Multiradar observations of substorm-driven ULF waves

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Abstract  A recent statistical study of ULF waves driven by substorm-injected particles observed using Super Dual Auroral Radar Network (SuperDARN) found that the phase characteristics of these waves varied depending on where the wave was observed relative to the substorm. Typically, positive azimuthal wave numbers, \( m \), were observed in waves generated to the east of the substorms and negative \( m \) to the west. The magnitude of \( m \) typically increased with the azimuthal separation between the wave observation and the substorm location. The energies estimated for the driving particles for these 83 wave events were found to be highest when the waves were observed closer to the substorm and lowest farther away. Each of the 83 events studied by James et al. (2013) involved just a single wave observation per substorm. Here a study of three individual substorm events is presented, with associated observations of multiple ULF waves using various different SuperDARN radars. We demonstrate that a single substorm is capable of driving a number of wave events characterized by different azimuthal scale lengths and wave periods, associated with different energies, \( W \), in the driving particle population. We find that similar trends in \( m \) and \( W \) exist for multiple wave events with a single substorm as was seen in the single wave events of James et al. (2013). The variety of wave periods present on similar \( L \) shells in this study may also be evidence for the detection of both poloidal Alfvén and drift compressional mode waves driven by substorm-injected particles.

1. Introduction

Three case study substorm events are presented where each substorm is associated with multiple observations of ultra low frequency (ULF) pulsations in the frequency range of 0.7 to 3.5 mHz. The ULF waves in each event exhibit westward phase propagation and are likely to be driven by westward drifting populations of recently injected protons. This study aims to extend the work of James et al. (2013), where 83 ULF pulsations were each associated with substorm activity and whose characteristics were found to vary depending upon azimuthal distance from the location of the particle injections. This study makes use of SuperDARN (Super Dual Auroral Radar Network) [Greenwald et al., 1995; Chisham et al., 2007] data supplemented by ground magnetometer and auroral images to study each multiple ULF wave event in detail.

Magnetospheric ULF waves include Alfvén waves standing between two conjugate points in the Earth’s ionosphere, and compressional waves, and can have sources both internal and external to the magnetosphere. Waves driven by energy sources external to the magnetosphere (e.g., Kelvin-Helmholtz instability on the magnetopause or solar wind buffeting) are often characterized by low azimuthal wave numbers (\( m \)), or large azimuthal scale sizes. In contrast, wave energy sources internal to the magnetosphere, such as drift-bounce resonances and other wave-particle interactions, often generate waves with high-\( m \) numbers or small-scale sizes. It should be noted that there is also evidence that some low-\( m \) and intermediate-\( m \) ULF waves may also be driven by wave-particle interactions within the magnetosphere [Yeoman et al., 2010; James et al., 2013].

Multispacecraft case studies [e.g., Hughes et al., 1979; Takahashi et al., 1990; Eriksson et al., 2006; Schafer et al., 2007, 2008; Liu et al., 2013; Dai et al., 2013] and statistical studies [Takahashi et al., 1985; Anderson et al., 1990; Woch et al., 1990; Engebretson et al., 1992; Agapitov and Cheremnykh, 2011] have associated high-\( m \) ULF waves with ion populations gradient curvature drifting westward as part of the global ring current. One such population high-\( m \) waves, which peaks in occurrence around noon during the recovery phases of geomagnetic storms, is associated with dayside drift mirror instabilities [Takahashi et al., 1985; Woch et al., 1990; Engebretson et al., 1992]. Another population is most commonly observed in the dusk sector, during the onset of geomagnetic storms [Anderson et al., 1990; Woch et al., 1990]. The westward phase propagation of these wave populations suggests that they were generated by clouds of westward drifting ions injected by substorm activity.
A special population of the high-\textit{m} ULF waves, so-called “the storm time compressional Pc5 pulsations,” has periods longer than the shear Alfvén waves on the same \textit{L} shells. They can represent a manifestation of the drift compressional modes [Crabtree et al., 2003; Crabtree and Chen, 2004; Klimushkin and Mager, 2011; Mager et al., 2013], the most common kind of the particle driven compressional ULF modes that can exist in finite pressure inhomogeneous plasmas. The coupling of these modes with the Alfvén waves leads to the possibility of the observation of high-\textit{m} modes at the same time [Mager et al., 2015]. If the \textit{m} number is high enough, the Alfvén and drift compressional modes are merged into the single drift ballooning coupling mode, a subject of the ballooning instability; the same effect is achieved if strong pressure gradient is present in the magnetosphere [Klimushkin et al., 2012].

The ionosphere acts as a reflection point for ULF wave activity, where \textit{E} region Pedersen currents screen the wave field from the ground, and associated Hall currents provide a signal rotated by 90° [Hughes, 1974; Hughes and Southwood, 1976; Walker et al., 1978]. Wave activity below the \textit{E} region is highly evanescent, so waves become highly attenuated between the ionosphere and the ground such that pulsations with scale sizes less than the ionospheric height cannot usually be resolved at the ground. This makes the observation of high-\textit{m} ULF waves using ground based magnetometers difficult, although examples have been seen during disturbed conditions. During the main phase of an intense geomagnetic storm, Pilipenko et al. [2001a, 2001b] was able to use ground magnetometers to identify high-\textit{m} waves among Pi3 pulsations, where Pi3 waves can be the ground counterparts of Pc5 pulsations observed using satellites, as was found in Vaivads et al. [2001] for Ps6 waves, a variety of Pi3 wave. It is possible for large amplitude waves with moderately large azimuthal wave numbers, \(|m| = 15–40\), such as giant pulsations, Pg [e.g., Chisham, 1996; Chisham et al., 1992; Mager and Klimushkin, 2013], to overcome the screening of the ionosphere in order to be observed by ground magnetometers. The westward phase velocity of ground Pg, Pi3, and Ps6 pulsations, like the majority of poloidal pulsations observed by spacecraft is consistent with the idea that the energy source of high-\textit{m} waves is within populations of westward drifting energetic protons.

