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Summary of Proposal Personnel and Work Efforts

Individual		Year 1	Year 2	Year 3
Michael Mendillo Principal Investigator	Effort Cost	0.05 XXX	0.05 XXX	0.05 XXX
Paul Withers Research Associate, Co-I	Effort Cost	0.85 XXX	0.85 XXX	0.85 XXX

A. OBJECTIVES AND EXPECTED SIGNIFICANCE OF PROPOSED WORK

We propose a comprehensive program of data analysis and modeling to probe the causes of variability in the coupled thermosphere-ionosphere system at Mars. Using data analysis tools and comparative approaches developed in our initial MDAP grant, plus new expertise offered by a new staff member (Dr. Paul Withers), we strive for a period of significant advancement in upper atmospheric science at Mars. In the sections below, we describe three tasks, each a focus of important, outstanding problems in martian aeronomy. Yet, these are not truly isolated topics since they involve coupling between neutrals and plasmas. We will analyze data from Mars Global Surveyor's (MGS) Radio Science (RS) and Accelerometer (ACC) instruments, Odyssey's (ODY) ACC instrument, and results from a photochemical model and a general circulation model in order to study ionospheric variability due to day-to-day changes in solar irradiance, to episodic solar flares and coronal mass ejections, to changes in neutral atmosphere composition, and finally to neutral atmosphere dynamical properties including tides, waves, temperatures, and winds.

This proposed research is responsive to NASA's Strategic Goal-II, Theme-SSE, Science Objective-4, RFA-a (Mars Climate) in sections B.III.3-4 and B.IV.2-4, Strategic Goal-II, Theme-SSE, Science Objective-1, RFA-c (Terrestrial Planet Diversity) in section B.II.3, and Strategic Goal-II, Theme-SEC, Science Objective-1, RFA-c (Atmospheric Response) in sections B.II.2-5, B.III.4, and B.IV.3.

A.1 Results from Previous Grant

NASA grant #NAG5-11077 ($50K/year for two years) supported our initial work with MGS data, with a no-cost-extension used to stretch resources to three years. The need for “program stretch-out” was due to the limited funding being unable to support any team member for more than a small percentage effort each year. Nevertheless, the PI (Mendillo), post-doc (Smith), graduate student (Martinis), staff researcher (Wroten) and visiting professor (Rishbeth) succeeded in completing three major studies, and made presentations on our interim results at several meetings. As we hope will be apparent from the publications listed in Table 1, we established Boston University as a new group able to contribute to the study of the wonders of martian atmospheric science.

Our first effort was to identify a sequence of RS occultation data that occurred during a period of pronounced solar variability (March 1999), and to use simultaneous terrestrial ionospheric observations to conduct the first-ever study of observed day-to-day variability of two planetary ionospheres. The main results appear in Fig. 1, taken from Mendillo et al. (2003a). This paper presents a general discussion of photochemical processes in the solar system, with emphasis on observable ionospheric layers at Mars and Earth. This data analysis work was followed by a period of model development, testing and use to explore how daily values of solar irradiance (energy flux versus wavelength) from the SOLAR2000 model (Tobiska et al., 2000; Tobiska, 2003) can define the extent of photochemical control of Mars’ ionospheric variability (see Fig. 2, taken from Martinis et al., 2003). Finally, using two additional MGS/RS datasets, and our fully-tested model, we conducted an environmental impact study of how ionospheric-imposed time delays can affect proposed radio communications and navigation systems under study for the Mars Exploration Program (see Fig. 3, taken from Mendillo et al., 2003b).

Preprints of our three papers are available at: http://sirius.bu.edu/aeronomy/preprints.html

B. INVESTIGATION AND TECHNICAL PLAN

B.I Overview

A coordinated and fully-integrated study of the neutral and ionized components of an atmosphere is a particularly appropriate approach to upper atmospheric science at Mars. Photochemistry dominates the behavior of its two ionospheric layers, and large-scale dynamics is a key element of its thermosphere. Both are controlled ultimately by changes in the Sun, both its photon component and via solar wind interactions. Careful data analysis and use of advanced modeling will help to unify our understanding of those influences. We now describe our three main objectives in some detail, and then address coupling and management issues to ensure a fully-integrated program of research.

B.II Task-1: Ionospheric Studies

Prior to the arrival of MGS at Mars, there were <500 published electron density profiles for Mars. Spread over solar cycles, seasons, local times, latitudes and longitudes, these remarkable and pioneering datasets defined the field of ionospheric physics at Mars, and their analysis and interpretation led to advances in theory and simulation (see Mendillo et al. (2003a) for a recent summary of past work). Yet, in comparison to a single day of observations of the Earth's ionosphere at a single location (e.g., probing the ionosphere-thermosphere-mesosphere regions above Arecibo with its incoherent scatter radar), ~500 profiles seems like a trivial number. It is a tribute to the modeling community that we know so much about the basic structure and behavior of Mars' ionosphere from this sparse dataset!

What don't we know? The easy answer is consistency and variability. With so few samplings, do we employ the cosmological principle of uniformity, i.e., whatever is measured on one day is typical of all days? Geophysics has taught us differently. MGS presents us with an extraordinary chance to go beyond "discovery mode" observations and take the first steps into the "maturity" of aeronomic science on Mars. This proposal is our attempt to begin that journey.

B.II.1 Data Availability. Table 2 shows the periods of MGS/RS datasets for which we have conducted a preliminary analysis, plus the new periods that await study. In addition, during the course of our proposed studies, there will be opportunities for additional MGS/RS experiments, and ones that we can help organize. For example, at about the time this proposal is submitted, Mars will be at opposition and a new dataset of MGS Ne(h) profiles will be taken that are ideal for Earth-Mars comparisons, as we demonstrated with the March 1999 RS data (Mendillo et al., 2003a). We have already mobilized colleagues responsible for terrestrial ionosonde stations to take data at a higher resolution and duty cycle in August, 2003, in order to enhance compatibility of the martian and terrestrial data. This has been possible by the cooperation of Dr. David Hinson at Stanford, our key MGS/RS contact point for this work. In summary, a wealth of MGS ionospheric data exists for Mars, and new observations will follow, that will provide a strong basis for the studies proposed.

B.II.2 Ionospheric Variability at Mars Caused by Changes in the Sun. In our initial study of ionospheric variability on Mars, we focused on a single 19 day period with Mars in opposition, when both planets were subjected to the same characteristics of solar irradiance measured near 1 AU (and appropriately scaled with distance for Mars). This allowed us to study intrinsic day-to-day variability at Mars and its photochemical source in a far more precise way than had ever been done before (Martinis et al., 2003). We were also able to conduct comparative studies using a network of stations monitoring the ionosphere on Earth for the very same days (Mendillo et al., 2003a). While photochemical processes were clearly the dominant ones acting, there was far from ideal closure between the model's results for Mars' two ionospheric layers and the Sun's spectral variabilities available for that period. In particular, the low altitude layer near 100 km had *less* observational variability than the model! The uncertainties involved are, of course, the solar irradiances available, but also the largely unknown efficiency factors for the production of multiple ion-electron pairs from a single photon (particularly for the X-rays that are the dominant source of the lower $N_e(h)$ peak at Mars). Energetic photons do not cause multiple ionization of the dominant molecule (CO_2), but rather the initial ionization produces an ion (CO_2^+) and an electron (e*) that is energetic. In turn, e* can impact-ionize neighboring CO_2 molecules, perhaps as many as ten (Martinis et al., 2003; Fox et al., 1995). We propose to use additional MGS datasets to study this process in more detail, seeking constraints on the efficiency factors via multiple model runs. Mars' ionosphere is thus used as a controlled laboratory-in-space experiment to study important photochemical processes that, of course, occur on other planets as well (and for CO_2, particularly Venus). The efficiency factor issue is also important for molecules ionized in the Earth's E-layer (at ~ 100 km), and thus same-day data analysis and modeling for both planets provides a highly constrained way to study secondary ionization using the same set of photons striking both planets. Thus, in approaching this study from a comparative perspective will also serve as a way to study all three of the terrestrial planets in a unified way.

For data periods when Mars in not in opposition, we propose to test the concept of rotating solar active regions seen from the vicinity of Earth (groundbased and spacebased) to the orbital longitude of Mars, and compare the day-to-day behavior of its photochemical layers via "lagged correlation analysis" methods spanning the several days (less than 2 weeks) required to create the same or effective "overhead Sun" at Mars.

Turning to the non-photon component of solar energy, there is great interest in the solar wind interaction with Mars' ionosphere. MGS *in-situ* instruments have been used to study this effect using signatures indicative of the spacecraft being within the ionosphere or beyond its topside termination or "ionopause" (e.g., Mitchell et al, 2001; Crider et al., 2001). To date, we have not seen direct signatures of the ionopause in the RS experiments. We are not sure why this should be so. Perhaps it is the limited local times and latitudes sampled to date (see Table 2), or due to non-disturbed solar wind conditions at those times, or the rejection of "weird" electron density profiles from the occultation inversion technique. We will work with Dr. Hinson to extend the profiles to altitudes above 200 km (the height used currently to terminate the inversion technique), and to search carefully for cases when an ionopause is detected below 200 km. Such cases may well be few, but such effects below 200 km were seen using Viking-1's orbiting radio science experiment in 1976 (Kliore, 1992). If found, they will be important. The remarkable advances in simulations of the solar wind interaction with Mars made in the last few years (see Brecht (2002) for a general review and Ma et al. (2002) for an important new study of how Mars' crustal magnetic fields affect this interaction) need to be constrained by actual measurements, and especially now that supporting diagnostics of the solar wind conditions are also available.

