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WAVELET ANALYSIS OF ULF WAVES IN THE MERCURY'S MAGNETOSPHERE

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ABSTRACT. Ultra-low-frequency (ULF) waves have been observed in the Mercury's magnetosphere. In this work, Mariner-10 and MESSENGER high resolution magnetic field data are studied with wavelet analysis. Two ULF wave intervals have been selected: 29 March 1974 (Mariner-10) and 14 January 2008 (MESSENGER). Non-stationary oscillations, with strong amplitude and narrow bandwidth have been found. The Mariner-10 ULF wave interval showed periods of ∼1.5-3.0 s, and the MESSENGER ULF wave interval had periods of ∼0.5-1.0 s. These periods of ULF waves are slightly longer than the proton gyroperiods (∼0.8 and ∼0.5 s, respectively). Therefore, these waves are most likely kinetic, not magnetohydrodynamic waves.

Keywords: Mercury's magnetosphere, ULF waves, wavelet analysis.

RESUMO. Ondas de frequência ultrabaixa (ULF) foram observadas na magnetosfera de Mercúrio. Neste trabalho, dados de campo magnético de alta resolução das sondas Mariner-10 e MESSENGER são estudados com análise por ondeletas. Dois intervalos de ondas ULF foram selecionados: 29 de março de 1974 (Mariner-10) e 14 de janeiro de 2008 (MESSENGER). Oscilações não estacionárias, de banda estreita e forte amplitude foram encontradas. As ondas ULF do intervalo da Mariner-10 tinham períodos entre ∼1,5-3,0 s, e as ondas ULF do intervalo da MESSENGER tinham períodos de ∼0,5-1,0 s. Esses períodos das ondas ULF são ligeiramente maiores que os giro-períodos do próton (∼0,8 s e ∼0,5 s, respectivamente). Portanto, essas ondas não são ondas do tipo magnetohidrodinâmico, mas são provavelmente ondas do tipo cinético.

Palavras-chave: magnetosfera de Mercúrio, ondas ULF, análise por ondeletas.

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INTRODUCTION

Mercury is the inner planet of our solar system, and it has been known since ancient times (Strom & Sprague, 2003). However, it is one of the less investigated planets by *in situ* measurements, visited only by the Mariner-10 spacecraft in 1974-1975, and recently by MESSENGER spacecraft in 2008-2009. Mercury's surface is heavily cratered, and its atmosphere is very thin, which makes it something similar to the Moon (Ness, 1978; Strom & Sprague, 2003). Nevertheless, the most unexpected discovery was the existence of an intrinsic planetary dipole magnetic field and a magnetosphere (Ness et al., 1974, 1975a, b, 1976; Ness, 1979; Russell, 1981; Russell et al., 1988; Slavin, 2004; Slavin et al., 2008; Anderson et al., 2008). This finding and the high average planetary density (5.4 g/cm^3) led to the idea that Mercury has a differentiated core and mantle, with an active planetary dynamo (Ness, 1978; Russell et al., 1988).

However, Mercury's magnetic field intensity is very weak, around only 1% of the Earth's field. Mercury has a magnetopause, a magnetotail and a bow shock, but not a radiation belt. This is because the planet is very large compared to its magnetosphere (Russell et al., 1988; Slavin, 2004). Interplanetary conditions at Mercury's orbit are very different than those at Earth's one: the interplanetary magnetic field is stronger and more radially oriented, the solar wind pressure is higher, and the bow shock Mach number is lower (Russell et al., 1988). As a consequence of weak planetary field and very strong solar wind pressure, the sub-solar Mercury's magnetopause and bow shock positions are much closer to the planet than the Earth's magnetopause and bow shock.

Possible substorm activity has been observed during the outbound part of the first Mariner-10 flyby (Siscoe et al., 1975). However, it is not known at present if Mercury's magnetosphere shows some similar kind of magnetospheric activity as auroras and ring current/magnetic storms seen in the Earth's magnetosphere (e.g., Echer et al., 2005).

