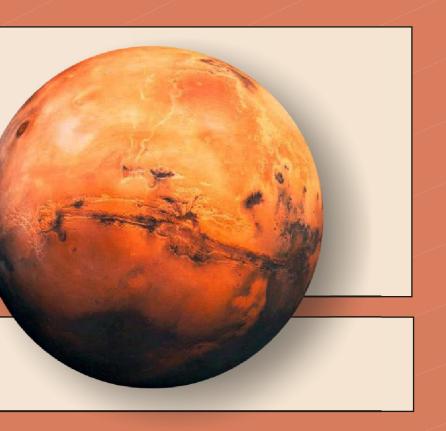# Atmospheric Photoelectron Peaks Observed in the Martian Ionosphere and Magnetosphere

R. A. Frahm, J. D. Winningham, J. R. Sharber, (*Southwest Research Institute, 6220 Culebra Road, San Antonio, Texas 78228, United States*) A. J. Coates, D. R. Linder (*Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking RH5 6NT, United Kingdom*) and M. W. Liemohn (*University of Michigan, Ann Arbor, Michigan 48109, United States*)

Abstract

The Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) experiment on board the Mars Express spacecraft conducts measurements of electrons by using the Electron Spectrometer (ELS), ions by using the Ion Mass Analyzer (IMA), and neutral particles by using the Neutral Particle Imager (NPI) and the Neutral Particle Detector (NPD). The ELS instrument detects peaks in the photoelectron spectrum at 21-24 eV and 27 eV which come from the interaction of a carbon dioxide molecule or an atomic oxygen atom with a 30.4 nm photon. These peaks are strongest in the dayside ionosphere where they are mainly generated, but are also observed at large distances in the Martian tail. Observations in the tail show the most intense flux at times when the ELS sensor look direction points toward the Sun. At these times, the ELS observes distinct peaks which are narrow in energy. Recently, the instrument detects these nightside fluxes as a single, broad, degraded photoelectron peak instead of the two distinct peaks as observed in the dayside ionosphere. Modeling of the electrons which create these peaks has shown that away from the source region, the electrons lie within a small pitch angle range. Electron flux is determined from the distinct photoelectron peak region of 19 June 2007, and combined with 2004 statistics of the locations where spectra with distinct photoelectron peaks were observed, the loss of electrons from 2004 is estimated to be 2.7x10^{24} electrons representing 1.35x10^{10} ergs.

Introduction

Since December 25, 2003, the Mars Express (MEx) spacecraft has been orbiting Mars. MEx measurements of the Martian particle environment have been performed by the Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) experiment [Barabash *et al.*, 2004], which measures electrons with the Electron Spectrometer (ELS), ions with the Ion Mass Analyzer (IMA), and neutral particles with the Neutral Particle Detector (NPD) and Neutral Particle Imager (NPI). Since arriving at Mars, ELS has measured peaks in the photoelectron spectrum [Coates *et al.*, 2004; Frahm *et al.*, 2006a; Lundin *et al.*, 2004]. These photoelectron peaks are attributed to both carbon dioxide and atomic oxygen, and are theoretically located in energy between 21 eV and 24 eV, and 27 eV [Mantas and Hanson, 1979; Fox and Dalgarno, 1979]. The relevant photoelectron peaks in the energy spectrum are mainly due to ionization by Solar 30.4 nm photons, more specifically:

1) $CO_2 + h\nu \longrightarrow CO_2^+ + e^-$
   $X^2\Pi_g$ ionization potential 13.77 eV $\longrightarrow$ 27.01 eV electron
   $A^2\Pi_u$ ionization potential 17.32 eV $\longrightarrow$ 23.46 eV electron
   $B^2\Sigma_u$ ionization potential 18.10 eV $\longrightarrow$ 22.68 eV electron

2) $O + h\nu \longrightarrow O^+ + e^-$
   ^4S ionization potential 13.62 eV $\longrightarrow$ 27.16 eV electron
   ^2D ionization potential 17.10 eV $\longrightarrow$ 23.68 eV electron
   ^2P ionization potential 18.50 eV $\longrightarrow$ 22.28 eV electron

The ELS observation of photoelectron peaks in the energy spectrum are mainly due to ionization of carbon dioxide near the Martian exobase with subsequent transport to higher altitudes [Mantas and Hanson, 1979]. Near the Martian exobase, the concentration of carbon dioxide at about 50 times greater than atomic oxygen. The energy resolution of ELS (about 8%) is too large to distinguish between the energy spectrum of electrons photoionized from carbon dioxide and those from atomic oxygen. At altitudes above about 210 km, atomic oxygen becomes the dominant species over carbon dioxide down by about a factor of 1000 from its peak production rate) and the atomic oxygen to carbon dioxide ratio continues to increase with increasing altitude even though the amount of atomic oxygen exponentially decreases [Krasnopolsky and Gladstone, 1996]. At spacecraft altitudes, locally produced electrons from ionization of the atomic oxygen (above 250 km) occur more frequently than by locally produced electrons from ionization of carbon dioxide. ELS can not distinguish between photoelectrons produced locally and those transported to the sensor.

After ionization of the carbon dioxide or atomic oxygen, the charged components are subject to the local magnetic field and are transported accordingly [Mantas and Hanson, 1979]. The ASPERA-3 ELS has observed photoelectron peaks in the Martian induced magnetosphere while orbiting the planet at various altitudes [Frahm *et al.*, 2006a,b]. During the nominal mission of Mars Express, the IMA sensitivity was tuned to measure escaping higher-energy ions and the capability to observe low-energy ions was limited. Late in the spring of 2007 the IMA was reprogrammed to increase its sensitivity to lower-energy ions. This resulted in the detection of low-energy planetary ions in the Martian ionosphere that were components of carbon dioxide. Ions in the Martian ionosphere are observed to be directional; however, their low-energy are near the IMA energy threshold, detection may be a result of ion flow caused by the ram pressure of the spacecraft motion combined with spacecraft potential (i.e., not a real flow) [Frahm *et al.*, 2007a,b].