As described above, a central theme of our studies involves the Sun-Mars connection. The concept of extending the terrestrial-focused "Space Weather" program to other planets has a pure scientific merit, as well as practical application to remote system (and potentially humans) operating in the martian environment. We addressed this initially using the concept that ionospheric conditions affect radio navigation and position-fixing systems (as with GPS on Earth) in a combined model-data study of the effects possible for a proposed Mars Navigation and Communications Network (Mendillo et al., 2003b). We propose to extend that type of analysis to the other datasets mentioned in Table 2.

As a new topic, we propose to begin a detailed science comparison between ionospheric disturbances and their solar source as determined by the SOHO spacecraft. Do solar flares monitored by its EIT instrument or coronal mass ejections (CMEs) imaged by its LASCO instrument provoke observable effects in the MGS $N_e(h)$ profiles ? Instrument descriptions are available for EIT (2003) and LASCO (2003a). Both can be studied when Mars is in opposition and measurements made at 1 AU can be "propagated" to Mars at ~1.5 AU. For such cases, flare photons reach both planets within minutes and both ionospheres can be observed. We have a long-standing interest in solar flare effects upon the terrestrial ionosphere (Mendillo and Evans, 1974; Mendillo et al., 1974). To our knowledge, flare effects are yet to be detected on any other planet, and we should to try with MGS at Mars.

For CME's directed towards the Earth (and therefore Mars at opposition), it is those special CMEs called "halo" events that would be studied. Perhaps even more exciting is a search for CME eruptions on a limb of the Sun that is in the direction of Mars when the planet is *not* in opposition. To our knowledge, there has not been an unambiguous detection of a CME affecting a planet other than Earth, and we will search for such a case using the MGS datasets.

For both of these SOHO-based correlative studies, there are ample events to look at in the online SOHO database (SOHO, 2003). In Table 3, we list the number of X, M, and C-class flares identified by Seaton (2003) for the MGS periods shown in Table 2. EIT data are available for the vast majority of these observations. We also list the number of CMEs identified for the same periods (LASCO, 2003b).

B.II.3 Non-solar Mechanisms for Variability. The ionospheric layers at Mars are photochemical layers, meaning that transport is not as important a mechanism for day-to-day change as are processes involving the neutral atmosphere. An interesting example of this is shown in Fig. 4 where the ionospheric parameter "slab thickness" is defined, a parameter that describes the first-order shape of an ionosphere. It is used on Earth in models and applications for radio propagation forecasts (Fox et al., 1991). As discussed in detail in our initial study of propagation effects for Mars (Mendillo et al., 2003b), the observed effect (that the martian ionosphere becomes thinner when its peak density is larger) is contrary to the behavior obtained from modeling the increases in peak density caused by stronger solar fluxes. So, there is some neutral atmosphere effect, perhaps tidal (and certainly dynamical) that causes such *integral-preserving* distortions of the $N_e(h)$ profiles. We plan to document this interesting behavior further using the new MGS datasets, and then do model runs to define the changes in the neutral atmosphere needed to produce such photochemical layers.

While our approach has been to form daily mean values of the MGS/RS electron density profiles, there are longitude effects (at the same local time) in these data. Our initial examination of two RS periods did not find a coherent pattern for longitude effects in peak electron density (N_{max}). Bougher et al. (2001), however, did find such effects in the height of the peak (h_{max}). To a first approximation, these are consistent findings in that photochemical production of an ionosphere depends on the optical depth, or pressure, rather than altitude. Yet, this needs to be studied in more detail with our model, and with the newer MGS datasets shown in Table 2. We are fortunate that variations in h_{max} with longitude will be analyzed further by Dr. Bougher, as discussed in his parallel MDAP proposal to this NRA. We will use these results to help us calibrate the assumed neutral atmospheric density profile in our photochemical model.

Individual $N_e(h)$ profiles also show variations on much smaller scales (~40 km) than we have studied. These wave-like structures are found in the topside portions of the MGS/RS profiles, and have recently been studied by Wang and Nielsen (2002, 2003a). There are also periods studied in association with dust storms (Wang and Nielsen, 2003b). In addition, Ness et al. (2000) have pointed out that the newly discovered crustal magnetic fields distributed non-uniformly on Mars can exert effects upon the ionosphere. While not central elements in our proposed studies, we will take these known sources of variability into account when trying to identify the roles played by solar flare, CME and neutral atmosphere effects as sources of departure from quiet photochemical behavior.

B.II.4 Modeling Work. We propose to enhance our existing photochemical model by adding plasma transport and, as mentioned above, the capability for ad hoc time-dependent adjustments to the neutral atmosphere's composition and temperature to produce distortions in N_e (h) shape. The need for plasma transport is shown clearly in Fig. 2 where the model results for the 17-day period in March 1999 obtained by Martinis et al. (2003) do a fine job on the peak density, but give high values of N_e at 200 km. These will be lowered by the inclusion of upward plasma diffusion. This model improvement will be a valuable step in understanding the transition from pure photo-chemistry to full continuity equation mechanisms. For comparisons with the Earth's E- and F1-layers, we will use the model of Titheridge (2000, 2003) recently provided to us.

B.II.5 Mars Reference Ionosphere. The PI has been asked to coordinate an international effort to create a COSPAR Reference Atmosphere for Mars (Mendillo et al., 2002). Our contribution to this effort will be the specification of ionospheric structure, using both the empirical approach of data representation, and the modeling approach to link regions with observations to those where they are lacking. Our proposed MDAP activities will contribute significantly to success of this international initiative.

B.III Task-2: Neutral Atmosphere Data Analysis

The basic aim of Task 2 is to analyse MGS and ODY densities to study thermospheric dynamics. We shall use the density data to develop a more complete picture of thermospheric dynamics in terms of winds, temperatures, and pressures, which will be important for understanding the thermal state of the thermosphere. This also has implications for the coupling to the lower atmosphere, material transport, and exospheric escape. These background, climate-mean properties affect a variety of small-scale and transient phenomena that we shall also study. These include gravity waves, mysterious large changes in derived density over very short times and/or distances, and other fluctuations. The relationships between large- and small-scale phenomena show how they couple, and how energy and momentum flow between them. Task-2 does not involve the use of general circulation models for interpretation, a topic included in Task-3 below.

B.III.1 Data Availability. The major datasets that will be used in this Task are atmospheric densities derived from MGS and ODY aerobraking ACC data. MGS data is fully archived at the PDS and ODY data is partially archived at the PDS (PDS, 2003a,b). Withers is a PDS reviewer for the ODY data. The PI of ODY's

ACC has been funded by NASA to archive the remainder of its data by July 2004, which will make it available near our proposed start date (Keating, pers. comm., 2003).

B.III.2 Science Objectives. It is important to understand the distribution of energy, mass, and momentum in the martian upper atmosphere, how its climate varies with such parameters as altitude, latitude, longitude, LST, Ls (areocentric longitude of the Sun, a seasonal measure), and the 11-year solar cycle, and how its weather varies from one day to the next. Basic phenomena of fluid mechanics, atmospheric science, aeronomy, and other scientific fields are displayed in this vast natural laboratory, which we can only observe, but not manipulate, where the boundary conditions and atmospheric composition are unique (eg Zurek et al., 1992). Also, we cannot hope to understand what makes our own Earth so special without a mature understanding of its planetary neighbours.

The present and past state of the martian atmosphere has played a key role in the history of water, organics, and possibly biology on Mars (Leovy, 2001; Fanale et al., 1992). Atmospheric escape has created today's tenuous atmosphere and dry, inhospitable climate (Hunten, 1993). The rate of atmospheric loss, which occurs from the exobase, is determined by processes in the thermosphere and ionosphere. By improving our understanding of the martian upper atmosphere, we improve our context for understanding atmospheric loss processes in the present and the past.

Aerobraking datasets cover a wide range of altitudes, latitudes, longitudes, LSTs, and seasons, as shown in Fig. 5. The effects of latitude can be well studied with the MGS Phase 2 data going from 60N to 90S at near-constant LST and Ls or with the ODY nightside data going from 90N to 20N at near-constant LST and Ls. The effects of LST can be well studied with the MGS Phase 2 data near the South Pole and with ODY data near the North Pole, both of which cross the terminator. Assuming small interannual variability, the effects of LST can also be studied at mid-northern latitudes and Ls of 280-300 between MGS1 (15 hours) and ODY (03 hours). Seasonal change can be well-studied between MGS1 (Ls ~240) and MGS2 (Ls ~60) data from mid-northern latitudes and mid-afternoon LSTs half a year apart.

B.III.3 Winds, Pressures, and Temperatures. There are two components to this part. One of these, deriving unbiased atmospheric temperatures, is relatively simple. The other, deriving consistent winds, pressures, and temperatures, is more complicated, but offers more significant potential results.

Atmospheric temperatures derived from non-vertical, along-track density scale heights, which are in the PDS archive, are biased by latitudinal effects and transient phenomena. We shall derive atmospheric temperatures more representative of the background martian climate using vertical density scale heights from maps of fitted density as a function of latitude, altitude, and longitude at fixed LST and season. There have been few measurements of upper atmospheric temperatures, and we will study the thermal balance and heat transport in the upper atmosphere, including the day/night differences and the approach to a constant exospheric temperature (Bougher et al., 1990).