Ultra-low-frequency (ULF) waves are magnetic field oscillations found in planetary magnetospheres, with frequency much lower than the natural plasma frequencies, such as the plasma and gyrofrequencies (Kivelson, 1995). They have been observed in every planetary magnetosphere (Glassmeier et al., 2004) including Mercury (Russell, 1989). In the case of Earth, ULF waves are standing MHD waves in the magnetospheric system with the north and south ionosphere being the boundaries where the oscillations exhibit a mode (Kivelson, 1995; Glassmeier et al., 2004). The magnetosphere of Mercury, on the other hand, has no significant ionosphere, and it is a rather stiff magnetosphere, and it can start to ring under the influence of solar wind dynamic pressure variations (Glassmeier et al., 2004).

ULF waves have been found in the Mercury's magnetosphere with Mariner-10 data. A spectral peak in the magnetic field data at 2 s was found by Russell (1989). Those ULF waves were suggested to be a resonance, the 4th harmonic of the fundamental of the standing wave, because the local proton gyrofrequency was 1.31 Hz (Russell, 1989). However, more recently, Othmer et al. (1999) and Glassmeier et al. (2003) presented a detailed analysis of Mercury's ULF waves and concluded that these waves are kinetic Alfvén waves, not MHD waves, because their periods are very close to the proton gyroperiod. Othmer et al. (1999) have modeled the ULF waves at Mercury using a multi-component cold plasma model and found the resonance point at the cross-over frequency instead of the local resonance frequency of a standing field line oscillation. ULF waves in Mercury have been also recently observed with MESSENGER data (Slavin et al., 2008; Boardsen et al., 2009a, b).

Classic spectral analysis techniques have been previously employed to investigate ULF waves within the magnetosphere (Russell, 1989). Recently, Boardsen & Slavin (2007) tried to detect Na+ cyclotron waves using FFT, with no conclusive detection. Wavelet analyses of magnetic field fluctuations in planetary plasma environments have been done in recent years, for example for Mars environment (Tarasov et al., 1998; Espley et al., 2004) and for Uranus and Neptune foreshock and magnetosheath regions (Echer, 2009). This paper aims to apply the wavelet technique to the Mercury magnetosphere environment and to identify the main frequencies and their non-stationary characteristics present in ULF waves observed during Mariner-10 (29 March 1974), and MESSENGER (14 January 2008) first flybys.

METHODOLOGY OF ANALYSES

Magnetometer data

In this work, high resolution magnetic field data are used to study ULF fluctuations in the Mercury's magnetosphere. These data were obtained from the Planetary Data Service (PDS), http://pds.jpl.nasa.gov (McMahon, 1996). The Mariner-10 magnetometer data have a resolution of 25 samples.s^{-1}. Detailed description of the instrument can be found in (Ness et al., 1971). The MESSENGER magnetometer data have a resolution of 20 samples. s^{-1}. (Anderson et al., 2007). The magnetic field vector data are in the Mercury solar orbital coordinates, where X is directed from the center of the planet toward the Sun; Z is normal to Mercury's orbital plane and positive toward the north celestial pole; and Y is positive in the direction opposite to orbital motion.

Wavelet analysis

Analogously to the Fourier analysis, which decomposes a signal in sine waves of several frequencies, the wavelet transform decomposes a signal in translated and scaled (dilated or compressed) versions of the mother wavelet, each one multiplied by an appropriate coefficient. By varying the wavelet scale and translating along the localized time index n, one can obtain a wavelet map showing both the amplitude of any feature versus the scale and how this amplitude varies with time. The time axis is the same as the data series and it is the abscissa of the graph. The ordinate axis corresponds to the scale and, in the case of time series it is approximately the period of the fluctuations. Short periods (or high frequencies) are plotted in the top of the map and long periods (or low frequencies) are plotted in the bottom of the map. For this work, the Morlet wavelet is used, which a continuous wavelet transform that can be used to study (quasi) periodical signals (Kumar & Foufoula-Georgiou, 1995; Torrence & Compo, 1998).

