

Electron oscillations in the induced martian magnetosphere

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Abstract

The Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) experiment flown on the Mars Express (MEX) spacecraft includes the Electron Spectrometer (ELS) as part of its complement. The ELS instrument measures the differential electron flux spectrum in a 128-level logarithmic energy sweep within a time period of 4 s. The orbital path of MEX traverses the martian sheath, cusps, and tail where ELS recorded periodic electron intensity oscillations. These oscillations comprised periodic variations of up to an order of magnitude (peak to valley) in energy flux, with the largest amplitudes in the tens to hundreds of eV range. The observed oscillations displayed periods ranging from minutes down to the instrument sweep resolution of 4 s. In the cases analyzed here, the frequency of the integrated electron energy flux typically peaked between 0.01 and 0.02 Hz. This frequency range is nearly the same as the typical O^+ gyrofrequency in the magnetosheath, calculated using magnetometer data from Mars Global Surveyor. Due to the motion of the spacecraft, it is unclear if the wave structures observed were permanent standing waves or rather constituted waves propagating past the spacecraft.

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1. Introduction

Espley et al. (2004) reported low frequency oscillations in the martian magnetosheath, magnetic pile-up region (MPR), and tail. Based on an extensive survey of magnetometer (MAG) data from the Mars Global Surveyor (MGS) spacecraft, these authors found that the fluctuations in the day side magnetosheath were mainly compressional, elliptically polarized with wave vectors at large angles to the mean field and with dominant frequencies significantly below the local proton gyrofrequency. Using kinetic plasma wave theory populations (see reviews by Gary, 1993 and Krauss-Varban et al., 1994), the authors tentatively identified the waves as due to mirror mode instabilities. Other workers (e.g., Sauer et al., 1998) used Phobos-2 observations and bi-ion fluid theory to identify nonlinear magnetoacoustic waves downstream of the martian bowshock. In the night side magnetosheath, Espley et al. found the waves to be mainly transverse elliptically polarized waves at somewhat higher frequencies. These waves have been interpreted as being due to ion/ion resonant instabilities arising from counterstreaming ion populations.

These results provide an impetus for analyzing similar observations recorded at Mars aboard the Mars Express (MEX) spacecraft. However, MEX carried no science or aspect magnetometer. MEX did carry an electron spectrometer (ELS) and an ion mass spectrometer (IMA) as part of the Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) experiment. The ELS measurement frequency (4 s per spectrum) is sufficient to observe most of the low frequency regime covered by the MGS magnetometer. Results will be presented from ELS that again demonstrate the presence in the close martian environment of electron oscillations. As with most wave structures observed by a spacecraft which is in motion, it is unclear if the wave structures observed were permanent standing waves or rather constituted waves propagating past the spacecraft. However, this does not change the fact that electron oscillations were observed.

Mars possesses no intrinsic planetary magnetic field; however, it does display localized crustal fields at the surface of the planet. These magnetic fields are described by Connerney et al. (2001). The solar wind and its interplanetary magnetic field (IMF) interact with Mars to form an induced magnetic field around the planet which stands off the solar wind. The solar wind interaction produces a bow shock (BS) in front of the planet. The region where the solar wind plasma is diverted around the planet is called the martian magnetosheath (MS). The boundary between the MS and the ionosphere/tail/inner magnetosphere is defined by Lundin et al. (2004) using ion signatures from MEX to constitute the induced magnetosphere boundary (IMB). The IMB is located at or very near the magnetic pile-up boundary (MPB) defined by MGS, the difference being that the MPB is defined using the magnetic field signature and the IMB is defined using the particle signature. At and

below the IMB, the crustal fields of Mars exert a significant influence on the shape of the IMB and on the behavior of its contained plasma (Brain et al., 2003).

2. Instrument

The MEX ELS is a spherical top hat, which samples electrons from a $4^\circ \times 360^\circ$ wide FOV, divided into 16 sectors, where each sector is 22.5° wide. The ELS k -factor or energy sensitivity (7.23 ± 0.05 eV/V) and resolution ($\Delta E/E = 0.083 \pm 0.003$) (Sablík et al., 1990) are slightly sector dependent and were determined by laboratory measurements at 10 keV. Energy deviations of the k -factor and resolution were folded into an energy-dependent relative microchannel plate (MCP) efficiency factor. This allowed the energy independent physical geometric factor to be determined (5.88×10^{-4} cm² sr). A more complete description can be found in Barabash et al. (2004). The 360° acceptance plane of the ELS FOV is coplanar with the spacecraft XZ plane which, during this period is parallel to the ecliptic (Chicarro et al., 2004).

ELS covers the energy range from 1 eV to 20 keV and incorporates a deflection power supply which has two ranges. The ELS deflection voltage ranges from 0 to 20.99 V in its low range and from 0 to 2800.0 V in its high range. The energy conversion is sector dependent, but is approximately 150 eV (20 keV) at its maximum low (high) range value. Each supply range has a control resolution of 4096 linear voltage values within its full range. Of the 8192 possible deflection voltage values, 128 are selected to comprise the ELS energy sweep, which occurs in 4 s.

Currently the ASPERA-3 data processing unit (DPU) is programmed to telemeter instrument engineering data instead of science data in place of every 8th electron spectrum. This causes a time gap in the ELS spectrum information which, in the case of the Fourier analysis herein, is filled by linear interpolation between the adjacent measurements.

3. Observations

On August 9, 2004 (2004/222), the Mars Express spacecraft (orbit 711) traveled almost perpendicular to the flow in the magnetosheath in the dawn (~ 06 h) sector. In planetodetic coordinates (Duxbury, 1979; Lieske et al., 1977) it was at $\sim 0^\circ$ latitude. Fig. 1 shows the orientation of the Mars Express orbit as it traveled away from periapsis through the MS, and into the solar wind at about 21:00 UT. While in the sheath, ELS observed periodic oscillations in the electron energy intensity (differential energy flux in units of ergs/(cm² sr eV s)).

