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Title: Exploring the ionosphere of Mars

Short title: Exploring the ionosphere of Mars

Summary of proposal:

We will use two newly-available datasets, each with unique strengths, to explore the ionosphere of Mars. The first dataset is the collection of ionospheric electron density profiles acquired by the **Mariner 9 radio occultation experiment** in 1971-2. We have rediscovered these on archived microfilm and are in the process of converting them to usable digital files. These profiles extend to 400 km, much higher than the corresponding MGS profiles, enabling studies of the high altitude ionosphere, and cover a massive dust storm, enabling studies of lower-upper atmosphere coupling. The second dataset contains **ionospheric electron densities from MARSIS** on Mars Express, both local densities at the spacecraft (275-1200 km) and remotely-sensed densities at lower altitudes (120-275 km). These data cross the ionopause (typically 400 km, but highly variable) and their rapid sampling cadence reveals horizontal and temporal gradients in unprecedented detail. Nevertheless, several unusual features, particularly at the 275 km transition between the two data types, demonstrate a clear need for a careful comparison of MARSIS electron densities against those measured by the well-characterized technique of radio occultations.

We shall first make the Mariner 9 ionospheric dataset publicly available (**Task A: Archiving the Mariner 9 electron density profiles**). Next, we shall study this dataset bearing in mind the many discoveries made at Mars since the Mariner 9 instrument team last analyzed it (**Task B: Scientific interpretation of the Mariner 9 electron density profiles**). Finally, we shall compare several synthesized representations of ionospheric electron densities that have been published by the MARSIS team to Mariner 9 and MGS radio occultation electron density profiles (**Task C: Comparison of MARSIS and radio occultation ionospheric measurements**).

At the conclusion of this project, we expect to have deposited a valuable dataset into NASA's permanent archives, ensuring its availability to future generations, to have used it to study features of the ionosphere of Mars that are not accessible to current datasets, such as the topside ionosphere and the response to a massive dust storm, and to have compared two types of MARSIS electron density measurements against independent radio occultation measurements, including profiles that span the transition region between MARSIS data types.

Summary of personnel and effort:

Name	Role	Institution	Funded Effort per year	Unfunded Effort per year
Paul Withers	PI	Boston Univ.	0.04	As needed
Katy Fallows	Graduate Student	Boston Univ.	0.75	N/A
Dave Morgan	Collaborator	Univ. Iowa	N/A	As needed
Dave Hinson	Collaborator	SETI Institute	N/A	As needed
Steve Joy	Collaborator	UCLA	N/A	As needed

1 – Introduction to the ionosphere of Mars

"The Mars thermosphere (~100-200 km) is an intermediate atmospheric region strongly impacted by coupling below with the lower atmosphere (via gravity waves, planetary waves and tides, dust storms) and coupling above with the exosphere and ultimately the Sun (via solar soft X-ray, EUV, UV and near IR fluxes, and solar wind particles) (see Bougher, 1995; Bougher et al., 2002, 2009) … Embedded within the thermosphere is the ionosphere, a weakly ionized and cold plasma (Fig 1)" (Bougher et al., 2011). Plasma densities are controlled solely by photochemical processes (CO_2 + photon -> CO_2^+ + e, CO_2^+ + O -> O_2^+ + CO, O_2^+ + e -> O + O) below about 170-200 km, where photochemical time constants are shorter than those of plasma transport by advection and related processes (e.g. Barth et al., 1992; Fox, 2004). "The primary charged particles that make up the Mars ionosphere (e.g., O_2^+, CO_2^+,O^+, CO^+, NO^+) are formed by (1) solar EUV fluxes and subsequent photo-electrons that ionize local neutral thermospheric species (e.g., CO_2, N_2, CO, O, etc.), (2) precipitating particles (e.g., suprathermal electrons) that ionize these same neutral species (especially on the nightside), and (3) subsequent ion-neutral photochemical reactions (e.g., Fox, 2004, 2009; Fox and Yeager, 2006). Since Mars has a negligible intrinsic magnetic field, the variable solar wind (including its particles and interplanetary magnetic field) interacts with the Mars near-space environment (including the thermosphere, ionosphere, and exosphere), resulting in ionization, neutral heating, pickup ion escape, ion outflow, hot species escape, and ion sputtering (see Chassefière and Leblanc, 2004)" (Bougher et al., 2011).

