COMPARATIVE AERONOMY: Photo-Chemistry and Neutral-Plasma Coupling at Earth and Mars

Goal: To compare the ionospheres of Earth and Mars using data and theory in order to better understand the basic physical processes that are common to both.

Objectives:
(1) Test the predictions of simple photochemical equilibrium models for how peak electron densities in the ionospheres of Earth and Mars vary with solar flux, distance from the Sun, and solar zenith angle using standard terrestrial observations and martian observations from the Radio Science experiment on the Mars Global Surveyor spacecraft.
(2) Study the effects of solar flares and coronal mass ejections on simultaneous observations of the terrestrial and martian ionospheres to understand how Space Weather impacts these different environments. This will examine how the weak and spatially inhomogeneous magnetic field of Mars causes its ionosphere to differ from Earth's, testing theories of connections between ionospheres and magnetic fields.
(3) Examine the effects of waves and tides in the neutral atmosphere of Mars on the ionosphere, and then compare to predictions from models developed for Earth for ionosphere-neutral atmosphere coupling. Areas of weakness and potential improvement in the models will be identified.

Intellectual Merit. The proposed research will improve our understanding of ionospheric processes by testing predictions derived from terrestrial experience on simultaneous observations of the ionospheres of Earth and Mars. The coordination of terrestrial and martian observations is a creative and original concept that will build links between the disciplines of planetary and terrestrial aeronomy. The proposed postdoctoral fellow, Paul Withers, has worked extensively on the martian upper atmosphere for his doctoral research and has outstanding academic qualifications in physics and planetary science. The Principal Investigator, Michael Mendillo, leads a well-known research program in terrestrial aeronomy and also has research interests in related areas of planetary science.

Broader Impacts. By studying the effects of solar changes on more than one planet, any shortfalls in models for how the terrestrial ionosphere responds to the Sun will be identified and areas for potential improvement highlighted. This will facilitate the separation of solar and anthropogenic impacts on the terrestrial atmosphere, a goal of **NSF's Global Change Program**. Simultaneous studies of the effects of space weather on more than one planet will similarly benefit the **National Space Weather Program.**

Relevance to CEDAR's program objectives. Since the physics governing ionospheric processes should be the same on Earth and beyond Earth, models based on terrestrial observations should be valid beyond Earth's ionosphere. These models will be tested, especially in the areas of solar variability and the effects of magnetic fields, by comparing **Solar-Terrestrial Interactions** on Earth and Mars. Studies of waves and tides will address how ionospheres **Couple with Lower Altitudes** and test whether waves and tides are as important in coupling different atmospheric regions on Mars as they are on Earth.

Technical Plan

The aim of this proposal is to compare the ionospheres of Earth and Mars using data and theory in order to better understand the basic physical processes that are common to both.

The main goal of my (Paul Withers) PhD dissertation was to study the martian upper atmosphere using neutral density measurements around 130 km altitude made by the Mars Global Surveyor (MGS) spacecraft [1,2]. This dataset revealed that densities varied by factors of a few over tens of degrees of longitude and that this structure persisted for many weeks over wide ranges in altitude and latitude. These variations are caused by thermal tides. I used these observations and classical tidal theory to identify the dominant tidal modes influencing the atmospheric dynamics. I also examined day-to-day variability in the neutral atmosphere and developed techniques to derive pressure, temperature, and zonal wind speed measurements from these density measurements.

I now want to extend my work by studying the ionized portions of the martian upper atmosphere and by contrasting the aeronomy of Mars with that of better-studied Earth. The same general processes affect the ionospheres of both planets; differences between them are due to differences in boundary conditions such as distance from the Sun, magnetic field strength, and the properties of the neutral atmosphere [3]. Comparative planetology, the study of a phenomenon or behavior on more than one planet, helps us distinguish the processes that are common to all ionospheres from the effects of boundary conditions and hence better understand these general physical and chemical processes.

Professor Mendillo's research group at Boston University's Center for Space Physics has worked extensively on Earth's ionosphere, has played a leading role within CEDAR since its inception, and is beginning to study other ionospheres. A cross-disciplinary partnership between their established expertise in general ionospheric studies and my specialized knowledge of the martian upper atmosphere will enhance the linkage between the often-separated fields of planetary and terrestrial atmospheric science and should lead to important results from our comparative studies of the terrestrial and martian ionospheres.

Mars Global Surveyor's datasets are particularly suited to studying martian aeronomy [4]. Its accelerometer has measured neutral upper atmospheric densities. Its radio science (RS) experiment has measured vertical profiles of electron number density. These profiles typically show a primary peak in electron density near 135 km and a smaller, secondary peak near 115 km altitude. Since ionospheric photo-chemistry is strongly influenced by the neutral atmosphere, profiles of electron and neutral density need to be studied jointly. One possible effect of the neutral atmosphere is shown in Fig 1, which shows that the equivalent slab thickness of the ionosphere decreases when peak electron density increases. Bougher et al. have demonstrated that the peaks in electron density at Mars move up and down in altitude to remain at constant pressure levels in the neutral atmosphere [5].