In this presentation we show peaks in the photoelectron spectrum in the Martian ionosphere along with the low-energy ions and we show photoelectron peaks in the Martian tail. The purpose is to demonstrate that photoelectrons from the Martian atmosphere are being transported down the Martian tail. We then estimate the atmospheric spectra electron loss in 2004 due to ionizations causing the photoelectron peaks.

Ionosphere

Photoelectron peaks are observed in the ionosphere on almost every transit of the spacecraft through the ionosphere. Figure 1 shows an orbit of the MEx spacecraft on 19 June 2007. On this figure, the Sun is to the left. The average shapes of the bow shock and magnetopause are determined by Vignes *et al.* [2000] and drawn in blue. The spacecraft enters the ionosphere from the night side of the planet and observes peaks in the photoelectron spectrum beginning at about 1535 UT (625 km altitude) until it exits into the dayside magnetosheath around 1558 UT (725 km altitude). The general location of these peaks is shown by the shaded region on the plot of the spacecraft orbit.
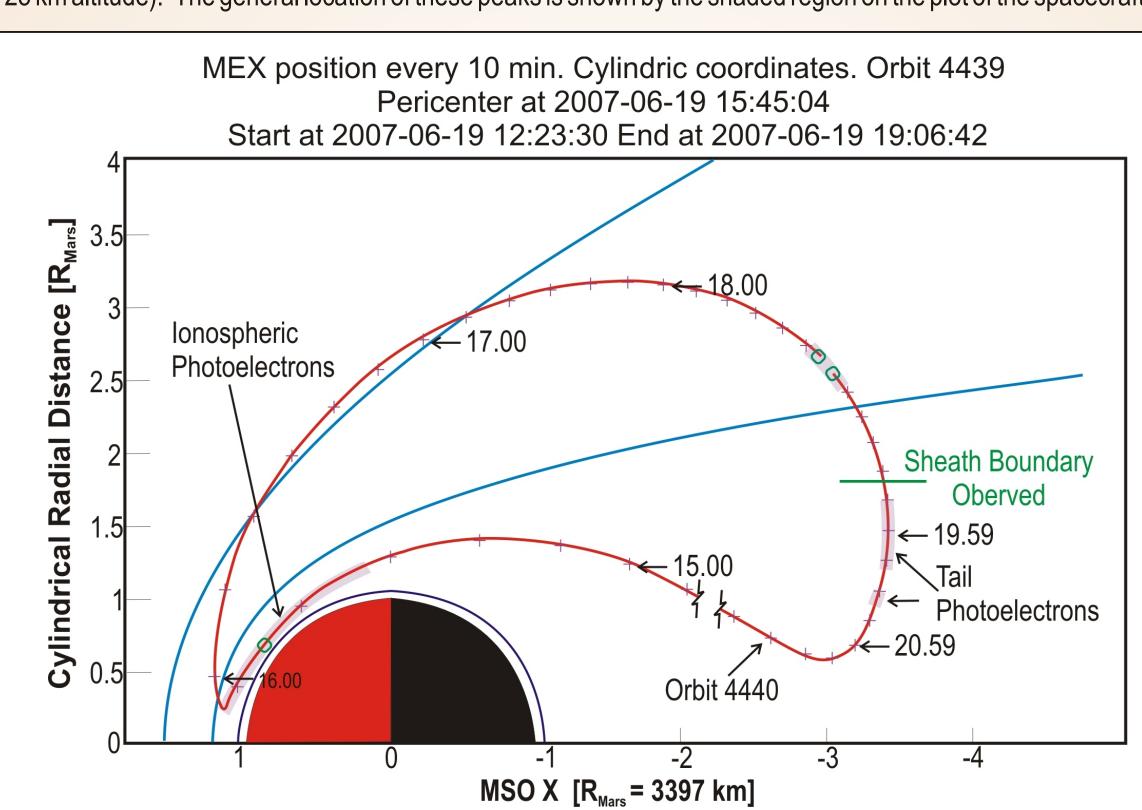

Figure 1. The orbit of MEx is shown on 19 June 2007. Included are highlighted regions where measurements of photoelectron peaks in the ionosphere and tail are generally observed. The bow shock and magnetopause are drawn for reference using Vignes *et al.* [2000].

Ionosphere (cont.)

