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Investigation of $\sim$ 20–40 mHz ULF waves and their driving mechanisms in Mercury's dayside magnetosphere

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Abstract. Ultra-low-frequency (ULF) waves in the $\sim$ 20–40 mHz range are frequently observed in the Mercury magnetosphere using Mercury Surface Space Environment Geochemistry, and Ranging (MESSENGER) magnetic field data. The majority of these waves have very similar characteristics to the waves likely driven by Kelvin–Helmholtz (KH) ULF waves (which are retained as a subset of the wave events studied in this paper) identified in a previous study. Significant ULF wave activity is observed in the dawn sector of the magnetosphere. This indicates that Mercury KH waves may be more common between 6 and 12 magnetic local time than previously predicted and that magnetospheric ULF waves in the frequency band $\sim$ 20–40 mHz can be used as a detection tool for Hermean KH waves.

Keywords. Magnetospheric physics (magnetopause cusp and boundary layers; magnetospheric configuration and dynamics solar wind–magnetosphere interactions)

1 Introduction

Ultra-low-frequency (ULF) waves were first observed in the magnetic environment of Mercury with Mariner 10 (Russell, 1989). These were narrowband $\sim$ 0.5 Hz waves with a polarization changing from right-hand circular to linear as the spacecraft moved towards the planet. Since the arrival of Mercury Surface Space Environment Geochemistry, and Ranging (MESSENGER), Mercury magnetospheric ULF waves have been observed a number of times, ranging from $\sim$ mHz (Liljeblad et al., 2016; James et al., 2016) up to $\sim$ 1 Hz (Boardsen et al., 2009, 2012).

In the ULF wave context, much focus has been directed toward the nature of the ULF wave generation. Dungey (1954) introduced the idea that certain ULF waves detected in the terrestrial magnetosphere could be standing Alfvén waves on geomagnetic field lines referred to as field line resonances (FLRs). Different internal and external driving mechanisms, such as resonance with energetic particle populations (e.g., Southwood et al., 1969), pressure fluctuations in the solar wind (e.g., Sibeck et al., 1989) or the Kelvin–Helmholtz instability (KHI) (e.g., Dungey and Southwood, 1970), have been proposed. In particular, terrestrial toroidal-mode Pc 5 pulsations have been proposed to likely be driven by the KHI (e.g., Samson et al., 1971).

The study by Liljeblad et al. (2016) investigated all 131 MESSENGER magnetospheric traversals just prior to or after the observation of Kelvin–Helmholtz waves (KHWs) at the magnetopause during 2011–2013, which in turn were identified in an earlier study by Liljeblad et al. (2014). Distinct ULF wave signatures in the mHz range could be detected in 44 out of these 131 magnetospheric passages. The KHWs situated at the dayside could be connected to clear ULF wave activity nearly 50 % of the time. The ULF waves followed the KHW occurrence asymmetry and appear mainly at the duskside magnetopause between 14 and 17 magnetic local time. These waves were observed most often in the narrow frequency range of 20–40 mHz and in the same range as the KHWs. The overall results, including similar characteristics and the close temporal connection between the ULF waves and the KHWs, argue for the KHI as a driver. These results manifest the importance of the KHI for the energy and momentum transport throughout the Mercury magnetic system and motivate a general study of magnetospheric ULF waves, in particular in the 20–40 mHz frequency range, to learn more about possible KHI-driven ULF waves.

This study will analyze the magnetic field of all dayside magnetospheric crossings of MESSENGER during the year 2011 to identify clear ULF wave activity. Such ULF waves will be investigated by evaluation of their characteristics and by comparing them to the dayside likely KHI-generated ULF waves reported in Liljeblad et al. (2016) to discern possible driving mechanisms.