In addition to past MGS datasets, neutral density measurements from Mars Odyssey are also available. For ionospheric measurements, new MGS/RS measurements will be collected during campaigns lasting a few weeks, each over a restricted range of latitudes, local solar times (LSTs), and solar zenith angles [6]. Most of the prior campaigns collected data from 60-70^{o}N and nighttime LSTs, but one observed at 70^{o}S and noon LSTs. The high latitudes of these observations makes them relevant to CEDAR's "Polar Aeronomy" science initiative. Comparable observations of Earth's ionosphere are made regularly around the globe with both incoherent scatter radars and ionosondes. All these datasets are publicly available via the CEDAR Data Base.

I plan to compare the mean behavior of, and variations in, the altitudes and strengths of electron density peaks using terrestrial and martian datasets. My three objectives are:

(1) Mendillo et al. make several predictions concerning peak electron density on Mars and simultaneous E-layer peak density on Earth, and test them on a small subset of the MGS RS data [7]. I plan to test them on the full dataset to determine what conditions must hold for the predictions to be correct. Figure 2, taken from [7], shows that the square of the peak electron densities in the Earth's E-layer and in the martian ionosphere scale linearly with solar EUV flux, but that the scaling factors are different. Mendillo et al. predict that the ratio of the scaling factors should be the ratio of the inverse square of the planets' distances from the Sun, $(1.52)^2$ or 2.3, which is close to the observed ratio of 3. In pursuing this objective, and in the details of production by photons and secondary electrons, CEDAR's "Solar-Terrestrial Interactions" science initiative can be addressed, especially "outstanding scientific questions" concerning the role of solar variability [10].

(2) I plan to study the responses of both ionospheres to coronal mass ejections (CMEs) and flares. Since Mars lacks Earth's strong magnetic field, its ionosphere should respond more strongly to the influx of charged particles from CMEs, and since Mars has a spatially inhomogeneous, but weak, magnetic field I will also investigate whether the response of the martian ionosphere depends on latitude and longitude. Responses to an increase in extreme ultraviolet flux due to flares should be similar in both ionospheres for direct photo-production, but secondary ionization due to photo-electrons remains a poorly understood mechanism on both planets. SOHO and other archives will be searched to identify CMEs and flares that occurred during MGS RS campaigns. The past few years have been particularly rich in solar activity, thus enabling a significant number of potential events to be studied.

(3) I plan to compare the effects of waves and tides in the two neutral atmospheres on their ionospheres. Bougher et al. demonstrated that electron densities in the ionosphere track up or down due to tidal changes in the neutral atmosphere [5]. MGS neutral density profiles from some regions and/or seasons are essentially smooth and undisturbed whereas those from other regions/seasons exhibit strong wave-like structure [8]. Similar small-scale structure may be present in the electron density profiles. This objective addresses CEDAR's "Coupling with Lower Altitudes" science initiative, especially the "outstanding scientific questions" concerning atmospheric waves. Studying small-scale structure is a key CEDAR measurement philosophy [10].

Comparisons with terrestrial observations will be most useful if the terrestrial observations are made at solar zenith angles, LSTs, and latitudes that match those of

MGS RS observing campaigns. When an MGS RS observing campaign is scheduled I will identify the terrestrial ionospheric observing sites that have the best potential match to the MGS RS observing conditions and coordinate with them so that observations can be made simultaneously. In addition to the scientific yield from such work, cross-disciplinary linkage between groups making simultaneous observations of ionospheres on two planets offers an opportunity to excite and inform the public about this work.

In addition to data analysis work, a major effort will be in comparisons with theoretical models. Available models include simple analytical models, see [7], and detailed numerical models, see [9]. Models are tools for interpreting the observations and identifying which physical processes are dominant. As done on Earth, both radio and optical observations can be used to constrain models. Boston University is currently planning observations of Mars at wavelengths of 6300 A and 5577 A to study airglow in atomic oxygen. Earth's airglow at these wavelengths is monitored routinely, and is a sensitive "response function" for our aeronomic system. I plan to apply those same types of restraints to the Mars system, with comparisons and contrasts relevant to both.

In Year 1, I will complete Objective (1) by testing the predictions of Mendillo et al. on the full MGS RS dataset and start Objective (2) by identifying subsets of the MGS RS and terrestrial datasets affected by CMEs and flares and characterizing ionospheric responses. I will also identify opportunities for simultaneous terrestrial and MGS observing campaigns. In Year 2, I will complete Objective (2) by applying models to analyze and interpret those responses and complete Objective (3) by exploring small-scale structure in terrestrial and martian neutral and ionospheric data. I will also study observations from successful coordinated campaigns. The results of this work will be broadly disseminated by presentations at scientific meetings. The results of each Objective will be published separately in the peer-reviewed literature. Existing facilities and equipment at Boston University will be used in this work.