A more detailed view can be obtained when examining the combined ion and electron spectrogram. Figure 2 shows the ion spectrogram measured by IMA sector 0 (IMA-00) and the electron spectrogram measured by ELS sector 4 (ELS-04). At this time, IMA is observing low-energy ions in its fast sample rate mode (96 energy measurements from 10 eV to 30 keV in 12 sec); its elevation analyzer is not stepping. The ELS instrument collects peaks in the photoelectron spectrum. ELS is also measuring in its fast sample range mode (31 energy measurements from 9 eV to 150 eV in 1 sec) and the ASPERA-3 scanner is parked. This condition also generates a 2D measurement.
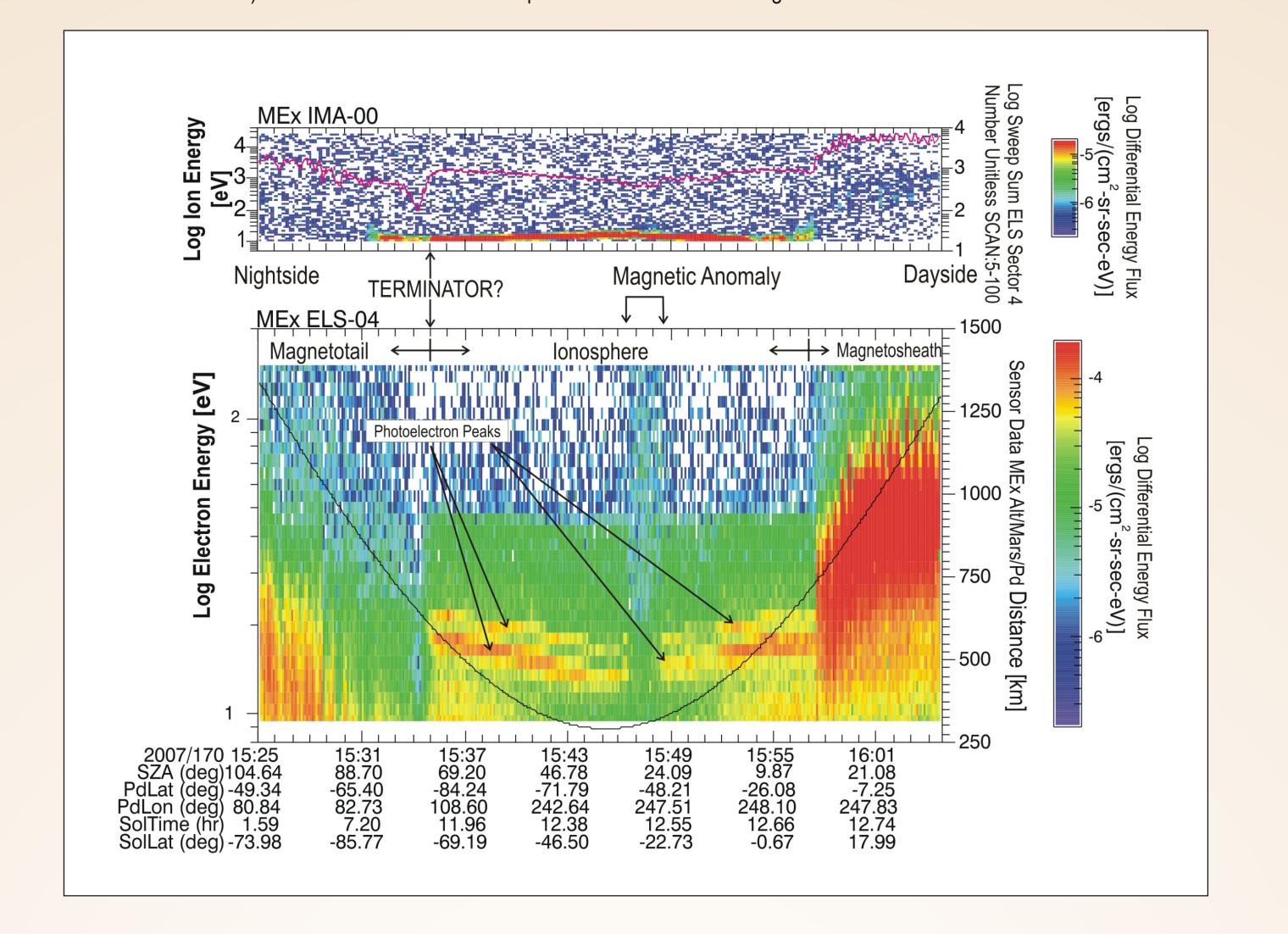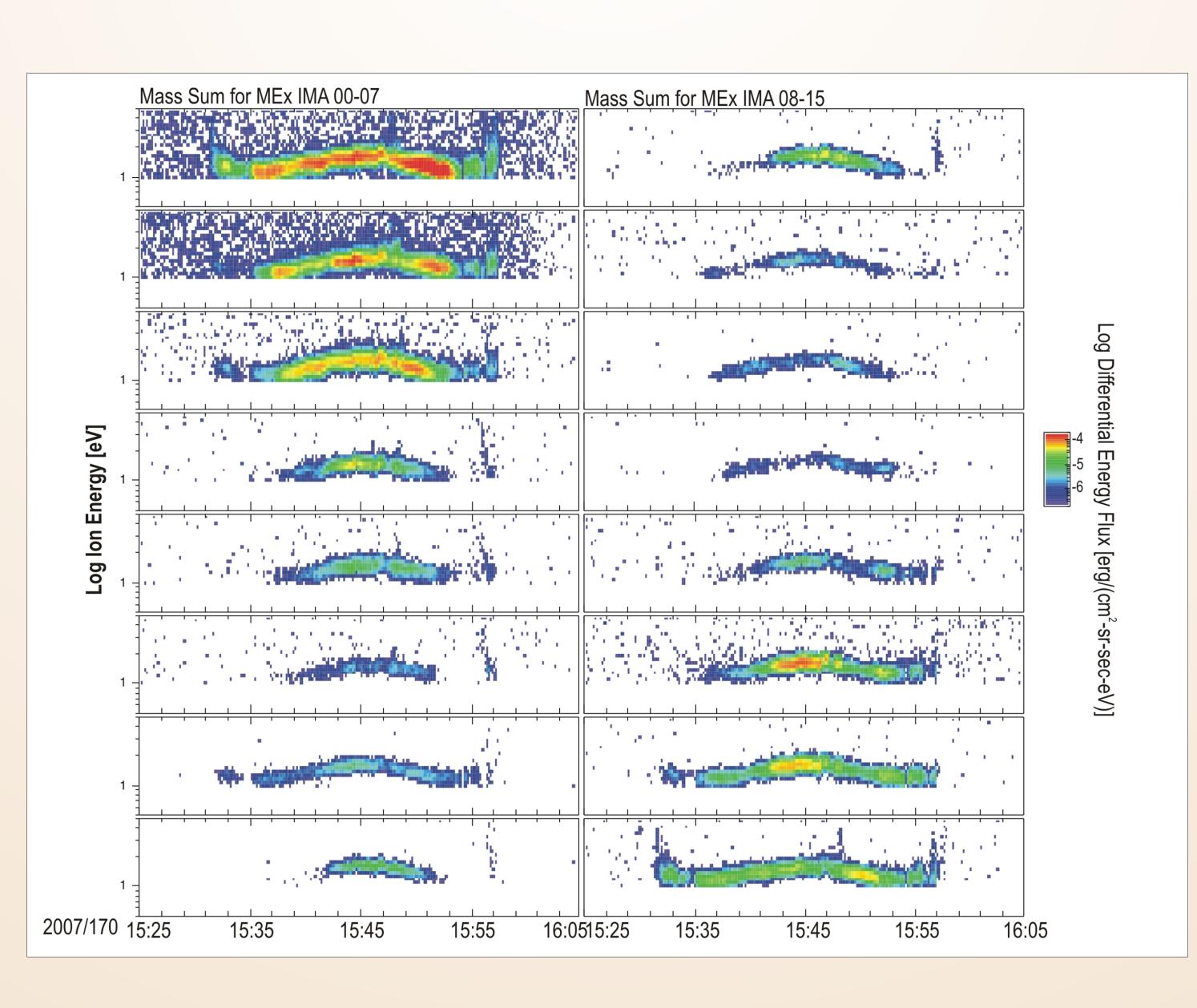
In Figure 2, photoionization peaks in the electron spectrogram from CO_2 and O are observed in the ionosphere at the same time that low-energy ions are observed. The peaks in the electron spectrogram are observed to decrease in energy with decreasing altitude, and at the same time the trace in ion flux increases. During this pass, the spacecraft charges negatively, forcing the detected electrons to decelerate and lose energy as they fall to the spacecraft. At the same time, the ions are accelerated as they fall through the potential well created by the spacecraft charging.

