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Reply to comment by K. Liou and Y.-L. Zhang on "Wavelet-based ULF wave diagnosis of substorm expansion phase onset"

Kyle R. Murphy,[1] I. Jonathan Rae,[1] Ian R. Mann,[1] Andrew P. Walsh,[2] David K. Milling,[1] Clare E. J. Watt,[1] Louis Ozeke,[1] Harald U. Frey,[3] Vassilis Angelopoulos,[4] and Christopher T. Russell[4]

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1. Introduction

[1] In our recent paper, *Murphy et al.* [2009] (hereinafter referred to as M09), we presented results demonstrating in detail how Pi1/2 ULF waves can be used to locate the first magnetic signatures of substorm onset in the ionosphere. M09 extended the work of *Milling et al.* [2008] and presented results from a blind comparison of the location of Pi1/2 ULF wave onset during six substorm events, determined using a wavelet-based timing analysis, with the location marking the optical substorm expansion phase onset as inferred from the global-scale auroral intensification determined by *Frey and Mende* [2006] (hereinafter termed FM06). In these six events, the ULF wave onset first occurred in the long-period Pi1/short-period Pi2 ULF wave band (hereinafter referred to as Pi1/2) in a localized epicenter that was independently determined to be closely coincident in latitude and longitude with the global FM06 auroral intensification location. This blind study verified the utility and value of the wavelet algorithm as a reliable technique for determining substorm onset location. Furthermore, since the ULF onset analysis can also be used to time when ULF power rises above presubstorm noise, M09 also compared the ULF onset time with the time of the global auroral intensification determined using the FUV imager onboard the IMAGE satellite of FM06. We concluded that the Pi1/2 onset typically occurs several minutes in advance of the global auroral brightening as defined and identified by FM06 and as measured by the FUV satellite-borne global auroral imager.

[2] In a comment on M09, *Liou and Zhang* [2009] (hereinafter referred to as LZ09) disagree with our conclusion that Pi1/2 onset occurs in advance of the optical auroral substorm onset, stating that "the conclusion of the study is, in our opinion, premature." Although it is made clear by LZ09 that "[their] concern is not about the wave analysis technique" which they state is "a potentially powerful tool for timing and locating substorm onset," further analysis of the FUV imager data of LZ09 leads them to conclude that auroral brightening occurs simultaneously or prior to ULF wave onset within instrument uncertainty. In this reply we demonstrate that the time interval during which optical onset occurs is consistent with the idea that the ULF wave onset precedes the global intensification of the aurora and that the conclusion of M09, that the ULF onset occurs in advance of the global auroral intensification, remains valid and is not "premature."

[3] Recent work [*Rae et al.*, 2009a, 2009b] clearly demonstrates that the physics of the onset process, the sequence of events following expansion phase onset, and the spatial and intensity resolution of the FUV imager naturally lead to the conclusion that the times in the FM06 database will be delayed compared to the first signatures of onset, which are visible to imagers and magnetometers with better spatial, temporal, and amplitude/intensity resolution. The times in the FM06 database indicate the time at which auroral intensification becomes clearly visible in global images. As we demonstrate in this reply, this is often later than the first Pi1/2 onset signatures seen by magnetometers on the ground and indeed is later than auroral intensification observed using ground-based optical imagers, which generally have better temporal and spatial resolution than satellite-borne auroral cameras. We assert that the substance of the LZ09 criticism can be refuted simply by studying observations from instruments with increased spatial resolution and sampling rates.

[4] Because of the ~2-min cadence of the IMAGE FUV instrument, the times of global auroral brightenings identified by FM06 and used by M09 should "be given as a window that includes the time of the "onset" image and the time of the previous image," (LZ09). We agree with this comment. Further, LZ09 revisited the times of global auroral intensification which FM06 identified and argue in every case that there is evidence in previous images for small-scale and small-amplitude activity in advance of the FM06 onset time. Indeed, the comment is largely focused on the definitions of the onset times in the FM06 database. In some cases, the reassessments of the FM06 onset times presented by LZ09 are appropriate. However, this highlights the subjective

[1]Department of Physics, University of Alberta, Edmonton, Alberta, Canada.
[2]Mullard Space Science Laboratory, University College London, Dorking, UK.
[3]Space Sciences Laboratory, University of California, Berkeley, California, USA.
[4]Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA.

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nature of visual analyses of intensifications, especially as seen by global imagers.