The higher spatial resolution of ionospheric radar observations makes them a powerful tool for studying high-\textit{m} ULF waves [e.g., Fenrich et al., 1995; Yeoman and Wright, 2001; Yeoman et al., 2008]. Such waves tend to appear mainly during periods of increased geomagnetic activity [Yeoman et al., 2000], although large populations of high-\textit{m} waves can also be observed during less active times. Low-energy injected protons are usually considered to be the source for these quiet time waves, where small convection electric fields and the low disturbance levels would be required for the protons to be able to drift westward and drive wave activity at the dawn flank [Chisham, 1996]. Recently, the dependence of the drifting particle energies and the azimuthal scale sizes of such waves on \textit{L} shell was examined by Yeoman et al. [2008] who found that larger \textit{m} numbers were observed at higher \textit{L} shells, which implied that there is a decrease in the energy of the drifting particles as latitude increased. Alongside the azimuthal phase propagation, radars are also able to detect the ULF wave phase propagation in the radial (latitudinal) direction, where it has been shown that high-\textit{m} waves typically exhibit an equatorward phase velocity component, in contrast to low-\textit{m} waves which typically exhibit poleward phase propagation [Grant et al., 1992; Yeoman et al., 1992].

A strong indicator that high-\textit{m} ULF waves are driven by energetic particles has been provided by a number of cases when pulsations appear at some azimuthal location coinciding with a cloud of energetic particles injected during substorm expansion [Chisham et al., 1992; Wright et al., 2001; Zolotukhina et al., 2008]. The injected particles may form a bump-on-tail velocity distribution, which could provide an energy source for wave-particle interactions. Drift or drift-bounce resonances could form from this instability, where the excited waves oscillate with the eigenfrequency of the field line on which the particles are drifting [Baddeley et al., 2005a, 2005b; Mager and Klimushkin, 2005]. Mager and Klimushkin [2007, 2008] suggested another theory for this process, where poloidal waves were generated by nonsteady azimuthal currents associated with azimuthally drifting clouds of substorm-injected plasma. This mechanism is able to explain the equatorward phase propagation present in poloidal ULF waves as observed using radars [Mager et al., 2009]. Pilipenko et al. [2001a] had earlier associated a moderately high-\textit{m} Pi3 wave event with a fluctuating transverse current which developed during a large storm. The nonsteady current of Pilipenko et al. [2001a] and Mager and Klimushkin [2007, 2008] may provide a seed for the oscillation, which is then further amplified as it extracts energy from the bump-on-tail instability provided by the substorm-injected particles.
The radar observations of waves exhibiting westward phase propagation [e.g., Chisham et al., 1992; Fenrich et al., 1995; Yeoman et al., 2008] are typically associated with westward drifting proton populations with energies in the range 10–100 keV. A more recent case study by Yeoman et al. [2010] investigated the observation of another equatorward propagating wave which occurred immediately following the expansion of a nearby substorm. Unlike the events considered in Yeoman et al. [2008], this wave exhibited eastward phase propagation. The direction of the phase propagation suggested that this particular wave may have been driven by an eastward drifting cloud of recently injected, energetic electrons. The energy of these electrons was estimated at 25–70 keV between L shells of 7.5 and 15. The 580s period of the wave observed by Yeoman et al. [2010] was somewhat longer than in previous observations. Yeoman et al. [2010], in agreement with the theory developed by Mager and Klimushkin [2007, 2008], attributed this long period to the wave occurring close to midnight shortly after substorm onset, where the field lines would have been stretched, resulting in lower eigenfrequencies. With an unusually low azimuthal wave number of \( m = 13 \) and a higher than expected inferred driving particle energy (\( \sim 33 \) keV at the central L shell), Yeoman et al. [2010] suggested that the characteristics of the wave could be controlled by the proximity of the wave to the substorm.

A statistical study of substorm-driven ULF waves similar to that analyzed by Yeoman et al. [2010] which was later undertaken by James et al. [2013] in order to examine the suggestion that the proximity of the wave to the substorm had an effect upon the wave's phase characteristics. James et al. [2013] examined 83 events, in each of which a ULF pulsation was observed shortly after the onset of a substorm. The \( m \)-numbers of the waves in this study were found to vary such that waves with positive \( m \) were observed to the east of the location of the substorm and negative \( m \) to the west, while the magnitude of \( m \) appeared to increase with the azimuthal separation of the substorm and the observed wave. The sign change in \( m \) near the substorm location was interpreted as proton-driven waves to the west of the substorm and electron-driven waves to the east. Similarities in the characteristics of the eastward and westward propagating waves provided strong evidence for the viability of electrons as drift-resonant driving particles. Estimates of the driving particle energies were made for each event ranging from \( -1 \) to 70 keV, where the most energetic estimates typically existed within close proximity of the substorm, while the waves driven farther away were associated with much lower energy particles.

Each of the events presented by James et al. [2013] consisted of a single wave observation associated with each substorm. As such there was no clear indication as to whether a single substorm particle injection could drive waves with a variety of characteristics at different times and locations, or whether similar trends to those described in James et al. [2013] would be reflected in any such multiple wave observations driven by an individual substorm event. In this study we address this issue by studying three events where data from multiple SuperDARN radars were available to diagnose the wave events at different azimuthal separations during three different substorms to ascertain whether \( |m| \) increases in magnitude with azimuthal separation from the substorm and whether the highest energy particles drive wave events closest to the substorms in individual substorm events.

2. Instrumentation

To study each of these three events we used data from various SuperDARN (Super Dual Auroral Radar Network) [Greenwald et al., 1995; Chisham et al., 2007] radars located in North America and Iceland. For event 1 we observed ULF waves using the Kapuskasing (kap), Saskatoon (sas), and Kodiak (kod) radars as described in section 3.1. In event 2 we used Prince George (pgr) and Kodiak (kod) as presented in section 3.2. Finally, in event 3 we used Saskatoon (sas) and Prince George (pgr), as presented in section 5. Typically, these radars use a 16 beam scan, where each beam contains 75 range gates and is separated by 3.24°. Each range gate is separated by 45 km, where the first range gate exists 180 km from the boresite of the radar. A variety of scan modes were in operation during the events studied here where data cadences for individual beams ranged from 3 to 120 s.

Events 1 and 2 are associated with substorm expansions taken from the list of substorms identified by Frey et al. [2004] using the FUV (Far Ultraviolet Imager) instrument on board the IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) [Mende et al., 2000a, 2000b] spacecraft. This list contains the time and location of 4193 substorms between May 2000 and December 2005. Here we use the WIC (Wideband Imaging Camera) data from IMAGE FUV to track the location of the substorms as they expanded after onset as discussed in sections 3.1 and 3.2.
In event 3 the substorm was identified by means of the CARISMA (Canadian Array for Realtime InvestigationS of Magnetic Activity) [Mann et al., 2008] fluxgate ground magnetometer network, formerly the CANOPUS (Canadian Auroral Network for the OPEN Program Unified Study) [Mann et al., 2008] network. The substorm itself was identified within a list of substorm Pi1 and Pi2 onsets detected using the Pinawa (PINA) flux gate magnetometer in Manitoba [Mann et al., 2008].