An energy-time spectrogram showing the ELS measured electrons from sector 3 (pointing approximately perpendicular to the orbit direction in the sheath flow ram direction) is displayed in the top panel of Fig. 2. This spectrogram was recorded during the transit of Mars Express across the MS. Before 20:59:00 UT, ELS observes inner magnetosphere electron

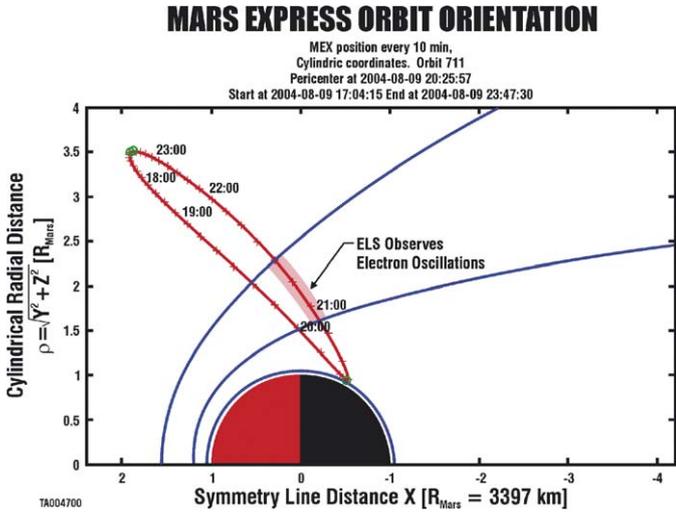


Fig. 1. Mars Express orbit 711 on August 9, 2004. The Mars Express spacecraft traveled from periaispis, through the sheath, and into the solar wind nearly perpendicular to the sheath flow. While in the sheath, ELS recorded oscillations in the electron plasma. This plot is in Mars cylindrical coordinates and the outer two blue curves represent the nominal bow shock and induced magnetospheric boundary.

plasma (characterized by energy peaks around 10 eV). From 20:59:00 UT until 21:24:30 UT ELS observed MS electrons which showed a characteristic energy of about 50 eV. The differential energy flux intensity of the electrons oscillated during the crossing of the sheath. After 21:24:39 UT, the characteristic energy again decreased as ELS entered the solar wind plasma.

The ASPERA-3 experiment also contains an Ion Mass Analyzer (IMA) (Barabash et al., 2004). The IMA is a three stage analyzer: a 16 step elevation analyzer to select a polar angle, a top hat to select one of 96 ion energies, and a magnetic deflection system to determine mass from a 32 element anode. IMA cycles through its 96 energy steps and 16 elevation steps in 192 s to create an energy–mass–azimuth–elevation measurement set. This 192 s cycle time of IMA is too long when compared to the period of the electron oscillations observed in Fig. 2. Thus, ion oscillations at the frequencies discussed in this paper could not be observed at this time.

A line plot of the differential electron energy flux integrated over energy for sensor 3 is included in the bottom panel (red curve) to emphasize the very regular nature of the electron oscillations recorded. Such pulsations are routinely observed by the MEX ELS. Statistical results will be presented in a later pa-

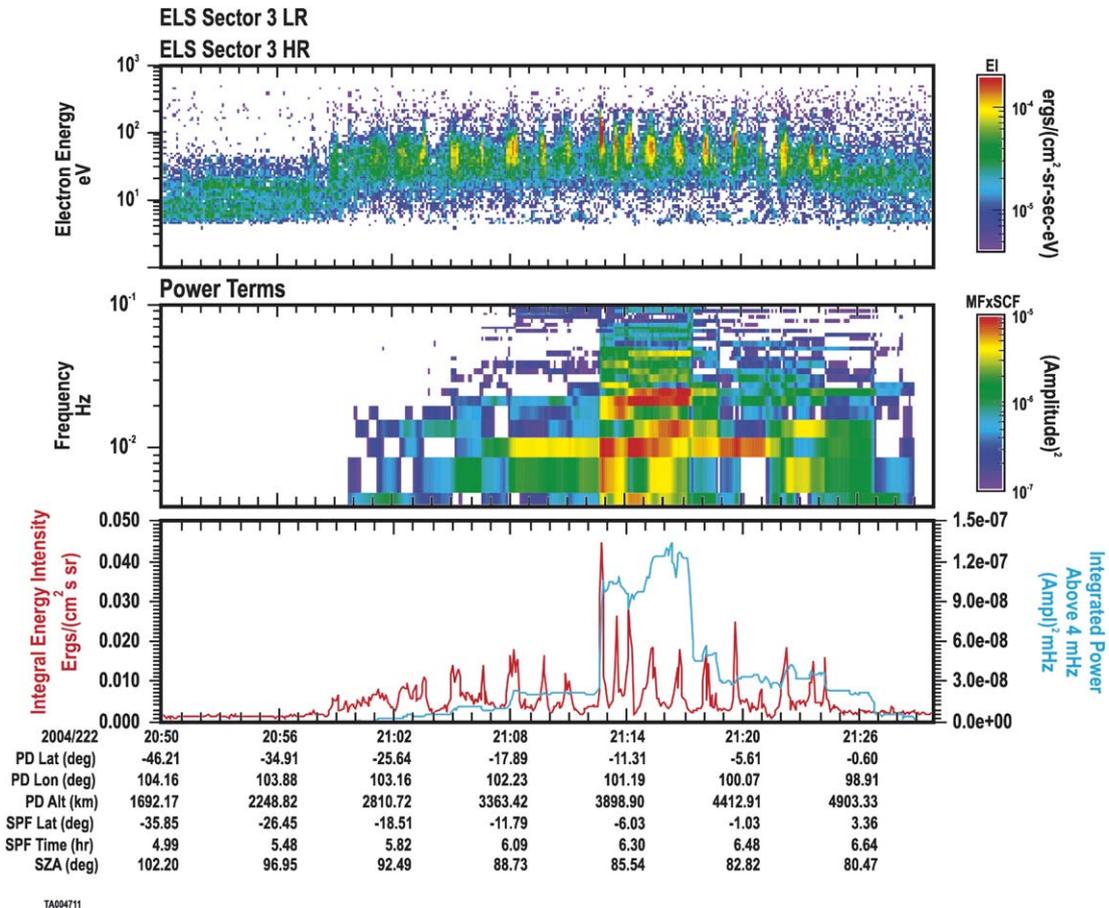


Fig. 2. Electron spectrogram (top panel) of electron oscillations for orbit 711, August 9, 2004. Shown are data from the ELS measurements of the energy intensity oscillations (upper panel). This energy intensity was Fourier analyzed and the resulting frequency spectrogram is shown in the center panel. The bottom panel shows the integrated energy flux (left annotation) and integrated power (right annotation) above the line of significance (shown in Fig. 3).