[5] In some cases, the new analysis presented by LZ09 indicates that the ULF onset might have occurred within the 2-min window spanned by the cadence of the FUV images or within a window spanning a FUV data gap. This implies that the ULF onset and the global auroral intensification could be simultaneous within the ~2-min uncertainty arising from the cadence of the global satellite imager. One further implication of this assertion is that the large-scale auroral onset could precede Pi1/2 onset, argued, for example, by LZ09 for the 20 June 2005 event discussed in section 3.5. A similar conclusion was reached by *Liou et al.* [2000], although the idea has provoked debate and has been refuted by *Kepko and McPherron* [2001]. In this reply, we reassert that the observations indicate that ULF onset generally precedes global-scale auroral breakup. In addition, for two cases shown in section 3 we are able to use higher-cadence ground-based optical data to show that the Pi1/2 onset occurs in advance of poleward motion of the onset arc and auroral breakup. Our reply reinforces our original assertion that Pi1/2 ULF wave onset occurs in advance of the global auroral intensification determined using satellite-borne global auroral imagers.

2. Auroral Substorm Expansion Phase Onset

[6] Historically, substorm expansion phase onsets are identified by the brightening of a preexisting quiet and discrete arc or in some cases by the formation of a new discrete arc, which subsequently moves poleward and breaks up [*Akasofu*, 1964, 1977]. It is likely that global satellite imagers do not have the sensitivity or resolution to record the initial dynamics or formation of an individual quiet discrete arc. Such small-scale and discrete auroral phenomena can be resolved more easily with ground-based all-sky imagers at a higher temporal and spatial resolution, such as those now offered by the white light imagers within the ground-based observatory network in the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission [*Mende et al.*, 2008]. Initially, the brightening of a small-scale arc will likely only have a small impact on the global-scale auroral intensity monitored by a global-scale satellite imager. Recent observations by *Sakaguchi et al.* [2009], for instance, have shown that the onset arc can be structured at ~30- to 60-km scales before intensifications of the arc are observed and in advance of the subsequent and eventual auroral breakup of the arc in the substorm sequence [see also *Rae et al.*, 2009a, 2009b]. This emphasizes that the global-scale auroral brightening seen by global-scale satellite imagers will typically occur later than the auroral onset time determined from the ground by small-scale discrete auroral arc dynamics in the Akasofu sense. It is important to remember that a global imager such as IMAGE FUV has a spatial resolution of $\sim 50 \times 50$ km^2 around apogee. Indeed, in other parallel work [e.g., *Rae et al.*, 2009a, 2009b], we have shown that ULF onset in the Pi1/2 (24–96 s period) wavelet band is intimately linked to the formation of small-scale (approximately tens of kilometers) discrete auroral features prior to auroral breakup, suggesting that the physical mechanism for generating the Pi1/2 ULF waves and the initial discrete auroral arc structuring and brightening are related. In the sequence of events shown, for example, by *Rae et al.* [2009b], the Pi1/2 ULF onset and the arc structuring occur contemporaneously, to within the temporal uncertainty of the ULF technique. However, in these events, larger-scale breakup follows minutes later, and this is likely to be the element in the onset sequence which becomes visible to satellite-borne global auroral imagers.

[7] It is clear that in any substorm scenario the brightening of the onset arc must precede the global-scale auroral brightening associated with the auroral surge [*Akasofu*, 1964]. Because of the spatial and temporal limitations of the FUV instrument discussed above, the Frey substorm database [*Frey et al.*, 2004; FM06] can only provide the location and timing of global auroral brightening. We assert here, and consistently in the original paper, that auroral substorm onset and global auroral intensification are two phenomenologically different events in the substorm chronology, the first occurring minutes prior to the second. We demonstrate in this reply that apparent timing discrepancies are naturally generated by instruments of differing spatial resolution and temporal cadence. However, the discussion generated by M09, the comment by LZ09, and this reply clearly illustrates that care must be taken in defining substorm "onset," especially now that we have techniques which can determine the start of physical processes to within tens of seconds. We suggest that future research should take care to define exactly which instruments, measured quantities, and analysis techniques were used to determine an onset time and state clearly any sources of uncertainty.

3. Substorm Events

[8] In this section, we briefly revisit the times of global auroral brightening identified by FM06 and augment the data sets of M09 with those from the Northern Solar Terrestrial Array (NORSTAR) Meridian Scanning Photometers (MSP) array where appropriate. A summary of the conclusions from this reanalysis and a comparison to the reanalysis of the FM06 timings completed by LZ09 is given in Table 1.

