Electron Oscillations In The Martian Sheath

J. D. Winningham, R. A. Frahm, J. R. Sharber (Southwest Research Institute, San Antonio, Texas, 78228, USA), A. J. Coates, D. R. Linder, Y. Soobiah, (Mullard Space Science Laboratory, University College London, United Kingdom), Esa Källio, (Finnish Meteorological Institute, Box 503 FIN-00101 Helsinki, Finland), J. R. Espley, (Department of Physics and Astronomy, Rice University, Houston, Texas, 77005, USA), S. Barabash, R. Lundin, and the Aspera-3 Team (Swedish Institute of Space Physics, Kiruna Division, Kiruna, Sweden)

Abstract

The Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) experiment flown on the Mars Express (MEx) spacecraft includes the Electron Spectrometer (ELS)instrument as part of its complement. The ELS instrument measures the differential electron flux spectrum in a 127 logarithmic energy sweep within a time period of 4 sec. The orbital path of MEx traverses the Martian sheath where ELS frequently measures periodic electron oscillations (see Figure). These oscillations are seen as periodic variations of up to an order of magnitude (peak to valley) in energy flux with the largest amplitudes occurring in the tens of eV to ~100 eV range. Observed oscillations can have periods from minutes to the instrument sweep resolution of four seconds. For the oscillations shown in the Figure (2), the frequency of the integrated electron energy flux is about 0.02 Hz. Depending on the local magnetic field, this could be close to the typical O⁺ gyrofrequency found using the Magnetometer data from Mars Global Surveyor. Examples of electron waves in the Martian sheath will be presented. Due to the motion of the spacecraft, it is unclear if the wave structures observed are a permanent standing wave feature within the sheath or if waves are propagating past the spacecraft.

Introduction

The Mars Express (MEx) spacecraft reached Mars on December 25, 2003. Upon arrival, the Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) experiment began instrument checkout operations in low-resolution instrument modes. Designed to measure electrons in the vicinity of Mars, the ASPERA-3 electron spectrometer (ELS) began operations slowly. As the temporal resolution increased, electron plasma oscillations were observed. Oscillations are often observed in some locations around the planet.

ELS measures many electron oscillations of varying periods. Oscillations near the subsolar point in the sheath occur at a relatively high frequency whereas oscillations which appear along the edges of the planet in the sheath have a longer period and are better resolved. Oscillations observed by ELS are common, but their period is highly variable. We have examined electron intensity oscillations in one such pass, chosen for its distinct long-period signature. The pass that we have examined in detail occurred on August 9, 2004 (2004222) between 20:55 and 21:30 UT.

Instrument

The ELS is a spherical tophat which samples electrons from a 4° × 360° wide FOV, divided into 16 sectors, each sector is 22.5° wide. ELS k-factor (7.23 ± 0.05 eV/volt) and resolution (0.083 ± 0.003 ∆E/E) 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 determination of the energy independent physical geometric factor as 5.88 x 10⁻⁴ cm² sr.

ELS covers the energy range from 1 eV to 20 keV with two deflection power supplies. ELS deflection voltage ranges from 0 to 20.99 V for the low range and 0 to 2800.0 V for the high range (energy conversion is sector dependent, but approximately 150 eV and 20 keV for the max values). Each supply 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 sec.

Currently ELS operates by selecting to telemeter instrument engineering data instead of every 8th spectrum. This causes a time gap in the ELS spectrum information which, in the case of this analysis, is filled by linear interpolation between the adjacent two measurements.

Fourier Transform Technique

Fast Fourier Transform (FFT) techniques are commonly used when analyzing waves. FFT techniques require that the number points to be analyzed be evenly divisible by powers of 2. FFT techniques are used for frequency analysis because they are fast, accurate approximations which are needed when processing great quantities of (wave) data. Due to the fact that particle instruments slowly sample distributions compared to the average wave instrument which uses FFT techniques, every data value must be used in frequency analysis and the luxury of a large amount of data is not present. FFT techniques are over kill for this situation.