2 Observations and results

During 2011, MESSENGER crossed the dayside magnetosphere 542 times. Eight of these occurred in direct connection to a KHW and have thus already been investigated for ULF wave activity (Liljeblad et al., 2016). In the present study, the remaining 534 traversals are investigated. Using the procedure and criteria set by Liljeblad et al. (2016), in which a 2.5 s running average and a subtraction of a 50 s running mean value is applied to make any quasi-periodic signature between 0.02 and 0.4 Hz more clearly visible, and only events with a power spectral density of at least $1000\,\mathrm{nT^2\,Hz^{-1}}$ are included, 60 clear ULF wave events are identified, each on a separate traversal. An example of a magnetospheric traversal with such ULF wave activity can be seen in Fig. 1.

The methods by Means (1972) and Arthur et al. (1976), described in Liljeblad et al. (2016), are used for the derivation of polarization parameters such as coherence; ellipticity, ϵ; and wave normal angle, α. These parameters are derived only for those 39 events fulfilling the criteria of coherence > 70 % and eigenvalue ratio (intermediate to minimum) $\lambda_{\mathrm{int}}/\lambda_{\mathrm{min}} > 4$ of the eigenvectors of the spectral matrix. The data set including these 39 ULF events is analyzed and will from hereon be referred to as general ULF waves.

As mentioned above, the events from Liljeblad et al. (2016) were identified in direct connection to a KHI at the magnetopause. Of these events, 43 were detected in the dayside magnetosphere and 38 of these fulfill the same criteria as outlined above. The latter 38 have been included in this study as a reference and will from hereon be referred to as KHI-ULF waves.

Results of the analysis of the total 77 events from both the general and KHI-ULF wave group can be seen in Fig. 2. The large majority of both general ULF waves (circles) and KHI-ULF waves (triangles) clearly have a large perpendicular power spectral density component and a larger azimuthal than radial component, indicative of a shear Alfvénic wave type. On the dawnside, the majority of ULF events in both data sets are left-hand polarized ($\epsilon < 0$) with respect to the background magnetic field, while the duskside events are mainly right-hand polarized. Another distinct result is that the total power spectral density is generally larger for the KHI-ULF events (on average $6870 \pm 760\,\mathrm{nT^2\,Hz^{-1}}$, including standard error) than the general ULF events (on average $3850 \pm 1090\,\mathrm{nT^2\,Hz^{-1}}$), which is possibly explained by their distance in time to a KHI (see Sect. 3). The fact that the majority of events in both data sets are in the narrow frequency range of 20–40 mHz indicates that they might be driven by the same mechanism. Adding to this idea is the result that the majority of both general ULF waves and KHI-ULF waves, both at dusk and dawn, propagate more in the parallel than in the perpendicular direction; see Fig. 2f. The events with perpendicular to total power spectral density less than 0.7 (marked by empty symbols) have clearly different characteristics than the other ones, suggesting either that they are a different type of KHI-driven wave (e.g., compressional waves in an early stage before entering a region of an FLR where the waves are more azimuthally polarized) or that they are driven by a different mechanism.

