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Final Progress Report for:

Low Energy Electrons in the Mars Plasma Environment

Prepared by:
Richard Link, Ph.D.
Principal Investigator

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ATTN: Dr. Joseph M. Boyce
Research Program Management Division

SOUTHWEST RESEARCH INSTITUTE
Space Science and Engineering Division
6220 Culebra Road, San Antonio, Texas 78238
(210) 684-5111 • FAX (210) 647-4325

Project Abstract

The ionosphere of Mars is rather poorly understood. The only direct measurements were performed by the Viking 1 and 2 landers in 1976, both of which carried a Retarding Potential Analyzer. The RPA was designed to measure ion properties during the descent, although electron fluxes were estimated from changes in the ion currents. Using these derived low-energy electron fluxes, *Mantas and Hanson* [1979, 1985] studied the photoelectron and the solar wind electron interactions with the atmosphere and ionosphere of Mars. Unanswered questions remain regarding the origin of the low-energy electron fluxes in the vicinity of the Mars plasma boundary. *Crider* [1999], in an analysis of Mars Global Surveyor Magnetometer/Electron Reflectometer measurements, has attributed the formation of the magnetic pile-up boundary to electron impact ionization of exospheric neutral species by solar wind electrons. However, the role of photoelectrons escaping from the lower ionosphere was not determined. In the proposed work, we will examine the role of solar wind and ionospheric photoelectrons in producing ionization in the upper ionosphere of Mars. Low-energy (< 4 keV) electrons will be modeled using the two-stream electron transport code of *Link* [1992]. The code models both external (solar wind) and internal (photoelectron) sources of ionization, and accounts for Auger electron production. The code will be used to analyze MGS measurements of solar wind and photoelectrons down to altitudes below 200 km in the Mars ionosphere, in order to determine the relative roles of solar wind and escaping photoelectrons in maintaining plasma densities in the region of the Mars plasma boundary.

Summary of Results

Our first scientific results from this project show that neglecting photoelectron transport (the local equilibrium approximation) is not valid above 200 km, much lower than the currently-assumed 300-350 km region. This has serious implications for remote sensing of Mars upper atmospheric composition via Far Ultraviolet (FUV) emission spectroscopy, for which photoelectron impact is the major excitation source of upper atmospheric FUV emissions. The airglow contribution from precipitating shocked solar wind electrons has never been assessed, but this is readily obtainable from our model and will be addressed in future work.

A second important scientific issue already clarified by the model concerns the non-detection of the atomic carbon peak in the Auger spectra of Mars photoelectrons measured by the MGS/MAG-ER experiment [*Mitchell et al.*, 2000], although the atomic oxygen peak is readily apparent. The model shows that the flux of Auger electrons resulting from inner core ionization of CO_2 leading to the oxygen branch is nearly an order of magnitude larger than for the carbon branch, thus explaining these unexpected observations.

Specific Accomplishments

The stated objectives of the proposed work were to:

- model the MAG/ER observations of photoelectron and Auger electron spectra in the Mars ionosphere, as a function of electron energy, pitch angle, and altitude:

  - A multistream, discrete-ordinate electron transport technique accounting for pitch angle redistribution [*Link*, 1992] was adapted to Mars (and other planets). The model accounts for photoionization, Auger electron ejection, and incident (solar wind) electron fluxes from 1 eV – 4 keV (approximately). To our knowledge, this is the first calculation of the pitch angle distribution of Mars photoelectrons (and Auger electrons) above 100 eV.

    In our model, the number of pitch angles is specified *a priori* and is arbitrary. Once the number of streams (pitch angles) is specified, the actual pitch angles are chosen according to the zeros of the Legendre Polynomials in Double Gauss Quadrature. This produces accuracy of order $2m$-1 in evaluation of the scattering kernels, where m is the number of streams in each hemisphere ($2m$ total). Other multistream techniques (e.g., *Mantas and Hanson*, 1979, 1985) assume a linear variation in pitch angle, and are thus only first-order accurate.

  - Figures 1 and 2 show (the same) pitch angle distributions calculated at two altitudes in the Mars ionosphere: 152 and 308 km. The results indicate that the photoelectron flux is isotropic at 152 km, which lies near the production peak. At 308 km, the upward (escape) flux dominates. The transition between the collisional (isotropic) and collisionless (anisotropic) regimes occurs near 200 km; this is much lower the 300 – 350 km often assumed in local equilibrium (no transport) models such as *Fox and Dalgarno* [1979].

    The difference between Figures 1 and 2 is that the data have been binned in energy in Figure 2 in order to emphasize the pitch angle asymmetries, at the expense of spectral information. The sharp wall in Figure 2 is due to Auger electrons, appearing as the discrete peaks between 250 – 500 eV in Figure 1.

  - A detailed comparison with the MAG/ER data now is now underway through subsequent NASA funding.

- correlate the variations in photoelectron and Auger electron fluxes with EUV and soft X-ray measurements by the SOHO and GOES satellites:

  - The relative importance of EUV, K-shell (soft X-ray) photoionization and Auger processes is shown in Figure 4 of the Appendix.

  - Figure 3 shows our first comparison of our (2-stream) model with the MAG/ER photoelectron data [*Mitchell*, 2000]. Note the difference in energy resolution between the model (ΔE = 1 eV) and the MAG/ER data ($\Delta E/E$ = 25%); this accounts for most of the differences between the two curves. (The model results will be adjusted to the instrument resolution at a later date). The upper panel shows the results computed without allowing for photoionization by soft solar X-rays. The bottom panel shows the effects of solar X-ray fluxes for moderate solar activity. Clearly, the MAG/ER measurements demonstrate the importance of solar X-ray and Auger electron processes in the Mars ionosphere, which other models do not take into account.

- model the penetration of solar wind electrons into the Mars atmosphere, for simple magnetic field geometries, and compare with previous results [*Mantas and Hanson*, 1985]:
  - Calculations of solar wind penetration into the Mars atmosphere are presented in Figure 8 of the Appendix. The results are in fair agreement with *Mantas and Hanson* [1985], allowing for the limitations (isotropic scattering only, no energy cascading from above 100 eV) in that model.
- prepare the results for publication:
  - Results were presented at the March, 2001 Meeting of the European Geophysical Society (see Appendix).
  - A publication is in preparation.

Scientific Results

The current status of the modeling and the scientific results to date were presented at European Geophysical Society meeting in March, 2001. A copy of the presentation appears in the Appendix.