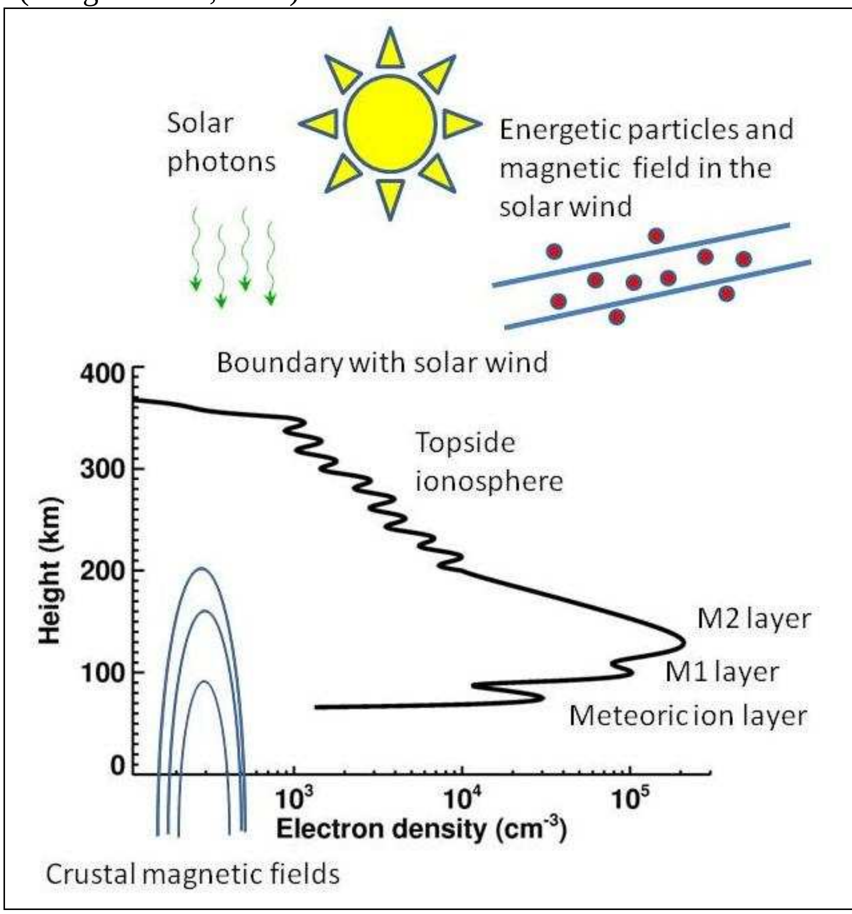

Fig 1. Schematic illustration of the ionosphere of Mars, which is predominantly O_2^+. The topside ionosphere lies above 200 km, where transport processes are significant and the abundance of O^+ is relatively large. Below it lies the strong M2 layer. Photo-ionization by solar extreme ultraviolet (EUV) photons between 10 nm and 90 nm produce most dayside plasma found in and above the M2 layer. X-rays shortward of 10 nm are ultimately responsible for most plasma in the lower M1 layer, although here most ions are produced by impact ionization due to energetic photoelectrons. Figure 1 of Withers et al. (2009).

2 – Outline of proposed investigation

The aim of this proposed investigation is to explore the state of the ionosphere of Mars, with a focus on areas that offer the highest probability of making significant new discoveries. We do not want to continue existing research projects blindly due to inertia and lack of new ideas. This aim leads to the following goals.

Goal A: To make a long-lost, yet uniquely valuable, dataset accessible to the community.
Goal B: To review these data in light of discoveries from today's era of Mars exploration.
Goal C: To validate MARSIS ionospheric data using well-characterized radio occultation electron density measurements.

We will concentrate on two newly-available datasets. First, the set of 118 dayside ionospheric electron density profiles acquired by the Mariner 9 radio occultation experiment from 1971-2. Although this experiment was conducted decades ago, its only easily accessible data products are published figures in journal articles. It is next-to-impossible to scientifically analyze such data. However, we have recently acquired images of archived printed data tables from the public archives of the National Space Science Data Center (NSSDC, 2011). We are partway through the tedious process of converting these images into usable ASCII tables. This old dataset is worthy of present-day study, despite the 5600 similar profiles acquired from 1998 to 2005 by Mars Global Surveyor (MGS), because the Mariner 9 profiles extend to considerably higher altitudes and span the rise and fall of one of the largest dust storms of the spacecraft era.

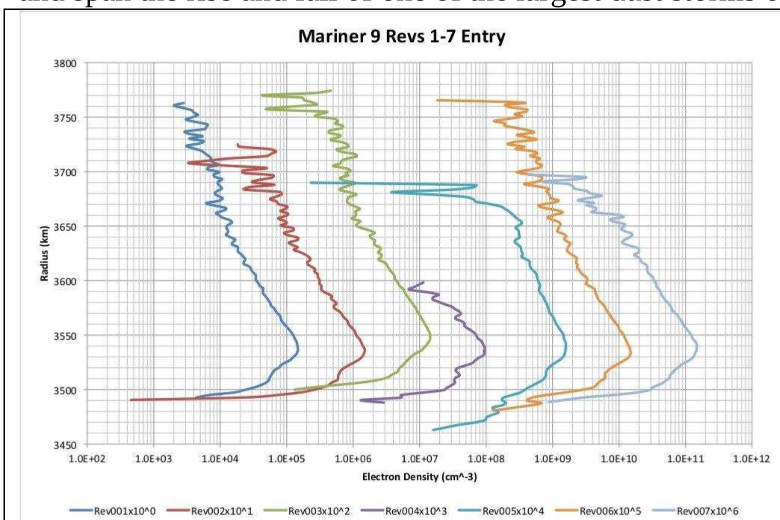

Fig 2. Electron density profiles from the first seven orbits of Mariner 9 plotted using data extracted from NSSDC microfilm. Each profile is offset by one decade from its predecessor. The agreement with published figures, such as Fig. 7 of Zhang et al. (1990) is reassuringly accurate, although we have not yet converted radius to altitude. A rough conversion for comparison purposes is to subtract the mean equatorial radius of 3400 km.

Second, the tens of thousands of ionograms and associated topside ionospheric electron density profiles obtained by the MARSIS topside radar sounder on Mars Express (MEX). This measurement technique has not operated beyond Earth orbit before and all papers published to date using this dataset have been led by MARSIS team members. Its ionograms have recently become publicly available (MARSIS, 2011) and the broader community is beginning to work with them. However, MARSIS's measurement technique has several unique features that affect the quality and characteristics of its data products. There are several indications in published papers that the MARSIS electron densities are not completely accurate (Fig. 3 and Section 6). As such, it is important to test the accuracy of its data products by comparing to those provided by a robust and well-understood measurement technique, namely radio occultations. To date, such validation has not been performed comprehensively. So doing will serve two purposes, benchmarking the accuracy of this important dataset for the benefit of all MARSIS users and supporting the initial surveys of archived ionograms by new MARSIS users.

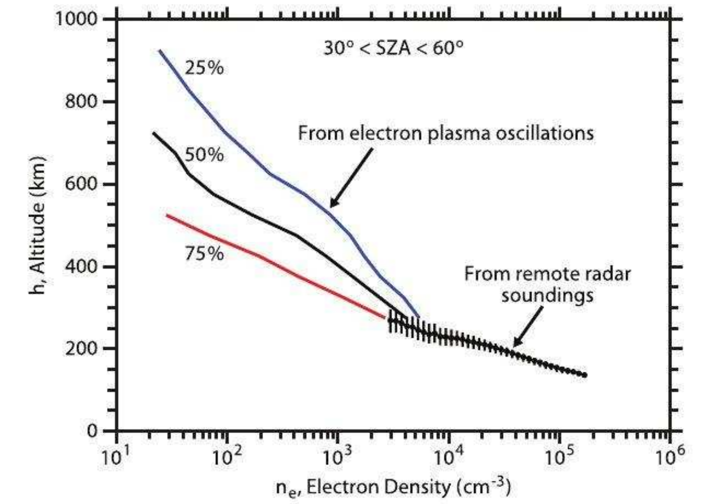

Fig 3. Local and remotely sensed electron densities measured by MARSIS show very different scale heights and moderately different electron densities at 275 km. Models (Fig. 4) do not predict the abrupt change in scale height at the instrument's transition altitude. Figure 13 of Duru et al. (2008).