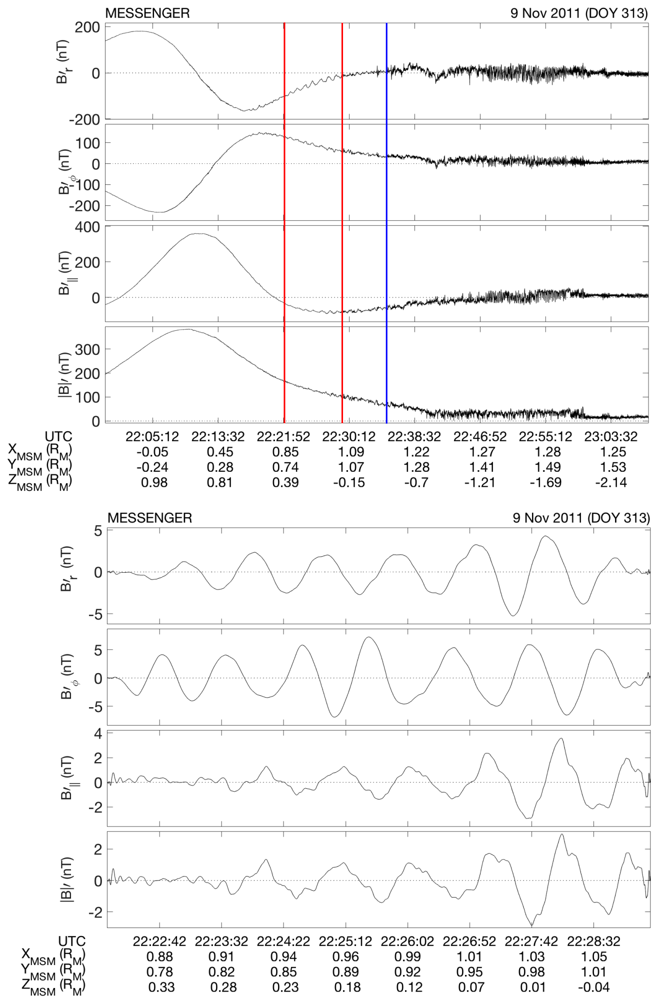

Figure 1. The upper panel shows an example of a magnetospheric traversal, in which red lines mark the ULF wave signature and the blue line marks the magnetopause. The lower panel shows the detrended and smoothed ULF wave region.

The obvious similarity between the duskside events of the general and KHI-ULF wave group is more clearly visible in Fig. 3. Again, the majority of events of both data sets are pos-