Interval of data and data processing

For this analysis, two ULF wave activity intervals have been selected. For Mariner-10 data, the period is the one studied by Russell (1989), from 20:45:00 to 20:45:38 UT on 29 March 1974. For MESSENGER data, the interval is the one showed by Slavin et al. (2008), from 19:07:00 to 19:08:00 UT on 14 January 2008. These intervals, the average magnetic field magnitude, and proton gyrofrequency are shown in Table 1.

Due to the long term trend in magnetic field data, which are caused by space variations of ambient magnetic field due to the spacecraft passing through different regions of the magnetosphere, it was necessary in some cases to detrend the magnetic field data using a linear fit. Then the Morlet wavelet transform was applied and wavelet spectra derived, with confidence level of 95%.

RESULTS AND DISCUSSION

Figure 1 shows the magnetic field data and wavelet spectra during the Mariner-10 inbound trajectory, near to the closest approach point, from 20:45:00 to 20:45:38 UT, 29 March 1974 (38 s duration). Only the By component was detrended with a linear fit, and panels are shown as: a) Bx, b) dBy, c) Bz and d) B magnitude. A large amplitude, non-stationary signal is seen in all wavelet spectra around 1.5-3.0 s. This corresponds to the ULF pulsations with spectral peak at 2 s as found by Russell (1989). It can also be seen that there is more power at the end of this ULF packet. These waves are slightly compressive, with strong spectral amplitude fluctuations seen in the wavelet spectrum of magnetic field magnitude, but these are low compared to the total field (∼0.05 B). The proton cyclotron period for this interval is ∼0.77 s (Table 1), thus the period of the ULF waves is only slightly longer than the proton gyroperiod (i.e., 2-4 times longer).

Figure 2 shows the magnetic field data and wavelet spectra during the MESSENGER first flyby. All components but By have been detrended with a linear fit and are shown as: a) dBx, b) By, c) dBz and d) dB magnitude. This event was observed after the closest approach and close to the planetary boundary layer, from 19:07:00 to 19:08:00 UT (60 s), 14 January 2008. A large amplitude, non-stationary signal is seen in all wavelet spectra with wave periods of 0.5-1.0 s. This corresponds to the ∼1 s signal reported by Slavin et al. (2008). These waves are slightly compressive, with strong spectral amplitude fluctuations seen in the wavelet spectra, but these waves have low amplitude compared to the total field (∼0.01 B). The proton cyclotron period for this interval is 0.48 s (Table 1), thus the period of these waves is only slightly longer than the proton gyroperiod (i.e., 1-2 times longer).

The spectral characteristics seen in both Mariner-10 and MESSENGER magnetic field wavelet spectra are similar for the components and for the field magnitude. It is interesting that only low-latitude flybys have observed ULF waves, and the high latitude Marinter-10 flyby did not seen it. It has been considered that these waves might be confined to the Mercury's magnetic equator (e.g., Boardsen et al., 2009b).

CONCLUSIONS

Wavelet analysis (Morlet) was applied to Mariner-10 and MESSENGER high resolution magnetometer data during ULF wave activity intervals. It has been found that:

- The spectra are dominated by strong amplitude and quasi-monochromatic waves. These signals have a very narrow bandwidth, but they are highly intermittent, i.e., the amplitude changes with time/position in the Mercury's magnetosphere.
- ULF waves have periods of ∼1.5-3.0 s for the Mariner-10 event.
- ULF waves have periods of ∼0.5-1.0 s for the MESSENGER event.
- Periods of ULF waves are slightly longer than the proton gyroperiod. Thus these waves are most likely kinetic, not MHD waves.
- The waves are slightly compressive (∼0.01-0.05 of average magnetic field, $\langle B \rangle$).

Table 1 – Period of analysis for the ULF waves, duration of the interval, average magnetic field magnitude and proton gyrofrequency.