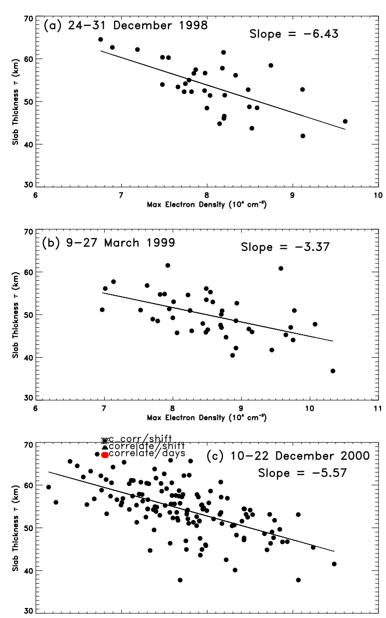

Fig 1

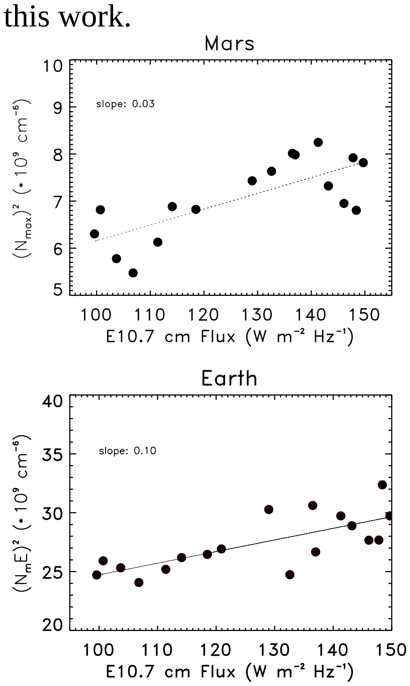

Fig 2

References

[1] P. Withers (2003) *Tides in the Martian Atmosphere – And Other Topics*, PhD dissertation, University of Arizona (http://www.lpl.arizona.edu/~withers/phd.html)

[2] G. M. Keating, S. W. Bougher, R. W. Zurek, R. H. Tolson, G. J. Cancro, S. N. Noll, J. S. Parker, T. J. Schellenberg, R. W. Shane, B. L. Wilkerson, J. R. Murphy, J. L. Hollingsworth, R. M. Haberle, M. Joshi, J. C. Pearl, B. J. Conrath, M. D. Smith, R. T. Clancy, R. C. Blanchard, R. G. Wilmoth, D. F. Rault, T. Z. Martin, D. T. Lyons, P. B. Esposito, M. D. Johnston, C. W. Whetzel, C. G. Justus, J. M. Babicke (1998) The Structure of the Upper Atmosphere of Mars: In Situ Accelerometer Measurements from Mars Global Surveyor, *Science*, **279,** 1672-1675

[3] A. F. Nagy and T. E. Cravens (2002) Solar System Ionospheres in *Atmospheres in the Solar System: Comparative Aeronomy* (Eds. Mendillo, Nagy, and Waite) 39-54

[4] A. L. Albee, F. D. Palluconi, and R. E. Arvidson (1998) Mars Global Surveyor Mission: Overview and Status, *Science,* **279,** 1671

[5] S. W. Bougher, S. Engel, D. P. Hinson, and J. M. Forbes (2001) Mars Global Surveyor Radio Science electron density profiles: Neutral atmosphere implications, *Geophysical Research Letters,* **28,** 3091-3094

[6] D. P. Hinson, R. A. Simpson, J. D. Twicken, G. L. Tyler, and F. M. Flasar (1999) Initial results from radio occultation measurements with Mars Global Surveyor, *Journal of Geophysical Research,* **104,** 26997-27012

[7] M. Mendillo, S. Smith, J. Wroten, H. Rishbeth, and D. P. Hinson (2003) Simultaneous Ionospheric Variability on Earth and Mars, submitted to *Journal of Geophysical Research*

[8] R. H. Tolson, G. M. Keating, S. N. Noll, D. T. Baird, and T. J. Shellenberg (2000) Utilization of Mars Global Surveyor Accelerometer Data for Atmospheric Modeling, *Advances in the Astronautical Sciences,* **103,** 1329-1346

[9] J. E. Titheridge (2000) Modelling the peak of the ionospheric E-layer, *Journal of Atmospheric and Solar-Terrestrial Physics,* **62,** 93-114

[10] CEDAR (1997) Coupling, Energetics, and Dynamics of Atmospheric Regions: CEDAR Phase III report (http://cedarweb.hao.ucar.edu/docs/CEDAR.pdf)