Additional ground based magnetometers from CARISMA/CANOPUS, IMAGE (International Monitor for Auroral Geomagnetic Effects) [Lühr, 1994], SuperMAG, and INTERMAGNET (International Real-time Magnetic Observatory Network, http://www.intermagnet.org/index-eng.php) were used in each of the three events to locate the ionospheric footprint of the substorm current wedge (SCW) [McPherron et al., 1973] associated with the substorms.

SuperMAG combines the data from more than 300 ground magnetometer stations. The data supplied to SuperMAG are processed such that each station has an identical time resolution and the data have baselines removed [Gjerloev, 2012]. This technique converts data from geographic to geomagnetic coordinates then removes slowly varying offsets and trends alongside any diurnal trends in order to leave perturbations due to ionospheric currents. We employed this technique of baseline removal to data from each of the CARISMA/CANOPUS, IMAGE, and INTERMAGNET arrays.

We compared the SCW of 27 substorms with the IMAGE FUV data, to ensure the use of magnetometers to infer the substorm location did not introduce any systematic offset in the substorm location identification; however, in event 3 the magnetometer data alone were used to identify the substorm location, as this event did not occur during the lifetime of the IMAGE spacecraft.

3. Data

The data treatment in this study closely follows the techniques used by James et al. [2013]. Substorms to be analyzed were selected from the above list such that their onset location occurred within ∼50° magnetic longitude of the field of view of any of the SuperDARN radars that were operational at the time of the substorm. Data from nearby radars were surveyed in order to find events in which ULF pulsations occurred following the onset of each substorm. The list of substorms was then reduced to only include those where waves, on which it was possible to perform reliable Fourier analysis, could be observed at multiple locations by different radars. Finally, each event where there were multiple substorms and those in which it was not possible to confidently locate the substorm onset and expansion using IMAGE FUV were eliminated to reduce the ambiguity in the location of particle injection. Two events remained where there were multiple wave observations at a range of longitudinal separations relative to their associated substorms.

In order to track the size and location of the substorm in both events, the background and dayglow of the auroral images provided by IMAGE FUV which was removed using the method described by Laundal [2010] and Reistad [2012]. Then the approximate azimuthal and latitudinal limits for each image of the auroral substorm were defined by a threshold where the auroral intensity drops below ~5% of its most intense value for the entire expansion phase. The 5% threshold was found to be reliable enough to allow the removal of most background auroral features without the removal of the initial brightening of the UV aurora at the time of substorm onset.

Fourier analysis was used to determine the dominant frequency for each of the ULF waves observed, which was typically the same everywhere that the wave could be seen within the radar's field of view. The azimuthal phase propagation for each wave was derived from the Fourier phase values at the dominant frequency of the wave, taken from several range gate and beam combinations covering a range of magnetic longitudes, while remaining approximately constant in magnetic latitude. The azimuthal wave number was then calculated as the gradient of Fourier phase as a function of magnetic longitude.

3.1. Substorm Event 1, 24 November 2000
3.1.1. Substorm Observations

The substorm UV aurora measured by the IMAGE FUV instrument are presented in Figure 1 in magnetic latitude-magnetic local time coordinates, where noon is at the top of each panel, magnetic latitude is represented by concentric circles in 10° increments and magnetic local time (MLT) is displayed in 1 h increments. Substorm onset occurred at ~04:21 UT on 24 November 2000 over Canada with the UV aurora expanding and strengthening over the next ~40 min. The ground instrumentation used to investigate the wave activity...
Figure 1. IMAGE FUV data during the substorm expansion phase shortly after onset on 24 November 2000 at 04:21 UT. Data are shown for the Northern Hemisphere and are oriented such that noon is at the top of each panel and dawn to the right where concentric circles represent magnetic latitude in 10° intervals and magnetic local time is displayed in 1 h intervals. IMAGE auroral data are shown for where the intensity is greater than 5% of the maximum intensity during the entire substorm event where green corresponds with low intensity aurora and red is the most intense. The figure includes the locations of the radar fields of view of Kodiak, Alaska (kod, blue); Saskatoon, Canada (sas, red); and Kapuskasing, Canada (kap, yellow) along with the two chains of magnetometers used. The radar beams and range gates used to characterize the waves are highlighted in each field of view. The black box present just before local midnight shows the approximate latitudinal and longitudinal extent of the substorm UV aurora. The time stamp for each image is displayed above each panel. The green and orange lines connecting magnetometers will be discussed in section 4.

generated by the substorm is also shown in Figure 1 in which the approximate location of the substorm at the time of onset given by Frey et al. [2004] is represented by a black box just west of local midnight. The latitudinal and longitudinal limits of the box are defined by where the number of WIC counts reaches ~5% of the peak counts observed during the substorm. This figure shows that the fields of view of the three radars used are all west of the substorm, where James et al. [2013] would suggest that each of these waves should have a westward phase propagation.