The Fourier technique used here decomposes a linear set of values into Fourier components and operates on an even number of data values [Bevington, 1969]. If a periodic function f is sampled N times at equally spaced intervals, the function at the kᵗʰ sampling point, fₖ, may be expressed as a Fourier series for the first N/2 frequencies:

$$f_k = \sum_{j=0}^{N/2} \left[A_j \cos\left(\frac{2\pi jk}{N}\right) + B_j \sin\left(\frac{2\pi jk}{N}\right) \right]$$

$$\text{for } k = 1, 2, \ldots, N \quad (9.1.2)$$

where

$$A_j = \frac{1}{N} \sum_{k=1}^{N} f_k = \bar{f} \qquad \text{for } j = 0, \quad (9.1.3)$$

$$B_j = \frac{2}{N} \sum_{k=1}^{N} f_k \sin\left(\frac{2\pi jk}{N}\right) \qquad \text{for } j = 0, 2, \ldots, \frac{N}{2}-1, \quad (9.1.4)$$

$$A_j = \frac{2}{N} \sum_{k=1}^{N} f_k \cos\left(\frac{2\pi jk}{N}\right) \qquad \text{for } j = 1, 2, \ldots, \frac{N}{2}-1, \quad (9.1.5)$$

$$A_j = \frac{1}{N} \sum_{k=1}^{N} f_k \cos(\pi k) \qquad \text{for } j = \frac{N}{2}, \quad (9.1.6)$$

$$B_j \equiv 0 \qquad \text{for } j = \frac{N}{2}; \quad (9.1.7)$$

and, N is large and even.

Here the amplitude at a frequency, j, is determined by the sum of the squares of the Fourier coefficients:

$$A_j^2 + B_j^2 \qquad \text{at } jw_o \text{ for } j = 0, 1, \ldots, \frac{N}{2} \quad (9.1.1)$$

where

A_j is the amplitude of the cosine term at frequency jw_o,

B_j is the amplitude of the sine term at frequency jw_o,

w_o is the fundamental frequency $2\pi/N$,

The locus of frequencies produces the power spectrum. Using this technique, the significance of a peak in the power spectrum can be judged by comparing the power at each frequency to $4\sigma^2/N$ (twice as large as that suggested by Reiff [1983]) by formulating the statistic:

$$\frac{N}{4\sigma^2} \left(A_j^2 + B_j^2 \right). \quad (9.1.18)$$

For the power distribution, one can determine the value of σ^2 by:

$$\sigma^2 = \frac{1}{N} \sum_{k=1}^{N} \left\{ \sum_{j=1}^{N/2} \left[A_j \cos\left(\frac{2\pi jk}{N}\right) + B_j \sin\left(\frac{2\pi jk}{N}\right) \right] \right\}^2. \quad (9.1.9)$$

There is some minimum frequency which can be obtained with any Frequency technique. We have chosen to require that waves must exhibit at least 3 periods in the linear structure to be valid. For a 10 minute sample representing 600 seconds of data, a 3 period requirement means that wave periods longer than 200 seconds cannot be determined accurately. This represents frequencies of 5 mHz and less.