3.1. The 3 June 2005, 0530–0600 UT Event

[9] Figure 1a of LZ09 shows three IMAGE FUV images of the auroral breakup sequence and Figure 1b of LZ09 shows a keogram through the ~21 magnetic local time (MLT) sector that encompasses these three times. There is evidence in the 0542:18 UT frame of an auroral feature, which could have occurred as early as 0540:13 UT. This would place the ULF onset (0540:48 UT ± 16 s) within, and near the start of, the 2-min window between 0540:13 UT and 0542:18 UT defined by the uncertainty of the IMAGE FUV imager. However, a closer inspection of Figure 1a of LZ09 demonstrates that the apparent poleward motion of the auroral feature at 22 MLT is a combination of two effects: first, the duskside auroral oval gradually entered the FUV field of view over this period (note the decrease in the low-latitude data gap between the three frames), and second, there is a small poleward progression of the auroral feature, which we discuss below.

[10] Figure 1a shows a keogram from the 21.5–22.5 MLT meridian which contains the central meridian of onset at

Table 1. Summary of ULF and Optical Substorm Onset Times

Date	FM06 Global Auroral Onset Time (UT)	ULF Onset Window (UT)	LZ09 Visual Optical Onset Time (UT)	Comments	Refined Optical Onset Window (UT)
3 Jun 2005 (Figure 1a)	0544:23	0540:32–0541:04	0540:13–0542:18	Breakup does not occur in the 21 MLT region shown by Figure 1b of LZ09, rather in the 22 MLT sector. WIC imager onset clear in time window of LZ09.	0540:13–0544:23
17 Jul 2005 (Figure 1b)	0714:15	0706:20–0706:36	0705:54–0714:15	Clear from MSP data in Figure 1b that auroral breakup occurs after ULF onset.	0707:45–0708:15
17 Jul 2005	0848:11	0835:32–0836:04	0833:33–0835:36 0835:36–0843:57	ULF onset occurs within window of global auroral breakup; insufficient evidence for auroral brightening between 0833:33 and 0835:36 UT.	0835:36–0843:57
17 Jul 2005 (Figure 1c)	0808:33	0806:44–080716	0806:28–0808:33	ULF onset within FM06 and LZ09 global auroral onset window; optical onset as identified in MSP is clearly after ULF onset in Figure 1c.	0807:15–0807:45
20 Jul 2005	0530:53	0524:08–0524:40	0526:42–0528:48[a]	Auroral breakup occurs after the ULF onset; insufficient evidence for auroral brightening at 0522:28 UT.	0526:42–0528:48
18 Nov 2005 (Figure 1d)	0609:29	0606:12–0606:44	0605:18–0607:23	Insufficient evidence for early auroral brightening at 0605:18 UT; feature is weak and spatially separated from Frey global auroral onset location.	0607:24–0609:29

[a]brightening at 0522:28

~22 MLT (note that Figure 1b of LZ09 shows the 20.5–21.5 MLT meridian). The three time frames shown by LZ09 are labeled in Figure 1a as 1, 2, and 3, respectively. There is a slight intensification and poleward progression of the aurora between times 1 and 2, but it does not intensify and monotonically expand poleward until after time 3, the time defined by FM06 as corresponding to global auroral intensification. Given these uncertainties, a more appropriate window for the global auroral intensification and breakup might span both frames, from 0540:13 to 0544:23 UT, whereas the ULF onset occurs near the beginning of this interval at 0540:48 UT ± 16 s.

3.2. The 17 July 2005, 0700–0730 UT Event

[11] In the work of M09, ULF onset is identified in a window centered on 0706:18 UT ± 8 s, ~8 min prior to the global auroral onset identified by FM06 (0714:15 UT). It is suggested by LZ09 that auroral breakup could occur any time between the frame that does not show breakup (0705:54 UT) and the next full hemispheric image at 0714:15 UT (the extended window is due to pointing and data gap issues). LZ09 hence conclude that the ULF onset and the global auroral intensification could have been simultaneous, given the imager cadence and data gaps. Figure 1b shows the 5577A Fort Smith MSP data from 0700 to 0715 UT, which is at the meridian of ULF wave onset identified by M09 and which has a cadence of 30 s (Figure 9a of M09). The time intervals identified by LZ09, M09, and FM06 of potential optical onset, ULF onset, and global auroral intensification, respectively, are indicated at the top of Figure 1b. The MSP window indicates the earliest possible optical onset determined from the Fort Smith MSP. This occurs 71–133 s after the ULF wave onset. Hence, Figure 1b clearly demonstrates that the ULF wave onset occurs ~1–2 min prior to auroral breakup, as seen by this ground-based MSP.