3.1.2. Wave Observations

Figure 2a shows the line-of-sight velocity as measured by the Kapuskasing radar between 04:20 and 05:00 UT as a function of magnetic longitude, where red represents flow velocities moving away from the radar and blue toward. The velocity traces are presented in Figure 2b, where each trace is separated by 100 m s⁻¹. Oscillations in the measured velocity, with a period of ~720 s (a frequency of 1.4 mHz), became apparent in the radar data shortly after the onset of the substorm (04:21 UT) at around 04:23 UT as would be expected due to the very close proximity of the radar to the substorm as seen in Figure 1. The repeating black lines in Figure 2a are derived from the Fourier analysis of the wave and represent the wave “crests” as calculated from the Fourier phase at the dominant frequency of the wave. The azimuthal wave number, m, of this wave calculated from the Fourier phase (shown in figure 2g) is −9 which corresponds with a westward phase propagation, as expected.
Figure 2. Color coded range-time-intensity (RTI) plots of the line-of-sight velocity as observed by (a) Kapuskasing, from 04:20 to 05:00 UT; (c) Saskatoon, from 04:40 to 05:20 UT; and (e) Kodiak, from 05:00 to 05:40 UT on 24 November 2000 in universal time-magnetic longitude coordinates, following the substorm onset at 04:21 UT depicted in Figure 1, where blue corresponds to flow toward the radar and red away from the radar. The radar beam and range cells used to collect the data are listed along the right-hand side of the RTI plots. Below each RTI plot is the corresponding line-of-sight velocity trace as measured by the radar, where each trace is separated by (b, d) 100 m s\(^{-1}\) and (f) 50 m s\(^{-1}\). Oscillations in the velocity as measured by Kapuskasing, Saskatoon, and Kodiak exhibit westward phase propagation at 1.47, 2.50, and 3.51 mHz, respectively, where the Fourier phases for each radar are plotted against (g–i) magnetic longitude. The phases are then used to determine the positions of black lines in each RTI plot to represent wave “crests” present in the data.
Figure 2c presents data from the Saskatoon radar in the same format as Figure 2a but now for a slightly later time interval of 04:40–05:20 UT. The raw line-of-sight velocity data are also plotted in Figure 2d, where each trace is separated by 100 m s\(^{-1}\). Wave activity is detected in the Saskatoon radar data between 04:40 and 04:50 UT, starting approximately 20 min after the onset of the substorm at 04:21 UT. In this case Fourier analysis of the wave revealed a period that was somewhat lower than that previously observed at Kapuskasing at \(\sim 400\) s (a frequency of 2.5 mHz). Figure 2h shows that this wave exhibited westward phase propagation, as at Kapuskasing, but the azimuthal phase propagation at Saskatoon was more rapid, with a derived azimuthal wave number, \(m\), being slightly larger at \(\sim -19\).

Figures 2e and 2f show data from the Kodiak radar in the same format as Figures 2a and 2b, with an even later time interval of 05:00–05:40 UT. Wave activity was present from \(\sim 05:12\) UT where Fourier analysis revealed a lower wave period than both the waves observed using Saskatoon and Kapuskasing at \(\sim 285\) s (a frequency of 3.5 mHz). With an azimuthal wave number of \(m = -44\), this wave exhibited a more rapid westward phase propagation than those at Kapuskasing and Saskatoon.

The azimuthal phase propagation frequency, \(\omega_w\), of these waves is given by

\[
\omega_w = \frac{2\pi}{\tau m} = \frac{\omega}{m},
\]

where \(\omega\) is the wave’s angular frequency, \(\tau\) is the wave period, and \(m\) is the azimuthal wave number discussed above. The angular frequency of the wave can be related to the angular drift frequency, \(\omega_d\), and bounce frequency, \(\omega_b\), of the driving particles, assuming a drift-bounce resonance is the wave source [Southwood, 1969],

\[
\omega - m\omega_d = N\omega_b,
\]

where \(N\) is the bounce harmonic number. In the situation where the driving particles are drift resonant (\(N = 0\)), equation (2) becomes

\[
\omega - m\omega_d = 0,
\]

which, when combined with equation (1), can be used to show that the azimuthal phase propagation of the wave, \(\omega_w\), is equivalent the angular drift frequency of the driving particles, \(\omega_d\).

The energy of the particles can also be estimated using the expression

\[
\omega_d = -\frac{6W(L(0.35 + 0.15 \sin \alpha))}{B_sR_E^2} + \frac{90 \left(1 - 0.159K_p + 0.0093K_p^2\right)^{-3}}{B_sR_E^2} L^3 \sin \phi,
\]

where \(W\) is the particle energy, \(L\) is the \(L\) shell, \(B_s\) is the equatorial magnetic field strength, \(\alpha\) is the equatorial pitch angle, \(K_p\) is the planetary magnetic activity index, \(R_E\) is the Earth’s radius, and \(\phi\) is the azimuthal position of the particle anticlockwise from local midnight [Yeoman and Wright, 2001].

Following the analysis of James et al. [2013] and assuming a drift-resonance condition as the wave source, the angular drift frequencies and inferred particle energies corresponding to the three waves portrayed in Figure 2 are presented in Table 1. The energies in Table 1 are presented as a range of energies, which are calculated from the range in \(L\) shells over which the wave is visible in the radar field of view. In each case, \(\omega_d\) is negative, corresponding to westward drifting ions as the energy source. In a similar manner to the results presented by James et al. [2013], the magnitude of \(\omega_d\) is higher nearer to the epicenter of the substorm where the lowest \(m\) number was observed by the Kapuskasing radar and is lower farther from the substorm where the \(m\) number is at its highest. Also similar to James et al. [2013], the particle energies appear to be highest closest to the substorm and get progressively lower as they drive the waves observed at larger azimuthal separations from where they were initially injected by the substorm.

### 3.2. Substorm Event 2, 6 September 2001

#### 3.2.1. Substorm Observations

Figure 3 shows the IMAGE FUV data in the same format as in Figure 1 where the onset of the substorm occurs over western Canada then proceeds to spread rapidly eastward and westward. The onset of the substorm occurred at \(\sim 06:25\) UT on 6 September 2001 and continued to expand for \(\sim 50\) min. In a similar manner to
Table 1. Attributes of the Waves, and the Particles That Drive Them, During All Three Events, Where $m$ is the Azimuthal Wave Number, $\omega_d$ is the Angular Drift Frequency, $W$ is the Inferred Particle Energy, and $\lambda$ is the Longitudinal Separation of the Wave Observation From the Substorm Onset and the Error Is Half the Width of the Substorm in Longitude.

| Radar      | Wave Period (s) | $m$   | $\omega_d$ (rad s$^{-1}$) | $W$ (keV) | $\lambda$ (deg) | $\delta T$ (min) | $\delta T_{\omega}$ (min) | $L$ shell |
|------------|-----------------|-------|---------------------------|-----------|------------------|-------------------|--------------------------|-----------|
| Event 1    |                 |       |                           |           |                  |                   |                          |           |
| Kapuskasing| 720             | −9    | $-1.0 \times 10^{-3}$     | 58−66     | −3 ± 7           | 2                 | 0.87 ± 2.03             | 7.21      |
| Saskatoon  | 400             | −19   | $-0.8 \times 10^{-3}$     | 27−42     | −33 ± 7          | 19                | 11.9 ± 2.52              | 9.98      |
| Kodiak     | 285             | −44   | $-0.5 \times 10^{-3}$     | 20−23     | −79 ± 7          | 51                | 46.0 ± 4.07              | 9.37      |
| Event 2    |                 |       |                           |           |                  |                   |                          |           |
| Prince George | 1440           | −12   | $-0.37 \times 10^{-3}$    | 8−19      | −12 ± 11         | 0                 | 9.35 ± 8.60              | 9.08      |
| Kodiak     | 1350            | −22   | $-0.25 \times 10^{-3}$    | 2−10      | −26 ± 11         | 23                | 30.3 ± 12.8              | 9.78      |
| Event 3    |                 |       |                           |           |                  |                   |                          |           |
| Prince George | 330            | −43   | $-0.44 \times 10^{-3}$    | 28−36     | −38 ± 44         | 52                | 25.2 ± 29.2              | 5.52      |
| Saskatoon  | 410             | −30   | $-0.51 \times 10^{-3}$    | 31−48     | −16 ± 44         | 43                | 9.16 ± 25.2              | 5.87      |