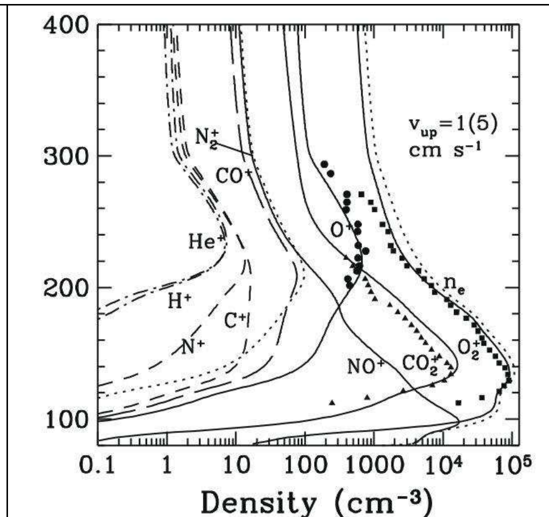

Fig 4. Simulated ion densities for low solar activity (lines) and Viking 1 data (symbols). The scale height at 275 km barely changes. Boundary condition on velocities is 10^5 cm s^{-1} shown as 1(5). Fig. 9b of Fox and Hac (2010)

This set of **Goals** has inspired a matching set of **Tasks**. We shall first make the Mariner 9 ionospheric dataset publicly available (**Task A: Archiving the Mariner 9 electron density profiles**). Next, we shall study this dataset bearing in mind the many discoveries made at Mars since the Mariner 9 instrument team last analyzed it (**Task B: Scientific interpretation of the Mariner 9 electron density profiles**). Finally, we shall compare several synthesized representations of ionospheric electron densities that have been published by the MARSIS team to Mariner 9 and MGS radio occultation electron density profiles (**Task C: Comparison of MARSIS and radio occultation ionospheric measurements**). The Mariner 9 profiles enable comparisons at relatively high altitudes and the MGS profiles provide an abundance of data.

The intellectual glue linking our **Goals** together and linking these disparate datasets together is the notion of exploring under-studied aspects of the ionosphere of Mars using newly available data. That is, we do not focus solely on the main ionospheric layers at 130 km and below.

3 – Status of current research on the ionosphere of Mars

Many groups are currently active in research concerning the ionosphere of Mars. The major themes that cross-cut these studies are: the exploration of new measurements, the application of numerical models, the interaction of the ionosphere with the neutral atmosphere and space environment, and the effects of magnetic fields.

Don Gurnett's group at the University of Iowa, which leads the ionospheric component of the MARSIS instrument, is conducting highly-productive discovery-mode investigations of MARSIS ionograms and derived topside electron density profiles, as well as in situ measurements of local electron density at the spacecraft from electron plasma oscillations (Duru et al., 2006, 2008; Gurnett, et al., 2005, 2008; Kopf et al., 2008; Morgan et al., 2008; Nemec et al., 2010, 2011). They have characterized the high altitude and nightside regions of the ionosphere and discovered extensive spatial and temporal variability. The German branch of the MARSIS team, led by Erling Nielsen, is using MARSIS's topside electron density profiles to study how the ionosphere responds to changes in the neutral atmosphere, the space environment, and the magnetic field (Nielsen et al., 2006, 2007a, b; Zou et al., 2005, 2006, 2010). They have characterized increased peak electron densities and scale heights in strongly-magnetized regions.

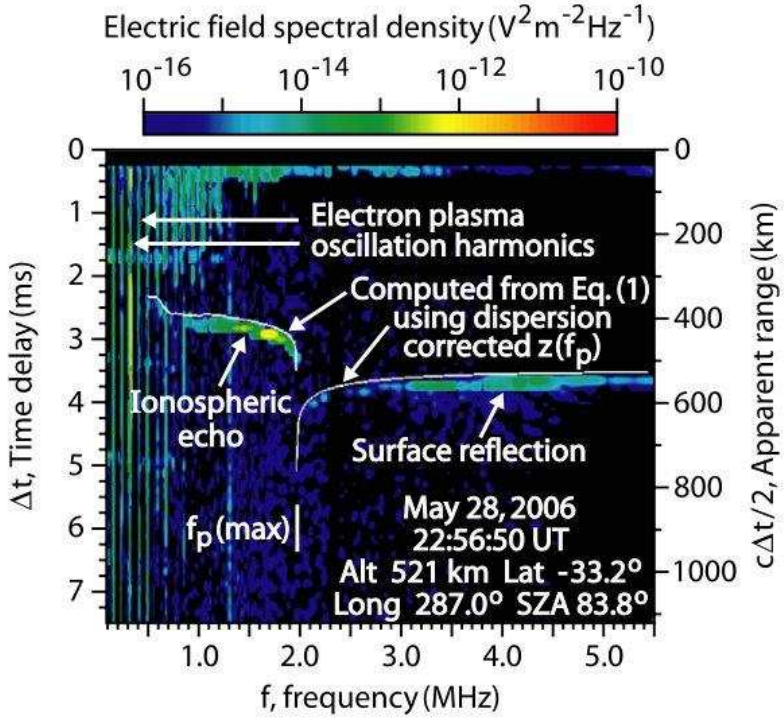

Fig 5. A MARSIS ionogram. MARSIS's basic measured quantity is strength of its reflected radio signal (here electric field spectral density) as a function of transmitted frequency and travel time. The apparent range is similar, but not identical, to the true range due to radio wave dispersion in ionospheric plasma. Extensive processing is required to obtain local electron densities from the highlighted electron oscillations and remotely sensed electron densities from the ionospheric echo. Measurements are only possible <u>above</u> the ionospheric peak. Fig. 2 of Gurnett et al. (2008).

Paul Withers and colleagues on the MEX radio occultation team are using these electron density profiles to study the vertical structure of the ionosphere with better sensitivity than was possible with MGS profiles (Girazian et al., 2011). Rob Lillis and colleagues at Berkeley are using ionospheric total electron content data from the MARSIS subsurface mode to characterize how the ionosphere responds to solar disturbances, such as solar energetic particle events and flares (Lillis et al., 2010). MARSIS data are much more suited to observing the nightside ionosphere than are radio occultation data. The MARSIS team is discovering the ionospheric density and variability on the nightside (Gurnett et al., 2008; Nemec et al., 2010) and the Berkeley group is simulating the nightside ionosphere produced by precipitating electrons (Fillingim et al., 2010).