We shall continue developing a technique, discussed in Chapter 3 of Withers (2003), to measure zonal winds from the MGS and ODY ACC data (Withers et al., 2002a, b, c). A scale analysis of the equations of motion for the martian upper atmosphere shows that latitudinal pressure gradients at mid-latitudes are controlled by the zonal wind speed, and the effective radial and latitudinal terms are (Holton, 1992):

$$\partial p/\partial r = g_{eff,r} \quad \partial p/\partial \theta = g_{eff,\theta} + 2\,\rho\, r\, \Omega\, v_{\phi} \cos\theta$$

where the symbols have their usual meanings for atmospheric dynamics in a spherical polar coordinate system. Assuming that v_ϕ is uniform in this atmospheric region, an expression for periapsis pressure using the inbound density profile can be derived:

$$p_{peri} = \int_{entry}^{peri} g_{eff,r} + \int_{entry}^{peri} g_{eff,\theta} + v_\phi \int_{entry}^{peri} 2\,\rho\,r\,\Omega\cos\theta$$

The inbound and outbound versions of this can be equated and solved for v_ϕ in terms of the known gravitational field and density profiles. v_ϕ can then be used to derive inbound and outbound pressure and temperature profiles that are consistent at periapsis. These will be the first data on winds in the upper atmosphere and will reveal the nature of its circulation (Lellouch et al., 1991; Gurwell et al., 1993; Luhmann, 1995; Schmulling et al., 1999; Moreno et al., 2001).

This technique should greatly increase the scientific impact of non-vertical density profiles. Even knowing which way the winds blow, without knowing their speed, is useful, since this affects heat transport and the vertical propagation of waves and tides. The equations above are reminiscent of geostrophic balance and corresponding cyclostrophic versions might be valid for slowly-rotating bodies like Venus and Titan, using Pioneer Venus Orbiter and Cassini mass spectrometer data (Withers, 2003). The approximations and assumptions behind this technique are not small ones, and we will attempt to validate it on terrestrial observations, such as those of Atmospheric Explorer, and numerical simulations.

B.III.4 Small-scale and Transient Phenomena. This divides into four parts, all of which have relevance for planning future aerobraking operations as well as their scientific interest.

We shall study the day-to-day variability in the ODY data, using the techniques that Withers et al. (2003) applied to MGS data. This is an important first step prior to fitting harmonics to zonal variations in density for tidal studies, since it measures the “noise” in the data, probably due to gravity waves. This is complementary to our studies of reponses to external forcings in Task-1.

We shall characterize small-scale oscillations on individual profiles in terms of their amplitude and along-track wavelength (Fig. 7 of Tolson et al., 2000). Such oscillations are also probably caused by gravity waves and reveal how they, not just global-scale tides, influence the upper atmosphere. We shall make use of previously developed techniques (Fritts et al., 1993; Kasprzak et al., 1988 and 1993). This will increase our understanding of atmospheric waves and of the coupling between the lower and upper atmosphere (Forbes 1995; Hooke, 1977).

We shall investigate the puzzling changes in derived atmospheric density of ~50% over temporal scales of ~3 s and spatial scales of ~15 km horizontal and ~1 km vertical (Fig. 10 of Tolson et al., 2000; Fig. 12 of Tolson et al., 1999). By quantifying the range in time, latitude, altitude, and horizontal distance over which these changes occur, we shall see if any physically-plausible mechanism can account for such behavior. This will shed light either on an unknown behavior of the spacecraft/instrument that significantly affects the derived atmospheric densities or on an unknown, but large, atmospheric disturbance.

We have previously characterized the zonal structure in the martian upper atmosphere (Withers et al., 2003). We will extend this to study how the actual state of the atmosphere is distributed around this background state by measuring the relative deviation of individual constant altitude density measurements from the fitted zonal structure. The class of distribution (e.g., Gaussian) and its width are influenced by how energy in the atmosphere moves from large scales to small scales.

B.IV Task-3: Comparison of Neutral Atmosphere to Numerical Simulations

The basic aim of Task 3 is to compare MGS and ODY observations of martian upper atmospheric densities to numerical simulations conducted by Dr. Bougher using the NCAR-Mars Thermospheric General Circulation Model, MTGCM (Bougher et al., 2000). Bougher's work on this task will be supported by other sources, such as his parallel MDAP proposal. We shall concentrate on zonal-mean densities, the polar atmosphere, and atmospheric tides. The background state of the atmosphere will be studied via the zonal-mean densities. The polar atmosphere is, surprisingly, dominated by an apparent warming in northern winter, and the poles in general are where model predictions are worst (Bougher and Keating, 1999; Keating et al., 2003b). At equatorial and mid-latitudes, the background state is strongly perturbed by atmospheric tides (Withers et al., 2003). Unlike Task-2, Task-3 does involve the use of general circulation models for interpretation.

B.IV.1 Science Objectives. The restricted coverage in latitude, altitude, LST, season, the solar cycle, and longitude of MGS and ODY ACC data makes it difficult to identify the mechanisms that transport energy, mass, and momentum through the upper atmosphere, since they typically have spatial and temporal scales that are not perfectly sampled by the data. Models are powerful tools for identifying important mechanisms, thus enabling broad-scale comparisons between planets. They can also make predictions for the future, which observations alone cannot. Finally, by comparing model output against observations, strengths and weaknesses of the model can be identified, and necessary improvements highlighted.

B.IV.2 Zonal-Mean Densities. Using the PDS constant altitude datasets, we shall derive the zonal-mean density as a function of latitude, altitude, LST, and season. This will summarize the background state of the martian upper atmosphere during these observations, providing a valuable resource for other investigations. This tabulation will be placed online. We shall also compare it to corresponding MTGCM predictions. Particular areas of interest for comparison include diurnal, vertical, latitude, seasonal and inter-annual trends. For example, studies of diurnal variations can use the terminator crossings of MGS and ODY or the observations at 60N by MGS (Phase 1) and ODY during different martian years.

B.IV.3 Atmospheric Tides. Withers et al. (2003) have characterized zonal structure, which is caused by atmospheric tides, in the MGS data, and we shall extend this to ODY data. We shall also extend their interpretation in terms of classical tidal theory to the ODY data. MTGCM simulations with detailed coupling to a lower atmosphere model will be processed to obtain corresponding predicted amplitudes and phases for each harmonic in the zonal structure (Bougher et al., 2003). We shall investigate how far poleward the zonal structure extends, which will test predictions for what tidal modes are dominant, investigate changes in harmonic amplitudes and phases with altitude, which will study the propagation and dissipation of these tides, make the first characterizations of nightside zonal structure over a significant latitudinal range, which will study the diurnal cycle, and investigate inter-annual variability. In addition, we shall compare observations to predictions from a linear steady state global scale wave model published by Forbes et al. (2002). This will increase our understanding of the importance of tides in Mars's atmosphere and of the coupling between the lower and upper atmosphere (Zurek et al., 1992).

B.IV.4 Polar Atmosphere. Preliminary, unpublished work (Keating et al., 2003a, b, c) using ODY data suggests that the north polar atmosphere in winter can be described as a polar vortex, with low densities and high temperatures. We shall develop a definition for the boundary of this feature, then study its width and latitude as a function of altitude, longitude, and LST in observations and MTGCM predictions. This vortex makes the polar atmosphere fundamentally different from that at mid-latitudes in terms of heat transport and atmospheric mixing, possibly reflected in Feldman et al.'s (2002) discovery of a nitrogen-rich atmosphere over the winter pole. We will then compare the north pole in winter (ODY data) to the south pole in winter (MGS data). Comparison between observations and predictions will study the implications of this polar feature for temperatures, heat transport, and dynamics in the rest of the atmosphere.

C. PERCEIVED IMPACT OF THIS WORK AND RELATION TO PREVIOUS GRANTS

Our summary of prior work shown earlier (Section A.I and Table 1) describes the basis for the proposed new studies in ionospheric science at Mars. Several other groups are also studying the martian ionosphere (e.g., Ness et al., 2000; Mitchell et al., 2001; Crider et al., 2001; Bougher et al., 2001; Wang and Neilson, 2003a, b). Our proposed work is unique in its focus on comparative aeronomy and the effects of space weather. Simultaneous observations of the terrestrial and martian ionospheres open up a new range of possible studies relating to the transport of ions, secondary ionization, and solar variability. SOHO data on solar flares and CMEs will reveal how the martian ionosphere responds to extreme events. Developing connections between the Sun, Earth, and Mars will show how Space Weather pervades the Solar System. In this context, the PI serves as the coordinator for a new MHD model of the solar wind-Mars interaction being conducted under sub-contract to Dr. Jackie Schoendorf at the Mission Research Corporation (NH), a project funded by the Mars Fundamental Research Program.

Despite the six years that have passed since MGS arrived at Mars, there have been few peer-reviewed publications using the ACC data (Keating et al., 1998; Bougher et al., 1999b; Wilson, 2002; Withers et al., 2003; Angelats i Coll et al., 2003). There have been no peer-reviewed publications on the ODY ACC data, only conference abstracts (Keating et al., 2003a, b, c). Basic work remains to be done, such as examining how typical atmospheric densities vary with latitude, altitude, season, and time of day, and examining the temperatures that can be derived from the density data. The high spatial resolution density profiles have not been touched. This proposal will complete our “discovery mode” studies of the ACC datasets, enabling us and other groups to develop more focused plans to fully exploit them.