Pulsations in the Electron Data

On August 9, 2004 (2004222), the Mars Express spacecraft traveled almost perpendicular to the flow in the sheath. Figure 1 shows the orientation of the Mars Express orbit as it traveled away from periapsis perigee, through the sheath, and into the solar wind at about 21:00 UT. While in the sheath, ELS observed periodic oscillations in energy intensity.
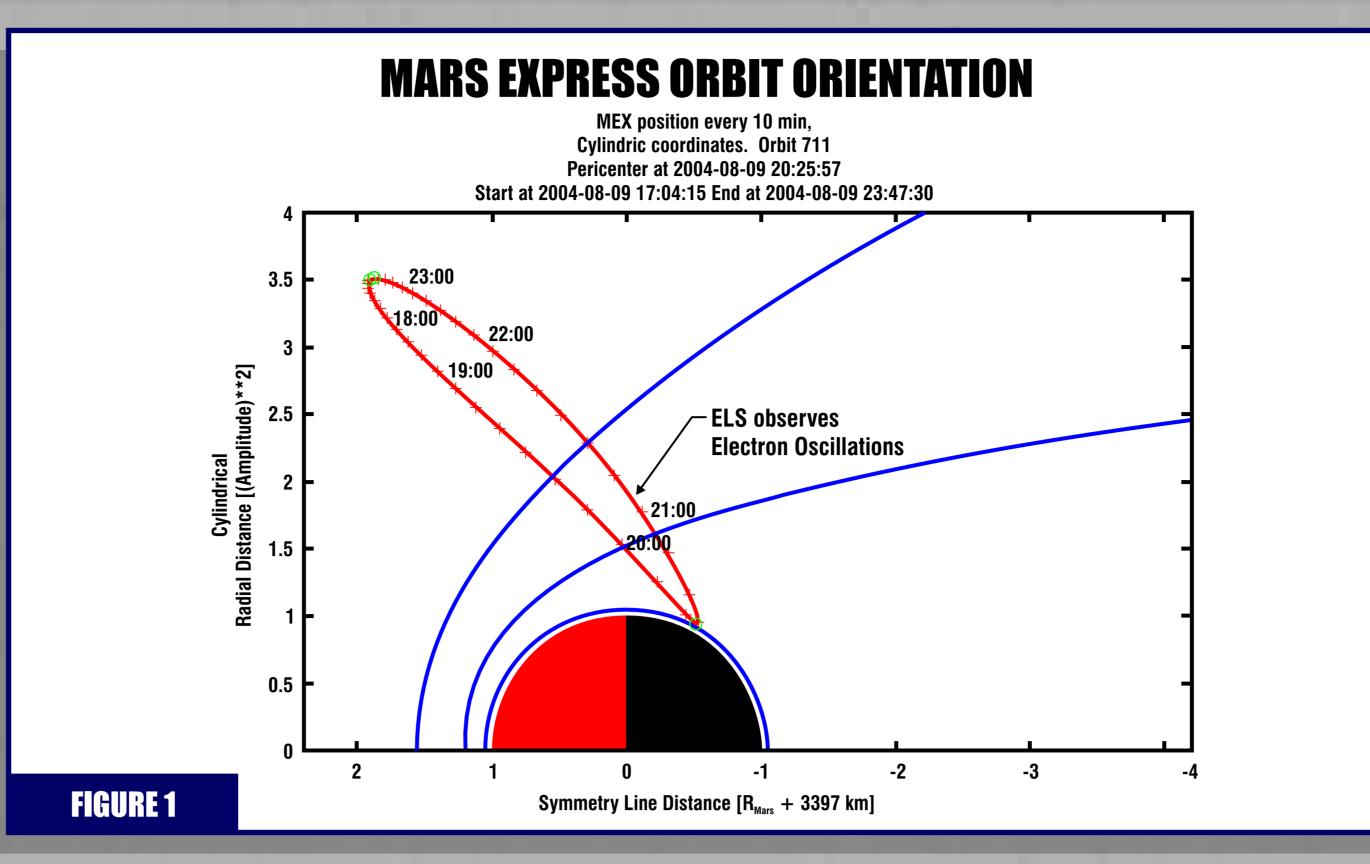

FIGURE 1

Figure 1. Mars Express Orbit. The Mars Express spacecraft traveled from periapsis, through the sheath, and into the solar wind nearly perpendicular to the sheath flow. While in the sheath, ELS observed oscillations in the electron plasma.