In the ionosphere, peaks in the photoelectron spectrum are nearly isotropic. At the same time, ions are observed to be anisotropic. Each spacecraft pass shows a different amount of detected ions. Figure 3 shows the ions observed in each sector of IMA corresponding to the time shown in Figure 2. Ions are observed in every IMA sector; however, the most intense flux is measured by IMA-00. At this time, IMA-00 is measuring plasma escaping from the planet. The ions spectra, shown in Figure 4, are comprised of dissociative ion products of carbon dioxide (CO_2^+, O_2^+, CO^+, C^+, and O^+).

Figure 2. Ion and electron spectrogram from the ionosphere on 19 June 2007. Ions measured by IMA-00 are shown in the top panel with the integral flux of the observed electrons overlaid. Electrons measured by ELS-04 are shown in the bottom panel with the altitude of MEx overlaid. The solar zenith angle (SZA), planetodetic latitude (PdLat), planetodetic longitude (PdLon), solar time (SolTime), and solar latitude (SolLat) of the spacecraft is given along the bottom.

Figure 3. Angular distribution of ion energy flux. Shown are the ion measurements below 50 eV for the time period of Figure 2. Shown are IMA sectors 00 through 07 on the left and sectors 08 through 15 on the right (sector numbers increasing top-to-bottom). IMA-00 points toward the planet and IMA08 faces the Sun. The plane of IMA measurements is tilted about 30° with respect to the Mars solar equator.
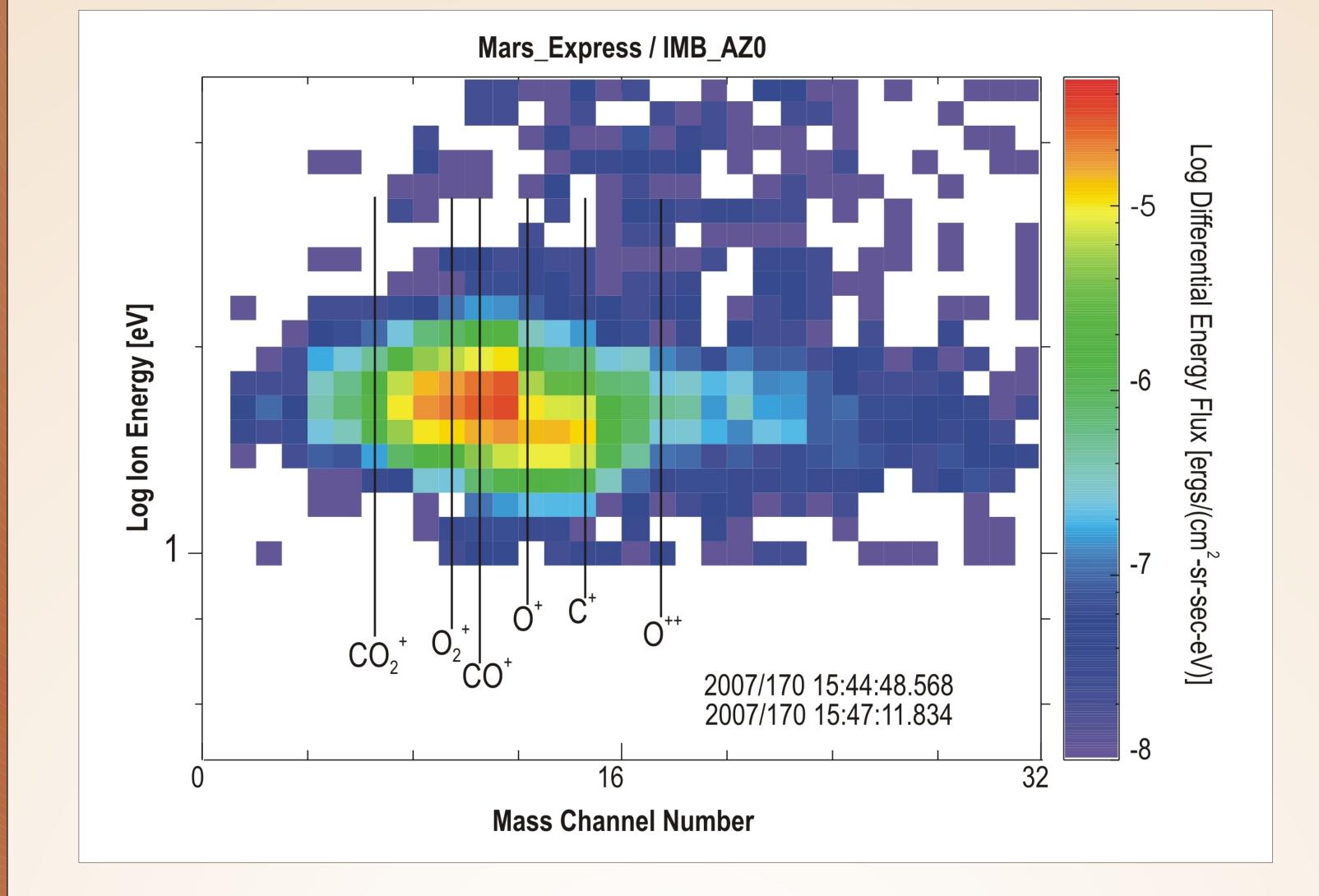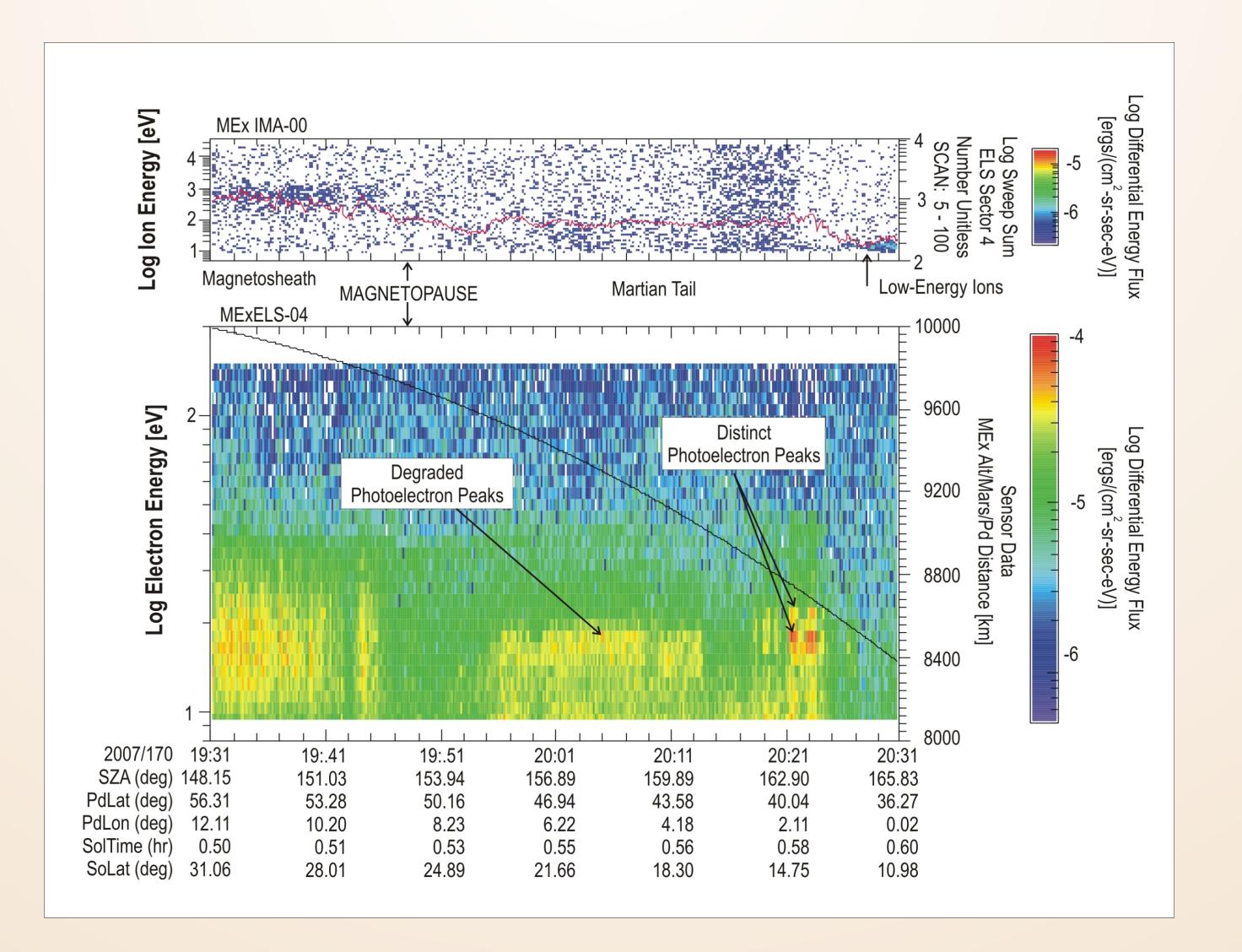
Tail Observations