$^a$The range in energy is calculated based upon the range of latitudes over which the wave is visible in the radar field of view. $\delta T$ is the time, in minutes, between the onset of the substorm and the onset of wave activity in the radar data. $\delta T_{\omega}$ is a predicted time lag between substorm onset and wave onset based on the angular drift frequency of the wave, uncertainties presented here are based solely on the width of the substorm and to not take into account any variation in particle drift velocity or errors in the onset times of the substorms or the waves.

Figure 1, the ground instrumentation used to observe the wave activity during this event is shown in Figure 3 in which a black box centered around ~22:00 MLT represents the approximate location of the substorm at the time of onset, the dimensions of which are defined by where the WIC counts reach the threshold of 5% of the peak number of counts during the substorm. During this event waves were observed in the Prince George and Kodiak radars, where Figure 3 shows that both fields of view are to the west of the substorm onset, similar to event 1.

Figure 3. IMAGE FUV data during the substorm expansion phase shortly after onset at 06:21 UT on 6 September 2001, where coordinate system is as described for Figure 1. Also included are the projections of the fields of view of Kodiak, Alaska (kod, purple) and Prince George, Canada (pgr, red).
Figure 4. (a, b) Line-of-sight velocity as measured by the Prince George radar between 06:10 and 07:10 UT and (c, d) the Kodiak radar between 06:40 and 07:40 UT, on 6 September 2001 in the same format as described in Figure 2. Oscillations in the line of site velocity are observed shortly after substorm onset in Figure 4a with a frequency of 0.69 mHz and ∼20 min after the substorm onset in Figure 4b with a frequency of 0.74 mHz. (e, f) The longitudinal Fourier phase profiles for the Prince George and Kodiak waves, where both exhibit westward phase propagation.

3.2.2. Wave Observations

Data from the Prince George radar are presented in Figures 4a and 4b between 06:10 and 07:10 UT in the same format as that in Figures 2a and 2b. Oscillations became visible immediately after the onset of the substorm at ∼06:25 UT with a period of 1440 s (a frequency of 0.69 mHz). The azimuthal wave number derived from the Fourier phase of the wave (shown in Figure 4e) was −12, corresponding to westward propagating phase, away from the epicenter of the substorm.

Figures 4c and 4d show the line-of-sight velocity as measured by the Kodiak radar between 06:40 and 07:40 UT in the same format as Figure 2. At approximately 06:48 UT, oscillations in the velocity were observed with similar characteristics to those observed using the Prince George radar. The wave period found using Fourier
analysis was similar to that observed by Prince George at \(\sim 1350\) s (a frequency of 0.74 mHz). Also similar to Prince George, this wave exhibited westward phase propagation away from the epicenter of the substorm, however with a higher \(m\) of \(-22\).

As with event 1, the angular drift frequencies and driving particle energies have been estimated using equations (1) and (4) and are shown in Table 1. The \(m\) numbers of the waves in this event became higher farther west of the location of the substorm. Angular drift frequency and particle energies also behave in a similar way to those shown in event 1 where the higher energy particles and higher angular drift frequencies are inferred closest to the substorm.

4. Locating Substorms Using Ground Magnetometers

James et al. [2013] presented the study of 83 ULF waves, each driven by an individual substorm. About half of these events were taken from the list of 4193 substorms published by Frey et al. [2004], thus showing that the chance of observing a wave and confidently associating it with a substorm is reasonably low. It follows then that the chance of finding an event where there was more than one wave observation is significantly lower. Sections 3.1 and 3.2 presented the only two of these events from the 4193 substorms detected using IMAGE FUV in which we could associate multiple ULF waves with a single substorm. In order to find more similar events it was necessary to look beyond the lifetime of the IMAGE spacecraft. As a substitute for auroral images, we chose to use magnetometers in order to detect the location of the substorm. In the case of event 3 studied here the substorm had already been detected using the Pinawa (PINA) magnetometer by band-pass filtering the data in order to see Pi1 and Pi2 waves appear as the substorm current wedge formed [Mann et al., 2008].

To find the location of the substorm current wedge, we used the bays (large, sustained aberrations of the magnetic field from its baseline value) in the \(D\) and \(Z\) components of the magnetic field. In order to determine the approximate azimuthal location of the substorm, we used the perturbations in \(D\) which occur as defined by McPherron et al. [1973] and Clauer and McPherron [1974], where we expect a large negative bay around the eastward (downward) field aligned current and a large positive bay around the westward (upward) field aligned current. \(Z\) was used to determine the latitude of the westward electrojet between the two upward and downward field aligned currents, where a negative bay would be seen equatorward of the current and a positive bay poleward of the current [Wu et al., 1991].

An example of this technique applied to the substorm presented in event 1 is presented in Figure 5. Figure 5a shows the perturbations in the \(Z\) component of the magnetic field as a function of magnetic latitude (left axis) and UT (bottom axis) during the interval of 04:00–06:00 UT on 24 November 2000 using the magnetometer chain highlighted in green in Figure 1 for event 1. The time series data from each of the magnetometer stations were low-pass filtered with a cutoff period of 1000s in order to remove most ULF waves from the data, then data were linearly interpolated across the gaps between each magnetometer station to a 1° resolution in latitude. The vertical dashed line at 04:21 UT represents the onset of the substorm as determined by Frey et al. [2004] and the three dotted lines represent the approximate latitudinal extent, and midpoint, of the aurora as observed by IMAGE in Figure 1 where the extent of the substorm’s UV aurora is defined by where the number of WIC counts drop below 5% of the peak value for the entire substorm. As suggested by Wu et al. [1991], a positive bay (indicated by red) in \(Z\) is observed to the north of the SCW and a negative bay (indicated by blue) to the south. Three solid lines represent the northern and southern edges of the substorm and the midpoint of these two lines as determined using the ground magnetometers. The perturbations caused by the SCW do not appear until around 4:50 UT as the substorm had not yet spread far enough west for the current wedge to be in the vicinity of the latitudinal chain of magnetometers. It is apparent that for this event, the latitude of the UV aurora and the bays in \(Z\) caused by the SCW are fairly consistent with each other for the short amount of time which the bays are observable using this latitudinal chain.