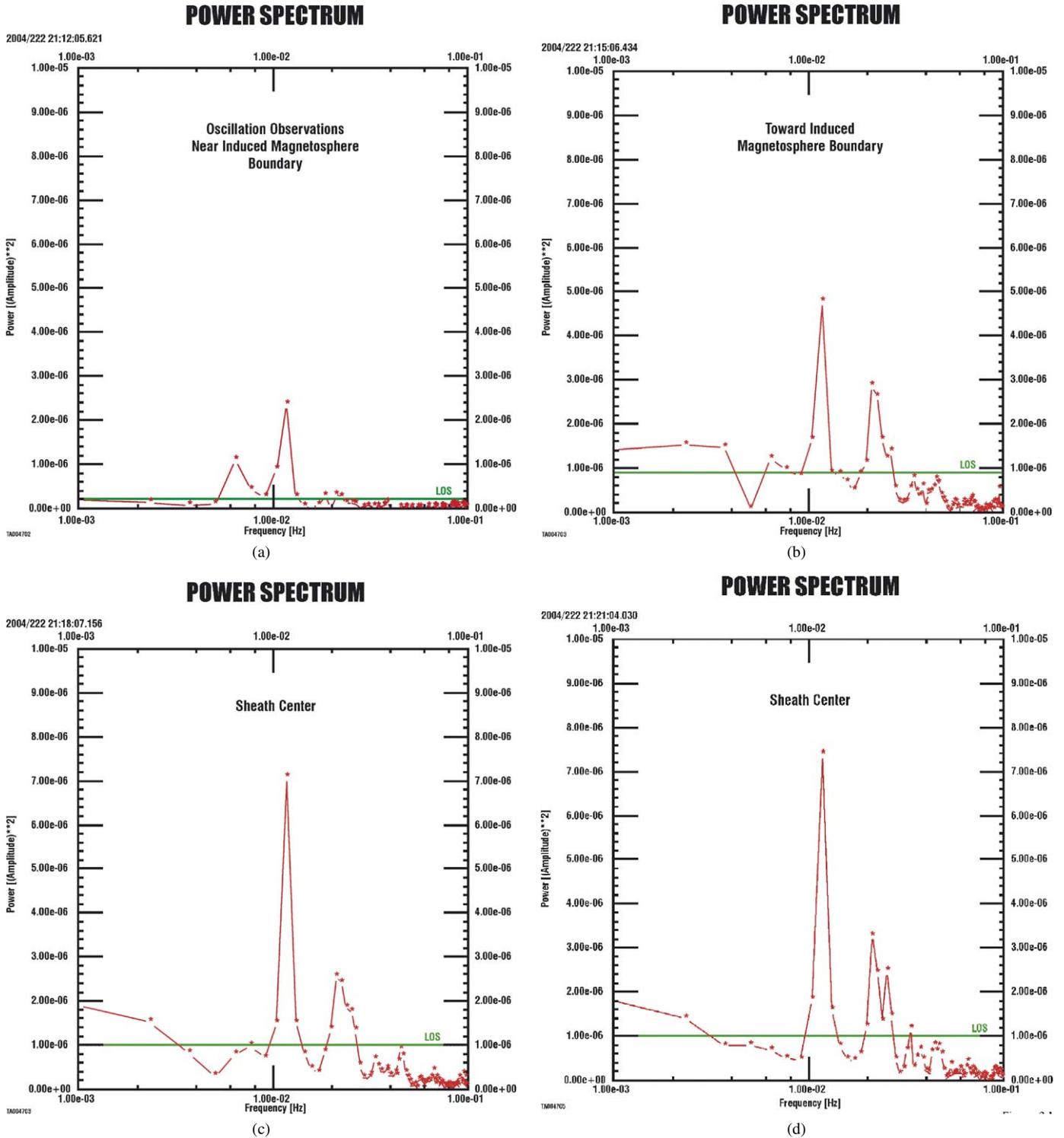


Fig. 3. Selected frequency spectra throughout the sheath transit. Power spectra from the Fourier analysis are displayed at intervals of about every 3 min to cover the period when Mars Express crossed the sheath; (a) near the inner magnetospheric boundary, (b) toward the inner magnetospheric boundary, (c) and (d) at the center of the sheath, (e) toward the bow shock, (f) near the bow shock. Significant frequencies are greater than 4 mHz. Significant amplitudes are above the line of significance (LOS).

per. The peak to valley ratio of the pulsations is about a factor of 10 (i.e., quite significant). Orbital parameters are provided at the bottom of the figure. In the middle panel a frequency time spectrogram of the power spectrum of the oscillations is provided. The power spectrum was created using a sliding Fourier Trans-

form Technique (Hamming, 1962; Blackman and Tukey, 1958; Bevington, 1969; Reiff, 1983) on the integrated differential energy flux. Very clear lines (~10 and 20 mHz) are seen in the f-t spectrograms, which show an orbital variation in both frequency and amplitude. In this analysis, a 5 min wide window

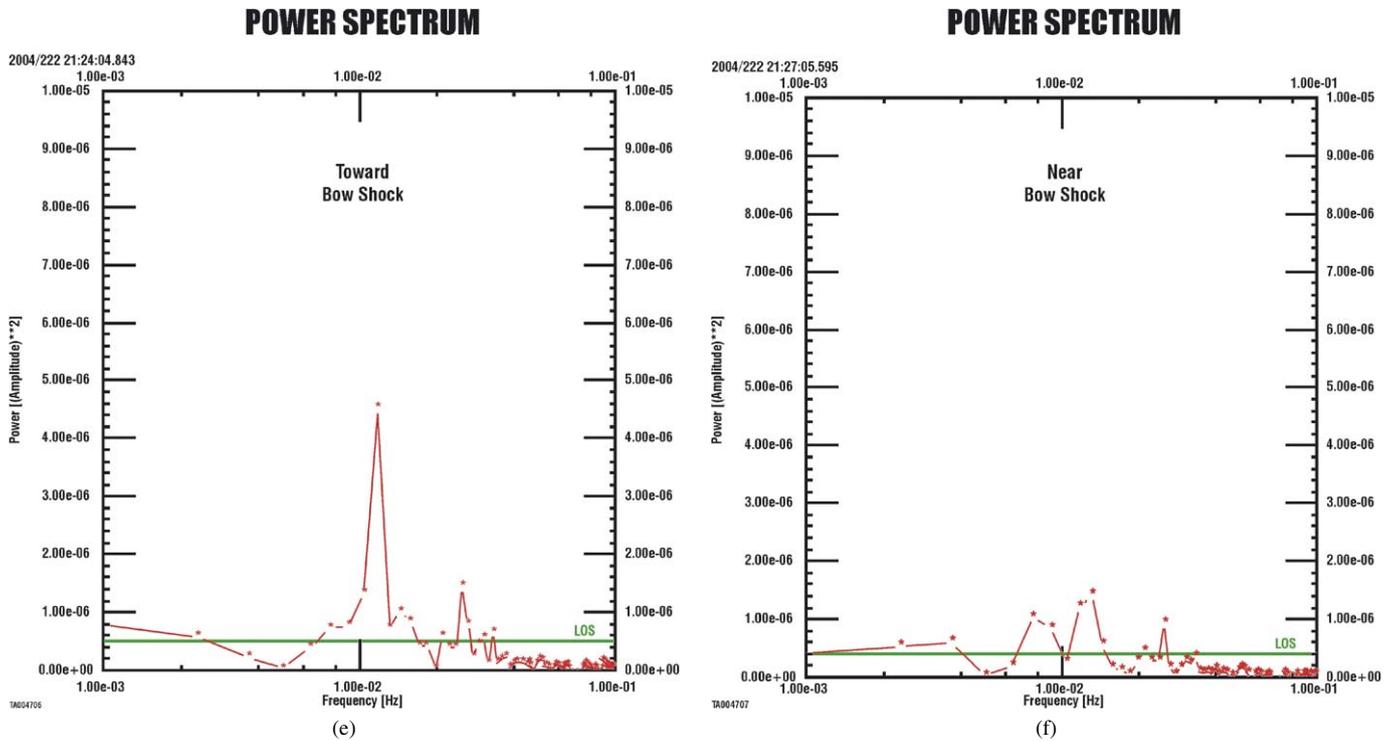


Fig. 3. (continued)

(150 spectra) was used which was consecutively slid forward by 4 s (1 spectrum at a time). The white gap is due to a lag of 5 min prior to the first calculated spectrum plotted. In the bottom panel the blue curve is the integrated wave power above 4 mHz. One can see the change in power as the spacecraft transited the sheath from the inside to the outside.