Figure 4. Ionospheric Ion Differential Energy Flux Spectra. Ion spectra and energy below 50 eV are shown from IMA. Locations of certain ion mass species are shown.

At times, ELS observes photoelectron energy peaks in the Martian tail. At most times when photoelectron peaks are observed, their signature is similar to those observed in the ionosphere, except they are highly directional. Examples of photoelectron peaks observed in the tail of Mars can be seen in Figure 5 between 2121 UT and 2024 UT. The format of Figure 5 is the same as Figure 2. The data shown in Figure 5 occurs later in the trajectory of MEx, when the spacecraft travels to the magnetotail. The data in Figure 5 also indicate that the magnetosheath is encountered closer to the planet than the average position. This location is also noted in Figure 1 for reference.

Figure 5. Plasma in the tail of Mars. This figure format is the same as in Figure 2. Photoelectron peaks are observed in the range between 2021 UT and 2025 UT. Degraded photoelectron peaks are observed between 1955 UT and 2014 UT. Low-energy ions are observed after about 2025 UT.

Distinct Photoelectron Peaks

Distinct photoelectron peaks have a sharp spectral intensity versus energy signature which stands out as discontinuous data values. This indicates that the energy width of electrons within the peaks is less than the approximate 8% energy resolution of ELS. When photoelectron peaks are observed in the Martian tail, they are always observed in the sensors measuring flow away from the planet in one or two ELS sectors, indicating a small pitch angle range. Beams showing photoelectron peaks can be as intense as spectra showing photoelectron peaks measured in the ionosphere. Figure 6 shows a comparison of these electron spectra (red in the ionosphere and green in the tail) from the data presented in Figures 2 and 5. Besides a shift in energy, these spectra have comparable magnitudes. The energy shift is due to spacecraft charging, about -5.6 V in the tail and about -10.8 V in the ionosphere for the spectra shown in Figure 6. ELS observes photoelectron peaks in the tail from only one of its 16 planar sectors, meaning that the photoelectron beam has a full width of at most 22.5°, in agreement with calculations of Liemohn *et al.* [2006]. The majority of photoelectron peaks identified by ELS to date are described as distinct photoelectron peaks.
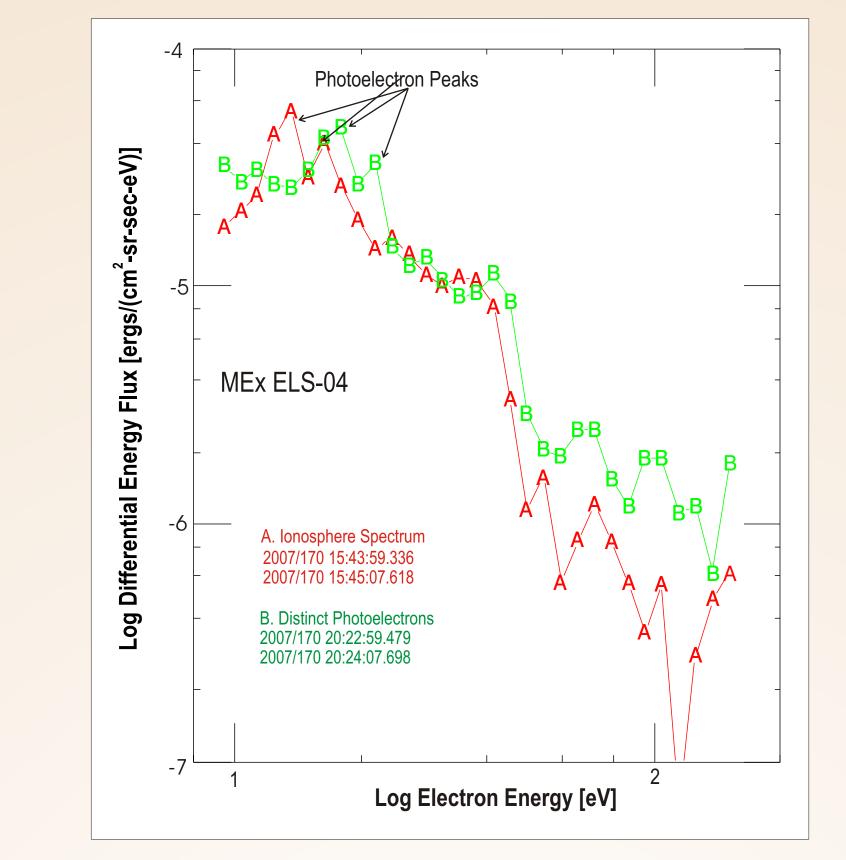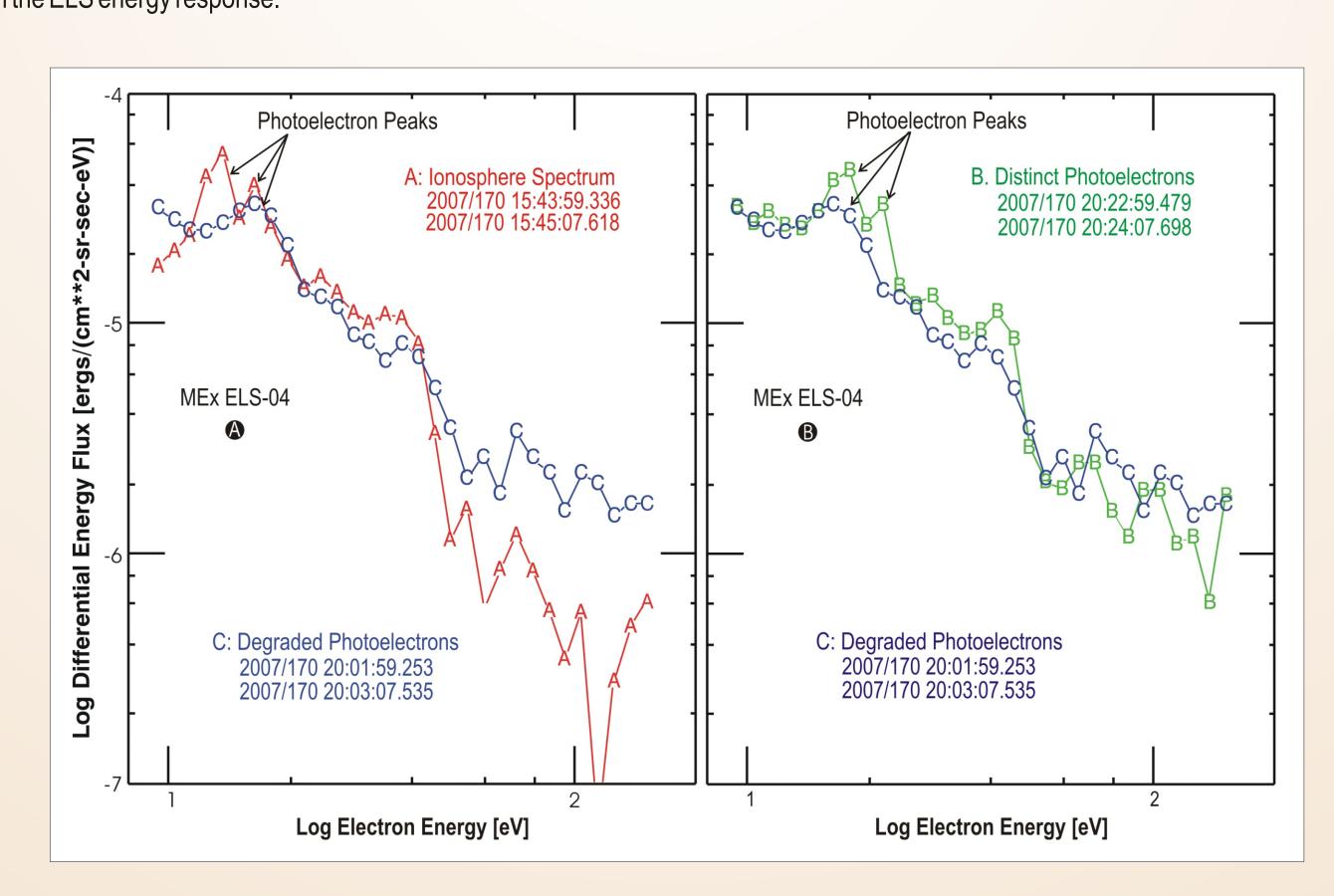
Degraded Photoelectron Peaks

Figure 6. A comparison between tail and ionosphere electrons spectra. A tail electron spectrum is shown in green and ionosphere electron spectrum is show in red. Estimated spacecraft charging levels of about -5.6V in the tail and about-10.8V in the ionosphere cause energy shifts in each spectrum.