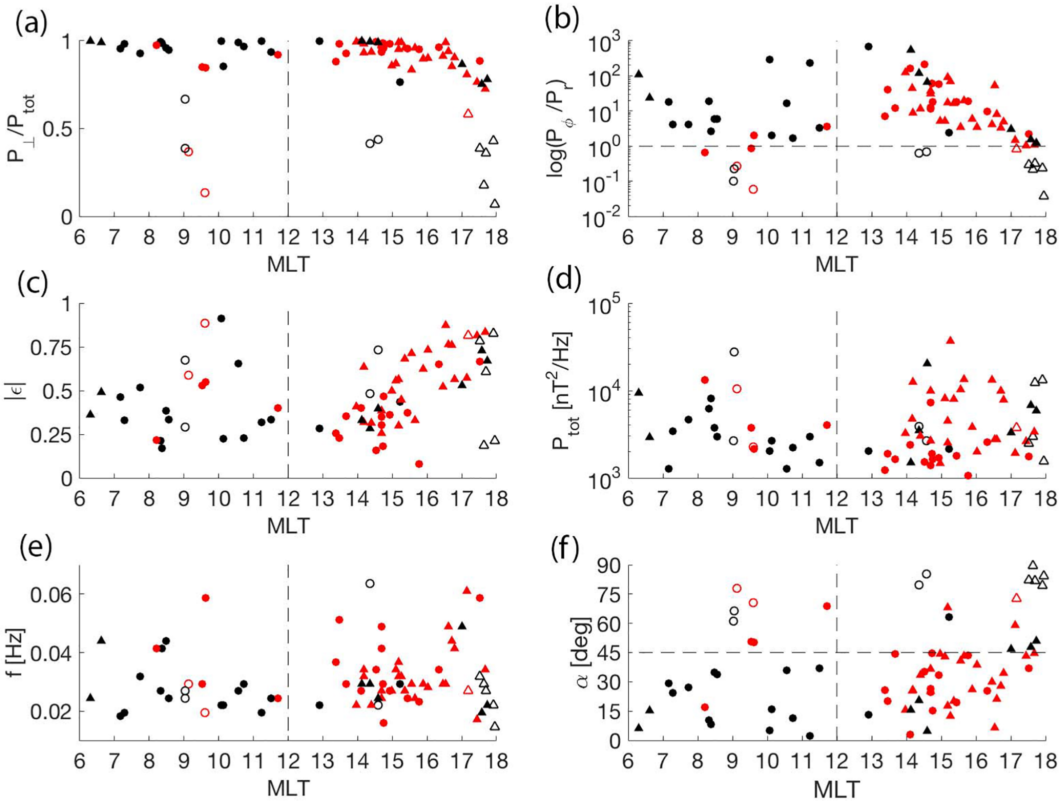

Figure 2. Results versus magnetic local time (MLT) of ULF events fulfilling the polarization analysis criteria outlined in Sect. 2. **(a)** Perpendicular over total power spectral density, **(b)** azimuthal over radial power spectral density in log scale, **(c)** absolute ellipticity, **(d)** total power spectral density in log scale, **(e)** frequency, and **(f)** wave normal angle, all evaluated at maximum power spectral density. Red and black colors represent positive and negative ellipticity, respectively; dots and triangles represent general ULF events and KHI-ULF events, respectively; and empty symbols represent events with a low perpendicular over total power spectral density (< 0.7).

itively polarized with a significant perpendicular component, they decrease in azimuthal power with distance from noon, and they are in the same frequency range with similar wave normal angles.

The location of the events, which can be seen in Fig. 4, shows that the KHI-ULF waves (marked by red) span over a larger region than the general ULF waves. Also significant is the fact that a large number of the general ULF waves are observed at the dawnside, unlike the KHWs (and the KHI-ULF waves), which are observed mainly at the duskside magnetopause (magnetosphere).

3 Discussion

The study by Liljeblad et al. (2016) indicates that the identified ULF waves are generated by KHWs at the magnetopause. In addition, a study by James et al. (2016) covering MESSENGER magnetosphere crossings over the time period 2011–2015 also suggests that ULF waves (occurring mainly at the dayside), with similar characteristics as those KHI-ULF waves reported in Liljeblad et al. (2016), could be KHI driven.

This study shows that the duskside general ULF waves are clearly similar to the duskside KHI-ULF waves in all investigated characteristics. Due to a small number of dawnside KHI-ULF events, it is not meaningful to compare these to the dawnside general ULF waves. However, as can be seen, the dawnside general ULF waves are similar to the duskside KHI-ULF waves with regard to their relative perpendicular power spectral density, main frequency and wave normal angle. As for the KHI-ULF events, they also have a larger azimuthal than radial component but do not show a gradual change with distance from noon in both the ratio of azimuthal to radial power spectral density and absolute ellipticity; see Fig. 2b and c. In addition, the dawnside general ULF waves most often have a negative ellipticity in contrast to the positive ellipticity for the duskside general ULF waves. However, this last discrepancy may not mean that the dusk- and dawnside general ULF waves are driven by two different mechanisms. According to Samson et al. (1971) and Southwood (1974), and as visualized by Hughes (1994), the polarization of the KHI-driven ULF waves should be different depending on if they are situated in the morning- or eveningside of the magnetosphere. The result of opposite polarization in the