The power spectrum has been examined in more detail by means of the frequency spectral plots shown in Fig. 3 which were recorded while traversing the sheath. These show that different frequency components tend to dominate at different locations within the MS. Fig. 3a from 21:07 to 21:12 UT shows the power spectrum near the induced magnetospheric boundary (IMB), which is the envelope of the induced martian magnetosphere (Lundin et al., 2004). The horizontal line labeled LOS is the level of significance (Reiff, 1983) and represents the 2σ level. Peaks at frequencies of about 6.5 mHz and 12 mHz are observed. These frequencies are fairly constant until about 21:12:30 UT.

Toward the center of the MS, a disruption in the beating pattern took place. The frequency pattern (Fig. 3b from 21:10 to 21:15 UT) shows the inclusion of high frequency peaks (with frequencies about 23, 35, and 47 mHz) and a reduction in amplitude at the lower frequencies. At the same time, the 12 mHz peak became more dominant in the power spectrum.

In the center of the MS (Fig. 3c from 21:13 to 21:18 UT, and Fig. 3d from 21:16 to 21:21 UT), the lower frequency components vanished, and the amplitude and frequency patterns suggest that multiple harmonics of the 12 mHz signal are present. Toward the bow shock (Fig. 3e from 21:19 to 21:24 UT), the higher frequency terms decayed in amplitude leaving behind the 12 mHz fundamental. Near the bow shock (Fig. 3f from

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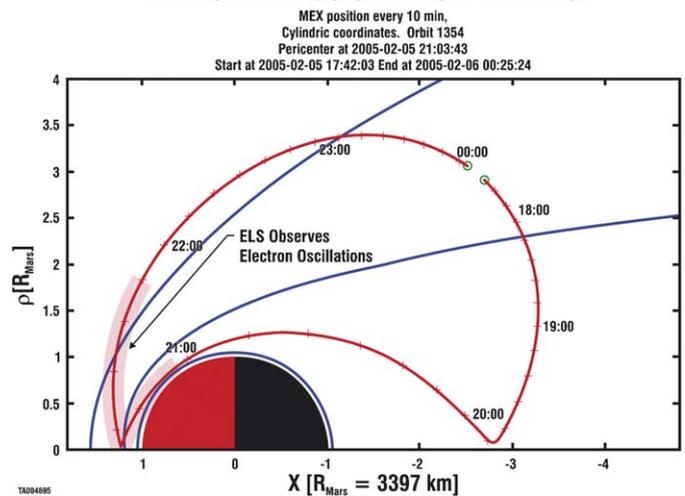


Fig. 4. Same as Fig. 1 for orbit 1354 on February 5, 2005.

21:22 to 21:27 UT), a peak at about 8 mHz appears; however, the peak at 12 mHz remained the larger.

Fig. 4 shows the projected orbit for February 5, 2005 (2005/036, orbit 1354). The electron data can be seen to be collected near noon (11–14 h solar or local time) as the spacecraft passed from north to south of the planetodetic (PD) equator. At $\sim 21:10$ UT MEX crossed the IMB into the MS and entered the solar wind at $\sim 21:50$ UT. The electron data for the sheath region during this pass is displayed in Fig. 5. In the top panel of Fig. 5 the same plasma oscillations are again seen, although they are more complex than in the earlier example. In general, this pass covered lower altitudes (450–3000 km as

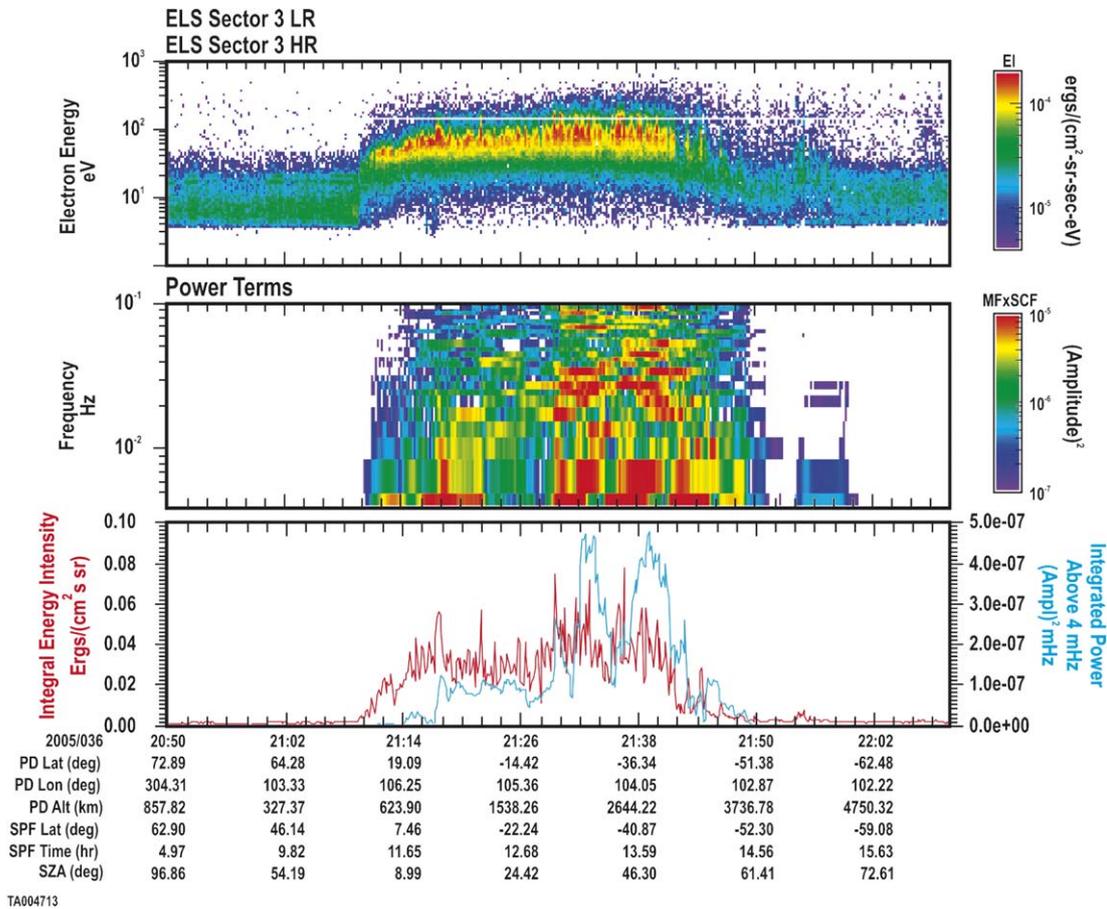


Fig. 5. Same as Fig. 2 for orbit 1354 on February 2, 2005.

opposed to 2600–4800 km) with a smaller solar zenith angle (SAZ) (less than 60° as opposed to 80°–95°) than in the earlier example.