3.3. The 17 July 2005, 0830–0900 UT Event

[12] The ULF wave onset is 0835:48 UT ± 16 s during this interval. The location of ULF wave onset was found to be colocated with the subsequent region of global auroral breakup independently identified by FM06, who identified a global onset time of 0848:11 UT. It is suggested by LZ09 that a more appropriate window for optical onset may be 0835:36–0843:57 UT, which encompasses the FUV imager data gap present in this interval. The two bounding time frames with data (0835:36 UT and 0843:57 UT) are ~8 min apart, and the faint auroral activation in the first frame is identified by LZ09 as the first evidence of the large auroral surge seen in the latter frame. Alternatively, it is also suggested by LZ09 that the first activation could be an isolated pseudobreakup or additional small isolated substorm. Because of the lack of data for ~8 min between these two images, there is no strong evidence to suggest that the very small and localized brightening at 0835:36 UT is necessarily linked to the auroral breakup seen in the latter 0843:57 UT image. We therefore conclude that the optical onset occurs in a window 0835:36–0843:57 UT. The ULF wave onset at 0835:48 UT ± 16 s occurs at the beginning of this window, and so in order for auroral intensification to be contemporaneous with the ULF onset, the global auroral intensification would have to have taken place at

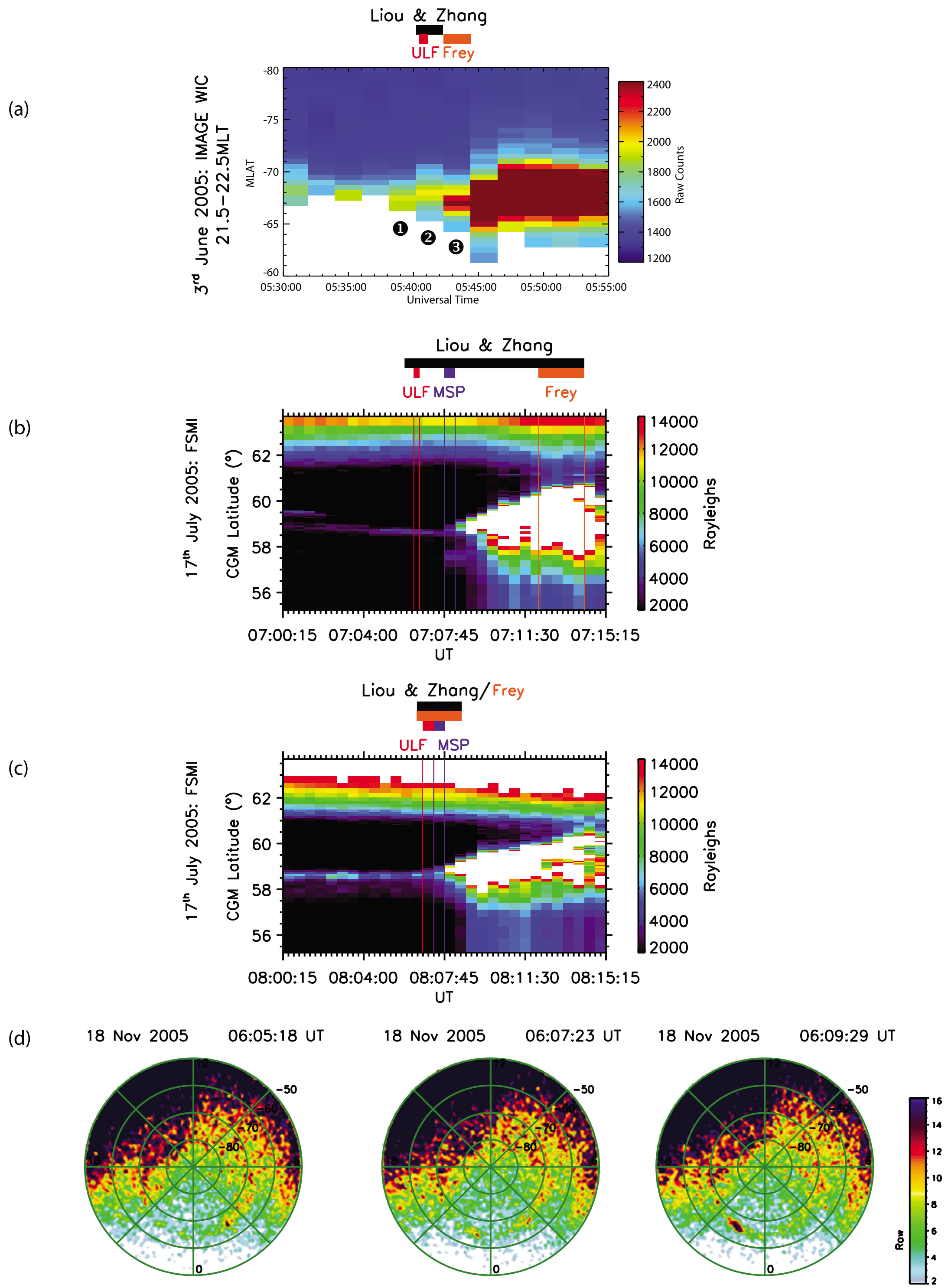

Figure 1. (a) A keogram from the 3 June 2005 spanning the MLT sector of the auroral intensification observed between 0540:13 and 0544:23 (21.5–22.5 UT). The black bar indicates the onset time identified by LZ09, the red bar indicates the ULF onset time, and the orange bar indicates the FM06 onset time. (b) Observations of the 5557A auroral emissions between ~0700 and 0715 UT from the Fort Smith meridian scanning photometer (MSP) located in the same meridian as the auroral onset identified by FM06 during the initial event observed on 17 July 2005. The black bar depicts the auroral onset window identified by LZ09, the red bar indicates the ULF onset window, the orange bar indicates the FM06 auroral onset window, and the blue bar indicates the initial brightening and poleward motion identified in the MSP and classified as auroral breakup. (c) Same as Figure 1b for the second event identified on the 17 July 2005 between ~0800 and 0815 UT. (d) A sequence of three IMAGE FUV images of the auroral emission observed by the SI13 instrument during the 18 November 2005 event.