The main results are summarized as follows:

- On Mars, most (95%) photoelectrons are produced below 200 km by solar EUV photoionization of CO_2, as CO_2 is the major gas below 200 km and the photoelectron flux peaks near 150 km.
- Above 200 km, electron transport from below dominates local production from N_2 and O due to the low ambient gas densities. Above this altitude, the upward and downward photoelectron fluxes are not isotropic and, hence, local equilibrium (no transport) models are not valid above 200 km. This is much lower than the 300-350 km altitude limit usually assumed in current photochemical modeling of the Mars thermosphere and ionosphere.
- Coulomb collisions between suprathermal solar wind electrons and photoelectrons with thermal electrons in the ionosphere of Mars are unimportant, due to the low ambient ionospheric plasma density.
- The altitude profiles of C and O Auger electrons are congruent since both are produced by photodissociative ionization of CO_2. There is little contribution from K-shell photoionization of atomic oxygen, the major neutral species above 200 km.
- The model explains the absence of a detectable carbon peak in the MAG/ER measurements [*Mitchell et al.*, 2000].

References

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Mantas, G. P., and W. B. Hanson, Photoelectron fluxes in the Martian ionosphere, *J. Geophys. Res.*, **84**, 369, 1979.

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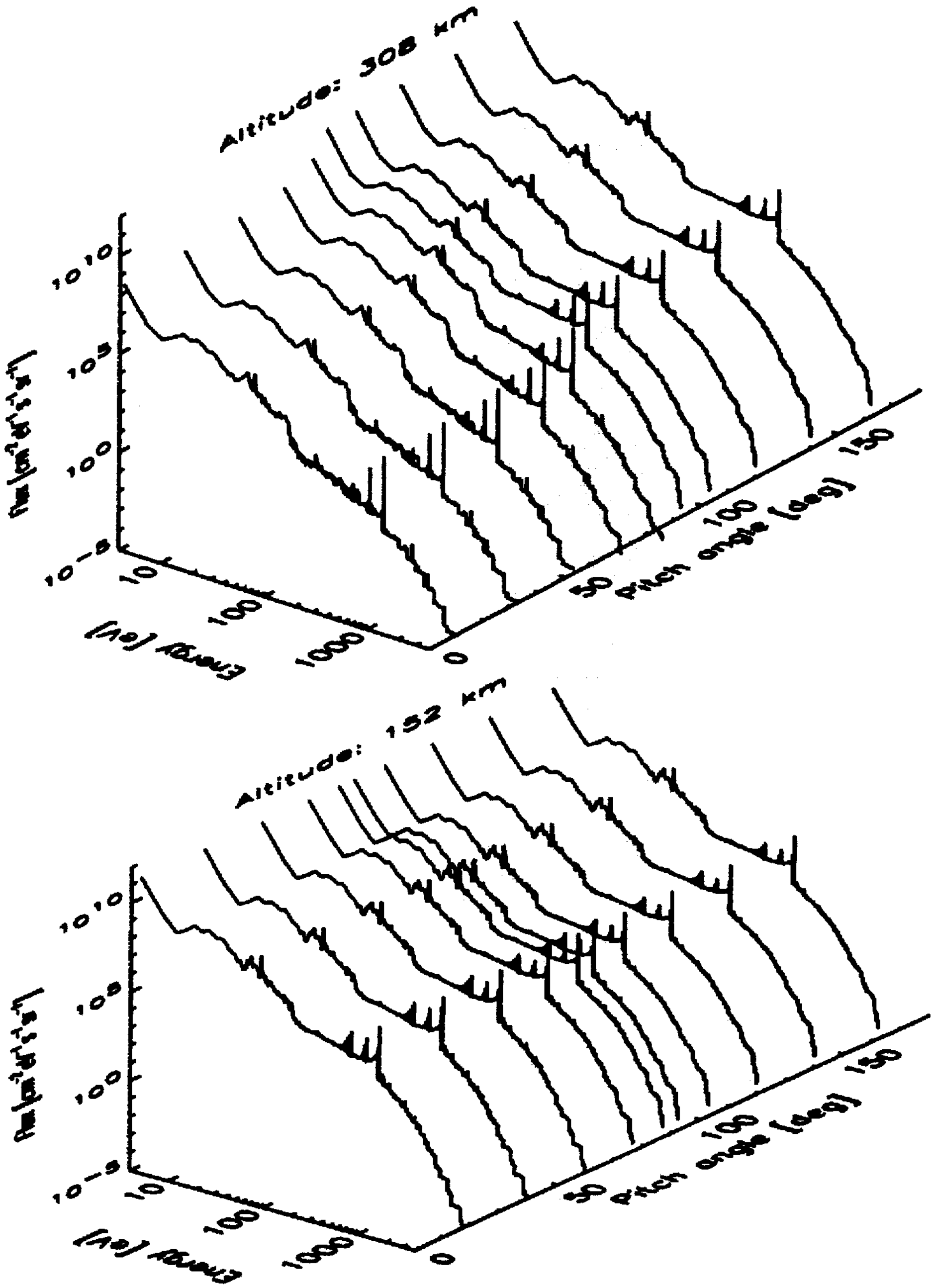


Figure 1. Mars photoelectron fluxes at 308 km (upper panel) and 152 km (lower panel) calculated using our revised multistream transport model.