Viewing the data in Fig. 5 from the direction of the solar wind interacting with the planet (right to left in Fig. 5), one sees the amplitude of the oscillations building up as MEX crossed the bow shock (BS) from 21:50 to 21:42 UT. As the spacecraft then passed from the BS through the sheath and to the IMB, panels 2 and 3 of Fig. 5 show a very dynamic frequency spectrum whose power and frequency peaks significantly vary. In general, the power decreases from the BS to the IMB as was also seen in the earlier case. As the spacecraft moved inward from the BS to the mid-sheath, higher frequency harmonics appeared and the power decreased. In this inner sheath region, one sees frequency peaks at ~10–20 mHz. By 21:33 UT, in mid-sheath, a strong peak at 6 mHz is observed along with many harmonics up to 100 mHz. As the IMB was approached from the mid-sheath, the higher order harmonics diminished and the power dropped. (See the integrated power in the blue curve in the bottom panel.)

Next we examine the dusk to nightside region which was traversed on March 1, 2004 (2004/061, orbit 162) from 8 to 11 UT, see Fig. 6. At approximately 08:30 UT (13 h local time) MEX entered the sheath region from the ionosphere at ~700 km. Throughout the remainder of the plot, MEX was located between the nominal martian bow shock and the IMB (see

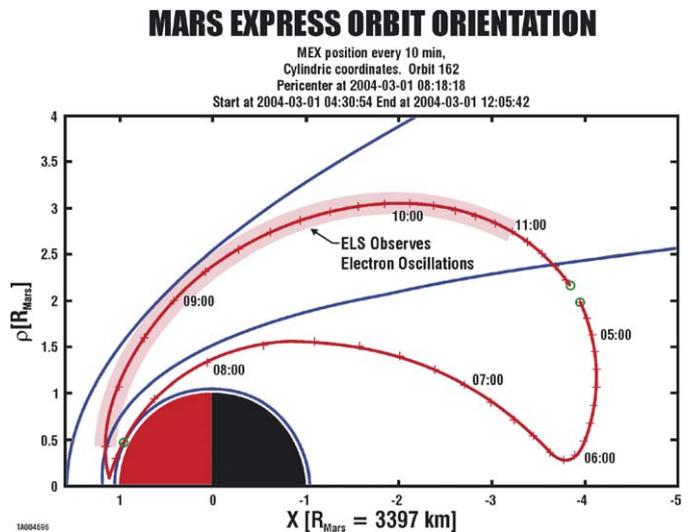


Fig. 6. Same as Fig. 2 for orbit 162 on March 1, 2004.

Fig. 7). MEX traversed the dusk sector at ~09:15 UT, ~58° PD lat, and 6000 km altitude. From there it moved towards the equator and 22 h local time near periapsis. As in the previous two examples, the record shows significant wave activity featuring multiple peaks. The power decreased progressively from noon to dusk to near midnight in the MS (see the blue curve in panel 3). Based on the three passes discussed, significant ULF

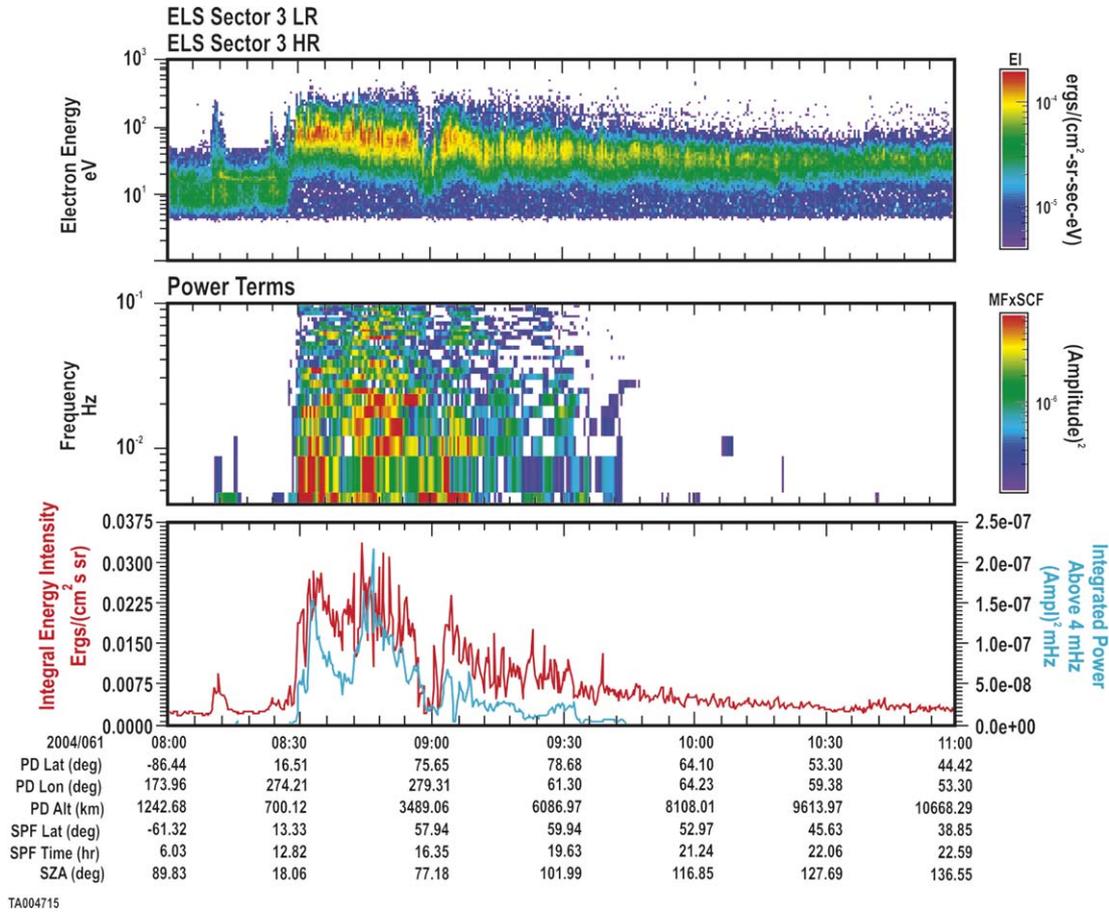


Fig. 7. Same as Fig. 1 for orbit 419 on March 1, 2004.