Jane Fox is comparing data to predictions from her highly sophisticated ionospheric model (Fig. 4) in order to identify the physical processes responsible for the observed vertical structure and infer the chemical composition of the ionosphere (Fox, 2004, 2009; Fox and Yeager, 2006; Fox and Hac, 2010). S. A. Haider and colleagues from India are conducting a wide-ranging program of comparing data to model predictions (Haider et al., 2008, 2009). Paul Withers and Boston University colleagues are using an ionospheric model to simulate the response to solar flares, the effects of magnetic fields on plasma motion and densities, and the importance of hydrogen species (Withers, 2008; Withers and Mendillo, 2009; Matta et al., 2011). Yingjuan Ma and

UCLA/Michigan colleagues are extending magnetohydrodynamic (MHD) simulations of the space environment at Mars down into the ionosphere (Ma et al., 2004). Several other groups simulating the space environment at Mars also touch on the ionosphere, although rarely as a focus (e.g., Brain et al., 2010). Steve Bougher is using a neutral atmospheric general circulation model to relate ionospheric conditions to the dynamics and chemistry of the neutral atmosphere (Bougher et al., 2001, 2002, 2009, 2011; Valeille et al., 2009a, b, 2010).

The MEX ASPERA team is conducting a broad survey of the interaction of the Mars ionosphere with the magnetosheath, solar wind, and other aspects of the space environment (e.g., Lundin et al., 2004; Barabash and Lundin, 2006; Dubinin et al., 2008). Many researchers are investigating how the unique magnetic environment of Mars affects its ionosphere. Norm Ness and Russian colleagues found high electron temperatures and densities in strongly magnetized regions (Ness et al., 2000; Krymskii et al., 2002, 2003, 2004), as did Nielsen et al. (2007a, b). Paul Withers found unusual features in the vertical structure over strongly magnetized regions (Withers et al., 2005) and Opgenoorth et al. (2010) examined how magnetic fields affect ionospheric conductivities and resultant currents and induced electromagnetic fields.

The work proposed here <u>complements these ongoing studies</u> of the interaction of the ionosphere with the space environment and the neutral atmosphere. The Mariner 9 profiles encompass a major dust storm and extend as high as 400 km, the typical boundary between solar and ionospheric plasma, whereas MGS profiles rarely passed 200 km. It also supports the extensive range of projects conducted with MARSIS data by <u>benchmarking the performance of MARSIS</u> measurements against well-understood radio occultation measurements. Section 11 outlines how this work is aligned with NASA and MDAP priorities, including synergies with MAVEN.

The work proposed here is also <u>aligned with broader themes in Mars science</u>. It tackles conditions in the exospheric reservoir of planetary plasma from which much escape occurs, which relates to the history of martian climate and habitability. It addresses lower-upper atmosphere coupling during an historic dust storm, which relates to atmospheric dynamics and thermal structure. This work can also be considered in a framework of comparative studies of planetary ionospheres and their interactions with their surrounding space environments.

<u>4 – Mariner 9 radio occultation observations of the ionosphere of Mars</u>

Mariner 9, the first spacecraft to orbit another planet, conducted radio occultation measurements of the atmosphere and ionosphere of Mars in 1971 and 1972. These discovered the immense topographic range of the planet, the strong response of the atmosphere and its embedded ionosphere to suspended dust, and the day-to-day stability of the ionosphere. Mariner 9 acquired several hundred radio occultation measurements. However, only about 118 viable ionospheric electron density profiles were obtained. This is because all egress opportunities relied on the stability of the onboard radio oscillator, which was sufficient to detect the strong neutral signal, but not the weak ionospheric signal, whereas ingress opportunities could use a two-way technique stabilized by an Earth-based oscillator. Also, nightside occultations rarely produced robust electron density profiles due to low nightside densities.

The Mariner 9 electron density profiles have been published graphically in Kliore et al., (1972, 1973), Zhang et al. (1990), and Kliore (1992). They were archived as microfilmed data tables and images at the National Space Science Data Center (NSSDC, 2011). However, they have never been made readily available in digital format. Hence they have slumbered during the renaissance of Mars studies initiated by Mars Global Surveyor over a decade ago. Despite the resurgence of interest in the ionosphere and space environment stimulated by the MGS radio occultation, electron reflectometer, and magnetometer datasets and the MEX radio occultation, MARSIS, and ASPERA datasets, most of which are widely available as high-level digital datasets, <u>the Mariner 9 electron density profiles have not been resurrected by any group</u>.

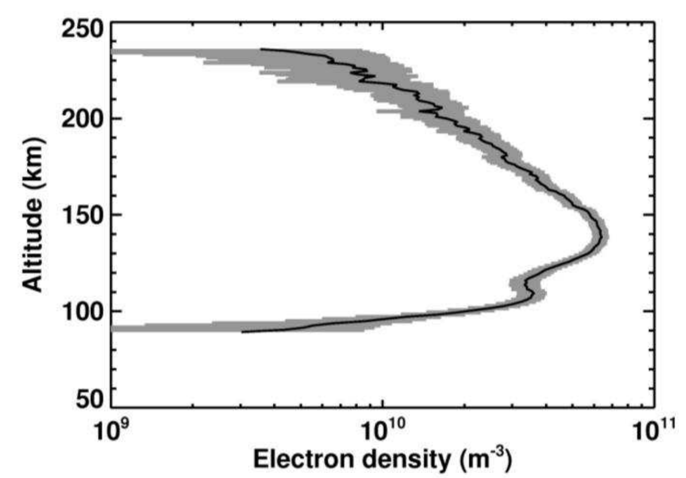

Fig. 6 (left) A typical MGS electron density profile with SZA 83^o. Note its limited vertical extent by comparison to the Mariner 9 profiles (Fig 2).