The presence of ion observations at times when photoelectrons appear is inconclusive. Since the IMA energy sensitivity has been changed to detect lower energy ions, low-energy ion measurements simultaneous with photoelectrons measured in the Martian tail have been observed randomly. Low-energy ions are observed in Figure 5 beginning around 2025 UT to have an intensity level less than that observed in the ionosphere. In most cases in the tail, ion intensities have been observed to be reduced with increasing altitude. The lack of ion observations here may be due to a weakening of ion flux such that it is below the instrument threshold, a reduction in the spacecraft charging level causing the ions reaching the spacecraft to be less energetic and possibly below the energy threshold of IMA, and/or since IMA is measuring in a 2D plane at this time, at an angle not measured by IMA.

There have been a few observations of degraded photoelectron peaks observed by ELS. These are also observed in Figure 5 between 1955 UT and 2014 UT. The overall energy spectrum is similar to spectra showing the distinct tail photoelectron peaks existing in the ionosphere except in the region of the photoelectron peaks spectra. Examples are shown in Figure 7. The distinctness of the two photoelectron peaks has degraded from the sharpness of the distinct peaks observed in the tail (7a) and in the ionosphere (7b) by broadening in energy such that only one wider peak is observed. In degraded spectra, the energy width of the photoelectron peak is larger than ELS energy response.
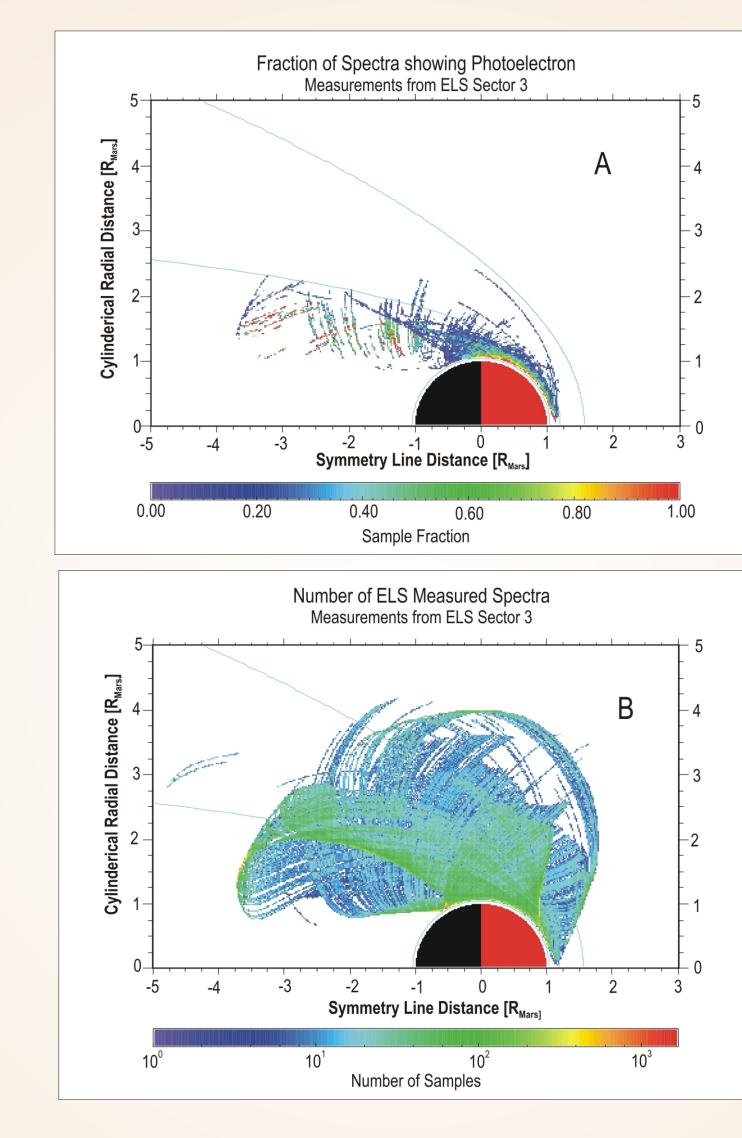

Figure 7. Comparison with a degraded photoelectron peak spectrum. The comparison of the degraded photoelectron spectrum with that of the a) tail and b) ionosphere electron spectra shown in Figure 6 shows that the region of the photoelectron peaks shows a smoother transition indicating some thermalization and/or scattering is taking place.

Discussion

Photoelectron peaks observed in the Martian tail must come from the dayside exobase where the density is large enough to produce the observed electrons. The 19 June 2007 MEx pass through the tail measured photoelectron peaks which had comparable intensity to those observed in the ionosphere, which was shown in Figure 6. For the region in the tail of electrons in the peak, the added integral flux of electrons above a spectrum baseline generated by connecting values outside of the peak region and determining the difference in flux is about 6.7x10^4 erg/(cm^2 s) in the distinct peak region. This corresponds to about 2.25x10^5 electrons/(cm^2 s) for this same region. Both of these calculations assumed a -5.6 volt spacecraft charge, the flux is present only over one ELS sector (11.25° half angle), and the flux is uniformly spread over the measured energy sample. Fluxes in the ionosphere are about 300 times these values since they are detected with about the same intensity and in all ELS sectors, independent of the orientation of ELS with respect to the Mars-Sun line. As can be seen in Figure 5, the distinct peaks are observed for about 180 sec; however, the degraded photoelectrons last for about 950 sec. These are observation times and it is not known if the flow of these electrons past the spacecraft is continuous or time variable, nor do we know what is happening at positions away from the spacecraft. However, we can estimate that for a spacecraft charge of -6.9 volts, the flux from the spectrum showing the degraded photoelectrons (Figure 7) generates about 3.4x10^4 erg/(cm^2 s) and about 1.3x10^5 electrons/(cm^2 s) pass the spacecraft. So despite the fluxes being half the distinct fluxes, they are observed to last 5 times longer.