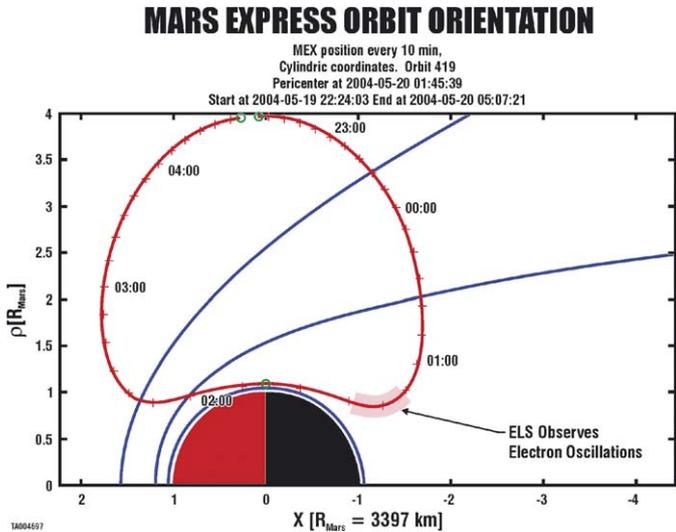


Fig. 8. Same as Fig. 2 for orbit 419 on May 20, 2004.

power was a characteristic feature from dawn to noon to dusk and up to mid-martian latitudes.

Heated, pulsating electrons were also recorded inside the martian magnetotail. An example is shown in Fig. 8 covering the interval 01:00–01:41 UT May 20, 2004 (2004/141, orbit 419). From the beginning of these observations MEX was within the shadow of Mars (see Fig. 9). Up to ~01:12 UT, UV

radiation from the distant martian UV limb created spacecraft photoelectrons. A population of heated electrons endured beyond this time up until ~01:28 UT. Dramatic oscillations are seen in the particle data in the top panel. In the middle panel a clear peak develops at ~16 mHz, with associated high harmonics. At ~01:25 UT a peak at about 5 mHz appears and the power also jumps up (see bottom panel blue curve). The oscillations end at ~01:30 UT. This case provides an observation of “nightside” oscillations with interesting implications for martian magnetospheric topology. It is also possible that these observations could be due to tail flapping or surface waves. In this heated region no ions were observed.

We present in Fig. 10 data from the pass immediately following the one discussed in the previous paragraph (orbit 420). A similar burst of oscillating, heated electrons is observed centered at ~07:50 UT. Fig. 11 shows that this pass was very similar to that of Figs. 6 and 7 from about 06:10 UT, where MEX exited the solar wind near apoapsis at ~19 h local time and moved across the sheath towards the nightside. Once again the power decreased as MEX progressed crossstream. At approximately 07:20 UT we see a burst in electron flux and wave power in the same frequency regime as that discussed earlier, near the nominal IMB. Beyond this boundary the electrons cooled until ~07:38 UT where the heating increased until it peaked at ~07:50 UT and faded by ~08:01 UT. The heating recorded at the maximum was quite variable. Possible physical reasons for

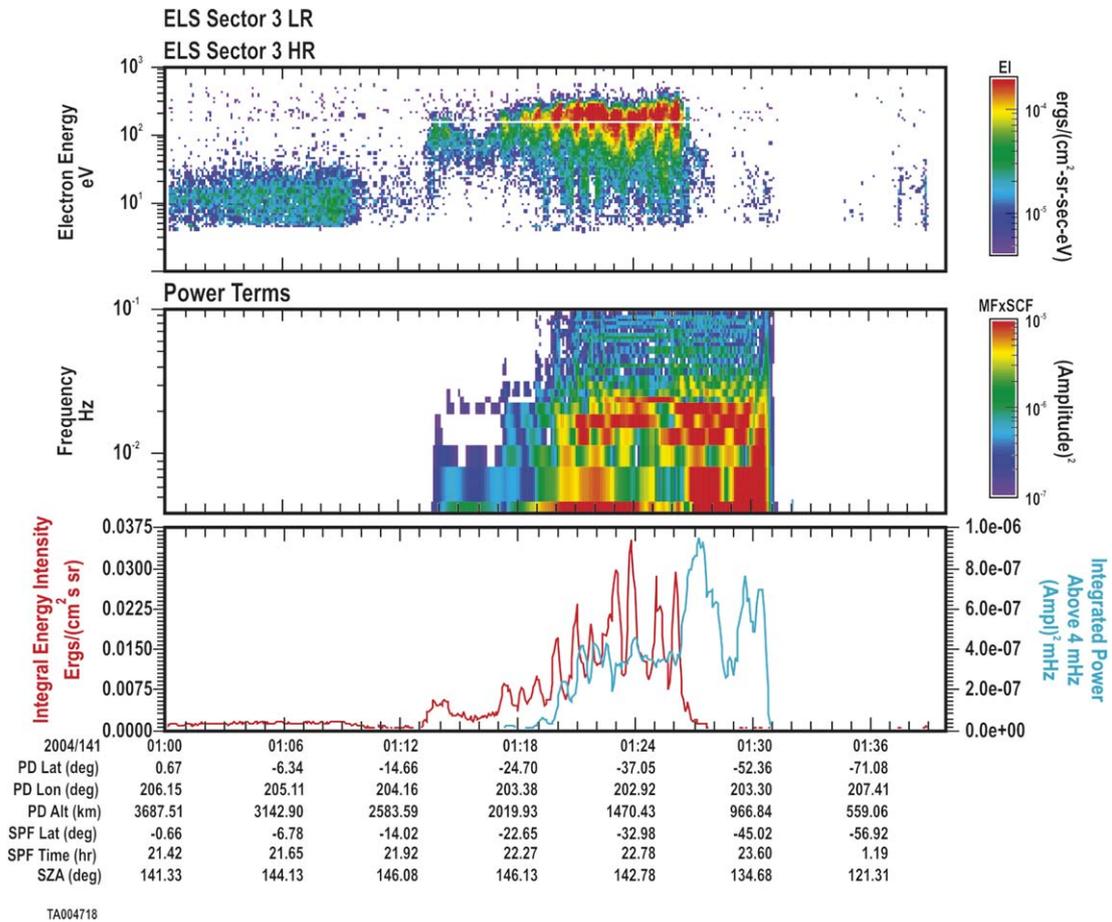


Fig. 9. Same as Fig. 1 for orbit 419 on March 20, 2004.