D. RELEVANCE TO NASA PROGRAMS

This proposed work will benefit future Mars aerobraking missions in general and Mars Reconnaissance Orbiter (MRO) in particular. Although we are not *directly* developing specific climate models that could be used for weather forecasting during future aerobraking operations, we will test predictions made by one of the two major models that have dominated MGS and ODY aerobraking operations and that are currently used by the MRO project (Bougher et al., 2000, Justus et al., 2000). Sudden, large jumps in density profiles were of great concern to JPL managers during MGS and ODY aerobraking. Our studies of them will help MRO's preparations. Our various studies of small-scale variabilities will constrain martian weather phenomena inaccessible to current climate models. MRO has classified its ACC as a science, not engineering, instrument, unlike MGS and ODY, and its current two person science team is too small to provide all the scientific support JPL will need during aerobraking or to adequately characterize the data prior to PDS archival. Either Participating Scientists or Atmospheric Advisory Group members must be added. Our proposal will make us members of the small pool of scientists with the necessary skills and experience to assist in this important task.

For the ionospheric tasks, our work on Mars radio propagation effects upon navigation and communications systems are intended as design aids for systems not yet fully specified. We have worked with JPL colleagues to point out the issues, their magnitudes, and the role to be played by modeling in the specification of ionospheric environmental impacts for such systems (Mendillo et al., 2003b).

E. MANAGEMENT AND SCHEDULE

E.I Personnel

While the proposed work stresses continuity in approach, plus a broadening of scope, there will be a major adjustment to the team involved in the proposed work. For our initial grant, research staff (post-doc Steve Smith and graduate student Carlos Martinis) were involved at levels relatively minor in comparison to their major (funded and/or doctoral research) activities (i.e., Dr. Smith works in areas of terrestrial mesospheric dynamics, and Mr. Martinis in terrestrial equatorial aeronomy). While considerable productivity occurred, the stretch-out of the grant from 2 to 3 years signaled clearly that if Boston University was to make major progress in Mars science, we needed a full-time person working on this goal. We were most fortunate to recruit Dr. Paul Withers, a recent Ph.D. recipient from the University of Arizona, and a prominent young researcher in martian upper atmospheric science, to our Center for Space Physics. In addition to Dr. Withers, we will maintain our informal collaboration with Smith and Martinis, and most importantly, our collaboration with Professor Henry Rishbeth, recently retired from the University of Southampton (UK).

Principal Investigator (Michael Mendillo). Professor Mendillo will serve as coordinator of the overall project. He brings many years of experience in studies of the terrestrial ionosphere using radio and optical observations and, in recent years, in the use of models. For the past decade, he has worked increasingly in the field of planetary atmospheres, merging observational and modeling expertise of colleagues Jeffrey Baumgardner and Jody Wilson in studies of sodium exospheres at Io/Jupiter, the Moon, Mercury, and comets. For the past three years, with the most recent being a sabbatical year, considerable progress was made in new studies of the upper atmosphere of Mars. Task-1 in our investigation will be his primary research responsibility. Full academic year support is provided by Boston University (BU), and thus only 0.5 month of summer salary support is requested in the budget.

Co-Investigator (Paul Withers). Dr. Withers joined BU as a one-year post-doctoral Research Associate, supported by seed research funds from the university to foster Mars science in the Center for Space Physics. With this proposal, we seek to regularize his appointment for an additional three years, requesting 10 months of support from MDAP, with the remaining 2 months to be provided by BU sources. Dr. Withers is the ideal person to help our Mars program utilize MGS and ODY data to study upper atmosphere processes. He provides the expertise needed to understand the strong coupling between the neutral atmosphere and the ionosphere at Mars. Task-2 offers new science for us at BU, and he will provide leadership in that area. Task-3 involves ongoing collaborative studies with Dr. Bougher at Michigan. Thus, Dr. Withers' time will be divided as 4-months to work with the PI on Task-1, 4-months to work on Task-2, and 2-months for Task-3.

Collaborator (Professor Henry Rishbeth). Henry Rishbeth is arguably the world's senior ionospheric physicist, and we are most fortunate to have him available to work with us on these projects. Professor Rishbeth visits Boston twice a year to work on both Mars and terrestrial problems. He continues to work on these topics in emeritus status at Southampton and is unsalaried at BU, with all travel support and living expenses covered as a Research Fellow in our Center. His availability is a major asset to the proposed work.

Collaborator (Dr. Stephen Bougher). Dr. Bougher recently moved from Arizona (where he was Paul Withers' doctoral advisor) to the University of Michigan. We want to maintain (and indeed enhance) the collaboration between BU and UMich, and thus his advice and expertise will be important to our work. For Task-1, Dr. Bougher is interested in comparisons between the longitude patterns seen in his analysis of ionospheric layer heights and our finding of no longitude effects in layer densities (a Task-1 topic). Task-2 (and particulary Task-3) will be of particular importance in fostering a broad scope of collaborations. His work will be supported by a parallel MDAP proposal to this NRA.

E.II Schedule

Year-1, Task-1 **(a)** Analyze new periods of MGS ionospheric observations, **(b)** Begin model enhancements, **(c)** Identify case-study periods with SOHO data, **(d)** Assess day-to-day variabilities for Aug 2003 data.

Year-1, Task-2 **(a)** Study day-to-day variability, **(b)** Test and validate technique for deriving winds, **(c)** Derive unbiased atmospheric temperatures

Year-1, Task-3 **(a)** MTGCM comparison for zonal-mean densities

Year-1, All tasks - Present results at meetings and prepare publications.

Year-2, Task-1 **(a)** Coordinate new MGS observing periods with terrestrial ionospheric measurements, **(b)** Analyze new data and conduct comparisons with model results, **(c)** Model ionospheric shape distortions, **(d)** Test solar-rotation of active regions' influence on Mars ionosphere.

Year-2, Task-2 **(a)** Quantify oscillations in density profiles, **(b)** Investigate large, sudden changes in derived density, **(c)** Derive upper atmospheric winds.

Year-2, Task-3 **(a)** MTGCM comparison for polar atmosphere.

Year-2, All tasks - Present results at meetings and prepare publications.

Year-3, Task-1 **(a)** Synthesis of day-to-day variability studies using several years of simultaneous MGS and terrestrial ionospheric data, **(b)** Summarize all case studies of SOHO flare and CME effects upon Mars' ionosphere, **(c)** Summarize modeling results for solar variability and for solar flare effects, **(d)** Finalize contribution to COSPAR Mars Reference Ionosphere.

Year-3, Task-2 **(a)** Characterize fluctuation spectrum about zonal structure, **(b)** Derive upper atmospheric pressure and temperature profiles, **(c)** Interpret winds, pressure, and temperature results.

Year-3, Task-3 **(a)** MTGCM comparison for atmospheric tides.

Year-3, All tasks - Present comprehensive results at meetings and in published papers.

TABLES

Table 1: Publications and Presentations Supported by MDAP Grant #NAG5-11077

Refereed Journal Articles:
(1) Mendillo, M, Smith, S, Wroten, J, Rishbeth, H, and Hinson, DP (July 2003) Simultaneous Ionospheric Variability on Earth and Mars, J. Geophys. Res. (revised version submitted)
(2) Martinis, C, Wilson, J, and Mendillo, M (2003) Modeling Day-to-Day Ionospheric Variability on Mars, J. Geophys. Res., (in press)
(3) Mendillo, M, Pi, X-Q, Smith, S, Martinis, C, Wilson, J, and Hinson, DP (2003) Ionospheric Effects Upon a Satellite Navigation System at Mars, Radio Science (submitted)
Presentations at Meetings:
(1) Mendillo, M, Smith, S, and Rishbeth, H (April 2001) Ionospheric Variability at Earth and Mars, Magnetosphere-Ionosphere-Solar-Terrestrial (MIST) annual meeting, York, Great Britain
(2) Mendillo, M, Smith, S, Pi, X-Q, and Hinson, DP (December 2001) Day-to-Day Fluctuations in Mars' Total Electron Content: Implications for Navigation and Position Fixing on Future Missions to Mars, AGU meeting, San Francisco, December 2001.
(3) Mendillo, M, Smith, S, Wroten, J, Rishbeth, H, and Hinson, DP (December 2001) Ionospheric Variability on Earth and Mars, AGU meeting, San Francisco.
(4) Mendillo, M, Smith, S, Martinis, C, Wilson, J, Wroten, J, Moore, L, and Hinson, DP (October 2001) Comparison of Simultaneous Ionospheric Measurements on Mars and Earth, DPS Meeting, New Orleans, LA.
(5) Mendillo, M, Kliore, A, and the Mars International Reference Atmosphere (MIRA) Team (October 2002) The Ionosphere of Mars: Sources, Variability and Coupling to the Solar Wind, 34th COSPAR Meeting, Houston, TX
(6) Mendillo, M (January 2003) Comparative Ionospheres in the Solar System (Invited Review), Royal Astron. Soc., London, Great Britain
(7) Rishbeth, H, Mendillo, M, Wroten, J, Smith, S, and Hinson, DP (April 2003) Day by Day Comparison of Mars and Earth Ionospheres, MIST annual meeting, Leicester, Great Britain
(8) Mendillo, M, Smith, S, Martinis, C, Wroten, J, Rishbeth, H, and Hinson, DP (April, 2003) Solar Control of Ionospheric Variability on Terrestrial Planets, EGS/AGU meeting, Nice, France

Preprints of our three papers are available at: http://sirius.bu.edu/aeronomy/preprints.html

Table 2: Available MGS Radio Science Datasets

Dates (Data Used in Publication # in Table 1)	Number of Profiles (Release Date)	Ls (degrees)	Solar Zenith Angle (degrees)	Latitude (degrees)	Mars-Earth-Sun angle (degrees)
24-31 Dec 1998 (3)	32	74-77	78-81	65-67 N	80
9-27 Mar 1999 (1,2,3)	43	108-116	77-78	70-73 N	120-140
5-29 May 1999	220	135-146	79-87	65-69 S	140-160
9-21 Dec 2000 (3)	134	87-93	81-82	68-69 N	60
22 Dec 2000 - 31 Jan 2001	314	93-111	75-81	69-78 N	60-80
1 Nov - 8 Dec 2000	>200, Aug2003	70-87	82-86	63-67 N	40-60
1 Feb - 1 Jun 2001	>500, Jan 2004	110-170	71-85	67-85 N	80-160

Data are either already available on PDS or, if anticipated release date is noted, will be available before start of MDAP funding (Dave Hinson, pers. comm., 2003).