Spacecraft	Period	Duration (s)	<B> (nT)	$<f_{cH+}>$ (Hz)
Mariner-10	20:45:00-20:45:38 UT 29 March 1974	38	86	1.3
MESSENGER	19:07:00-19:08:00 UT 14 January 2008	60	140	2.1

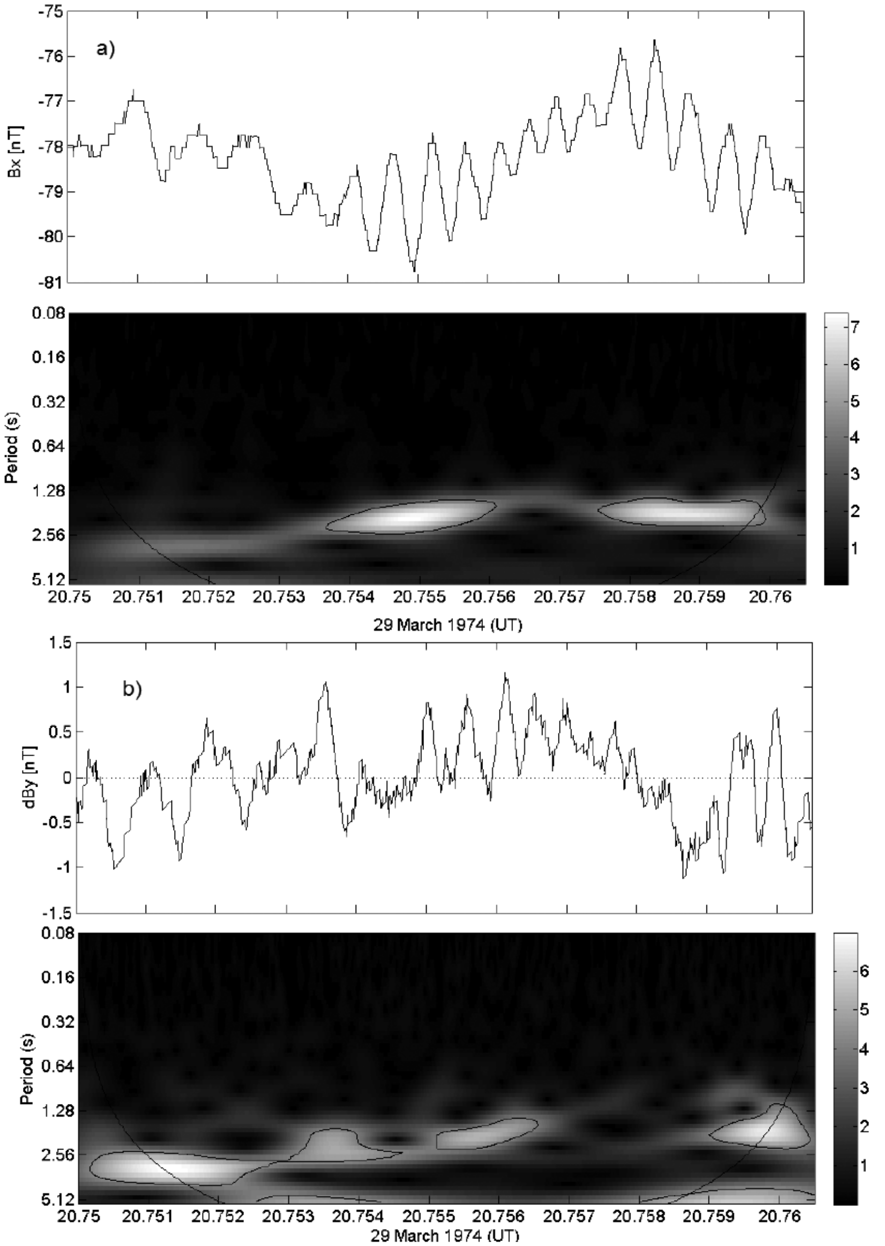

Figure 1 – Magnetic field vector and magnitude data, and Morlet wavelet spectra, for the Mariner-10 first flyby, 29 March 1974: a) Bx; b) dBy.