Figure 5b shows the perturbations in the \(D\) component of the magnetic field as a function of both longitude (bottom axis) and UT (left axis) for event 1 using the magnetometer chain highlighted in orange in Figure 1. Here the horizontal dashed line at 04:21 UT represents the substorm onset, while the dotted lines show the longitudinal extent and midpoint of the substorm estimated using the IMAGE FUV data presented in Figure 1. Positive (indicated by red) and negative (indicated by blue) bays in \(D\) are observed near to the upward and downward field aligned currents respectively as predicted by McPherron et al. [1973] and Clauer and McPherron [1974]. The solid black lines surrounding the bays show where we would have predicted the longitudinal extent and midpoint of the substorm based on the magnetometer data alone.
Figure 5. Magnetic perturbations during the substorm of 24 November 2000. (a) Perturbations in $Z$ as a function of UT (bottom axis) and magnetic latitude (left axis). (b) Perturbations in $D$ as a function of UT (left axis) and magnetic longitude (bottom axis). In both panels, dashed lines parallel to UT axis represent the magnetic coordinate of each magnetometer station, and the dashed line at constant UT represents the onset of the substorm. Dotted lines in both panels represent latitudinal and longitudinal extents and midpoints of the UV aurora in Figures 5a and 5b, respectively. Solid lines surrounding the bays in both plots represent where the perturbations in $B$ due to the substorm current wedge return close to the background field.

In order to demonstrate that the use of magnetometer data produces a substorm location and extent consistent with our previous use of the IMAGE FUV data, we used IMAGE data from 27 substorms and compared this to bays observed in the ground magnetometer data. The 27 substorms chosen for this purpose were a subset of the 83 events studied by James et al. [2013] where suitable magnetometer chains were available to allow the comparison. The edges of the bays observed in the magnetometer data were defined by where the magnetic field value dropped below a certain threshold value. This threshold value was different for both the positive and negative bays in both the latitudinal and longitudinal cases and was based upon the magnitude of the largest perturbation within that bay. The threshold values were chosen such that they minimized the difference between the edges of the substorm as defined by IMAGE observations and the outer edges of the magnetometer bays.
Figure 6. Histograms showing the differences in the (a) central magnetic longitude and (b) central magnetic latitude between measurements made using IMAGE data and magnetometer data.

The threshold percentages that gave the closest fit to the northern and southern edges of the substorms for the bays in $Z$ were both found to be at $\sim 50\%$ of the peak bay magnitude. When these were used and compared to the UV aurora, the errors were found to be within about $\pm 2.5^\circ$ (1 standard deviation) magnetic latitude. The thresholds for the bays in $D$ used to determine the azimuthal location of the substorm current wedge were slightly different, where 20% was used for the positive (westward) bay and 25% was used for the negative (eastward) bay. The errors associated with the eastward limit of the substorm were found to be $\pm 38^\circ$ magnetic longitude and $\pm 29^\circ$ for the westward edge.

Figure 7. A magnetic latitude-magnetic local time projection of the fields of view of Prince George (pgr) and Saskatoon (sas) radars, both in Canada, and Stokksýri (sto) and Þykkvibær (pyk), both in Iceland with the two chains of magnetometers used in a similar format to Figure 1. The black box present between 18 and 24 MLT shows the approximate latitudinal and longitudinal extent of the bays in $D$ caused by the substorm current wedge at the time of onset from Figure 9.
Figure 8. $H$ component measured by a subset of four magnetometers that make up part of the latitudinal magnetometer chain displayed in green in Figure 7. (a) The $H$ component as measured by the Pinawa (PINA) station band-pass filtered to show periods between 20 and 1000s. (b) The unfiltered $H$ component as measured by the Baker Lake (BLC), Fort Churchill (FCC), and Gillam (GIM) magnetometer stations, where a drop of over 300 nT is observed by all three magnetometers at the time of substorm onset. The substorm onset time of 3:26 UT is displayed as a vertical dashed line in each panel.

The azimuthal separation between the waves and the substorm observations as used in James et al. [2013] are measured from the center of the wave to the center of the substorm so the most relevant comparison between the substorms detected using magnetometers and those using IMAGE is that of the midpoint between the bays compared to the midpoint of the UV aurora. Figure 6 shows the differences in magnetic longitude and latitude of all of the times during the 27 events at which WIC images could be compared with the bays in the magnetometer data (this gives a total of 409 comparison points). The midpoints of the eastern and western edges of the magnetometer bays are compared to the midpoints of the UV aurora in Figure 6a where the peak in the graph is at 0° longitude difference and 67% of all of these values are contained within ±20° of 0, which means that there is little overall difference between the midpoints in longitude calculated using either method. The midpoints measured using both IMAGE FUV and ground magnetometers in Figure 5b appear to remain within the ±20° uncertainty mentioned above for the duration of that particular substorm.

Similarly, Figure 6b shows the latitudinal differences between central point of each measurement using IMAGE and magnetometers during the substorms. The difference between the northern and southern edges as measured using ground magnetometers and IMAGE is much smaller than the longitudinal differences. Figure 6b shows that there is no overall difference in latitude between the midpoint measured using both methods and that there is an error of about ±2°.

5. Substorm Event 3, 8 September 2008
5.1. Substorm Observations
Figure 7 shows the ground instrumentation used for event 3, along with the large spatial extent of the bays in $Z$ and $D$ as detailed below represented by the large black box centered around local midnight, within which the substorm current wedge would have existed. The center of the substorm is marked with a red circle. This figure shows that both radars were located to the west of the substorm.