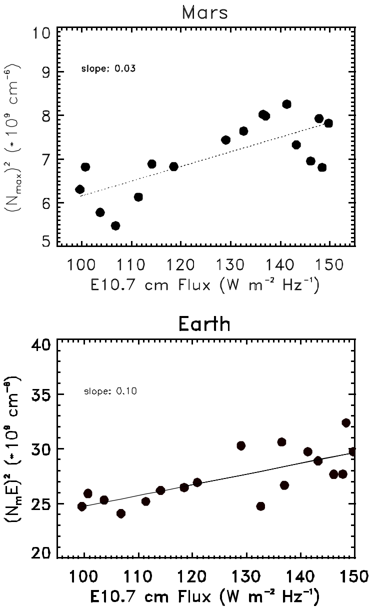
Table 3: SOHO Flares and CMEs

Dates	Number of Flares	Number of CMEs
24-31 Dec1998	3 M, 0 C	0
9-27 Mar 1999	0	50 (0 haloes)
5-29 May 1999	3 M, 2 C	63 (2 haloes)
9-21 Dec 2000	1 C	45 (6 haloes)
22 Dec 2000 - 31 Jan 2001	3 M, 3 C	~150 (6 haloes)
1 Nov 2000 - 8 Dec 2000	3 X, 8 M, 2 C	~160 (14 haloes)
1 Feb - 1 Jun 2001	7 X, 55 M, 63 C	~360 (19 haloes)
Aug 2003, projected	6 M, 6 C	~70 (4 haloes)

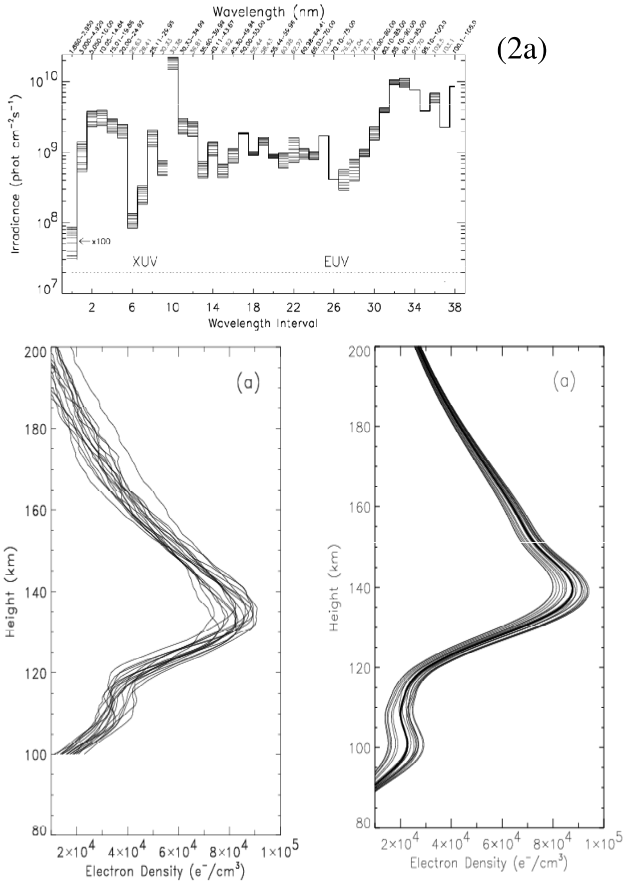
In order of decreasing energy, X, M, and C are classes of flares. Seaton (2003) notes that his flare compilation is incomplete for the weakest C-class flares.

FIGURES

Figure 1. (Right) Comparisons of maximum electron density at Mars (Nmax) from MGS/RS and the same-day values of E-layer peak densities (NmE) on Earth with the corresponding solar flux indices (E10.7) for 17 days within the period 9-27 March 1999. Daytime (11-13 LT) values were averaged from the ionosonde stations at Bermuda and Eglin (Florida) to form the terrestrial daily values with uncertainties levels comparable to the MGS daily means (2-3%). Within the framework of photochemical equilibrium, the square of the electron density is related linearly to solar flux (from Mendillo et al., 2003a).



(1a)



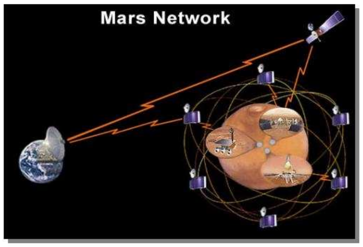
(2a)

(2b)

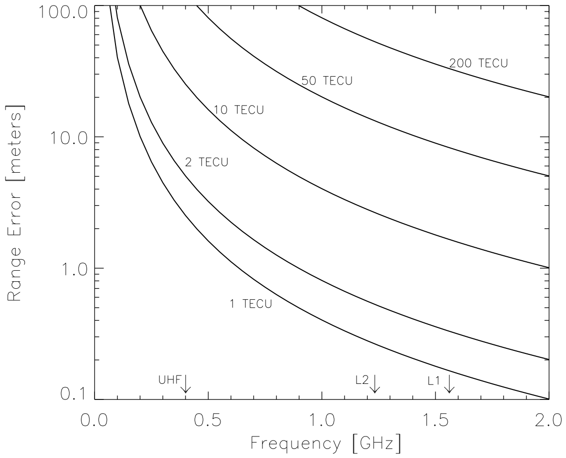
(2c)

Figure 2. (Left) Modeling day-to-day photochemical processes at Mars (from Martinis et al., 2003). (a) Solar photon flux versus wavelength from SOLAR2000 for 9-27 March 1999. The first wavelength bin has been multiplied by 100 for display purposes. (b) MGS/RS electron density profiles averaged over longitude each day to obtain daily mean profiles at the same local time. (c) Calculated electron density profiles for the same MGS period using the 17 days of solar irradiance in (a). Note that the variability at the peak (observed and modeled) is 5-6 %, while the variability at the bottomside layer is 10% (observed) and 19% (modeled). The lack of variability at 200 km in the simulation (c) is due to plasma transport not yet included in the model.

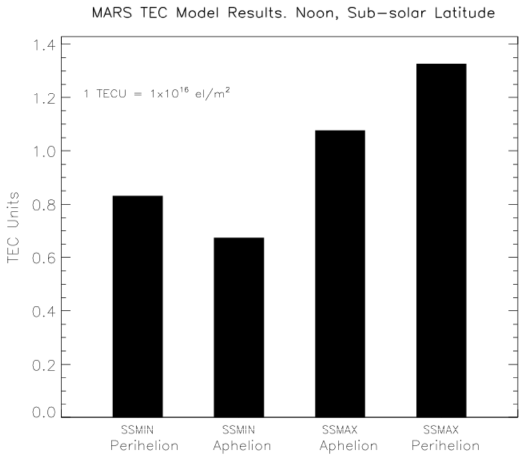
Figure 3. (Right and Next Page) Example of ionospheric impact effects upon proposed communications and navigation systems for Mars. (a) Depiction of a proposed Mars network of satellites that would use trans-ionospheric radio propagation for precise position fixing (Courtesy of JPL). (b) Range errors due to radiowave retardation effects shown as a function of the column integrated Ne(h) at Mars (called total electron content,



TEC) and frequency choice for transmitters. Arrows indicate the terrestrial GPS frequencies used. For lower frequencies at Mars, comparable errors could occur with the much smaller TEC values. (c) model results for maximum TEC values at Mars for conditions ranging from Mars at perihelion during a solar maximum year to Mars at aphelion during a solar minimum year (from Mendillo et al., 2003b).



(3b)



(3c)

Figure 4. (Right) (a) Definition of equivalent slab thickness (τ) of an ionosphere with maximum electron density (Ne_{max}) and vertical total electron content (TEC). (b) Computed values for three MGS/RS periods of $N_e(h)$ observations versus the Ne_{max} value for each profile. The finding that the martian ionosphere becomes thinner as its peak density increases is counter to simple photochemical effects, and thus is probably associated with dynamics and composition changes of Mars' neutral atmosphere. (4a)

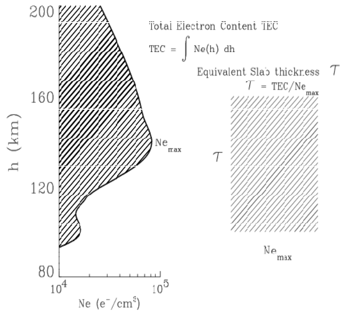
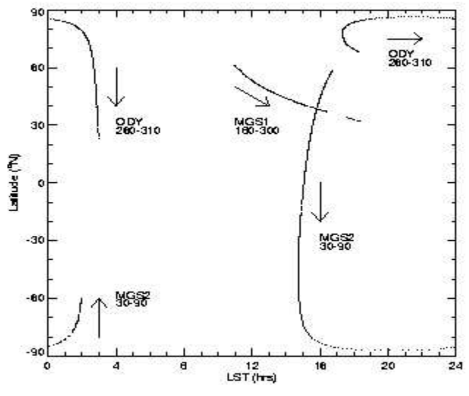
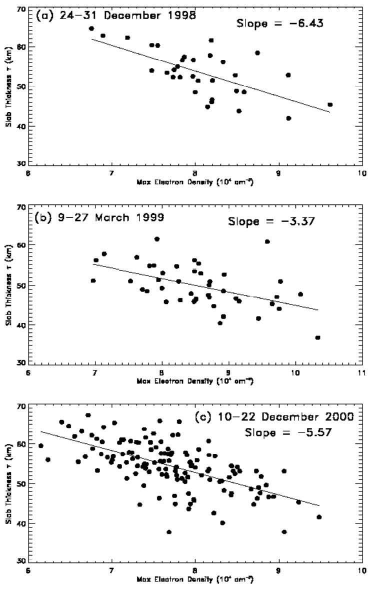


Figure 5: (Below) Locations of MGS Phase 1, MGS Phase 2, and ODY periapses. Arrows show the direction of motion of periapsis and number ranges show beginning and ending Ls values.