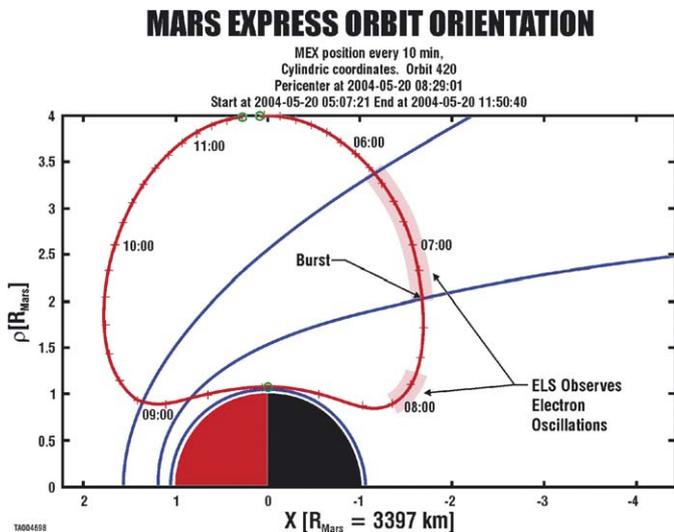


Fig. 10. Same as Fig. 2 for orbit 420 on May 20, 2004.

this will be explored in future papers. Again, this was approximately the time when scattered UV from the martian limb was no longer present. Typical ULF spectral peaks were observed. In this example, ions were identified to be present during the heating event.

Now we turn to the dayside below the IMB. As seen in Fig. 12 the spacecraft at just past noon was near periapsis at

the planetodetic equator on January 9, 2005 (2005/009, orbit 1257). From ~17:12 to 17:16 UT heated oscillating electrons were recorded (Fig. 13). In addition, ions were concurrently observed, as in the case of the second nightside heated population discussed above. Plasma oscillations in the same ULF frequency regime are seen in the middle panel. The power is much less (see bottom panel) than in the MS from ~17:22 UT onward. This sheath is in the morning, southern region. Soobiah et al. (2006) presented observations consistent with martian “magnetic cusps” resulting from the vertical component of the remnant field. In this event the observations were not made over one of these remnant features but they show the same ion and electron signatures characteristic of direct MS plasma access.

We also report evidence in ELS data for ULF plasma waves in the martian MS, tail and cusps (similar to the MGS MAG results), over a range of local times, latitudes, and regions. These features were found to be present in essentially all of these regions based on the present random sampling. In a later paper we will present a statistical study of this material.

4. Discussion

Periodic fluctuations of electron fluxes were observed in the magnetosheath, magnetotail and magnetic “cusps” of Mars. They were observed on both the dawn and dusk sides of Mars as well as above and below the planetodetic equator. A Fourier

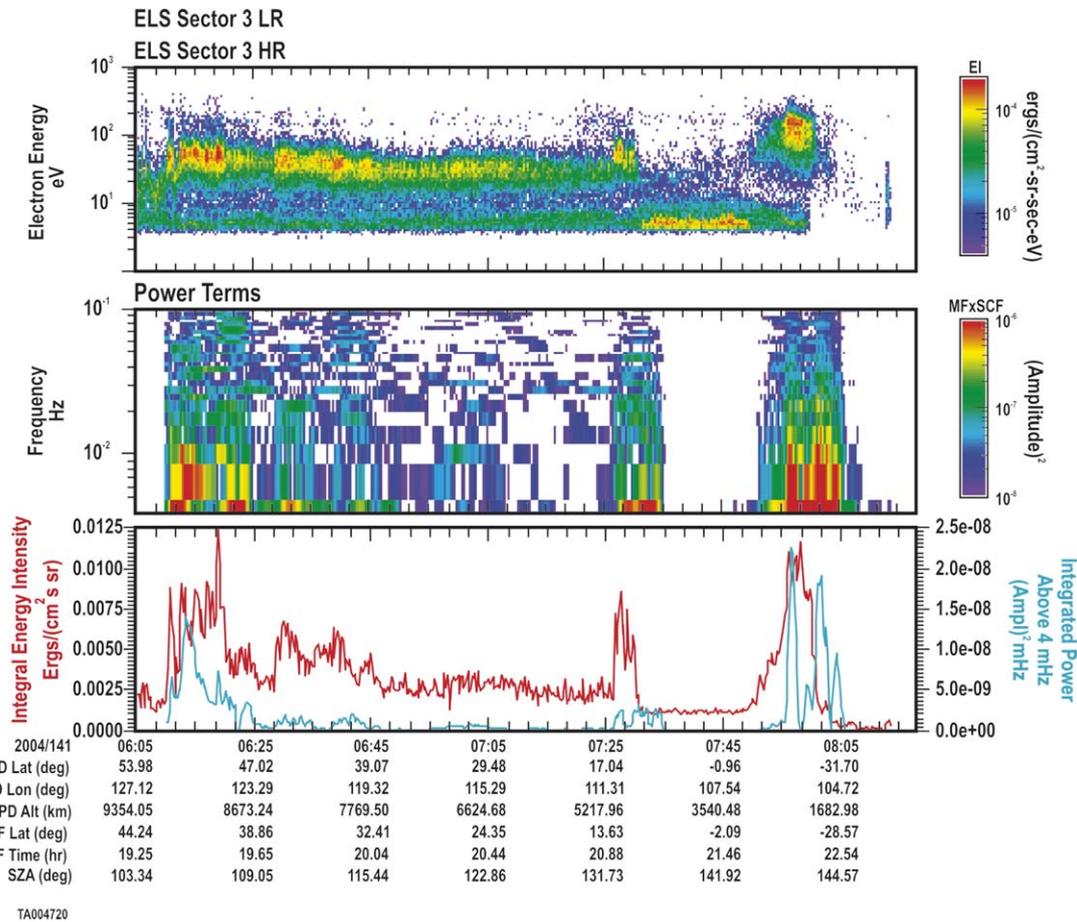


Fig. 11. Same as Fig. 1 for orbit 420 on May 20, 2004.

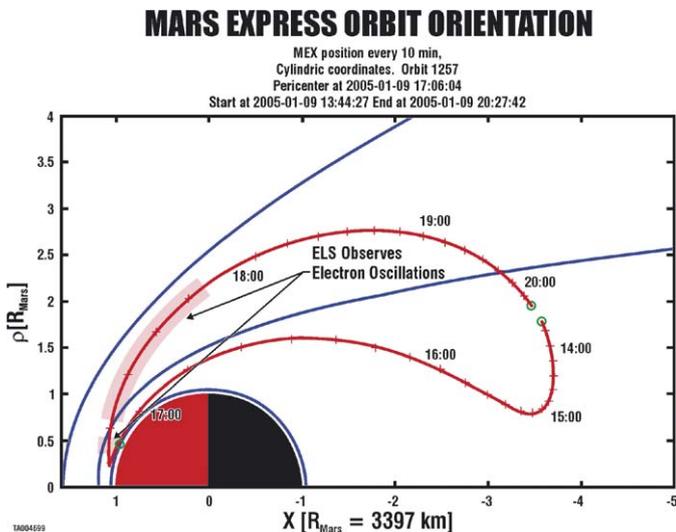


Fig. 12. Same as Fig. 2 for orbit 1257 on January 9, 2005.

analysis was performed on the integral of the electron flux. The resulting power spectra demonstrated that there was significant power in the ULF range, in conformity with the report of the MGS magnetometer team (Espley et al., 2004). Detailed examination of the power spectra revealed peaks from 5 mHz (the lower frequency limit is ~4 mHz) upwards. At times, fundamentals and harmonic tones were clearly visible in the spectra.

