactions.

Finally, while ULF waves are known to be important for radial transport of radiation belt electrons, the current state of the art relies on empirical relationships of ULF wave power to geomagnetic indices (e.g., Kp) to model this transport. But ULF power departs significantly from these empirical representations on short timescales, and empirical representations are often unable to accurately describe the diffusion rates (e.g., Mann et al., 2016) that these periodic density structures exist in the solar wind and drive global compressional oscillations, and are not contained in these empirical relationships, may be an important missing piece to specifying accurate rates of energy-dependent acceleration, transport, and loss within Earth’s radiation belts. Additionally, it is believed that preconditioning of Earth’s magnetosphere is an important factor in dictating whether the radiation belts are enhanced or not during a particular event. These solar wind mesoscale structures form, along with the magnetic field, the structures that control this preconditioning.

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