(5a) (4b)

REFERENCES (in addition to those in Table 1)

Angelats i Coll, M, Forget, F, Hourdin, F, Talagrand, O, Wanherdrick, J, Lewis, SR, Read, PL, and Lopez-Valverde, MA (2001) Waves in the martian upper atmosphere: A study withe the LMD General Circulation Model, American Astronomical Society, DPS Meeting #33, #44.06, available online at http://www.aas.org/publications/baas/v33n3/dps2001/315.htm

Angelats i Coll, M, Forget, F, Lopez-Valverde, MA, Lewis, SR, and Read, PL (2003) The upper atmosphere of Mars up to 120 km: 2. Mars Global Surveyor Accelerometer Data Analysis with the LMD General Circulation Model, J. Geophys. Res., under review.

Appleton, E (1959) Global morphology of the E- and F1-layers of the ionosphere, J. Atmos. Terr. Phys., 15, 9-12.

Bougher, SW, Roble, RG, Ridley, EC, and Dickinson, RE (1990) The Mars Thermosphere: II. General Circulation with coupled dynamics and composition, J. Geophys. Res., 95, 14811-14827.

Bougher, SW, Keating, GM, Zurek, RW, Murphy, JR, Haberle, RM, Hollingsworth, JL, and Clancy, RT (1999) Mars Global Surveyor Aerobraking: Atmospheric Trends and Model Interpretation, Adv. Space Res., 23, 1887-1897.

Bougher, SW, and Keating, GM (1999) Structure of the Mars Upper Atmosphere: MGS Aerobraking Data and Model Interpretation, Abstract #6010 for the Fifth International Conference on Mars, Pasadena, California, available online from http://www.lpi.usra.edu/meetings/5thMars99/pdf/6010.pdf

Bougher, SW, Engel, S, Hinson, DP, and Forbes, JM (2001) Mars Global Surveyor Radio Science electron density profiles: Neutral atmosphere implications, Geophys. Res. Lett., 28, 3091-3094.

Bougher, SW, Roble, RG, and Fuller-Rowell, T (2002) Simulations of the Upper Atmospheres of the Terrestrial Planets, in Atmospheres in the Solar System: Comparative Aeronomy, (M. Mendillo, A. Nagy, J.H. Waite, eds), AGU Monograph #130.

Bougher, SW, Engel, S, Hinson, DP, and Murphy, JR (2003) Mars Global Surveyor Radio Science Electron Density Profiles: Interannual Variability and Implications for the Neutral Atmosphere, Abstract #3266 for the Sixth International Conference on Mars, Pasadena, California, available online from http://www.lpi.usra.edu/meetings/sixthmars2003/pdf/3266.pdf

Brecht, SH (2002) Numerical techniques associated with simulations of the solar wind interaction with non-magnetized bodies in Atmospheres in the Solar System: Comparative Aeronomy, (M. Mendillo, A. Nagy, J.H. Waite, eds), AGU Monograph #130.

Crider, DM, Acuna, MH, Connerney, JEP, Mitchell, D, Lin, RP, Cloutier, P, Reme, H, Mazelle, C, Brain, D, Ness, NF, and Bauer, S (2001) Magnetic field draping around Mars: Mars Global Surveyor results, Adv. Space Res., 27(11), 1831-1836.

EIT (2003) http://umbra.nascom.nasa.gov/eit/

Fanale, FP, Postawko, SE, Pollack, JB, Carr, MH, and Pepin, RO (1992) Mars: Epochal Climate Change and Volatile History, in Mars (Eds: Kieffer, HH, Jakosky, BM, Snyder, CW, and Matthews, MS), pp. 1135-1179.

Feldman, WC, Boynton, WV, Prettyman, TH, Squyres, SW, and Tokar, RL (2002) Time Variation of the North Polar Seasonal Frost Cap of Mars, AGU Fall Meeting, San Francisco, USA, Abstract #P11B-03, available online at http://www.agu.org/meetings/fm02/waisfm02.html

Forbes, JM (1995) Tidal and Planetary Waves. In RM Johnson and TL Killeen (Eds.) The Upper Mesosphere and Lower Thermosphere: A Review of Experiment and Theory, pp. 67-87.

Forbes, JF, Bridger, AFC, Bougher, SW, Hagan, ME, Hollingsworth, JL, Keating, GM, and Murphy, JR (2002) Nonmigrating tides in the thermosphere of Mars, J. Geophys. Res., 107, DOI 10.1029/2001JE001582.

Fox, JL, Zhou, P, and Bougher, SW (1995) The Martian Thermosphere/Ionosphere at High and Low Solar Activities, Adv. Space Res., 17(11) 203-218.

Fox, MW, Mendillo, M, and Klobuchar, JA (1991) Ionospheric equivalent slab thickness and its applications, Radio Sci., 26, 429-438.

Fritts, DC, Wang, D-Y, and Blanchard, RC (1993) Gravity Wave and Tidal Structures between 60 and 140 km Inferred from Space Shuttle Reentry Data, J. Atmos. Sci., 50, 837-849

Gurwell, MA, Muhleman, DO, and Berge, GL (1993) Observations of middle atmospheric winds on Mars, American Astronomical Society, DPS Meeting #25, #11.02, Bulletin of the American Astronomical Society, 25, 1060.

Holton, JR (1992) An Introduction to Dynamic Meteorology, Academic Press.

Hooke, WH (1977) Rossby-Planetary Waves, Tides, and Gravity Waves in the Upper Atmosphere. In The Upper Atmosphere and Magnetosphere, pp. 130-140, published in Washington, USA, by the National Research Council Studies in Geophysics.

Hunten, DM (1993) Atmospheric Evolution of the Terrestrial Planets, Sciencem 259, 915-920

Justus, CG, James, BF, Bougher, SW, Bridger, AFW, Haberle, RM, Murphy, JR, and Engel, S (2000) Mars-GRAM 2000: A Mars atmospheric model for engineering applications, Adv. Space Res., 29, 193-202.

Kasprzak, WT, Hedin, AE, Mayr, HG, and Niemann, HB (1988) Wavelike perturbations observed in the neutral thermosphere of Venus, J. Geophys. Res., 93, 11237-11245.

Kasprzak, WT, Niemann, HB, Hedin, AE, and Bougher, SW (1993) Wave-like perturbations observed at low altitudes by the Pioneer Venus Orbiter Neutral Mass Spectrometer during orbiter entry, Geophys. Res. Lett., 20, 2755-2758.

Keating, GM, and 27 colleagues (1998) The Structure of the Upper Atmosphere of Mars: In Situ Accelerometer Measurements from Mars Global Surveyor, Science, 279, 1672-1676.

Keating, GM, Tolson, RH, Noll, SN, Schellenberg, TJ, Stephens, RS, Bradford, MS, Baird, DT, Ellis, LJ, Bougher, SW, and Hollingsworth, JL (1999a) First In Situ Atmospheric Measurements of Mars Southern Hemisphere, American Geophysical Union Spring Meeting, Boston, USA, Abstract #P31A-05, available online at http://www.agu.org/meetings/waissm99.html

Keating, GM, Tolson, RH, Noll, SN, Schellenberg, TJ, Stephens, RS, Bradford, MS, Bougher, SW, and Hollingsworth, JL (1999b) First Global Mapping of the Mars Thermosphere,American Astronomical Society, DPS Meeting #31, #76.02, available online at http://www.aas.org/publications/baas/v31n4/dps99/497.htm

Keating, GM, Dwyer, A, Wilson, RJ, Tolson, RH, Bougher, SW, Withers, P, and Forbes, JM (2000) Evidence of Large Global Diurnal Kelvin Wave in Mars Upper Atmosphere, American Astronomical Society, DPS Meeting #32, #50.02, available online at http://www.aas.org/publications/baas/v32n3/dps2000/591.htm

Keating, GM, Tolson, RH, Dwyer, A, Bougher, SW, Withers, P, and Forbes, JM (2001) Persistent planetary-scale wave-2 and wave-3 density variations observed in Mars upper atmosphere from MGS accelerometer experiment, Abstract for the European Geophysical Society

Meeting, Nice, France, March 2001, available online at http://www.copernicus.org/EGS/egsga/nice01/programme/overview.htm

Keating, GM, Theriot, M, Tolson, RH, Bougher, SW, Forget, F, and Forbes, JM (2003a) Brief review on the results obtained with the MGS and Mars Odyssey 2001 Acclerometer Experiments, Abstract for "Mars Atmosphere Modelling and Observations" Meeting held in Granada, Spain, January 2003, available online at http://www-mars.lmd.jussieu.fr/granada2003/abstract/abstract.html

Keating, GM, Theriot, M, Tolson, RH, Bougher, SW, Forget, F, and Forbes, JM (2003b) Global Measurements of the Mars Upper Atmosphere: In Situ Accelerometer Measurements from Mars Odyssey 2001 and Mars Global Surveyor, Abstract for the 34th Lunar and Planetary Science Conference, Houston, USA, March 2003, available online at http://www.lpi.usra.edu/meetings/lpsc2003/v31n4/dps99/390.htm

Keating, GM, Theriot, M, Tolson, RH, Bougher, SW, Forget, F, and Forbes, JM (2003c) The Mars Odyssey Accelerometer Thermospheric Experiment: Conditions Near the North Winter Pole and on the Nightside of Mars, Abstract for the European Geophysical Society Meeting, Nice, France, April 2003, available online at http://www.copernicus.org/EGS/egsga/nice03/programme/overview.htm

Kliore, AJ (1992) Radio occultation observations of the ionospheres of Mars and Venus, Geophys. Monograph 66 (J. G. Luhmann, M. Tatrallyay, R. O. Pepin, eds), 265-276, Amer. Geophys. Union.