Discussion (cont.)

Statistics have been collected on the occurrence of distinct peaks using ELS-03. Data was collected from January 5, 2004 through January 24, 2005. These data are shown in Figure 8. Figure 8a shows the fraction where photoelectron peaks were observed (white represents that no peaks were observed), and Figure 8b shows the number of times during which that spatial region was sampled. Statistics shown in Figure 8 indicate that photoelectron peaks are observed in ELS-03 about 6% of the time tailward of a vertical line at -1.5 Mars radii.

Figure 8. Statistics of occurrence of distinct photoelectron observations. Using ELS-03, the ratio of the number of samples where photoelectron peaks were observed is shown as a fraction of the number of times the spatial region was sampled (A). (B) represents the number of samples made by ELS-03.

For the statistics shown in Figure 8, the area of the tail at -1.5 Mars radii where data was sampled represents an area of about 1.14x10^8 km^2 (1.14x10^{18} cm^2). If the average flux was about 6.7x10^4 erg/(cm^2 s) [2.25x10^5 electrons/(cm^2 s)] escaping the planet from an area of 1.14x10^{18} cm^2, the amount of atmospheric loss is about 7.6x10^{23} ergs [about 1.5x10^{23} electrons]. If the given rate is representative of the average flux of photoelectron peaks and in 1 year (about 3x10^7 s) photoelectron peaks are observed 6% of the time, then Mars lost 1.35x10^{10} ergs of energy in 2.7x10^{24} electrons in 2004. By using charge neutrality arguments, ions must also have been lost. The ions which were lost are the dissociated products of CO_2^+ and O^+.

Conclusion

ASPERA-3 ELS and IMA observations have been used to show that photoelectron peaks are observed in the ionosphere by ELS and low-energy ion dissociation products of carbon dioxide are observed simultaneously by IMA. The spacecraft charge effects can be observed so that electron and ion spectra can not be taken at face value, but must be adjusted for spacecraft charge. Electron spectra observations are nearly isotropic in angle whereas low-energy ion angular distributions are anisotropic.

In the Martian tail, ion observations do not always occur at the same physical location where photoelectron peaks are measured. Photoelectron peaks are seen as distinct energy peaks, but in some cases, they are observed as degraded in energy. This implies that the peaks broaden in energy width. In the tail, different ELS sectors observe photoelectron peaks, but the angular width is limited to one sector (or 22.5°) most of the time.

Using the particulars of the distinct photoelectron peak spectrum from 19 June 2007 and statistics of the locations of distinct photoelectron peaks, estimates of electron loss from photoionization of carbon dioxide and atomic oxygen are 2.7x10^{24} electrons, representing 1.35x10^{10} ergs of energy in 2004. This value is estimated from the observation that distinct photoelectron peaks are seen to occur in about 6% of the ELS measurements and using the assumption that the measured flux in the distinct photoelectron peak portion of the energy spectrum [6.7x10^4 ergs/(cm^2 s); 2.25x10^5 electrons/(cm^2 s)] is representative of the average flux in 2004.

References

Barabash, S., *et al.* "ASPERA-3, Analyzer of Space Plasmas and Energetic Ions to the Mars Express," in Mars Express: The Scientific Payload, eds. A. Wilson and A. Chicarro, Eds, Scientific Coordination. European Space Research and Technology Centre, Noordwijk, The Netherlands, 121-139, August 2004.

Coates, A. J., *et al.* "Electron observations from Mars Express ASPERA-ELS," presented at International Mars Conference, Ischia, Italy, 19-23 September 2004.

Fox, J. L. and A. Dalgarno, "Ionization, Luminosity, and Heating of the Upper Atmosphere of Mars," Journal of Geophysical Research, 84, 7315-7333, 1979.

Frahm, R. A., *et al.* "First Observations from the ASPERA-3 ELS in the Mars Ionosphere," EOS Transactions of the American Geophysical Union, 89(11), Joint. Assembly Supplement, (A33C, Abstract SA23R-03, May 18, 2004.

Frahm, R. A., *et al.* "Carbon Dioxide Photoelectron Energy Peaks at Mars," Icarus, 182, 371-382, 2006a.

Frahm, R. A., *et al.* "Locations of Atmospheric Photoelectron Energy Peaks within the Mars Environment," Space Science Reviews, 126(1-4), 389-402, 2006b.

Frahm, R. A., *et al.* "Simultaneous Photoelectron and Ion Measurements in the Martian Ionosphere," presented at the European Mars Science and Exploration Conference: Mars Express & Exomars, European Space Research and Technology Centre (ESTEC), Noordwijk, The Netherlands, November 15, 2007a.

Frahm, R. A., *et al.* "Simultaneous Photoelectron and Ion Measurements in the Martian Tail," Eos Trans, AGU, 88(52), Fall Meet. Suppl., Abstract P41A-0195, December 13, 2007b.

Krasnopolsky, V. A. and G. R. Gladstone, "Helium on Mars: EUVE and PHOBOS Data and Implications for Mars' Evolution," Journal of Geophysical Research, 101, 15765-15772, 1996.

Lundin, R. *et al.* Solar Wind-Induced Atmospheric Erosion at Mars: First Results from ASPERA-3 on Mars Express," Science, 305, 1933-1936, 2004.

Mantas, G. P., and W. B. Hanson, "Photoelectron Fluxes in the Martian Ionosphere," Journal of Geophysical Research, 84, 369-385, 1979.

Vignes, D., *et al.* "The Solar Wind Interaction with Mars: Locations and Shapes of the Bow Shock and the Magnetic Pile-up Boundary from Observations of the MGSER Experiment on Board Mars Global Surveyor," Geophysical Research Letters, 27(1), 49-52, 2000.

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