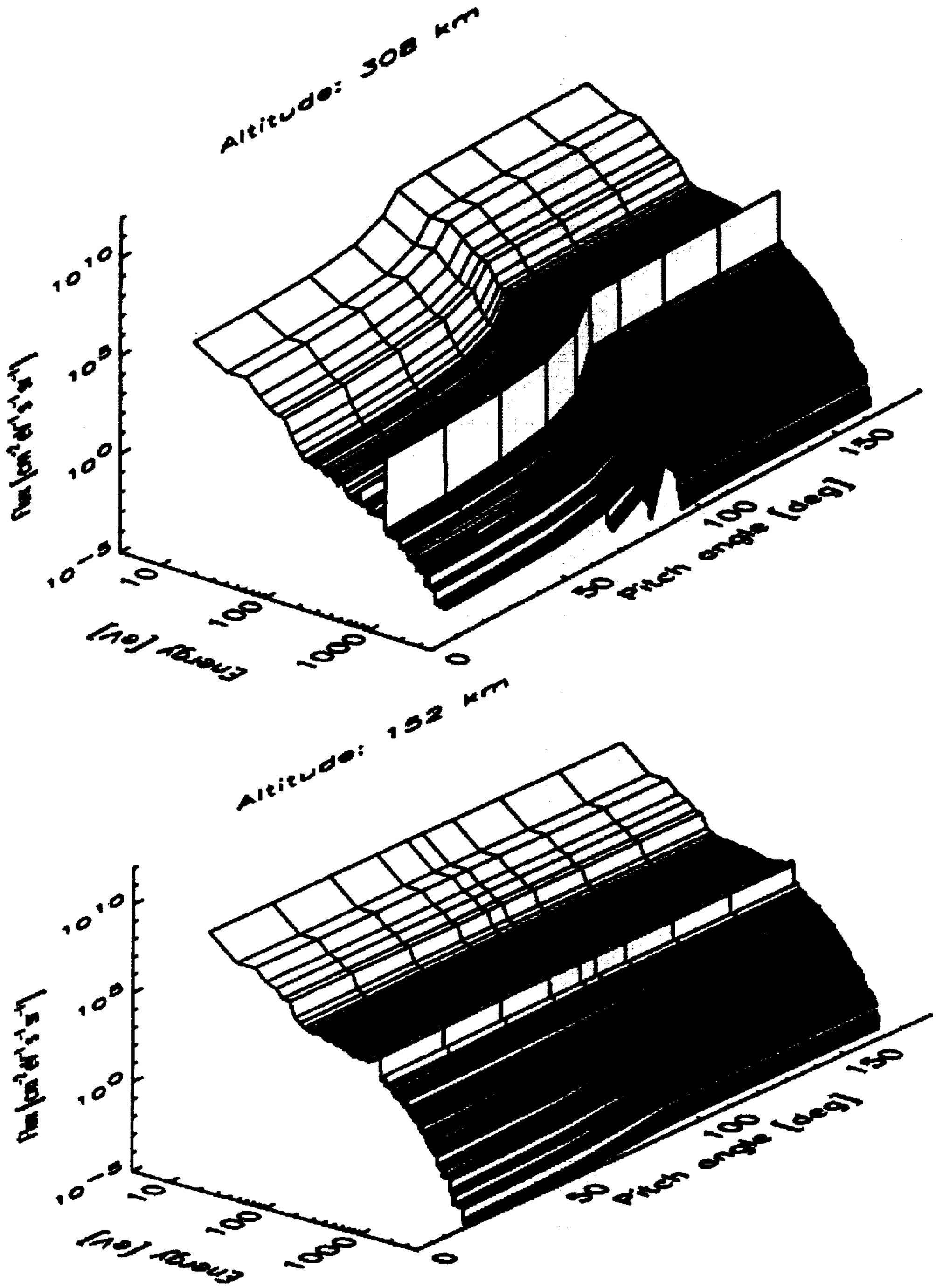


Figure 2. The same data as shown in Figure 1, but binned over energy for a clearer depiction of the pitch angle variation. The vertical 'fence' between 250 - 500 eV are Auger electrons ejected by C, N, and O.

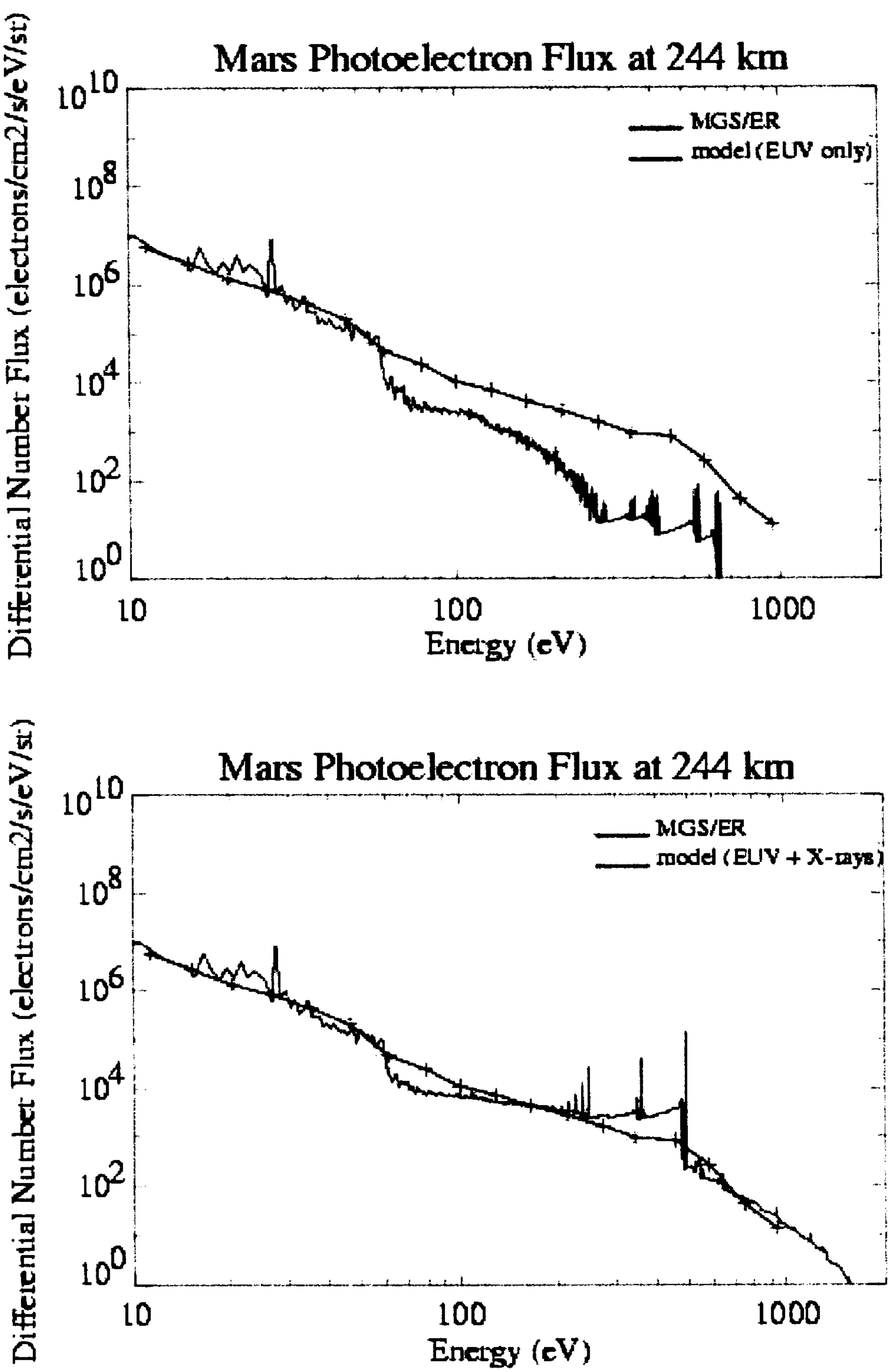


Figure 3. Comparison of MGS/ER photoelectron measurements [*Mitchell et al.*, 2000] with the model results at 244 km altitude. The upper panel shows calculations to 650 eV, ignoring Auger processes. The lower panel shows the effects of Auger electrons, with soft X-ray fluxes extending to 4 keV. The model has much finer spectral resolution (1 eV) then the measurements.