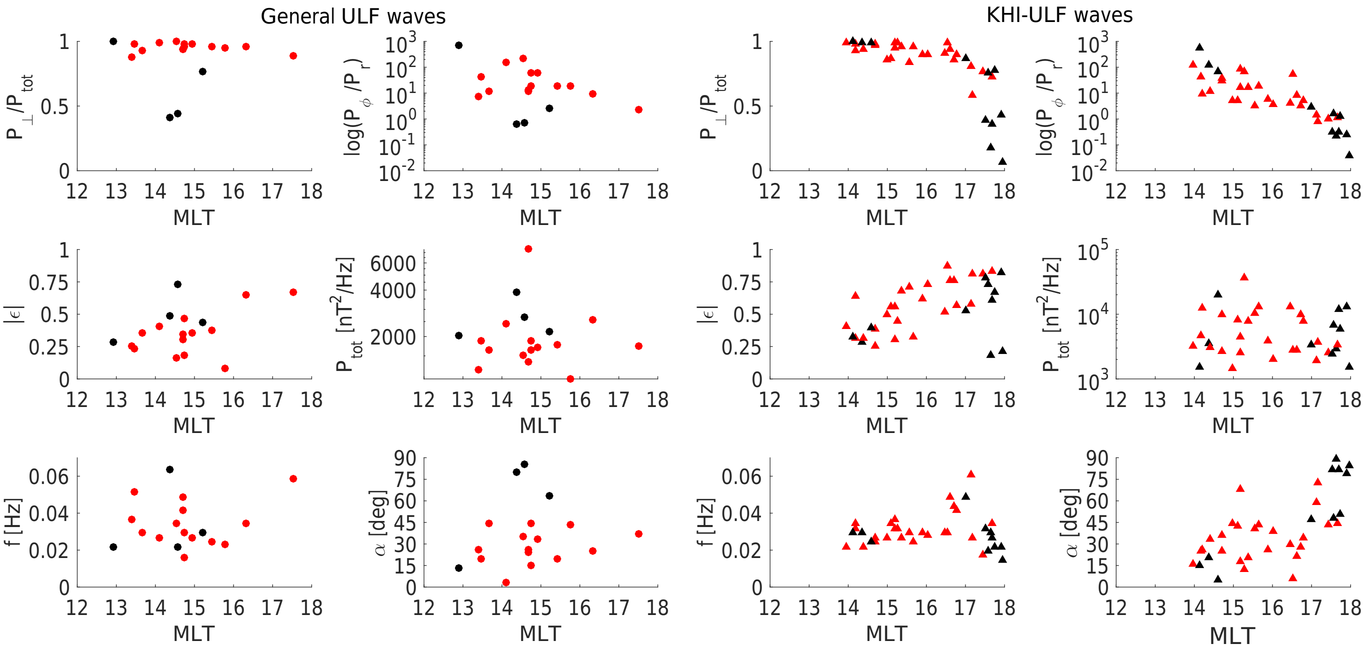

Figure 3. Comparison of the two data sets' general ULF waves and KHI-ULF waves, in which only duskside events are included. Panels and symbols follow the same format as in Fig. 2.

dusk- and dawnside magnetosphere thus supports the idea that the majority of not only the duskside but also the dawnside general ULF waves are driven by the KHI. Furthermore, James et al. (2016) observed the average polarization of their observed ULF waves to be left-handed on the dawnside and right-handed on the duskside (in agreement with the result in this study) and suggested this to be a consequence of the KHI.

The total power spectral density is on average larger for the KHI-ULF waves than the general ULF waves. Assuming that the majority of both general ULF waves and KHI-ULF waves are KHI driven, this difference could simply be due to their distance in time to a KHW. If the KHI-ULF waves are directly driven by the KHW observed just ~ 10 min earlier or after, the KHI-ULF waves might not have time to decrease in amplitude much, resulting in a strong magnetic signature and power spectral density for these ULF waves. The general ULF waves could also be driven by KHWs, and if so they are probably driven by weaker KHWs or are observed in a longer distance in time from these, resulting in weaker magnetic ULF wave signatures. This argument can also be used to explain why the KHI-ULF events are observed in a larger region of the magnetosphere than the general ULF waves.

Also supporting the idea that the general ULF waves both at dusk and dawn are KHI driven, is that their frequencies are mainly in the narrow band of 20–40 mHz, their wave normal angles are similar to those of the KHI-ULF waves and the majority of events in both data sets are distinctly azimuthally polarized. However, a few events clearly show different characteristics (i.e., those marked by empty symbols) both in power spectral density and wave normal angle. Hence, these could be driven by a different mechanism and/or belong to a different type of ULF wave. As discussed in Liljeblad et al. (2016), these waves might be compressional waves directly driven by the KHI (before they enter into a region of an FLR where they couple with the shear mode) or possibly cavity modes set up for example by pressure fluctuations in the solar wind (Samson et al., 1992).