the earliest possible time within the overall 8-min window of uncertainty.

3.4. The 17 July 2005, 0800–0830 UT Event

[13] Global auroral breakup occurs within the window 0806:28–0808:33 UT identified by both FM06 and LZ09 and which encompasses the ULF wave onset window at 0807:00 UT ± 16 s. However, for this event, there are ground-based observations which can refine the uncertainty in the auroral onset window as defined by LZ09. Figure 1c shows the 5577A Fort Smith MSP data from the ~0800–0815 UT interval, close to the meridian of ULF wave onset (Figure 11 of M09). The MSP data clearly show that the ULF wave onset and local auroral breakup windows do not overlap; rather, the ULF wave onset window is immediately prior to the earliest indication of auroral breakup as defined by the Fort Smith MSP. Using the MSP data, we are able to resolve optical onset more accurately in time than can be done with the IMAGE Wideband Imaging Camera (WIC) data. This new analysis verifies that in this event the auroral breakup occurred after ULF wave onset.

3.5. The 20 July 2005, 0515–0545 UT Event

[14] The onset window of 0526:42–0528:48 UT (LZ09) is more appropriate for the global auroral intensification rather than that identified by FM06 at 0530:53 UT. The LZ09 time for global auroral intensification is around 2 min after ULF wave onset. LZ09 speculate that a small premidnight auroral brightening at 0522:28 UT that fades prior to breakup could be an "auroral brightening [that] may have caused the ULF onset identified ~2 min later." We do not agree with this assertion. In fact, the brightening observed at 0522:28 UT does not stand out above the intensity of the adjacent auroral emissions and fades rapidly, and hence it fails to justify characterization as an independent onset. Although LZ09 state that they "will not make a conclusion" on the relative timing of auroral and magnetic onset in this case, the evidence from the FUV imager and the ground magnetometer analysis is consistent with our conclusion that ULF onset occurs before global auroral breakup.