Peaks in the spectra showed a variation when samples were taken at different positions with respect to Mars. Based on the limited data set presented, the wave power maximizes in the vicinity of the bow shock and decreases progressively downstream from the shock. Interestingly, similar results were obtained on the dayside in regions where martian magnetic cusps are formed due to the interaction of the remanent crustal fields with the solar wind magnetic field. This result is not surprising since one expects a direct connection with the sheath population via these magnetic cusps features. The presence of similar power spectra in the sheath and cusps points to the intimate interconnection of these regions.

A little more surprising is the observation of similar fluctuations in regions of electron bursts inside the martian magnetotail. In both the cusp and tail events ions were also observed, but not over 100% of the time (see Lundin et al., 2006). We have presented in this paper one event with and one without ions, separated in time by one orbit. The spectral peaks and power levels in these events are similar to those observed in the MS region. This raises the intriguing possibility of a direct connection between these regions. A likely mechanism would be the extension of the crustal field to large distances behind Mars near the magnetotail boundary. A later paper will explore the regions of occurrence of these electron bursts. A preliminary look indicates that they cluster near the umbra of Mars.

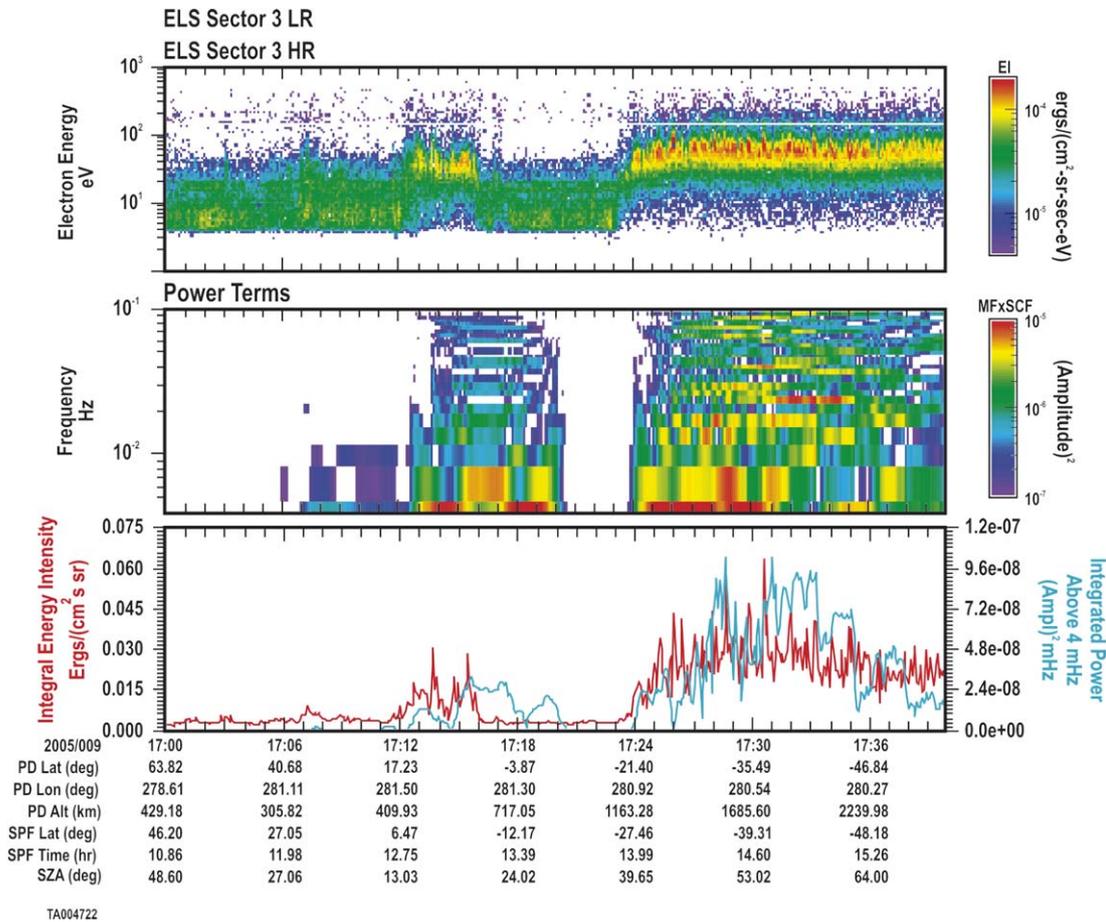


Fig. 13. Same as Fig. 1 for orbit 1257 on January 9, 2005.

In this data set, the predominant fundamental frequency is ~ 12 mHz. Unfortunately there is no magnetometer aboard MEX. Espley et al. (2004) suggested that some of the frequencies they observed are close to the O^+ ion gyrofrequency. Oxygen and heavier ions have been observed by the ASPERA-3 Ion Mass Spectrometer in some of the passes presented herein as well as others (Lundin et al., 2004; Lundin et al., 2006). Recall also the report of the detection of copious quantities of O^+ ions by the SLED instrument at Mars during the Phobos Mission (McKenna-Lawlor et al., 1998). If we use O^+ and 12 mHz the total magnetic field of 20 nT can be inferred, which is a reasonable value. The variation in the fundamental frequency could be due to changing composition and magnetic field values around Mars. In general, this is consistent with the work of Espley et al. (2004) and could be indicative of bunches of planetary ions gyrating out from the planet in resonance with the solar wind.

As mentioned earlier, the ion spectrometer cannot resolve these fluctuations. However, for scale lengths greater than the Debye length, the plasma should be electrically neutral. Therefore, when relatively large scale, relatively slow ion wave modes develop, they carry with them (on these large scales) the electrons that are associated with the oscillating ions. The electrons of course experience their own wave behavior, but at much higher frequencies and at much shorter wave lengths. When observed at ULF time scales, the electrons trace the motions of the ions and the ion wave modes.

Based on the MGS magnetic observations and the electron results of MEX one can speculate on the physical processes involved in generating these waves. For example, it is possible that between the magnetic field and the plasma the total particle and magnetic pressures remain constant, although there is an interchange of energy. Similar results have been observed at earth. Many other instabilities are possible as pointed out by Espley et al. (2004). Later papers will investigate these various possibilities in more detail.

5. Summary

The MEX ASPERA ELS experiment has clearly shown ULF fluctuations to be very common around Mars. Our preliminary observations indicate that the bow shock may be the source of the oscillations, but also the whole magnetosheath and nightside are responding. Their power spectra are similar to those observed by MGS MAG, pointing to a common physical source. These fluctuations also point to the possibility of the effects of the martian remanent field extending to great distances from Mars and interconnecting with the solar wind field on both the day and the nightside of Mars. The results also point to the presence of heavy ions ($>O^+$) around Mars. One can conclude that Mars is far from a passive environment despite its lack of a large permanent magnetic field.

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