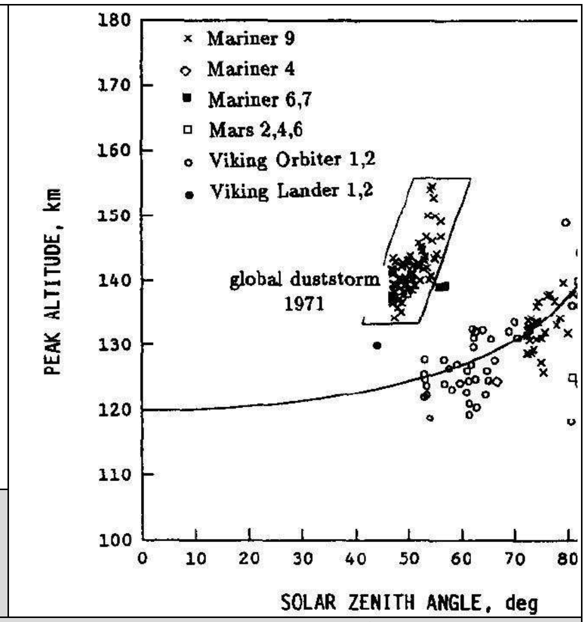

Fig. 7 (right). Ionospheric peak altitude versus SZA. Mariner 9 data near SZA 50^o were 20-30 km higher than normal due to a tremendous dust storm. Fig. 3 of Hantsch and Bauer (1990).

Relative to the MGS dataset, which contains the only electron density profiles for Mars that are readily available to the public today, the Mariner 9 dataset has some unique characteristics:

<u>1. High vertical extent</u>. The Mariner 9 profiles universally exceed 300 km (Fig. 2), with many approaching 400 km, which is the typical boundary between ionospheric and solar wind plasma (sometimes called the ionopause or photoelectron boundary, Mitchell et al., 2001), whereas MGS profiles rarely exceed 200 km. The 400 km circular orbit of MGS meant that the pre-occultation baseline, an important part of the data processing, was always affected by plasma in the 200-400 km range.

<u>2. Measurements during a tremendous dust storm</u>. Mariner 9's first images from orbit showed nothing but dust and the Tharsis volcanic peaks. An unsurpassed dust storm was raging. The ionospheric peak was 20-30 km higher during this storm than normal (Hantsch and Bauer, 1990), indicating immense expansion of the lower atmosphere due to suspended dust (Fig. 7).

<u>3. Global coverage</u>. The Mariner 9 profiles are globally distributed, whereas almost all of the 5600 MGS profiles are north of 60^{o}N. The only ones that are not are 220 profiles between 70^{o}S and 64^{o}S. This permits exploration of the ionosphere within the tropical neutral atmosphere and above a range of crustal magnetization conditions.

<u>4. Solar zenith angle (SZA) coverage</u>. SZA, or how high the Sun is in the sky, is the major factor controlling ionospheric conditions on Mars. All MGS profiles have SZAs of 71 degrees or

more, conditions in which the Sun is very low on the horizon. By contrast, the Mariner 9 profiles sample SZAs as low as 47 degrees, closer to the subsolar point, causing higher electron densities.

The Mariner 9 radio occultation electron density profiles represent unique and valuable observations of the ionosphere of Mars that have not been superseded by the MGS radio occultation dataset or the MARSIS ionograms. As described in more detail in Section 7, we have acquired copies of the NSSDC's microfilmed Mariner 9 data and are partway through converting them into digital files that are readily usable (Fig. 2).

5 – MARSIS observations of the ionosphere of Mars

The MARSIS topside radar sounder on Mars Express functions by transmitting electromagnetic energy at radio wave frequencies and recording the received power as a function of travel time and transmitted frequency. This is typically displayed as an ionogram (Fig 5). Radio waves are reflected when they encounter a region where the plasma frequency equals the radio wave frequency. Since the plasma frequency in Hz equals 9000 times the square root of the electron density in cm^{-3} (Gurnett et al., 2008), the time taken for a radio wave of a particular frequency to reflect from the ionosphere and return to the spacecraft determines the altitude at which the corresponding electron density occurs. That is the simple explanation; many subtleties associated with the propagation of electromagnetic waves introduce complexities into the data processing.

MARSIS provides three ionospheric measurements. First, a column-integrated total electron content from its subsurface mode (Lillis et al., 2010), which we will not discuss further. Second, an in situ measurement of local electron density at the spacecraft derived from electron plasma oscillations (Figs. 3 and 8 and Duru et al., 2008). Third, a remotely-sensed vertical profile of electron density from the spacecraft to the altitude of maximum electron density (Figs. 3 and 9 and Morgan et al., 2008). That is, a profile of topside electron density only.

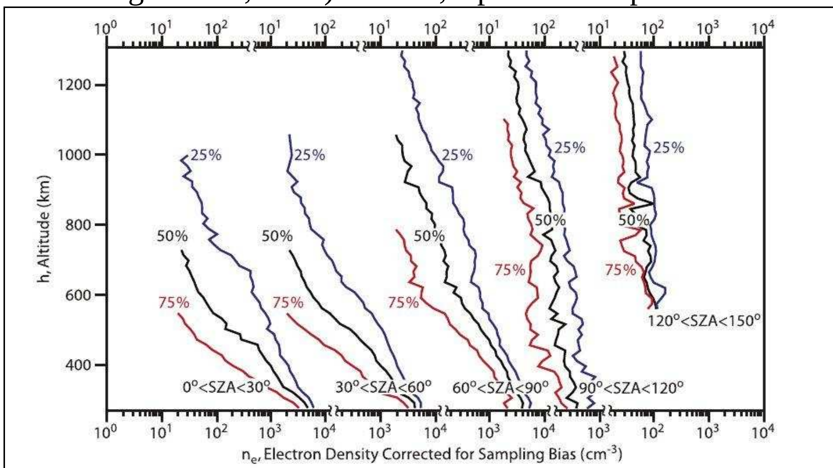

Fig 8. Lower quartile, median, and upper quartile local electron densities from MARSIS as a function of SZA and altitude. The dayside scale height increases with SZA. In Task C, we will digitally extract data from this figure for comparison against radio occultation observations. Large variability is apparent. Figure 8 of Duru et al. (2008).

The local electron density measurement has not been validated against independent electron density measurements at spacecraft altitudes. Indeed, the instrument was neither designed nor expected to make these local plasma measurements. Although Duru et al. (2008) summarize some of the technical details associated with these measurements, the fruitful exploitation of these fascinating measurements has not been accompanied by a comprehensive, high-fidelity, end-to-end simulation of instrument performance.