The onset time of the substorm in this event was found using a subset of the magnetometers which form the latitudinal chain presented in green in Figure 7. Figure 8 shows the $H$ component as measured at four
magnetometer stations between 3:00 and 7:00 UT on 8 August 2008, where Figure 8a shows the Pinawa data band-pass filtered between 20 and 1000s and Figure 8b shows the bays present in the data of three other stations, with the first data point of each plot set to zero. At ~3:26 UT, Figure 8a shows that there is a sudden spike in Pi 2 wave power, while Figure 8b shows that there is a large drop of more than 300 nT at approximately the same time. Pi 2 waves are commonly observed during the onset of substorms [e.g., Saito, 1961] due to the sudden dipolarization of the tail field [Takahashi et al., 1995], while large drops in the $H$ component on the ground are associated with the formation of a westward electrojet as part of the substorm current wedge.

Following the determination of the substorm onset time, we used the magnetic perturbations as described in section 4 to determine the location and approximate extent the substorm current wedge. Figure 9a shows the bays in $Z$ in the same format as that used for Figure 5a, using the magnetometer chain shown in green in Figure 7. Due to the large threshold values, smaller bays such as the negative bay between 4:00 UT and 4:40 UT at around $60^\circ$ magnetic latitude are not always detected by the algorithm described above, as shown by the
Figure 10. Line of sight velocity as measured by (a and b) the Saskatoon radar between 04:06 and 04:36 UT and (c and d) the Prince George radar between 04:15 and 04:45 UT on 8 September 2008. (e and f) The Fourier phase profiles show that both waves exhibited eastward phase propagation at frequencies of 2.1 and 2.0 mHz, respectively.

In order to detect the lower magnitude bays, the time series was split into three sections: 3:00 to 4:06 UT, 4:06 to 4:30, and 4:30 to 5:00. The latitudinal extent and central location calculated using this method is presented for each of the three time periods by three black lines. In this case, the low-amplitude negative bay in the second time period is detected correctly. The center of the current wedge was observed to vary between $\sim 65^\circ$ and $\sim 72^\circ$ magnetic latitude.

Figure 9b shows the longitudinal extent of the bays associated with the current wedge, using the chain of magnetometers again shown in orange in Figure 7. The algorithm that estimates the edges of these bays placed the substorm over a reasonably large range of magnetic longitudes ($\sim 92^\circ$ to $\sim 25^\circ$) at its largest point. The bays observed here are very variable, much like those in Figure 9a, and were determined using the technique described above.
5.2. Wave Observations

Data from the Saskatoon radar are displayed in Figures 10a and 10b within the time range of 04:06–04:36 UT. At approximately 04:09 UT the onset of a wave was observed by the radar where Fourier analysis revealed that the wave had a period of \( \sim 410 \text{ s} \) (a frequency of 2.4 mHz). This wave exhibited westward phase propagation with an azimuthal wave number of \( m = -30 \).

Figures 10c and 10d show data from the Prince George radar between 04:15 and 04:45 UT where oscillations became apparent at \( \sim 04:18 \). The period of this wave was found to by slightly shorter than that which was observed using the Saskatoon radar at 330 s (a frequency of 3 mHz). The wave was found to have an azimuthal wave number of \( m = -43 \) indicating a westward phase propagation similar to that observed using Saskatoon however with a smaller azimuthal scale size.

The waves, both observed to the west of the substorm, exhibited negative \( m \) numbers such that the direction of phase propagation was away from the location of the substorm. As with the results from James et al. [2013], the \( m \) numbers observed during this event were lowest for those waves closest to the substorm and highest for those farthest away. The angular drift frequencies and inferred particle energies for both waves are displayed in Table 1. It is apparent that the particle populations responsible for driving the waves in this event behave consistently with events 1 and 2 such that the populations with the largest angular drift frequencies and highest energies exist closest to the substorm location.

6. Discussion

In all three of the events presented, we observe waves at multiple locations following the onset of a substorm. Each of the waves display a unique set of characteristics, such as period and wave number, and these have been summarized in Table 1. The wave characteristics are clearly affected by their proximity to the substorm. Unlike the study by James et al. [2013], all of the waves observed in this paper exhibit westward phase propagation as we were unable to identify any eastward drifting waves which we were able to associate conclusively with a particular substorm onset. Using the interpretation of James et al. [2013] we would deduce that the westward propagating waves were being driven by westward drifting protons.

James et al. [2013] determined that, in general, for observations of single substorm-driven waves, the phase propagation, angular drift frequency, and particle energy depend on the proximity of the wave to the substorm. However, this study was not able to determine whether an individual substorm event would generate multiple waves and if so what the characteristics of these waves would be. The three events presented here give a clearer depiction of this situation.

In event 1 we observed three waves occurring at various azimuthal separations from the epicenter of a substorm. The closest of the three waves to the substorm, observed by the Kapuskasing radar, exhibits a very low \( m \) number of \( \sim -9 \) which corresponds to a driving particle energy of 58–66 keV. The waves observed farther to the west of the substorm by the Saskatoon and Kodiak radars exhibited progressively higher \( m \) numbers of \(-19\) and \(-44\), respectively, and lower inferred particle energies of \(27–42\) and \(20–23\) keV.

In event 2, two waves were observed to the west of the substorm onset with \( m \) numbers of \(-12\) at Prince George and \(-22\) at Kodiak. In a similar manner to those waves observed during event 1, the magnitude of the azimuthal wave numbers was higher in the wave observed farthest from the substorm. Event 2 differs from the other two events in that each of the waves observed here exhibit much larger wave periods than those in the other two events. They are not abnormal when compared to the distribution of wave periods presented by James et al. [2013], and indeed the characteristics of all of the waves studied here fit within the main bulk of that distribution. The other unusual thing about the waves in event 2 was that the angular drift frequencies and inferred particle energies were much lower than the other two events considering the proximity of the waves to the substorm. These relatively low particle energies of \(8–19\) keV (Prince George) and \(2–10\) keV (Kodiak) could be related to the occurrence of such low frequency waves.

Events 1 and 2 demonstrate that an individual substorm can inject particles with a wide variety of energies and that within these energy ranges subsections of the particle distribution can drive distinct wave events at locations where the drift-resonance condition is satisfied. The characteristics of these waves are consistent with the observations of individual events presented by James et al. [2013].

Event 3 differs from the other two events mainly due to the method of substorm detection, resulting in the larger uncertainty in the substorm’s location. Both waves were observed to the west of the substorm by the
Figure 11. Comparison of the results of events 1–3 with results from James et al. [2013], the previous results are displayed in grey, results from event 1 are in red, those from event 2 are blue and event 3 is in orange. (a) The comparison of azimuthal wave numbers, (b) the comparison of the angular drift frequencies, and (c) the comparison of the inferred particle energies.