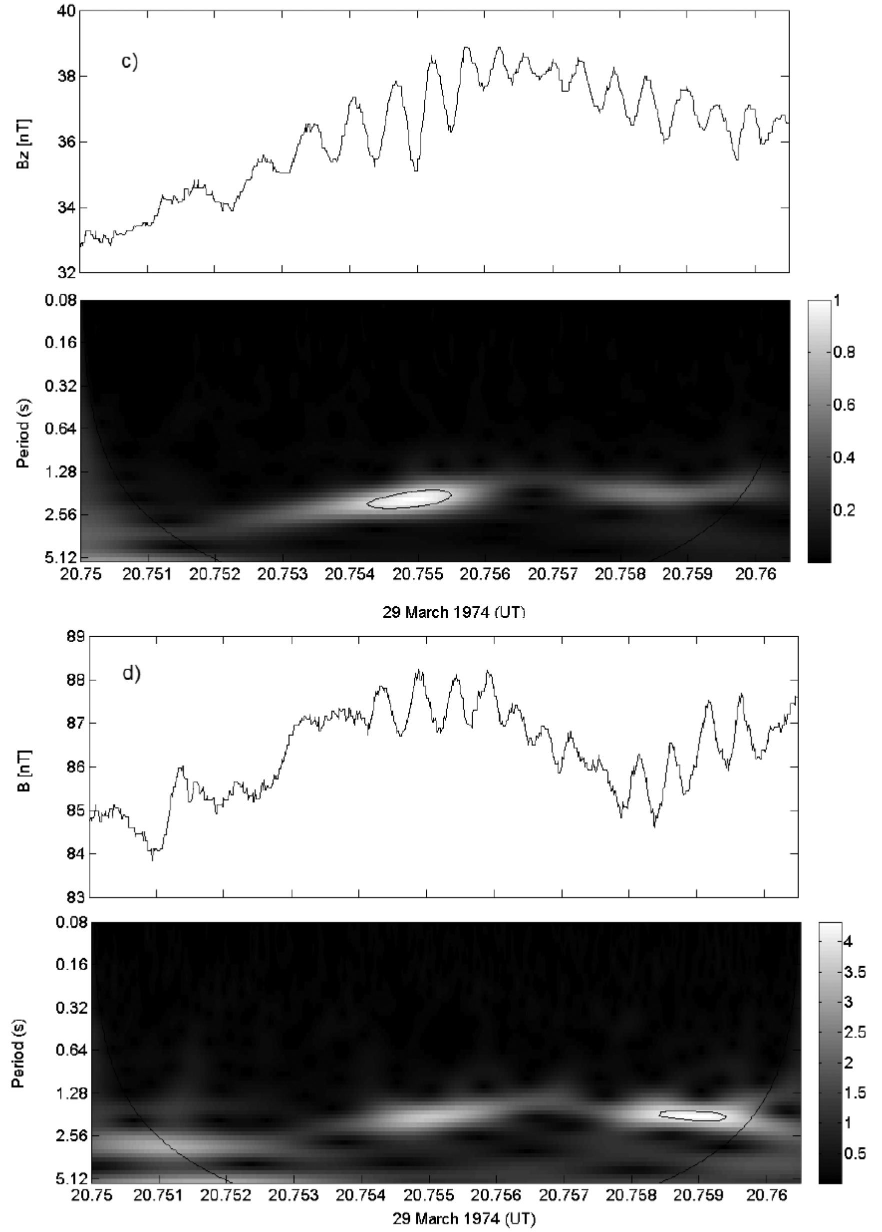

Figure 1 (continuation) – Magnetic field vector and magnitude data, and Morlet wavelet spectra, for the Mariner-10 first flyby, 29 March 1974: c) Bz; d) B magnitude.

Planetary magnetospheres in the solar system have very different internal (planet plasma, magnetic field environments) and external (solar wind) conditions. Thus it is very important to improve the current understanding of ULF waves to perform studies in other magnetospheres besides the Earth's one, such as it was done in the present work for Mercury. By studying comparatively different magnetospheres, it is possible to obtain information about different physical conditions that lead to the generation of ULF waves.