APPENDIX

Low Energy Electrons in the Mars Plasma Environment

R. Link

European Geophysical Society, Nice, 2001

Low Energy Electrons in the Mars Plasma Environment

European Geophysical Society
Nice, 2001

Richard Link
Space Science and Engineering Division
Southwest Research Institute
San Antonio, Texas 78228-0510
rlink@swri.org

Abstract

We describe a new model for the interaction of low-energy(0.5 - 4000 eV) electrons with the upper atmosphere and exosphere of Mars, based on the Link [1992] solution of the Boltzmann transport equation. With the new code, we can (simultaneously) model the penetration of shocked solar wind electrons into the atmosphere of Mars, and photoelectron production and escape from within the atmosphere. Our model performs a solar emission line-by-line calculation of photoelectron and photoion production, accounting for K-shell photoabsorption and Auger electron ejection. Comparisons will be presented with Mars Global Surveyor electron data. Our first results explain the lack of detection of carbon Auger electrons in the MGS data.

Introduction

In this talk, we present an update of the model results and validation efforts, and discuss future improvements. The latter primarily involves a more comprehensive assessment of the model input data (photoabsorption and electron collision cross sections) and inclusion of magnetic gradients in the Boltzmann equation to account for the crustal magnetization recently discovered by the Mars Global Surveyor (MGS) mission. The electron transport model is now being used to analyze the first direct measurements of photoelectrons and Auger electrons in the Mars environment by the MGS Magnetometer/Electron-Reflectometer experiment.

Introduction
(cont'd)

A screened Rutherford phase function controls the penetration depth of model solar wind electrons into the Mars atmosphere, and the escape flux of photoelectrons out of the atmosphere. Previously published models, which either ignore electron transport altogether (the local equilibrium approximation) or use an isotropic phase function, are inaccurate in a transport-dominated regime. In addition, our model performs a solar emission line-by-line calculation of photoelectron and photoion production, accounting for K-shell photoabsorption and Auger electron ejection. It is the only model which resolves the Auger energy peaks and their distribution in pitch angle.

Figure 1 Comments

- Composition of the upper atmosphere of Mars, showing the dominant gases CO_2, N_2, and O [*Krasnapolsky and Gladstone*, 1996]
- The number densities are about equal at 200 km, where photoelectron transport becomes important
- Below 200 km, CO_2 is the dominant gas
- Above 200 km, O dominates