An energy-time spectrogram of the ELS measured electron plasma for sector 3 (pointing approximately perpendicular to the orbit direction in the sheath flow ram direction) is shown in the top panel of Figure 2 during the transit of Mars Express spacecraft across the sheath. Before 21:59:00 UT, ELS observes inner magnetosphere electron plasma (characterized by a peak energy around 10 eV). From 21:59:00 UT until 21:24:30 UT ELS observes sheath plasma with about 50 eV characteristic energy. The energy flux intensity of the plasma oscillates during the crossing of the sheath. After 21:24:30 UT, the characteristic energy again decreases as ELS measures solar wind plasma.
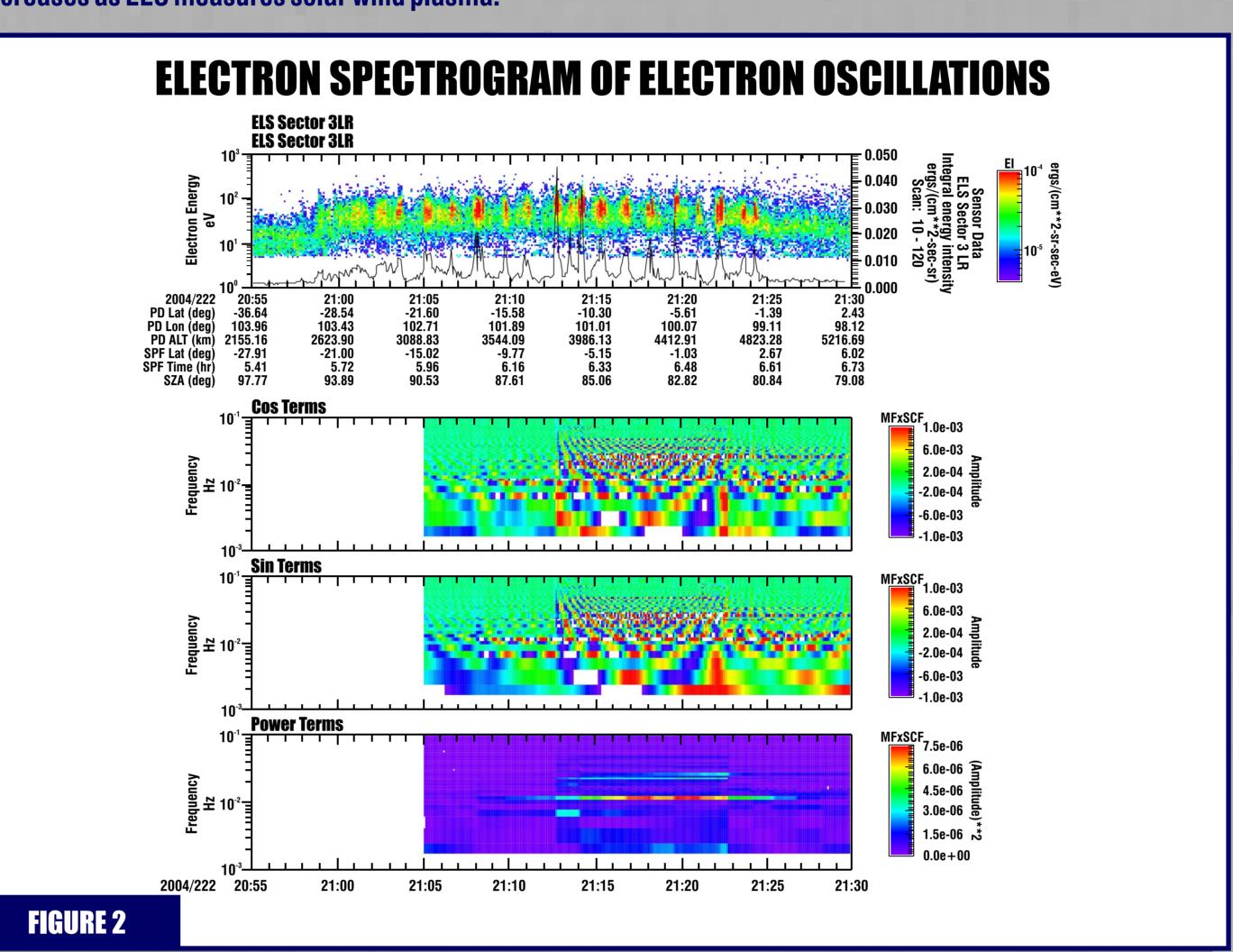

FIGURE 2

Figure 2. Electron Spectrogram of Electron Oscillations. Shown are data from the ELS instrument measuring the energy intensity oscillations (upper panel). This energy intensity is Fourier analyzed and the frequency spectrograms are shown in the bottom three panels.