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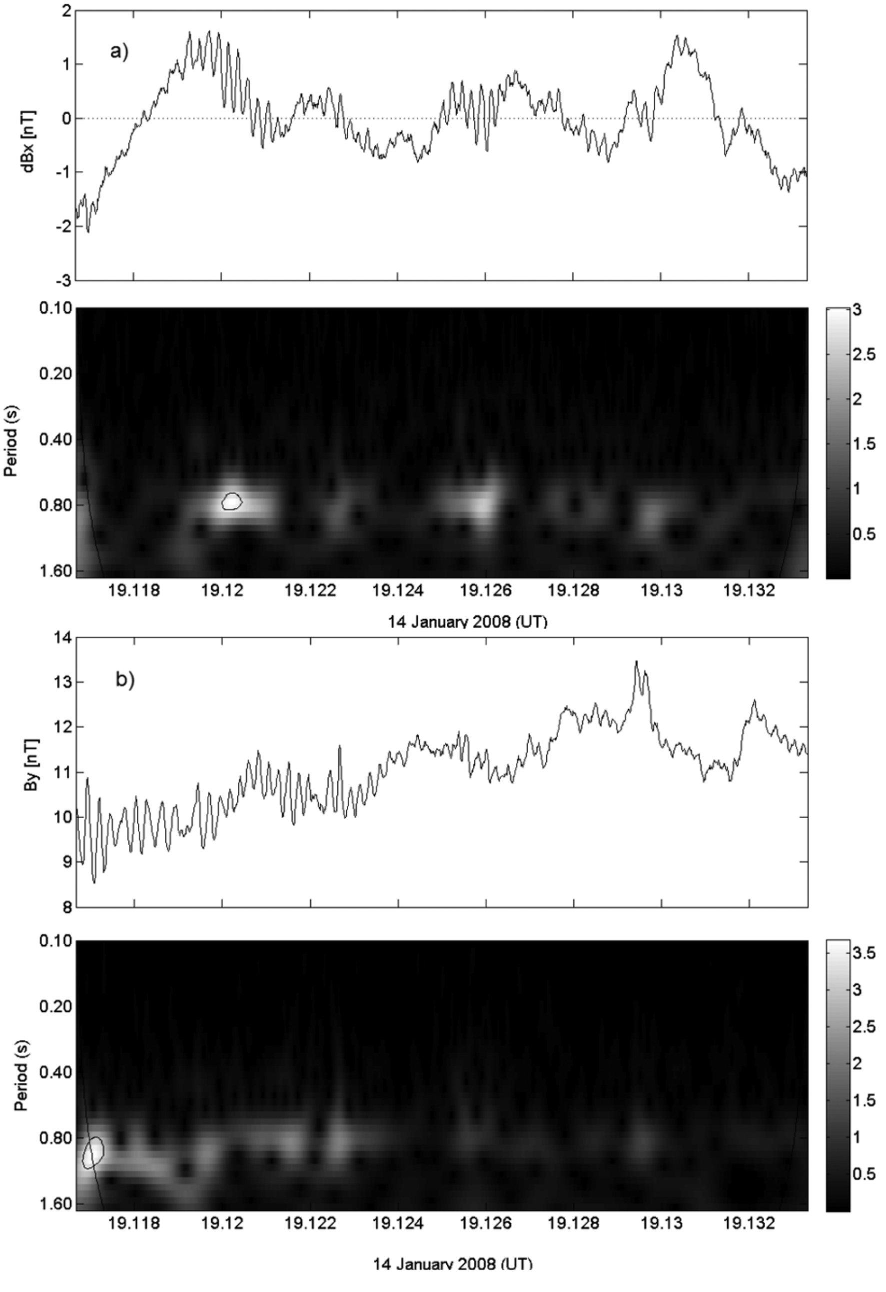

Figure 2 – Magnetic field vector and magnitude data, and Morlet wavelet spectra, for the MESSENGER first flyby, 14 January 2008: a) dBx; b) By.