Prince George and Saskatoon radars, and both exhibited westward phase propagation. The most distant of the two waves has the more rapid phase propagation, an $m$ number of $-43$, and the closest of the two exhibited an $m$ of $-30$. The particle energies calculated using the properties of these two waves were $31–48$ keV and $28–36$ keV in order of increasing distance from the center of the substorm.

This behavior is very similar to the behavior observed in events 1 and 2 where the lowest $m$ numbers and highest inferred particle energies were seen at smaller azimuthal separations with the substorm.

James et al. [2013] used the estimated angular drift frequency calculated for each wave in order to back track the azimuthal location of the driving particles prior to the formation of the waves within the radar field of view. The angular drift frequency, $\omega_d$, and the longitudinal separation of the wave observation and the substorm onset, $\lambda$, can be used to determine an expected time lag between substorm injection and wave onset, $\delta T_{\omega}$. This time lag is calculated under the assumption that $\omega_d$ remains constant as the injected particles gradient curvature drift around the inner magnetosphere. In James et al. [2013], $\delta T_{\omega}$ was compared to the actual observed time lag, $\delta T$, to find that there was, on average, an approximate 1:1 relationship between the two.

Table 1 includes both the observed and predicted time lags for each wave event, where errors in $\delta T_{\omega}$ were based solely upon the uncertainty in $\lambda$. Most of the wave onsets were observed either within the quoted uncertainty range $\delta T_{\omega}$ or a little later than predicted, where waves appearing later than the predicted time imply that the driving particles for these waves were not necessarily injected immediately at the time of substorm onset. The wave observed at the Prince George radar in event 2 appeared slightly earlier than predicted, this small discrepancy could be explained by the fact that the errors in $\delta T_{\omega}$ do not take into account any uncertainties in the onset time of the waves or the substorms nor do they take into account any error associated with the calculation of the angular drift frequency. It is also possible that assumption of constant angular drift frequency is not completely reliable if the $E \times B$ term, which is local time dependent, and is significant compared to the gradient curvature term of equation (4), thus contributing to any mistiming of the arrival of the driving particles.

Figure 11 presents a comparison of the three events investigated here with the results presented in James et al. [2013], where Figure 11a shows the $m$ numbers, Figure 11b shows the angular drift frequencies, $\omega_d$, and Figure 11c shows the inferred particle energies.
and Figure 11c shows the inferred particle energies, $W$, all of which are plotted against the wave location relative to the substorm at its most expanded state. In each panel, the grey points are the results from James et al. [2013], red points correspond to event 1, blue points are from event 2, and orange points are from event 3. The error bars in this plot are representative of the azimuthal extent of the substorm, while it is at its most expanded state; the substorm in event 2 having the largest expansion out of the three. In all of the events we do see that the trends for $m$, $\omega_d$, and $W$ all appear to be consistent with those observed by James et al. [2013]. The range of inferred particle energies observed in each event would suggest that during a substorm, the particle populations injected into the inner magnetosphere contain a wide range of energies, resulting in the range of $\omega_d$ and $m$ that is observed. When comparing the results from these three events to each other, it also becomes apparent that the range of particle energies varies from substorm to substorm, for example, those predicted in event 1 (in red) appear to be consistently higher than those of the other two events across the range of magnetic longitude separations where the waves are observed.

Table 1 shows that the waves in each of the three events discussed here exhibit a wide range of wave periods on a range of $L$ shells. The frequency of a ULF wave is dependent upon factors such as plasma loading and field line length, where field line length varies with local time and $L$ shell. The waves observed using Saskatoon and Kodiak in event 1 exist on similar $L$ shells to the waves in event 2, yet they exhibit vastly different frequencies. The waves in event 3 exist on lower $L$ shells than those of the other events and exhibit shorter wave periods to those in event 2, but longer wave periods than two of the waves in event 1. The wave periods across the total population of seven waves do not appear to be well correlated with $L$ shell when compared altogether. There is also no conclusive trend when compared on an event-by-event basis. While it is possible that the differences in local time between each wave could help account for the range of observed frequencies, it is also possible that we have observed a mixture of poloidal Alfvén and drift compressional modes [Mager et al., 2015] driven by the substorm-injected particles. The study by Mager et al. [2015] discusses the bimodal nature of ULF waves characterized by the coupling of Alfvén and drift compressional modes observed using SuperDARN, where the lower frequency was associated with the drift compressional mode and the higher frequency corresponded to the Alfvén mode.

7. Conclusion

Using the data from various SuperDARN radars alongside IMAGE FUV and ground magnetometers, we identified three substorm events associated with multiple observations of ULF waves. This enabled an examination of how these wave events evolve as the substorm-injected particles gradient curvature drift away from the injection source. In all three events we see multiple westward drifting, ion-driven waves, but no eastward drifting electron-driven waves, unlike James et al. [2013] who observed equal proportions of both.

In order to determine the location of the substorm in event 3, it was necessary to make use of ground magnetometer data in order to use the substorm current wedge location as a proxy for the auroral emission which would have been observed by IMAGE. This method of substorm location was refined with the comparison of magnetometer and auroral data collected during 27 substorms which had occurred within the lifetime of the IMAGE spacecraft. The midpoint of the substorm as defined using both auroral data and magnetometer bays appeared to be reasonably well correlated with an uncertainty of $\sim 20^\circ$. While this uncertainty was not small, it was small enough, when compared to the azimuthal extent of the substorms themselves (typically 50–200°), to allow us to define an approximate location of substorms which occurred beyond the lifetime of the IMAGE mission.

We observe a very similar picture in each individual event to what has been previously observed in the statistical study of events where only one ULF wave was observed per substorm. It is therefore evident that during a substorm, a range of particle energies exists within the population of injected particles, and that different energy particles within this range can drive ULF waves with distinct characteristics. The highest energy particles tend to drive waves much closer to the epicenter of the substorm, with lower azimuthal wave numbers, while lower energy particles drive waves at larger azimuthal separations from the substorm, with higher azimuthal wave numbers. The variety of wave periods observed at similar $L$ shells may be evidence for the detection of both poloidal Alfvén and drift compressional modes as detected by Mager et al. [2015].
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