On top of the spectrogram is drawn the integrated energy flux intensity. The differential flux was chosen because it emphasizes the changes in plasma intensity as opposed to the electron distribution function which emphasizes the intensity of the distribution. Periodic variations in the integrated energy flux intensity can be seen which reflect the differentially measured electrons. In addition, at time markers along the bottom axis of the spectrogram are some orbital parameters.
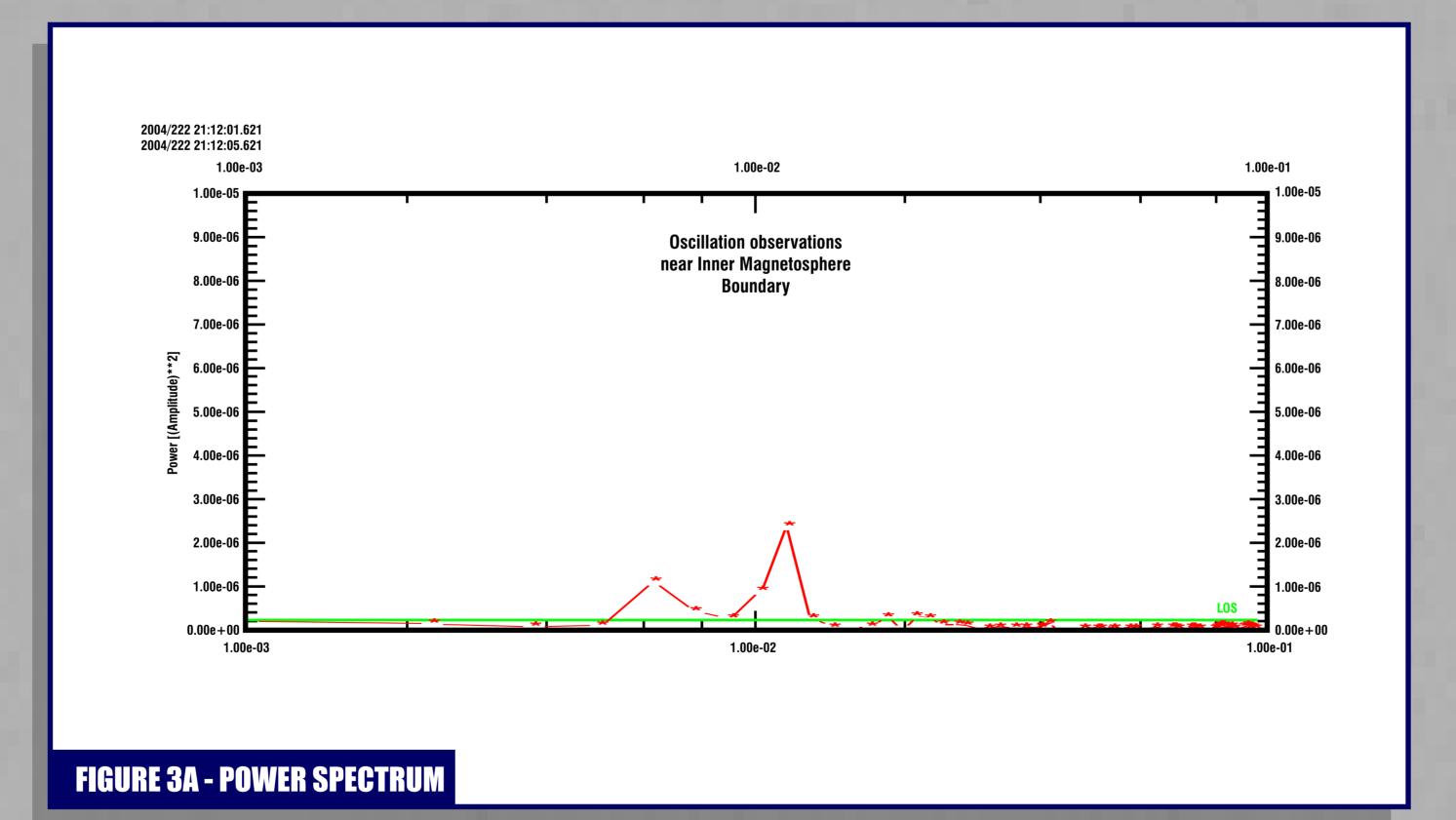
The frequency analysis was conducted on the integrated energy flux intensity described in the section labeled Fourier Transform Technique. The results of this frequency analysis are shown in the bottom three panels. The integrated energy flux intensity was Fourier analyzed with from a sliding window which was 10 min wide. This represented about 150 spectra in 600 sec. The window was slid every 4 sec spectral measurement.

The cosine and sine terms described by the Fourier technique are shown in the second and third panels. One observes the amplitude intensity become more intense in the sheath region. The cosine and sine terms are used to generate the power spectrum which is shown in the bottom panel. Larger amplitudes are seen in the power spectrum near the 10 mHz and 20 mHz regions.

The power spectrum has been examined in more detail with the frequency spectral plots shown in Figure 3 across the sheath. These show different frequency components are more dominate in different sheath regions. Figure 3a shows the power spectrum near the inner magnetosphere boundary. 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 sheath, a disruption in the beating pattern takes place. The frequency pattern (Figure 3b) shows inclusion of higher frequency peaks (with frequencies about 33 mHz, 35 mHz, and 47 mHz) and a reduction in amplitude of the lower frequencies. At the same time, the 12 mHz peak becomes more dominant in the power spectrum.

In the center of the sheath (Figures 3c and 3d), the lower frequency components vanish, and the amplitude and frequency pattern suggest that there are multiple harmonics of the 12 mHz signal. Toward the bow shock (Figure3e), the higher frequency terms decay in amplitude leaving the 12 mHz fundamental. Near the bow shock (Figure 3f), a peak at about 8 mHz appears; however, the peak at 12 mHz remains larger.