Figure 1

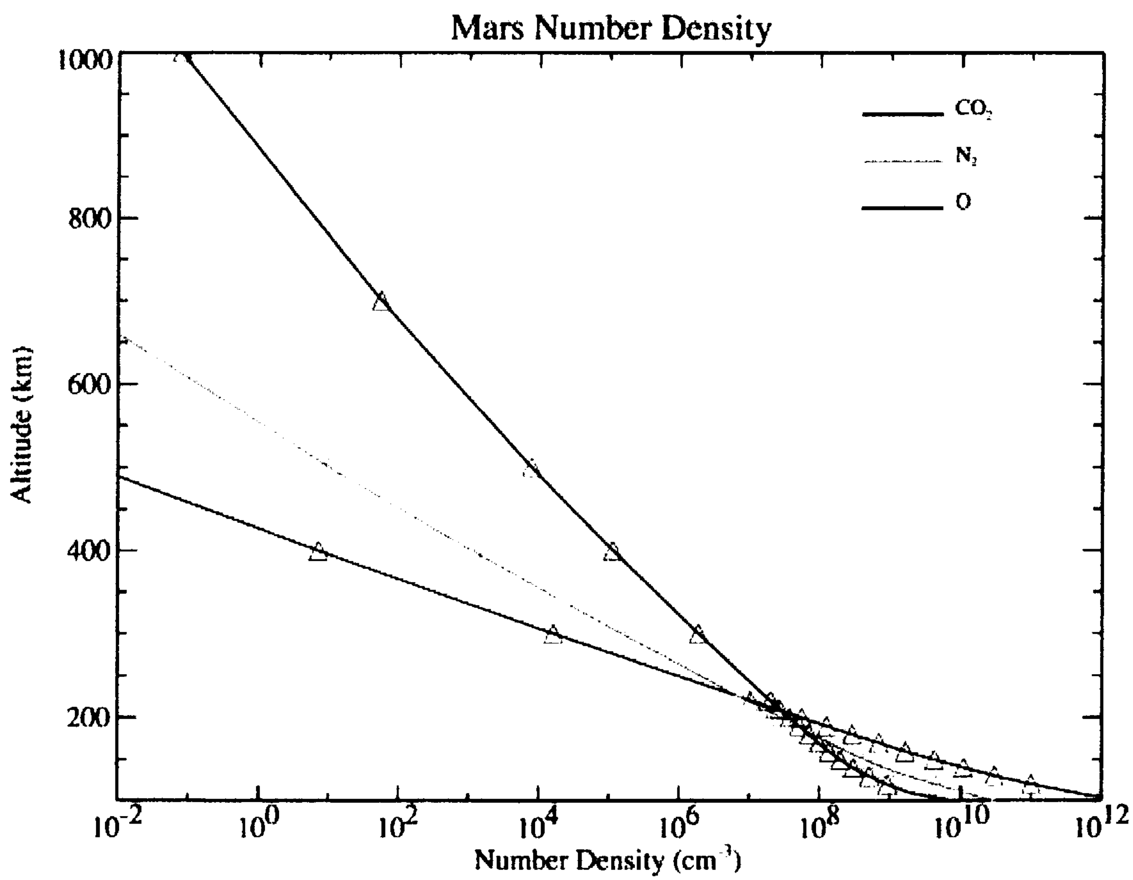
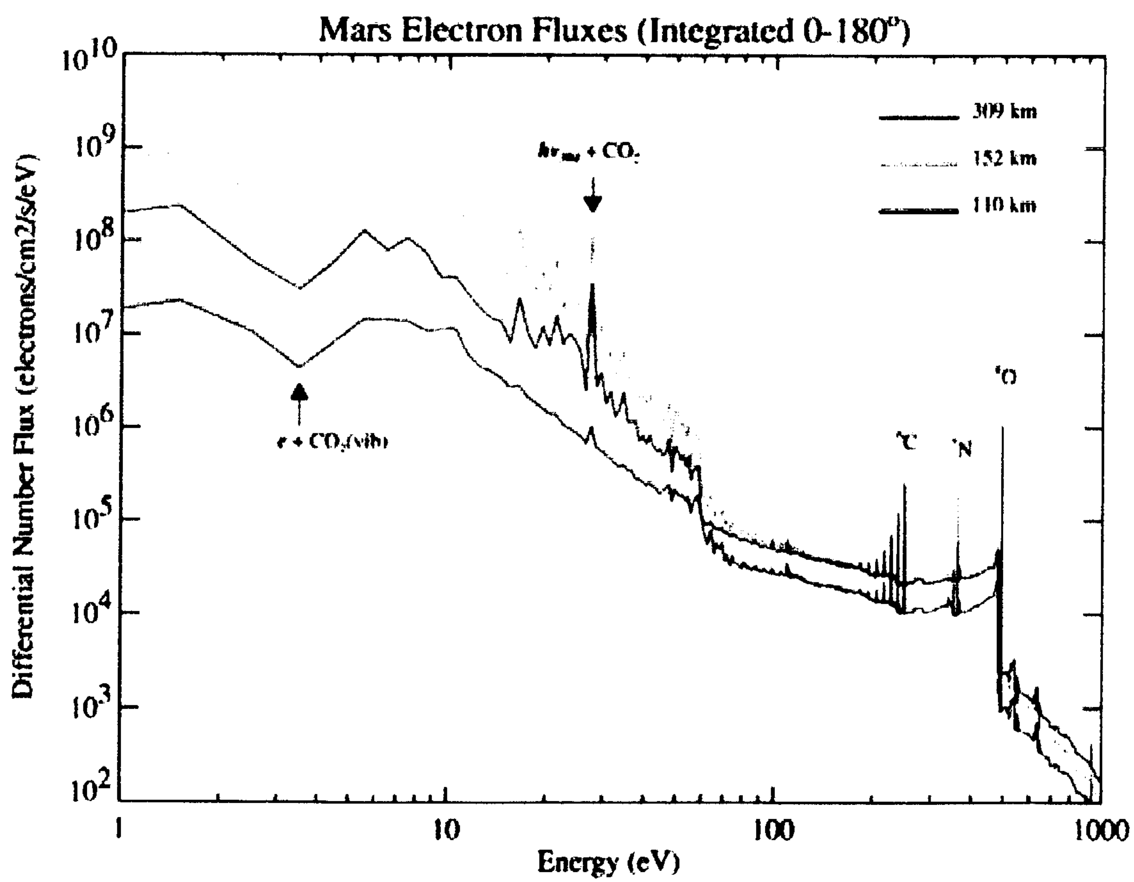

Mars Number Density
Altitude (km)
Number Density (cm^{-3})
1000
800
600
400
200
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
CO_2
N_2
O

Figure 2 Comments

- Photoelectron fluxes at 309 km, 152 km (peak), and 110 km
- Fluxes are integrated over 0 - 180° pitch angle
- Peaks in the spectra are due to photoionization into discrete ion states by discrete solar emission lines, *e.g.*,
  - the C, N, O Auger peaks
  - the He^+ 304 Åphotoionization peaks at 20 - 30 eV
- Valleys are due to discrete energy loss by electrons undergoing inelastic collisions with the atmospheric gases
- At higher energies (above 60 eV) and altitudes (above 150 km), the atmosphere is optically thin to energetic photons