The large majority of KHWs observed in Liljeblad et al. (2014) were identified at the duskside magnetopause. As shown by Liljeblad et al. (2015), MESSENGER covers the Hermean magnetosphere almost symmetrically during the year 2011. Therefore, observing a large part of the general ULF waves at the dawnside magnetosphere is surprising, assuming they are (as the duskside general ULF waves) likely driven by the KHI. This either means that the dawnside general ULF waves are not generated by the KHI (although our results indicate that they are) or that dawnside KHWs are more common on Mercury than previously thought. Perhaps these dawnside KHWs do indeed frequently develop at the magnetopause but are constantly repressed by certain conditions of the surrounding environment (such as a broader velocity shear layer or a low-latitude boundary layer present most often at the dawnside as reported in Liljeblad et al. (2015)) and will therefore not be as clearly visible as the duskside KHWs. Thus, they are more difficult to identify with the criteria used in Liljeblad et al. (2014).

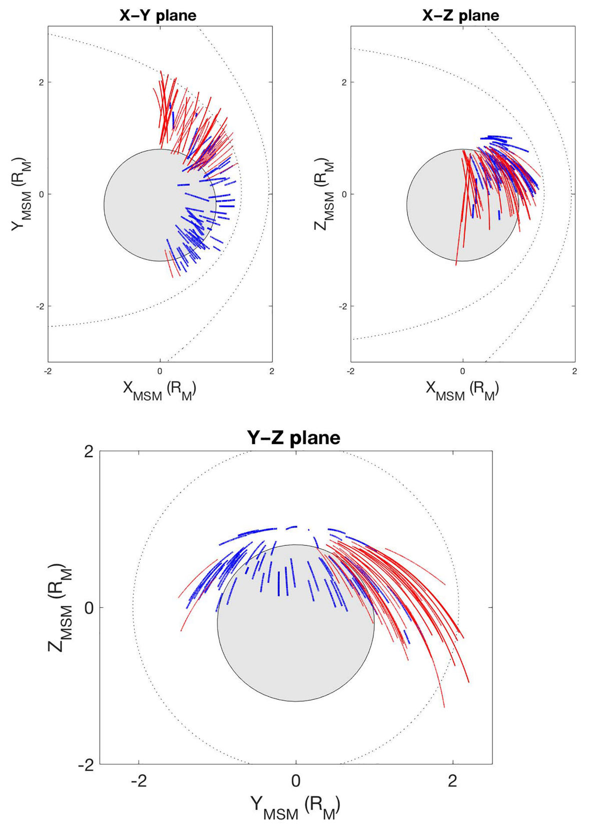

Figure 4. Location of ULF events in three different planes in Mercury solar magnetospheric (MSM) coordinates, in which blue lines mark the general ULF waves and red lines mark the KHI-ULF waves.

4 Conclusions

ULF waves in the ∼ 20–40 mHz range are frequently observed in the Mercury magnetosphere. The majority of these (in particular those on the dusk side) have very similar characteristics to the likely KHI-driven ULF waves identified in a previous study (Liljeblad et al., 2016). That a large number of the ULF waves are observed in the dawn sector of the magnetosphere and show similar characteristics as the KHI-driven ULF waves, including an opposite polarization compared to the duskside general ULF waves, indicates that KHWs at the dawnside may be more common than previously predicted. Assuming that the KHI-ULF waves are indeed KHI driven, this study advocates using ULF waves in the ∼ 20–40 mHz frequency range to identify KHI activity at the magnetopause. Thus, together with direct observations of KHWs at the magnetopause, an estimation of how frequently the KHI occurs in the Hermean magnetosphere can be obtained.

Data availability. The data for this paper are available at the NASA Planetary Data System: planetary plasma interactions node archive (http://pds-ppi.igpp.ucla.edu).

Competing interests. The authors declare that they have no conflict of interest.

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References

Arthur, C., McPherron, R., and Means, J.: A comparative study of three techniques for using the spectral matrix in wave analysis, Radio Sci., 11, 833–845, 1976.