FIGURE 3C - POWER SPECTRUM

FIGURE 3D - POWER SPECTRUM

FIGURE 3E - POWER SPECTRUM

FIGURE 3F - POWER SPECTRUM

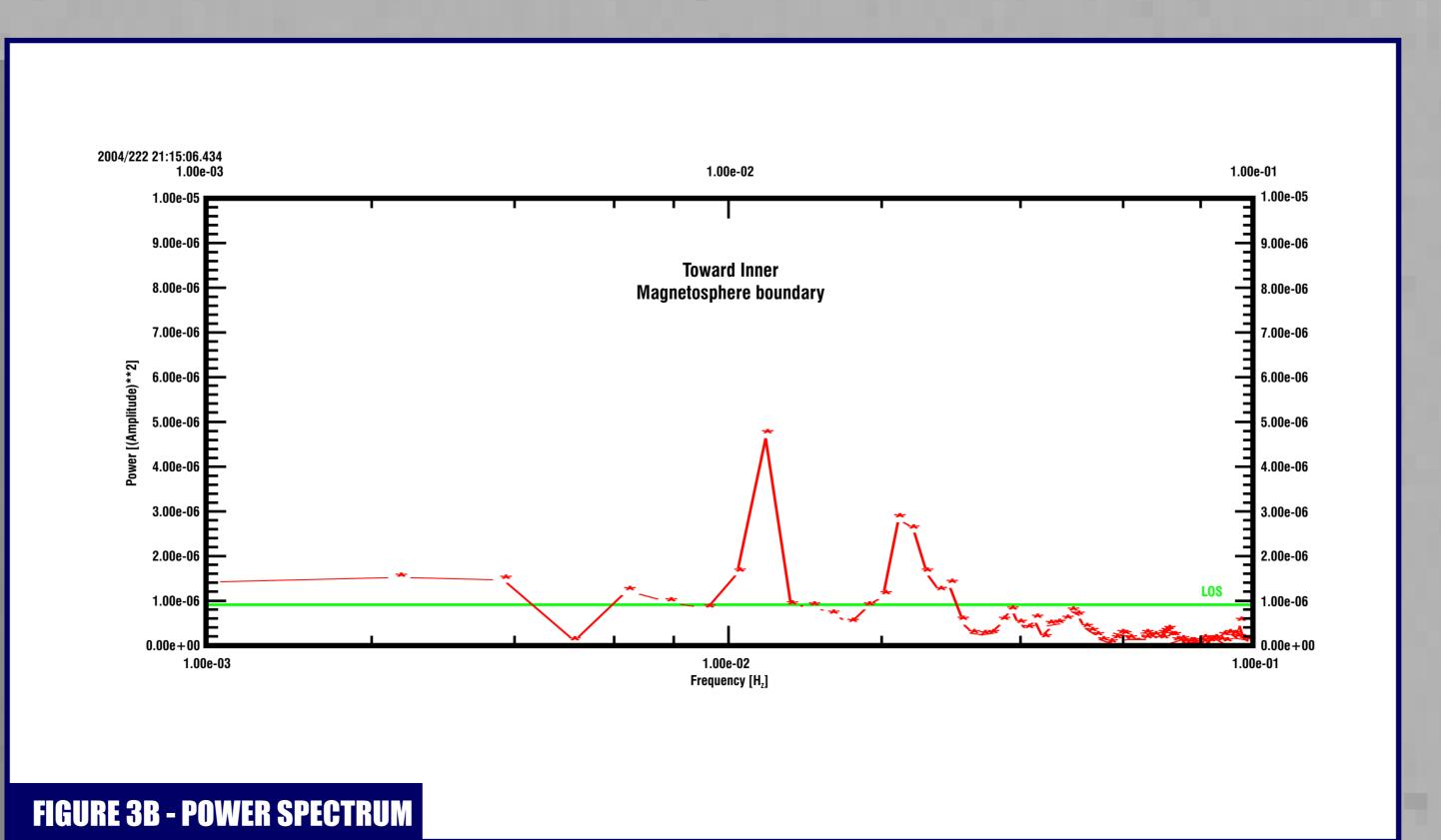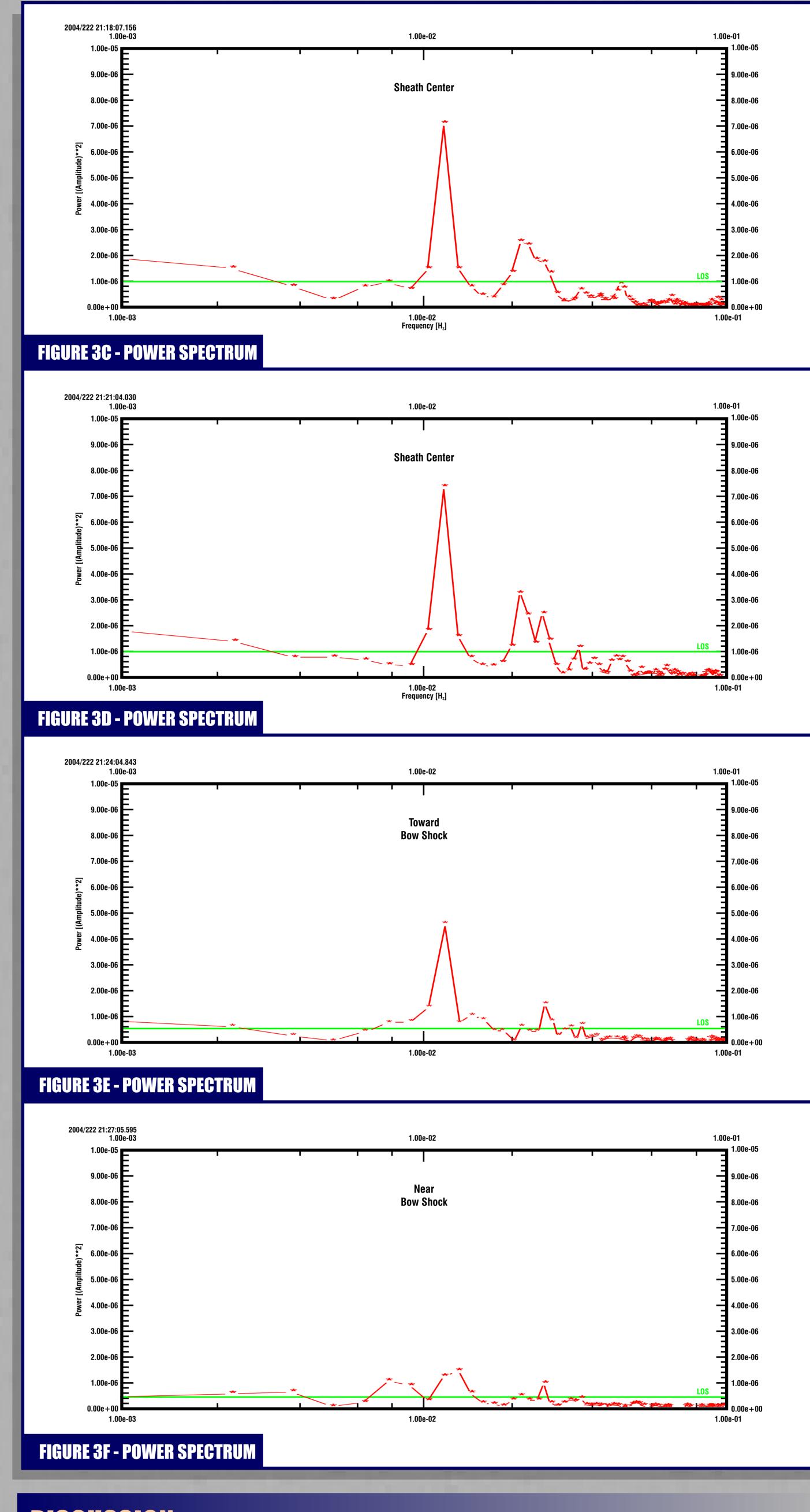**FIGURE 3A - POWER SPECTRUM**