Figure 2

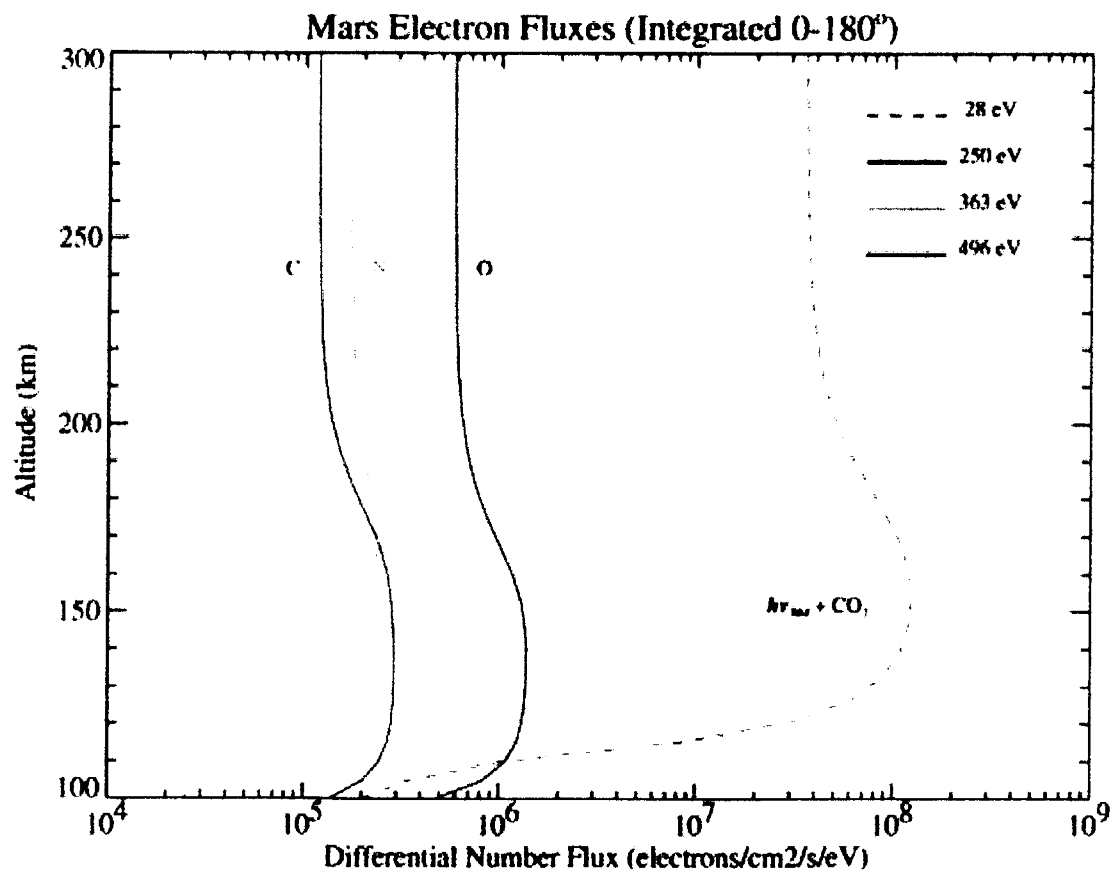


Mars Electron Fluxes (Integrated 0-180°)
Differential Number Flux (electrons/cm2/s/eV)
Energy (eV)
309 km
152 km
110 km
$h\nu_{ss}$ + CO_2
e + CO_2(vib)
C
N
O

Figure 3 Comments

- Altitude profiles of electrons at the energy peaks shown in Figure 2
- The curves to the left are the Auger peaks of C, N, and O
- The C and O profiles are very similar in shape, since both are formed by photoionization of CO_2
  - transport of oxygen Auger electrons from CO_2 dominates local production from O at higher altitudes
- The model results here explain the absence of a distinct carbon Auger peak by MGS MAG-ER [*Mitchell et al.*, 2000]

Figure 3



Mars Electron Fluxes (Integrated 0-180°)
Altitude (km)
300
250
200
150
100
10^4
10^5
10^6
10^7
10^8
10^9
Differential Number Flux (electrons/cm2/s/eV)
28 eV
250 eV
363 eV
496 eV
C
O
$h\nu$ + CO_2

Figure 4 Comments

- Photoelectron spectra at 309, 152, and 110 km, computed under different assumptions:
  - The green curves show EUV photoionization of L-shell photoelectrons only
  - The red curves show L-shell and K-shell *photoelectrons*
  - The blue curves include ejection of K-shell Auger electrons
- Above 150 km, the atmosphere is optically thin to solar EUV, so these photoelectrons dominate below 60 eV
- At the lowest altitude, the EUV has been absorbed, and the lack of spectral structure and separation of the curves at low energies is due to energy cascade of degraded primaries

Figure 4

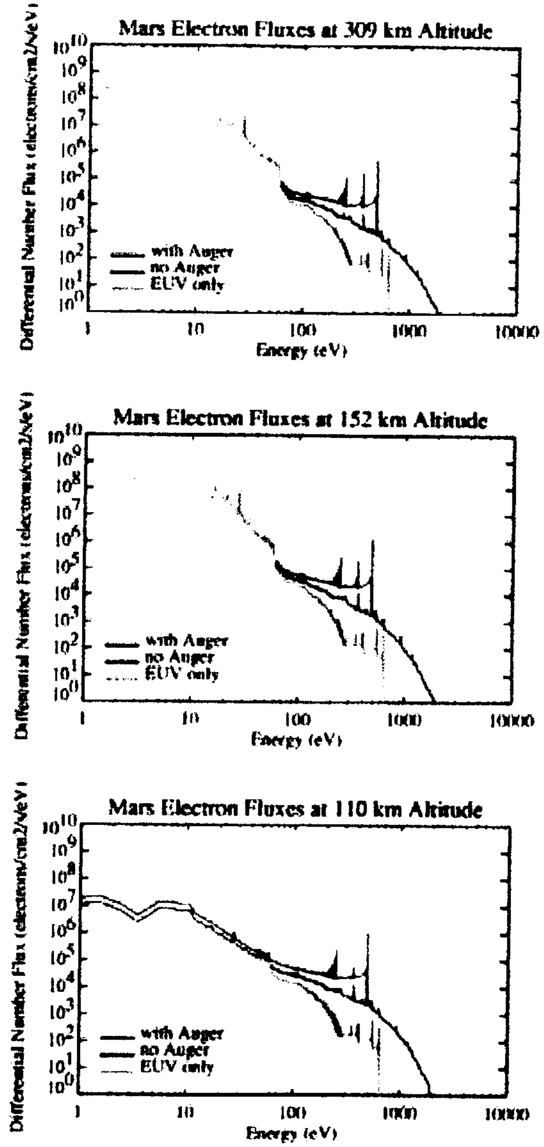
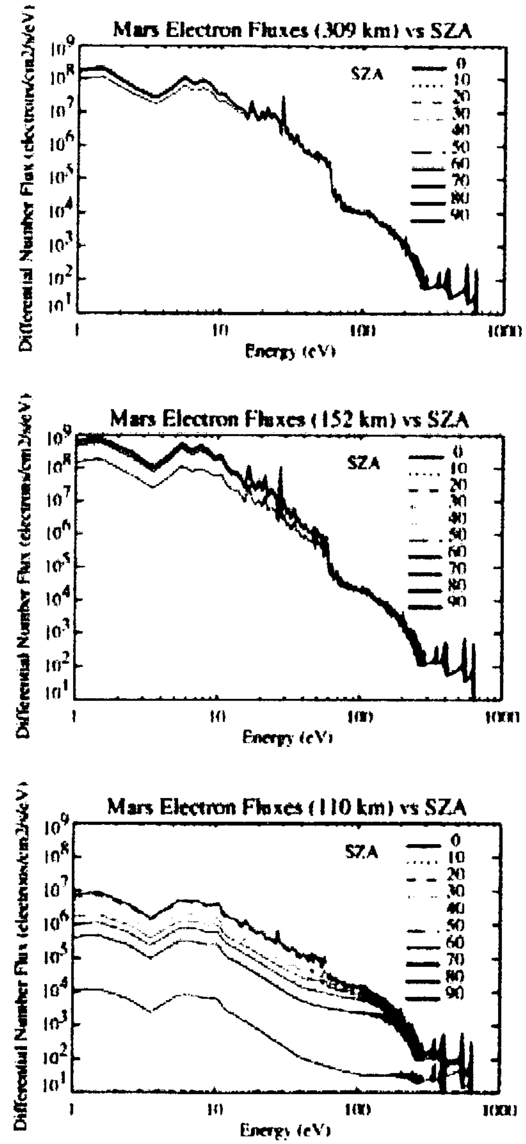