The derivation of remotely sensed vertical profiles of topside electron density relies on several assumptions. First, the electron density at the spacecraft altitude (275-1200 km) is as measured from local electron plasma oscillations. Second, the electron density between the spacecraft and the altitude of the first ionospheric reflection (~200-300 km) varies exponentially with altitude. Third, the electron density increases monotonically with increasing altitude. The structure of the real ionosphere is clearly more complicated than a uniform exponential decrease between ~200-300 km and as high as 1200 km. Changes in this assumption can cause the derived altitude of the main ionospheric peak to change by 10 km and the derived neutral scale height (related to the width of the peak) to change by 8 km (Gurnett et al., 2008). The third assumption is also not perfectly true. MARSIS itself has detected topside layering strong enough to produce local maxima in electron density (Kopf et al., 2008). The acquisition of MARSIS electron density profiles is further complicated by the instrument's relatively coarse temporal resolution of 91 microseconds (80 equal bins in full range of 7.31 milliseconds). Radio waves travel 27 km in this interval, meaning that all the received energy in a particular time window was reflected from a region 14 km deep. Thus the "apparent range" (related, but not identical, to the actual range) from the spacecraft to the altitude at which the ionospheric electron density equals a given value has a formal uncertainty of +/- 7 km – about one neutral scale height.

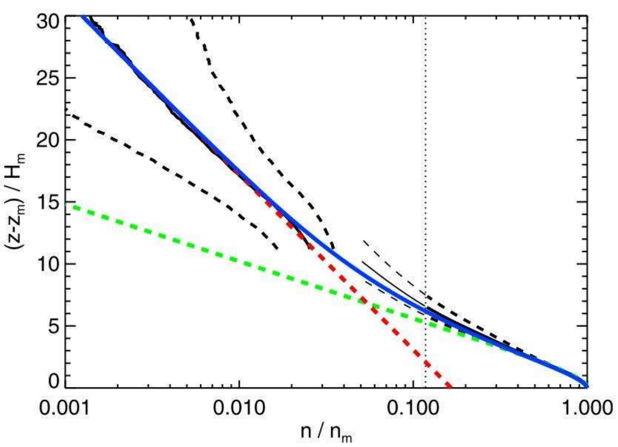

Fig 9. Summary representation of MARSIS electron densities. Electron density is normalized against peak electron density and altitude is expressed in units of neutral scale height above the peak altitude. The upper pair of black dashed lines shows upper and lower quartiles for local electron densities. The lower pair are similar, but for remotely sensed electron densities. Medians are shown by the obscured solid black lines, which do not join smoothly at the 275 km transition. The solid blue line shows the empirical model of Nemec et al. (2010), who also provide expressions for predicting the scale height, peak electron density, and peak altitude, which are function of SZA. The red and green dashed lines continue the high and low altitude limits of the blue line, respectively. Figure 2 of Nemec et al. (2010).

No MARSIS electron densities are archived at the Planetary Data System (PDS). Instead, raw ionograms (Fig. 5) are the highest level data product archived (MARSIS, 2011). Hence we began our first studies of MARSIS data by examining published findings. Duru et al. (2008) reported local electron density as a function of altitude (275-1200 km) for solar zenith angles between 0 and 150^{o}. Nemec et al. (2011) reported an empirical model of electron density as a function of altitude, SZA, and solar flux that extends from the ionospheric peak around 120 km to approximately 400 km. This is based upon both local and remotely sensed data and consists of low and high functional forms joined by a transitional region. These data contain some unusual features (Section 6) that prompted us to focus on understanding the basic characteristics of MARSIS observations before jumping into the raw MARSIS ionograms, attempting to obtain electron densities from them, and scientifically interpreting the results.

6 – Previous validation of MARSIS data products

Duru et al. (2008) compared local electron densities found via electron plasma oscillations to remotely sensed MARSIS electron density profiles, although all such profiles are derived using a local electron density as a boundary condition. Even so, the agreement is not perfect: Duru et al. (2008) reported (Fig. 3) that the average electron density at 275 km was 3 x 10^3 cm^{-3} for the remotely sensed data and 4 x 10^3 cm^{-3} for the local data. An enormous change in the vertical gradient in electron density occurs at the transition between local electron density measurements above 275 km (plasma scale height of 70 km) and remotely sensed electron densities below 275 km (plasma scale height of 30 km), which Duru et al. (2008) interpreted as real and caused by the transition from a photochemically-dominated ionosphere at low altitudes to a transport-dominated ionosphere at high altitudes. Nemec et al. (2011) also observed (Fig. 9) a change in gradient at the transition altitude between local and remotely sensed electron densities. However, physics-based models of the ionosphere of Mars persist in placing the photochemistry/diffusion boundary at 170-200 km (e.g. Barth et al., 1992; Fox, 2004, Mendillo et al., 2011), rather than the 275 km inferred by the above publications. A dramatic doubling of plasma scale height at 275 km is not seen in other data or models. The predominant impression formed by visible inspection of published Mariner 9 electron density profiles (e.g. Fig. 2) is of at most a slight increase in plasma scale height at 275 km. Similar behavior is seen in the ionospheric model of Fox and Hac (2010), as shown in Fig. 4, and in the MHD model of Ma et al. (2004, their Figure 6). This is (or should be) a major concern for MARSIS data users.

Nemec et al. (2011) confirmed that their empirical model based on MARSIS data accurately reproduced the magnitude and altitude of the main ionospheric peak. The peak width is over-predicted, which is a potentially major problem since the formulation of the empirical model of Nemec et al. (2011) relies upon the scale height to provide a vertical scale. They also found that the MARSIS-based electron densities are less accurate higher up, exceeding MGS electron densities by a factor of 2 at 200 km altitude. A similar factor-of-2 difference between MARSIS and MGS electron densities at 200 km was reported in Figure 3 of Morgan et al. (2008).

There is a clear need for a careful comparison of MARSIS electron densities against similar measurements from other, more fully characterized instrumental techniques. The abrupt change in scale height is particularly compelling.

- Duru et al. (2008) and Nemec et al. (2011) found a doubling in the plasma scale height at 275 km that is not seen in any independent data or models
- Duru et al. (2008) found an average electron density at 275 km of 3 x 10^3 cm^{-3} for the remotely sensed data and 4 x 10^3 cm^{-3} for the local data
- Nemec et al. (2011) found that remotely sensed electron densities are larger than their local counterparts at the 275 km transition altitude
- Morgan et al. (2008) and Nemec et al. (2011) found that remotely sensed electron densities at 200 km are double typical MGS values

7 – Task A: Archiving the Mariner 9 electron density profiles

Task A is designed to ensure that the long-lost Mariner 9 ionospheric dataset becomes readily available for widespread use. Its unique attributes for Mars science are summarized in Section 4.