LASCO (2003a) http://lasco-www.nrl.navy.mil/

LASCO (2003b) http://lasco-www.nrl.navy.mil/cmelist.html

Lellouch, E, Rosenqvist, J, Goldstein, JJ, Bougher, SW, and Paubert, G (1991) First absolute wind measurements in the middle atmosphere of Mars, Astrophys. J., 383, 401-406.

Leovy, CB (2001) Weather and climate on Mars, Nature, 412, 245-249.

Luhmann, JG (1995) Outstanding problems in Mars aeronomy, Ad. Space Res., 15(4), 143-157

Ma, Y, Nagy, AF, Hansen, KC, DeZeeuw, DL, and Gombosi, TI (2002) Three-dimensional multispecies MHD studies of the solar wind interaction with Mars in the presence of crustal fields, J. Geophys. Res., 107, doi:10.1029/2002JA009293.

Mendillo, M, and Evans, JV (1974) Incoherent scatter observations of the ionospheric response to a large solar flare, Radio Sci., 9, 1974.

Mendillo, M, and 14 co-authors (1974) Behavior of the ionospheric F-region during the great solar flare of August 7, 1972, J. Geophys. Res., 79, 665.

Mitchell, DL, Lin, RP, Mazelle, C, Rème, H, Cloutier, PA, Connerney, JEP, Acuña, MH, and Ness, NF (2001) Probing Mars' crustal magnetic field and ionosphere with the MGS Electron Reflectometer, J. Geophys. Res., 106, 23419-23428

Moreno, RS, Guilloteau, S, Lellouch, E, Encrenaz, T, Forget, F, Chassefiere, E, Jegou, F, and Hourdin, F (2001) Mars' wind measurements at Equinox : IRAM PdB Interferometric CO observations, American Astronomical Society, DPS Meeting #33, #19.21, available online at http://www.aas.org/publications/baas/v33n3/dps2001/464.htm

Ness, NF, Acuña, MH, Connerney, JEP, Kliore, AJ, Breus, TK, Krymskii, AM, Cloutier, P, and Bauer, SJ (2000) Effects of magnetic anomalies discovered at Mars on the structure of the Martian ionosphere and solar wind interaction as follows from radio occultation experiments, J. Geophys. Res., 105, 15991-16004

PDS (2003a) http://atmos.nmsu.edu/PDS/data/mgsa_0002/

PDS (2003b) http://atmos.nmsu.edu/PDS/review/odya_0001/

Schmulling, F, Kostiuk, T, Buhl, D, Rozmarynowski, P, Segal, K, Livengood, T, and Hewagama, T (1999) A new Infrared Heterodyne Instrument for measurements of Planetary Wind and Composition, American Astronomical Society, DPS Meeting #31, #08.03, available online at http://www.aas.org/publications/baas/v31n4/dps99/390.htm

Seaton, D (2003) http://hea-www.harvard.edu/SSXG/kathy/flares/flares.html

SOHO (2003) http://sohowww.nascom.nasa.gov/data/

Titheridge, JE (2000) Modelling the peak of the ionospheric E-layer, JASTP, 62, 93-114.

Titheridge, JE (2003) Model results for the daytime ionospheric E and valley regions, JASTP, 65, 129-137.

Tobiska, WK, Woods, T, Eparvier, F, Viereck, R, Flyod, L, Bouwer, D, Rottman, G, and White, OR (2000) The SOLAR2000 empirical solar irradiance model and forecast tool, J. Atmos. And Solar-Terr. Phys., *62*, 1233-1250.

Tobiska, WK (2003) SOLAR2000 irradiances for climate change, aeronomy, and space systems engineering, Adv. Space Res., in press.

Tolson, RH, Keating, GM, Cancro, GJ, Parker, JS, Noll, SN, and Wilkerson, BL (1999) Application of Accelerometer Data to Mars Global Surveyor Aerobraking Operations, Journal of Spacecraft and Rockets, 36, 323-329.

Tolson, RH, Keating, GM, Noll, SN, Baird, DT, and Shellenberg, TJ (2000) Utilization of Mars Global Surveyor Accelerometer data for atmospheric modeling, Advances in the Astronautical Sciences, 107, 1329-1346.

Wang, J-S, and Nielsen, E (2002) Possible hydrodynamic waves in the topside ionospheres of Mars and Venus, J. Geophys. Res., 107 (A4), 10.1029/2001JA900142.

Wang, J-S, and Nielsen, E (2003a) Behavior of the martian dayside electron density peak during global dust storms, Planet. Space Sci., 51, 329-338.

Wang, J-S, and Nielsen, E (2003b) Wavelike structures in the Martian topside ionosphere observed by Mars Global Surveyor, J. Geophys. Res., 108, E7,5078, doi:10.1029/2003JE002078.

Wilson, RJ (2002) Evidence for nonmigrating thermal tides in the Mars upper atmosphere from the Mars Global Surveyor Accelerometer Experiment, Geophys. Res. Lett., 29, DOI 10.1029/2001GL013975.

Withers, P (2003) Tides in the Martian Upper Atmosphere - And Other Topics, PhD dissertation, University of Arizona, USA.

Withers, P, Bougher, SW, and Keating, GM (2000) New results from the MGS accelerometer, Abstract for the 31st Lunar and Planetary Science Conference, Houston, USA, March 2000, available online at http://www.lpi.usra.edu/meetings/lpsc2000/

Withers, P, Bougher, SW, and Keating, GM (2002a) Measurements of winds in the martian upper atmosphere from the MGS accelerometer, American Astronomical Society, DPS Meeting #34, #05.05, available online at http://www.aas.org/publications/baas/v34n3/dps2002/58.htm

Withers, P, Bougher, SW, and Keating, GM (2002b) MGS Accelerometer-derived profiles of upper atmospheric pressures and temperatures: similarities, differences, and winds, American Geophysical Union Spring Meeting, Washington, USA, Abstract #P41A-10, available online at http://www.agu.org/meetings/waissm02.html

Withers, P, Bougher, SW, and Keating, GM (2002c) Winds in the martian upper atmosphere from MGS aerobraking density profiles, American Geophysical Union Fall Meeting, San Francisco, USA, Abstract #P61C-0353, available online at http://www.agu.org/meetings/fm02/waisfm02.html

Withers, P, Bougher, SW, and Keating, GM (2003) The effects of topographically-controlled thermal tides on the martian upper atmosphere as seen by the MGS accelerometer, Icarus, 164, 14-32

Zurek, RW, Barnes, JR, Haberle, RM, Pollack, JB, Tillman, JE, and Leovy, CB (1992) Dynamics of the Atmosphere of Mars, in Mars (Eds: Kieffer, HH, Jakosky, BM, Snyder, CW, and Matthews, MS), pp. 835-933.

Michael Mendillo

Education:
Boston University Graduate School, Boston, Massachusetts
    Ph.D. in Physics and Astronomy, 1971;
    M.A. in Physics and Astronomy, 1968
Providence College, Providence, Rhode Island
    B.S. in Physics, cum laude, 1966

Membership:
American Geophysical Union (AGU)
American Astronomical Society (AAS);
    Division of Planetary Science; History Division
International Union of Radio Science (URSI)

Address:
Boston University
Center for Space Physics
Boston, Massachusetts 02215
T: (617) 353-2629; F: 617-353-6463; e-mail, mendillo@bu.edu

Positions:
Professor of Astronomy, 1985 to present
Professor of Electrical and Computer Engineering, 1993 to present
Associate Dean for the Graduate School, 1978 to 1987
Associate Professor of Astronomy, 1978-1985
Assistant Professor of Astronomy, 1971-1972, 1974-1978
National Research Council/National Academy of Sciences
Post-doctoral Research Associate, 1972-1974
Air Force Cambridge Research Laboratories

Research Fields of Specialization:
Space Physics, Solar-Terrestrial Relations,
Active Experiments in Space Plasmas, Planetary Astronomy
History of Astronomy and Geophysics
Experimental: Low-light level optical imaging; incoherent scatter radar;
    satellite radio beacon techniques; groundbased atmospheric emission tomography (GAET)
Theoretical/Computer Modeling: Fluid Element Simulation (FES) techniques

Major Research Programs:
NASA Spacelab-2 Mission (1977-86)
NASA SPINEX Rocket Program (1984-86)
NASA ERIC & RED AIR Rocket Programs (1987-89)
NASA CRRES Mission (1984-92); NASA RED AIR-2 (1990-1992)
Boston University's Mobile Ionospheric Observatory (1983-1991)
NSF CEDAR Class-I Imager and Optical Tomography Facility (1987-)
NASA Sodium Atmospheres of Solar System Bodies (1989 --)

Teaching Experience: General Astronomy for Non-Science Majors (undergraduate), Space Physics (graduate), Celestial Mechanics (graduate), History of Astronomy (undergraduate); Celestial Navigation (undergraduate)

Awards: Elected Fellow of the American Geophysical Union 2000
Elected President for Space Physics & Aeronomy (SPA) Section AGU 2004-2006

Service: Membership and/or Chairmanship of Science Advisors Committees at National Science Foundation, NASA, NAS Space Studies Board, Naval Research Laboratory, Air Force Geophysics Laboratory.
Membership and/or Chairmanship of many academic committees at Boston University.