Mars Electron Fluxes at 309 km Altitude
Mars Electron Fluxes at 152 km Altitude
Mars Electron Fluxes at 110 km Altitude
Differential Number Flux (electrons/cm2/s/eV)
Energy (eV)
with Auger
no Auger
EUV only
1
10
100
1000
10000

Figure 5 Comments

- Photoelectron spectra at 309, 152, and 110 km, for solar zenith angles 0 - 90°
- At the higher altitudes:
  - the atmosphere is transparent to solar photons except at large zenith angles, where the slant path is longest
- At the lowest altitude:
  - the atmosphere is optically thick to EUV radiation
  - the atmosphere becomes optically thick to solar X-rays at large zenith angles

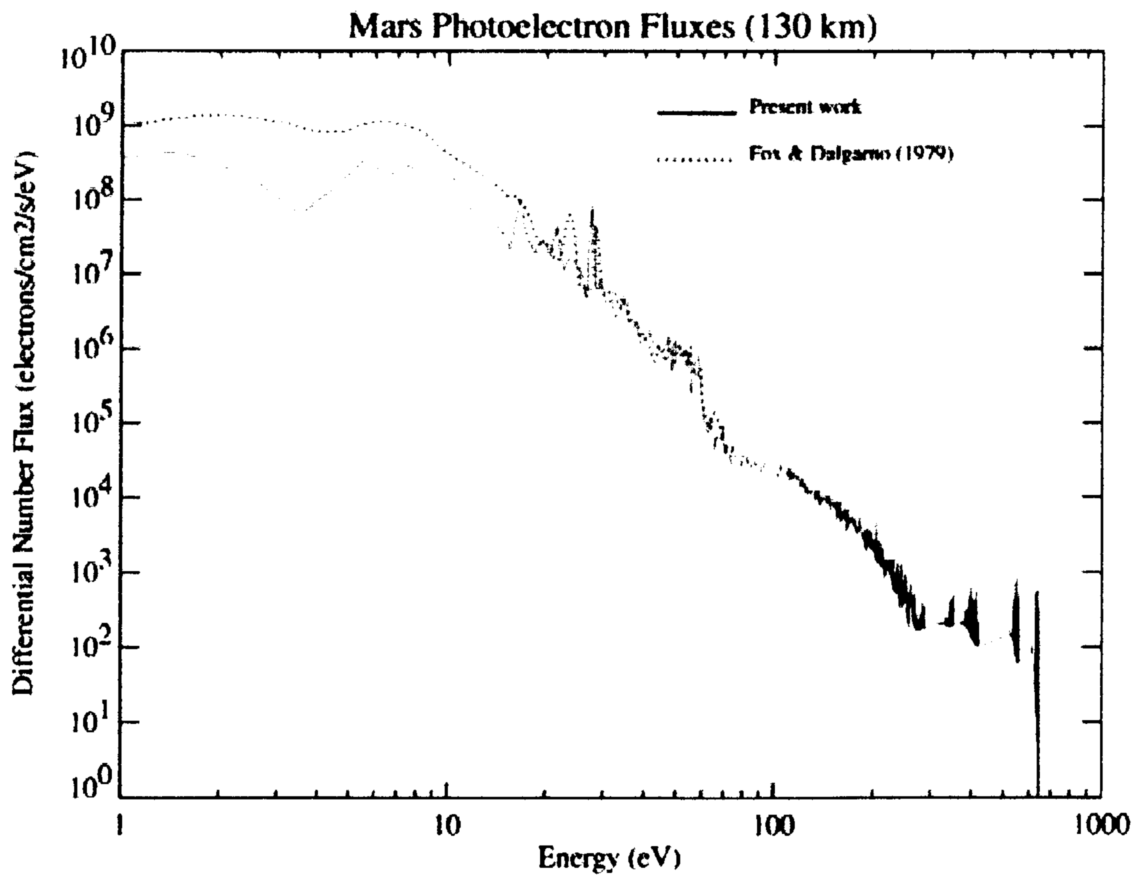
Figure 5


Mars Electron Fluxes (309 km) vs SZA
Mars Electron Fluxes (152 km) vs SZA
Mars Electron Fluxes (110 km) vs SZA
SZA
0
10
20
30
40
50
60
70
80
90
Differential Number Flux (electrons/cm2/s/eV)
Energy (eV)
1
10
100
1000

Figures 6 & 7 Comments

- Comparison of the present model results with *Fox and Dalgarno* [1979] and *O. Witasse* (personal communication, 2000)
- The adopted photon and electron cross sections, solar spectra, and model atmospheres differ
- No attempt has been made to normalize the results
- In the 10 - 60 eV region:
  - the results agree very well in magnitude
  - the location of specific peaks and their magnitude show some differences due to assumptions related to final-state ion product distributions

Figure 6



Mars Photoelectron Fluxes (130 km)
Present work
Fox & Dalgarno (1979)
Differential Number Flux (electrons/cm2/s/eV)
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
1
10
100
1000
Energy (eV)