These data will be utilized in **Tasks B and C** of this proposed work and we anticipate that they will also be used by other investigators.

The NSSDC holds microfilm copies of tabulated electron densities and radial distances for many Mariner 9 radio occultations. They are labeled by occultation number and date. A plot of electron density against radius is also provided. Ancillary information, including occultation number, latitude, longitude, and solar zenith angle, for these occultations is reported in Kliore et al. (1972, 1973). Radial distances can be converted into altitudes using the MOLA areoid and reported latitude and longitude. Conventions on the definition of position on Mars have evolved obscurely from mission to mission; we will initially assume that reported positions are consistent with MOLA areocentric coordinates. We have obtained digital images of all 118 ingress dayside profiles from the NSSDC and commenced a low-intensity effort to convert them into ASCII tables. During summer 2011, undergraduate Nick Ferreri converted about half the profiles into ASCII tables and verified consistency of the extracted values against the archived plot and published versions of the electron density profile.

The **Objectives** of **Task A** are:
Obj. A.1 To complete the conversion of the images of data tables into usable ASCII tables
Obj. A.2 To perform quality control inspections of the resultant ASCII tables
Obj. A.3 To document the generation of these data products, format them in accordance with PDS standards, and archive them at the PDS.

These **Objectives** will be met by completion of the following **Investigations**:
Inv. A.1 Continuation of ongoing conversion process until completion (**Obj. A.1**)
Inv. A.2 Ingestion of ancillary information from Kliore et al. (1972, 1973) and determination of altitude scale using MOLA areoid; verify data by re-doing simple studies of peak altitude, peak magnitude, and topside scale height (Bauer and Hantsch, 1989; Hantsch and Bauer, 1990; Zhang et al., 1990), such as dependences on SZA and solar flux (**Obj. A.2**)
Inv. A.3 Deposition of data products on personal website to ensure rapid public access; documentation of data processing; application of tried and tested tools to format data products and supporting materials into PDS-compliant data volume; delivery to PDS (**Obj. A.3**)

The uncertainty in these electron density measurements will be estimated as the reported electron density at the upper boundary of the archived profile. We will compare this to the scatter in the electron densities from the highest altitude regions to ensure it is reasonable.

We will archive the Mariner 9 electron density profiles at the PDS (UCLA's Planetary Plasma Interactions, or PPI, Node) using our established tools and procedures. Paul Withers has extensive experience working with the PDS. He has generated, formatted, documented, and delivered atmospheric data products from the Odyssey, Spirit, Opportunity, and Phoenix accelerometer experiments to the Atmospheres Node (Withers and Murphy, 2009; Withers et al., 2010), and coordinated the delivery of Venera 15/16 ionospheric data to the PPI Node. Collaborator Steve Joy, the PDS PPI Node Operations Manager, will design the necessary PDS metadata. Also, the Mariner 9 data will be deposited on Paul Withers's website at the time of delivery to the PDS to ensure its rapid accessibility to users.

8 – Task B: Scientific interpretation of the Mariner 9 electron density profiles

Task B is designed to exploit the Mariner 9 ionospheric dataset in light of the many advances in Mars science since 1972. The Mariner 9 investigators did not know the composition or temperature of the ionosphere, the magnetic environment at Mars, or the circulation or top-to-bottom thermal structure of the neutral atmosphere. Realistic attempts to simulate the ionosphere had to await the two Viking lander entry measurements and resultant computationally-demanding models tended to focus on reproduction of the two Viking ion composition profiles, rather than the many electron density profiles provided by orbital radio occultations.

The **Objectives** of **Task B** are:
Obj. B.1 To characterize the structure of the topside ionosphere
Obj. B.2 To determine the response of the ionosphere to an unsurpassed dust storm
Obj. B.3 To delineate the behavior of the ionosphere in different magnetic environments
Obj. B.4 To search for important features that have not previously been recognized

These **Objectives** will be met by completion of the following **Investigations**:
Inv. B.1 Determination of the plasma scale height as function of altitude and SZA, with identification of any outliers, and comparison to published models (**Obj. B.1, B.4**)
Inv. B.2 **i.** Identification and characterization of abrupt or other changes in the vertical gradient of electron density, such as near the 275 km transition between MARSIS data types. Small changes are present in some Mariner 9 profiles, such as the third and sixth profiles in Fig. 2, but large changes are never present. **ii.** Comparison to published models. (**Obj. B.1**)
Inv. B.3 Characterization of any bulges or layering in the topside, such as the layering around 200 km reported by Kopf et al. (2008) and the bulge of enhanced density at 160-180 km reported by Patzold et al. (2007) and comparison to published models. The models of Shinagawa and Cravens (1992) and Fox and Yeager (2006) predict a bulge of enhanced density around 160-180 km, but for two different reasons and without much supporting discussion. (**Obj. B.1, B.4**)
Inv. B.4 Identification of drastic decreases in plasma density at the tops of profiles or of atypically small electron densities, both of which might indicate the upper boundary of the ionosphere and its interface with the space environment. This will be limited by the observational uncertainties, although the fourth profile in Fig. 2 presents an "ionopause-like" feature consistent with significant compression of the topside ionosphere by the solar wind. No ionospheric models have published simulations that reproduce the substantial changes in topside structure with time at fixed SZA that are shown in this Figure. (**Obj B.1, B.4**)
Inv. B.5 **i.** Calculation of how the altitude, magnitude, and width of the main ionospheric peak changed during Mariner 9's immense dust storm. Hantsch and Bauer (1990) found that the ionospheric peak was 20-30 km higher during this storm than normal, but, as expected, found no changes in peak magnitude or width. We will confirm this using MOLA-based altitudes. **ii.** Characterization of the timescales for rise and fall of the peak altitude and comparison to published timescales for other atmospheric changes during a dust storm. **iii.** Determination of neutral number density at a fixed reference altitude and how it changes through the dust storm. Since the product of the CO_2 cross-section (3×10^{-17} cm^2), neutral number density at the peak, neutral scale height at the peak, and cos(SZA) equals unity (Withers, 2009), where the scale height can be found from the profile shape, the neutral number density at the peak altitude can be

found. This can be extrapolated to a reference altitude using the scale height. Just how much did thermospheric densities increase during this historic dust storm? (**Obj. B.2**)