FIGURE 3B - POWER SPECTRUM

Figure 3. Selected Frequency Spectra Throughout Sheath Transit. Power spectra from the Fourier analysis are displayed at intervals of about every 3 minutes while Mars Express crosses the sheath: a) near inner magnetosphere boundary, b) toward inner magnetosphere boundary, c) and d) at center of the sheath, e) toward bow shock, f) near bow shock.   LOS = Line of Significance

DISCUSSION

The overall pattern of frequencies suggests that as the solar wind is deflected around the planet in the sheath, the outer half of the sheath has slightly different properties than the inner half of the sheath. However through out the entire sheath, the fundamental frequency of 12 mHz remains a dominant feature. Since MEx does not contain a magnetometer we can ask if it is reasonable to assume that the electrons are responding to an oscillation in the plasma. Since heavy ions are observed near the bow shock of Mars [Nagy et al., 2004] and the electrons are periodic with long periods, it seems reasonable to consider that the electrons are responding to a plasma event driven by heavy ions. The magnetic field that would drive the ions with a gyrofrequency of 12 mHz can easily be determined since f = eB/m where f is the gyrofrequency, e is the charge of an electron, m is the ion mass, and B is the magnetic field:

$B = f*m/e = 0.012 \, Hz * Mu * 1.67e-27 \, kg / 1.602e-19 = 1.25e-10 \, Mu$

where Mu is the reduced mass of the ion.

An abundant ion in the Martian magnetosphere is O⁺, which has an Mu = 16. This gives B = 20 nT, which is not an unreasonable value for the magnetic field magnitude in the Martian sheath.

The O⁺ ion assumption above is reasonable. Espley et al. [2004] analyzed magnetic oscillations from a sheath crossing in a similar location using data from Mars Global Surveyor (MGS) and found that the magnetic power had a main spectral peak at ~0.01 Hz. This they point out is near the local oxygen gyrofrequency and matches the observations well.

As with any wave, it is not possible to determine whether the structure that is seen is a wave or a rarefraction with a single spacecraft. Penetration through a rarefraction may resemble a wave when there are stationary striations that are detected as the spacecraft moves by. A wave may also propagate past the spacecraft so the oscillating structure will be detected.

It should be pointed out here that an important measurement quantity is the total pressure between the magnetic field and particles. Both components of the particle pressure are measured by ASPERA-3, the electrons and the ions (with coarser resolution). However, the magnetic pressure is not measured and leaves doubt as to whether the features are pressure pulses which are traveling past the spacecraft or waves causing an exchange of pressure between the particles and the magnetic field.

CONCLUSION

The integral of the energy intensity from the ASPERA-3 ELS has been Fourier analyzed to recover the frequency spectrum of observed periodic differential energy intensity oscillations. The analyzed data was from August 9, 2004 between 20:55 UT to 21:30 UT. During this event, the MEx spacecraft was crossing the sheath nearly perpendicularly in the region of the planet flank. Observed oscillations near the inner magnetosphere boundary and near the bow shock showed a larger amplitude peak near 12 mHz with a second peak at lower frequency with a slightly smaller amplitude(6 mHz near the inner magnetosphere boundary and 8 mHz near the bow shock). In the center of the sheath, the 12 mHz peak dominates with harmonics at higher frequencies.

For this pass, the O⁺ gyrofrequency is suggested as the source of the oscillations with the electrons responding to the O⁺ gyrofrequency. From these oscillations, the magnetic field was estimated to be 20 nT. A similar published magnetic field oscillation study showed a similar major frequency to correspond to the O⁺ gyrofrequency.

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ASPERA-3 TEAM

R. A. Frahm, J. D. Winningham, J. R. Sharber, SwRI, San Antonio, USA
A. J. Coates, D. R. Linder, D. O. Kataria, Mullard Space Science Laboratory, UCL, UK
R. Lundin, H. Anderson, S. Barabash, M. Holmström, M. Yamauchi, Swedish Institute of Space Physics, Sweden
E. Källio, H. Koskinen, Finnish Meteorological Institute, Helsinki, Finland
J. Kozyra, Space Physics Research Laboratory, U. Michigan, Ann Arbor, USA
J. Luhmann, University of California Berkeley, USA
E. Roelof, D. Williams, JHU-APL, Laurel, USA
C.C. Curtis, K. C. Hsieh, B. R. Sandel, University of Arizona, Tucson, USA
J. A. Sauvaud, A. Federov, Centre d'Etude Spatiale des Rayonnements, France
S. McKenna-Lawlor, Space Technology Ltd, Maynooth, Ireland
S. Orsini, R. Cerulli-Irelli, Instituto di Fisica dello Spazio Interplantari, Italy
P. Bochster, P. Wurz, University of Bern, Bern Switzerland
K. Azamura, ISAS, Japan
M. Grande, Rutherford Appleton Laboratory, Oxfordshire, UK
N. Krupp, J. Woch, M. Franez, Max-Planck-Institut fur Aeronomie, Germany

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