RECENT PAPERS PUBLISHED IN SCIENTIFIC JOURNALS

Topics: Planetary Astronomy **Period**: 1990 - Present

1. The Extended Sodium Nebula of Jupiter, M. Mendillo, J. Baumgardner, B. Flynn and W.J. Hughes, *Nature, 348,* 312, 1990.
2. Imaging Observations of the Extended Sodium Atmosphere of the Moon, M. Mendillo, J. Baumgardner, and B. Flynn, *Geophys. Res. Lett., 18,* 2097, 1991.
3. Observations and Modeling of the Jovian Remote Neutral Sodium Emissions, B. Flynn, M. Mendillo and J. Baumgardner, *Icarus, 99,* 115, 1992.
4. Imaging Observations of Jupiter's Sodium Magneto-nebula During the Ulysses Encounter, M. Mendillo, J. Baumgardner, and B. Flynn, *Science, 257,* 1510, 1992.
5. A Picture of the Moon's Atmosphere, B. Flynn and M. Mendillo, *Science, 261,* 184, 1993.
6. The Jovian Sodium Nebula: Two Years of Ground-based Observations, B. Flynn, M. Mendillo, and J. Baumgardner, J. *Geophys. Res., (Planets), 99,* 8403, 1994
7. Constraints on the Origin of the Moon's Atmosphere From Observations During a Lunar Eclipse, M. Mendillo and J. Baumgardner, *Nature, 377,* 404, 1995
8. Simulations of the Lunar Sodium Atmosphere, B. Flynn and M. Mendillo, *J. Geophys. Res. (Planets), 100,* 23271, 1995
9. Modeling the Moon's Extended Sodium Cloud as a Tool for Investigating Sources of Transient Atmosphere, M. Mendillo, J. Emery, and B. Flynn, *Adv. Space Res., 19,* 157, 1997
10. Eclipse Observations of the Lunar Atmosphere from the TNG Site, M. Mendillo, J. Baumgardner, G. Cremonese and C. Barbieri, the Three Galileos: The Man, The Spacecraft, The Telescope, C. Barbieri, J. Rahe, T. Johnson, and A.M. Sohos (eds) p. 393, Kluwer Academic Publishing, Dordrecht, The Netherlands, 1997
11. Groundbased Remote Sensing of Energetic Neutral Atoms In Jupiter's Magnetosphere, M. Mendillo, J.K. Wilson, J. Baumgardner and N.M. Schneider, in the Three Galileos: The Man, The Spacecraft, The Telescope, C. Barbieri, J. Rahe, T. Johnson, and A.M. Sohos (eds) p. 411, Kluwer Academic Publishing, Dordrecht, The Netherlands, 1997

12. An HST Search for Magnesium in the Lunar Atmosphere, S.A. Stern, J.W. Parker, T.H. Morgan, B.C. Flynn, D.M. Hunten, A. Sprague, M. Mendillo, and M.C. Festou, *Icarus, 127,* 523, 1997
13. Three Tails of Comet Hale-Bopp, J.K. Wilson, J. Baumgardner, and M. Mendillo, *Geophys. Res. Lett., 25,* 225, 1998
14. Discovery of the Distant Lunar Sodium Tail and its Enhancement Following the Leonid Meteor Shower of 1998, S.M. Smith, J.K. Wilson, J. Baumgardner and M. Mendillo, *Geophys. Res. Letts., 26,* 1649, 1999
15. Modeling an Enhancement of the Lunar Sodium Tail During the Leonid Meteor Shower of 1998, J.K. Wilson, S.M. Smith, J. Baumgardner, and M. Mendillo, *Geophys. Res. Letts.,* 26, 1645, 1999
16. Observational test for the solar wind sputtering origin of the Moon's extended sodium atmosphere, M. Mendillo, J. Baumgardner, and J. Wilson, *Icarus, 137,* 13, 1999
17. Dynamics of Titan's thermosphere, H. Rishbeth, R. Yelle and M. Mendillo, *Planet. Space Sci., 48,* 51, 2000
18. A digital high-definition imaging system for spectral studies of extended planetary atmospheres: 1. Initial results in white light showing features on the hemisphere of Mercury unimaged by Mariner 10, J. Baumgardner, M. Mendillo and J. Wilson, *Astron. J., 119,* 2458, 2000
19. The thermosphere of Titan simulated by a global three-dimensional time-dependent model, I.C.F. Muller-Wodarg, R.V. Yelle, M. Mendillo, L.A. Young, and A.D. Aylard, *J. Geophys. Res., 105,* 20833, 2000
20. Imaging the surface of Mercury using ground-based telescopes, M. Mendillo, J. Warell, S. Limaye, J. Baumgardner, A. Sprague, and J. Wilson, Planet. Space Sci., 49, 1501-1505, 2001.
21. Monitoring the Moon's transient atmosphere with an all-sky imager, S. Smith, M. Mendillo, J. Wilson, and J. Baumgardner, Adv. Space Res., 27, (6&7), 1181-1187, 2001.
22. The atmosphere of the Moon, M. Mendillo, Earth, Moon and Planets, 85-86, 271-277, 2001.
23. The 1999 Quadrantids and the lunar Na atmosphere, S. Verani, C. Barbieri, C. Benn, G. Cremonese, and M. Mendillo, Mon. NOt. R. Astron. Soc., 327, 244-248, 2001.
24. The dual sources of Io's sodium clouds, J. Wilson, M. Mendillo, J. Baumgardner, N. Schneider, J. Trauger, and B. Flynn, Icarus 157,476-489, 2002.
25. The Application of Terrestrial Aeronomy Groundbased Instruments to Planetary Astronomy, M. Mendillo., F. Roesler, C. Gardner and M. Sulzer, 329-338, Atmosheres in the Solar System: Comparative Aeronomy, (M. Mendillo, A. Nagy & J.H. Waite, eds), Geophys. Monograph #130, Amer. Geophys. Union, Washington, DC, 2002.
26. The outer limits of the lunar sodium exosphere J. Wilson, J. Baumgardner, M. Mendillo, Geophysical Reserch Letters, 30(12), 1649, 2003.

CV for Paul Withers

Education

PhD, Planetary Science, University of Arizona, 2003 Supervisor Dr. Stephen Bougher. "Tides in the martian upper atmosphere - and other topics"

MS, Physics, Cambridge University, Great Britain, 1998

BA, Physics, Cambridge University, Great Britain, 1998

Employment

Postdoctoral research associate with Dr. Michael Mendillo (Boston Univ.) 2003 - present.

Graduate research assistant with Dr. Stephen Bougher (Univ. of Arizona) 1998 - 2003. Research interests included developing software to analyse MGS accelerometer data for atmospheric variability, winds, and other properties. Played an advisory role in mission operations for MGS and Mars Odyssey aerobraking.

Research consultant with Dr. John Zarnecki (Open University, Great Britain) 2001 (summer). Developed techniques to analyze accelerometer data from entry probes, concentrating on the British Beagle 2 Mars Lander.

Fellowships, Honors, and Awards

Kuiper Memorial Award from the University of Arizona for excellence in academic work and research in planetary science, 2002

Galileo Circle Graduate Scholarship from the University of Arizona, 2001.

Highly Commended in annual British Young Science Writer Contest, 2000

Professional Activities

Invited to participate in PDS review of Mars Odyssey accelerometer data, 2003

Atmosphere Science Advisor for Landing of NASA's 2003 MERs, 2002 - present

Author of publicly available programs to analyze entry accelerometer data (http://www.lpl.arizona.edu/~withers/beagle2/), 2002

Reviewer for Icarus, Journal of Geophysical Research, Meteoritics and Planetary Science, and Science, 2001- present

Participated in PDS review of MGS accelerometer dataset MGSA_0002, 2000

Selected Peer Reviewed Publications

Withers, Bougher, and Keating, "The Effects of Topographically-controlled Thermal Tides in the Martian Upper Atmosphere as seen by the MGS Accelerometer" (2003) Icarus, 164, 14 - 32.

Withers, Towner, Hathi, and Zarnecki, "Analysis of Entry Accelerometer Data: Preparations for Beagle 2" (2003) 51, 541 - 561.

Withers, Neumann, and Lorenz, "Comparison of Viking Lander descent data and MOLA topography reveals kilometer-scale error in Mars atmosphere profiles", (2002) Icarus, 159, 259 - 261.

Withers and Neumann, “Enigmatic northern plains of Mars” (2001) Nature, 410, 651.

Withers, “Meteor storm evidence against the recent formation of lunar crater Giordano Bruno” (2001) Meteoritics and Planetary Science, 36, 525 – 529.