Figure 7

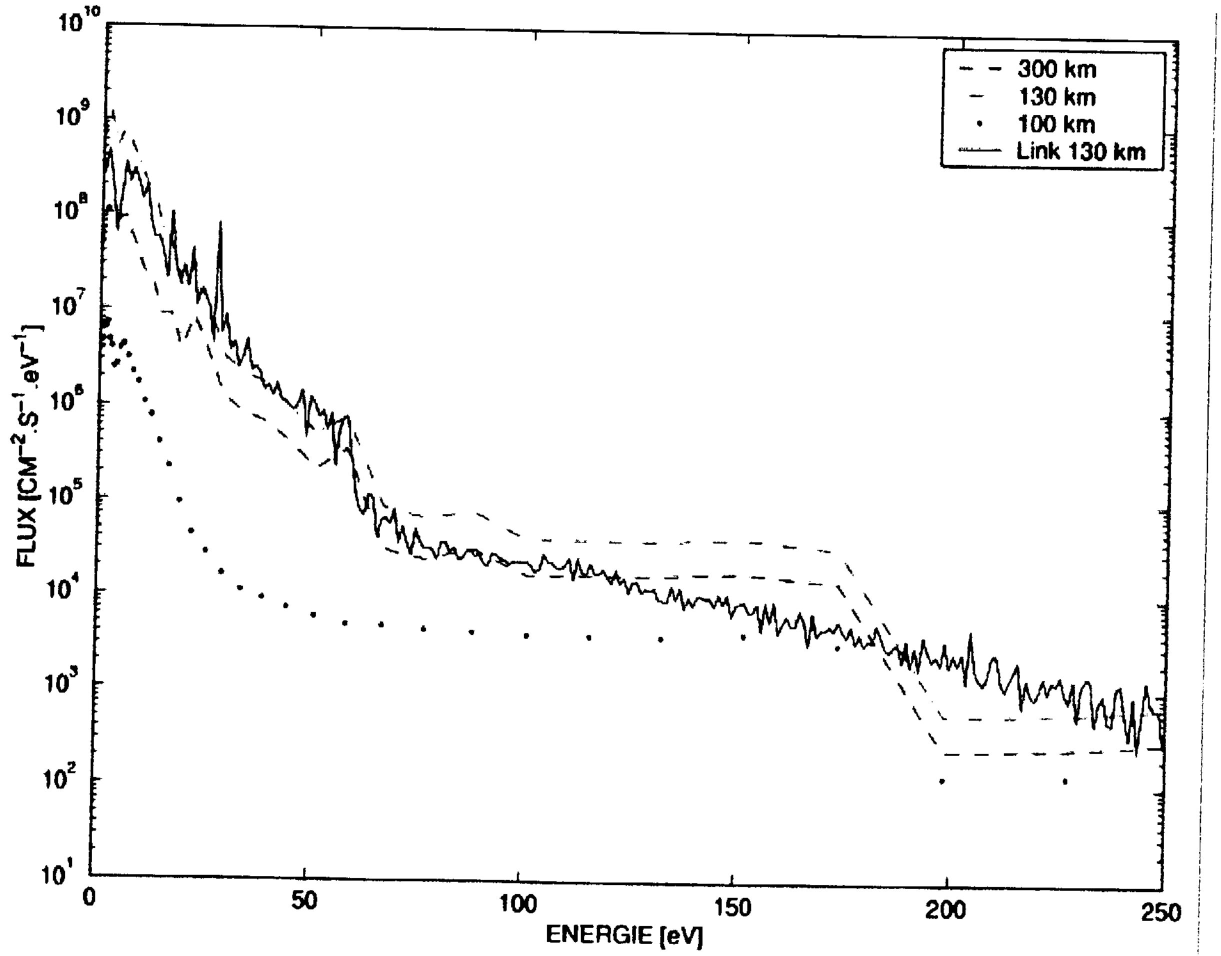
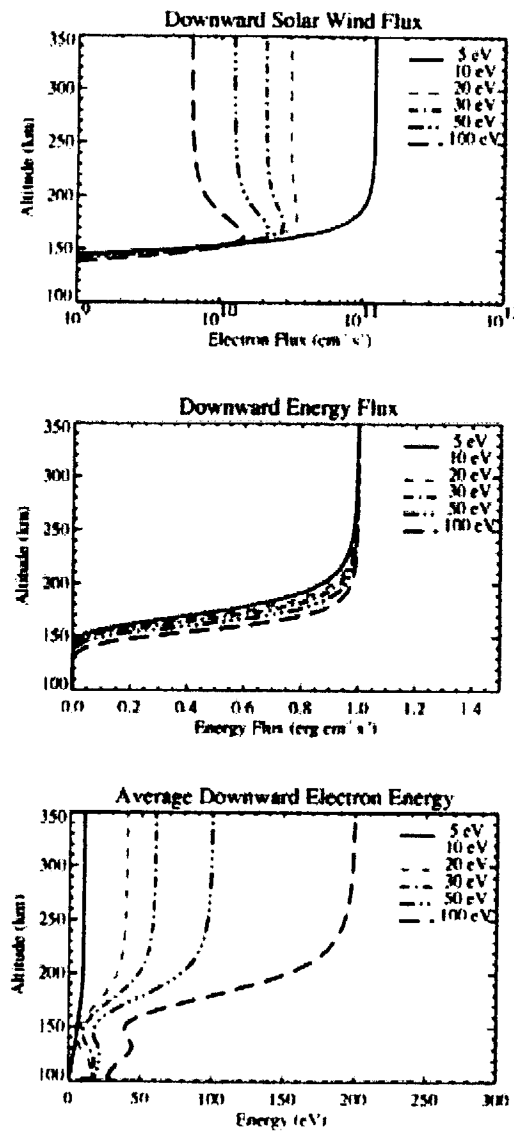

300 km
130 km
100 km
Link 130 km
FLUX [CM^{-2}.S^{-1}.eV^{-1}]
ENERGIE [eV]
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
0
50
100
150
200
250

Figure 8 Comments

- A ‘solar wind’ calculation:
- 1 erg cm^{-2} s^{-1} Maxwellian electrons with characteristic energies E_o = 5 - 100 eV are incident upon the atmosphere
- Upper panel:
  - the number flux at the top reflects the chosen normalization
- Middle panel:
  - penetration depth of electrons with different E_o
- Lower panel:
  - average energy of the downward electrons, equal to 2 E_o at the top of the atmosphere

Figure 8



Downward Solar Wind Flux
Altitude (km)
Electron Flux (cm⁻² s⁻¹)
5 eV
10 eV
20 eV
30 eV
50 eV
100 eV
Downward Energy Flux
Altitude (km)
Energy Flux (erg cm⁻² s⁻¹)
5 eV
10 eV
20 eV
30 eV
50 eV
100 eV
Average Downward Electron Energy
Altitude (km)
Energy (eV)
5 eV
10 eV
20 eV
30 eV
50 eV
100 eV

Summary

- On Mars, most (95%) photoelectrons are produced below 200 km by solar EUV photoionization of CO_2
  - CO_2 is the major gas below 200 km
  - the photoelectron flux peaks near 150 km
- Above 200 km, transport from below dominates local production from N_2 and O (low gas densities)
  - local (no transport) models are not valid above 200 km
- Altitude profiles of C and O Auger electrons are congruent
  - both are produced by photodissociative ionization of CO_2
  - the model explains the absence of a detectable carbon peak in the MGS MAG-ER measurements [*Mitchell et al.*, 2000]

Future Plans

- Update the photoionization branching ratios for CO_2^+, CO^+, O^+, and C^+ channels
- update the electronic and vibrational energy loss cross sections for CO_2
- incorporate magnetic gradients into the Boltzmann transport model
- perform analysis of MGS MAG-ER photoelectron and solar wind data (underway)