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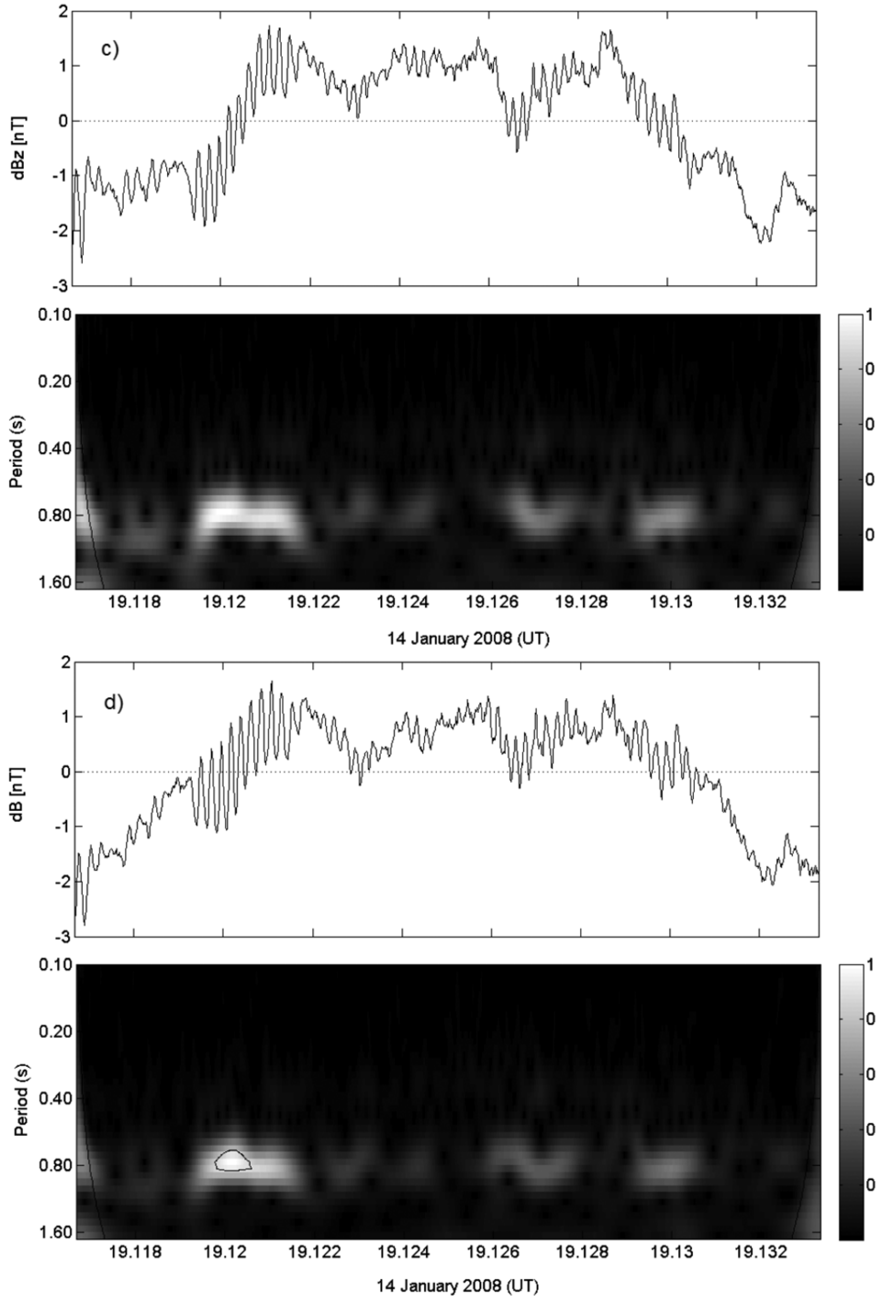

Figure 2 (continuation) – Magnetic field vector and magnitude data, and Morlet wavelet spectra, for the MESSENGER first flyby, 14 January 2008: c) dBz; d) dB magnitude.

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