3.6. The 18 November 2005, 0600–0630 UT Event

[15] Using a keogram of IMAGE SI13 data (Figure 1e of LZ09, from an unspecified MLT sector), it is argued that there is evidence of auroral intensification in the interval 0605:18–0607:23 UT, one frame earlier than defined by FM06. Figure 1d of this paper shows the full 2-D SI13 images from the relevant frames using the same color scale used in Figure 1e of LZ09. The earlier intensification identified by LZ09 is very weak in these full 2-D images, being close to the noise levels around the oval, and at least ~0.5 MLT away from the location identified by FM06 of global auroral breakup in the subsequent frame. There is therefore no conclusive evidence from the SI13 images to suggest that global auroral intensification begins any earlier than 0607:24 UT, and the ULF onset is again shown to be prior to the global auroral intensification. As discussed in section 2, there is good reason to expect a small-scale auroral signature visible in ground-based imagers to be associated with the ULF onset [cf. *Rae et al.*, 2009a, 2009b], but the FUV imager likely has insufficient spatial and temporal resolution to identify these small-scale features. As we have pointed out in this reply, resolution is a key issue in determining optical onset from global satellite-borne imagers, and we contend that the LZ09 commentary can be explained simply in terms of differences in spatial and temporal resolution between different instruments.

4. Conclusions

[16] By reanalyzing the global optical observations and adding evidence from ground-based instruments where appropriate, we have demonstrated that the conclusion of M09 that ULF onset precedes global auroral intensification remains valid in all but one event. In this event (17 July 2005 0830–0900 UT, section 3.3), ULF onset occurs within the first 2 min of the ~8-min window containing the onset of the global auroral intensification. Higher-cadence ground-based auroral data were not available for this interval. The evidence indicates that the physics of the substorm onset sequence involves ULF Pi1/2 waves which have been associated contemporaneously with small-scale discrete auroral brightening and undulations, such as those seen by ground-based all-sky imagers [e.g., *Rae et al.*, 2009a, 2009b]. These early discrete auroral fluctuations are observed several minutes prior to auroral breakup, and these fluctuations will be difficult, if not impossible, to resolve using a global satellite-borne auroral imager with a spatial resolution $\sim 50 \times 50$ km^2. Further, using additional higher-resolution ground-based MSP data, we show clear evidence that ULF wave onset precedes global auroral breakup in these cases.

[17] As we have discussed in this reply, we do agree with LZ09 that we did not properly consider the 2-min cadence of the IMAGE images of M09. Nevertheless, in this reply we have demonstrated that neither uncertainties from the onset window nor the LZ09 reexamination of the global onset timing in the FM06 database alter the conclusion of M09 that ULF wave onset precedes global auroral breakup. This comment and reply do, however, demonstrate very clearly the importance of carefully defining the measurement used to define substorm onset, especially when dealing with measurements from different instruments with differing temporal and spatial resolution.

[18] The conclusions of M09, repeated again here in our reply, are in agreement with the observations of *Rae et al.* [2009a, 2009b] and *Sakaguchi et al.* [2009] and in direct contrast to those presented by LZ09, who contend that optical onset either precedes or is contemporaneous with Pi1/2 ULF wave onset, "within the uncertainty of the IMAGE WIC image data." Indeed, without any evidence from instrumentation with smaller timing uncertainties, LZ09 suggest in some cases the opposite causality that an "auroral brightening may have caused the ULF onset identified ~2 min later." We reiterate that there is a growing body of work demonstrating the clear link between ULF wave onset and substorm expansion phase onset [e.g., *Milling et al.*, 2008; *Murphy et al.*, 2009; *Rae et al.*, 2009a, 2009b; *Gabrielse et al.*, 2009; *Angelopoulos et al.*, 2008]. The blind comparison of the time and location of magnetic and global optical onset (obtained from FM06) by M09 and extended here verifies the value of Pi1/2 ULF timing for substorm studies, clearly shows that Pi1/2 wave onset is located in an isolated epicenter colocated with auroral

breakup, and indicates that Pi1/2 onset occurs in advance of global-scale auroral intensification and breakup.

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V. Angelopoulos and C. T. Russell, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, Box 951567, 2712 Geology Building, Los Angeles, CA 90095-1567, USA.

H. U. Frey, Space Sciences Laboratory, University of California, Berkeley, 7 Gauss Way, Berkeley, CA 94720-7450, USA.

I. R. Mann, D. K. Milling, K. R. Murphy, L. Ozeke, I. J. Rae, and C. E. J. Watt, Department of Physics, University of Alberta, 412 Avadh Bhatia Physics Laboratory, Edmonton, AB T6G 2J1, Canada.

A. P. Walsh, Mullard Space Science Laboratory, University College London, Dorking RH5 6NT, UK.