Boardsen, S. A., Anderson, B. J., Acuña, M. H., Slavin, J. A., Korth, H., and Solomon, S. C.: Narrow-band ultra-low-frequency wave observations by MESSENGER during its January 2008 flyby through Mercury's magnetosphere, Geophys. Res. Lett., 36, L01104, https://doi.org/10.1029/2008GL036034, 2009.

Boardsen, S. A., Slavin, J. A., Anderson, B. J., Korth, H., Schriver, D., and Solomon, S. C.: Survey of coherent ∼ 1 Hz waves in Mercury's inner magnetosphere from MESSENGER observations, J. Geophys. Res.-Space, 117, A00M05, https://doi.org/10.1029/2012JA017822, 2012.

Dungey, J.: Electrodynamics of the outer atmospheres, Rep. 69, Ions, Res. Lab. Pa. State Univ., University Park, 1954.

Dungey, J. and Southwood, D.: Ultra low frequency waves in the magnetosphere, Space Sci. Rev., 10, 672–688, 1970.

Hughes, W. J.: Magnetospheric ULF Waves: A Tutorial with a Historical Perspective, in: Solar Wind Sources of Magnetospheric Ultra-Low-Frequency Waves, edited by: Engebretson, M. J., Takahashi, K., and Scholer, M., American Geophysical Union, Washington, D. C., https://doi.org/10.1029/GM081p0001, 1994.

James, M. K., Bunce, E. J., Yeoman, T. K., Imber, S. M., and Korth, H.: A statistical survey of ultralow-frequency wave power and polarization in the Hermean magnetosphere, J. Geophys. Res.-Space, 121, 8755–8772, 2016.

Liljeblad, E., Sundberg, T., Karlsson, T., and Kullen, A.: Statistical investigation of Kelvin-Helmholtz waves at the magnetopause of Mercury, J. Geophys. Res.-Space,, 119, 9670–9683, 2014.

Liljeblad, E., Karlsson, T., Raines, J. M., Slavin, J. A., Kullen, A., Sundberg, T., and Zurbuchen, T. H.: MESSENGER observations of the dayside low-latitude boundary layer in Mercury's magnetosphere, J. Geophys. Res.-Space, 120, 8387–8400, 2015.

Liljeblad, E., Karlsson, T., Sundberg, T., and Kullen, A.: Observations of magnetospheric ULF waves in connection with the Kelvin-Helmholtz instability at Mercury, J. Geophys. Res.-Space, 121, 8576–8588, 2016.

Means, J. D.: Use of the three-dimensional covariance matrix in analyzing the polarization properties of plane waves, J. Geophys. Res., 77, 5551–5559, 1972.

Russell, C. T.: ULF waves in the Mercury magnetosphere, Geophys. Res. Lett., 16, 1253–1256, https://doi.org/10.1029/GL016i011p01253, 1989.

Samson, J., Jacobs, J., and Rostoker, G.: Latitude-dependent characteristics of long-period geomagnetic micropulsations, J. Geophys. Res., 76, 3675–3683, 1971.

Samson, J., Harrold, B., Ruohoniemi, J., Greenwald, R., and Walker, A.: Field line resonances associated with MHD waveguides in the magnetosphere, Geophys. Res. Lett., 19, 441–444, 1992.

Sibeck, D. G., Baumjohann, W., Elphic, R. C., Fairfield, D. H., Fennell, J. F., Gail, W. B., Lanzerotti, L. J., Lopez, R. E., Luehr, H., Lui, A. T. Y., Maclennan, C. G., McEntire, R. W., Potemra, T. A., Rosenberg, T. J., and Takahashi, K.: The magnetospheric response to 8-minute period strong-amplitude upstream pressure variations, J. Geophys. Res.-Space,, 94, 2505–2519, 1989.

Southwood, D.: Some features of field line resonances in the magnetosphere, Planet. Space Sci., 22, 483–491, 1974.

Southwood, D., Dungey, J., and Etherington, R.: Bounce resonant interaction between pulsations and trapped particles, Planet. Space Sci., 17, 349–361, 1969.