Inv. B.6 **i.** Explore whether topside scale heights and peak electron density depend on magnetic field strength and inclination, as have been suggested by previous workers (Krymskii et al., 2002, 2003, 2004; Nielsen et al. 2007a, b). **ii.** Test the finding of Withers et al. (2005) that some Mariner 9 profiles over strong magnetic fields contain anomalous sharp variations in plasma density between 120 and 200 km. (**Obj. B.3**)

Comparison of observational trends and features to published predictions will be conducted wherever possible in order to relate observables to physical processes. We have a numerical model of the ionosphere of Mars that is currently being applied to a range of projects (Withers and Mendillo, 2009; Matta et al., 2011; Mendillo et al, 2011). If suitable questions arise in the course of this **Task**, we will use our modeling capabilities to address them to the extent permitted by our multiple external sources of modeling funds. Since it is not clear what we will find in the course of the multiple **Investigations** listed above, we do not offer specific modeling projects at this point and we do not request direct funding for doing any.

9 – Task C: Comparison of MARSIS and radio occultation ionospheric measurements

Task C is designed to evaluate the accuracy and biases of MARSIS electron density measurements by comparison to radio occultation measurements. Radio occultation datasets are not perfect, but their characteristics and imperfections are well-established and widely-known, such as their assumption of spherical symmetry over 200 km scales (Hinson et al., 1999). The same cannot yet be said for local and remotely sensed MARSIS electron density measurements, Section 6 outlined several arguments why users of published MARSIS results and of archived MARSIS raw data products would benefit from a thorough validation of MARSIS electron density measurements.

The **Objectives** of **Task C** are:

Obj. C.1 To compare MARSIS local measurements of local electron density (275-1200 km) against radio occultation data

Obj. C.2 To compare MARSIS remotely sensed electron density measurements (120-275 km) against radio occultation data

These **Objectives** will be met by completion of the following **Investigations**:

Inv. C.1 Construction of a 2-D synthesis of Mariner 9 radio occultation electron densities from 100 to 400 km and 0 to 90 degrees SZA, adjusting the Mariner 9 peak altitudes inflated by a dust storm downwards to nominal values if necessary (**Obj. C.1, C.2**)

Inv. C.2 Construction of a 2-D synthesis of MGS radio occultation electron densities from 100 to 250 km and 0 to 90 degrees SZA (**Obj. C.2**)

Inv. C.3 Comparison of the MARSIS local electron densities (275-1200 km) reported by Duru et al. (2008) to Mariner 9 electron densities (100-400 km) in the 275-400 km overlap region as a function of altitude and SZA (**Obj. C.1**)

Inv. C.4 Comparison of the high altitude component (based on MARSIS local electron densities) of the model of Nemec et al. (2011) to Mariner 9 electron densities in the 275-400 km overlap region as a function of altitude and SZA (**Obj. C.1**)

Inv. C.5 Comparison of the low altitude component (based on MARSIS remotely sensed electron densities) of the model of Nemec et al. (2011) to Mariner 9 electron densities in the 120-275 km overlap region as a function of altitude and SZA (**Obj. C.2**)
Inv. C.6 Comparison of the low altitude component (based on MARSIS remotely sensed electron densities) of the model of Nemec et al. (2011) to MGS electron densities in the 120-250 km overlap region as a function of altitude and SZA (**Obj. C.2**)
Inv. C.7 Comparison of both types of MARSIS electron densities with Mariner 9 electron densities near the transition altitude of 275 km (**Obj. C.1, C.2**)

The Mariner 9 primary mission (about half the profiles) was affected by a dust storm, but the extended mission was not. Ionospheric peak altitudes during this dust storm are 20-30 km higher than usual. We will explore 2 options for dealing with this in **Investigation C.1**, either ignoring the primary mission data, which reduces data quantity, or adjusting them. Since an altitude shift is likely to be the only impact of the dust storm on the ionosphere, we can reduce these altitudes such that the peak altitude equals 120 km + 10 km ln(sec(SZA)). This SZA-dependence for peak altitude is robust and has been reliably characterized by many groups (e.g. Withers, 2009). We will consider uncertainties introduced by this adjustment during our analyses.

Investigation C.7 focuses on the critical transition region between the two MARSIS data types at 275 km. Duru et al. (2008) (our Fig. 3) show an abrupt doubling in the plasma scale height here, although the empirical model of Nemec et al. (2011) smooths this sharp boundary (Fig. 9). They cannot both be accurate. A comparison against Mariner 9 electron density profiles that span this region will reveal which data type is unreliable here and in what manner.

The Mariner 9 uncertainties are discussed in Section 7 and the MGS uncertainties accompany the archived electron densities. Duru et al. (2008) provide lower and upper quartiles about their derived vertical distributions of electron density. Nemec et al. (2011) provide uncertainties on each parameter in their empirical model. We will use a Monte Carlo approach to calculate the uncertainty on electron densities predicted by the complicated functional form of the model of Nemec et al. (2011). These uncertainties will be considered when we compare datasets.

We do not propose any specific scientific analysis of the MARSIS electron densities. It would be premature for us to do so before we understand how reliable they are. Nevertheless, our scientific antennae will be twitching as we study these data. In particular, we will pay attention to physical explanations for changes in the plasma scale height with increasing altitude, making extensive use of comparison to published physics-based models of ionospheric vertical structure.

10 – Anticipated results

At the conclusion of this project, we expect to have deposited a valuable dataset into NASA's permanent archives, ensuring its availability to future generations, to have used it to study features of the ionosphere of Mars that are not accessible to current datasets, such as the topside ionosphere and the response to a massive dust storm, and to have compared two types of MARSIS electron density measurements against independent radio occultation measurements, including profiles that span the transition region between MARSIS data types.

MARSIS has already transformed our understanding of the ionosphere of Mars. From isolated, discrete ionospheric profiles clustered around the terminator, we now have countless thousands at all SZAs, latitudes, and longitudes separated in time by mere seconds. MARSIS can observe temporal and horizontal gradients in ionospheric properties inconceivable for radio occultation experiments. Yet these revolutionary data possess limitations, of which their coarse vertical resolution and sensitivity to assumptions in high altitude plasma density are just the most obvious. The involvement of Collaborator Dave Morgan ensures that the MARSIS team will be aware of our findings and able to comment on our work as it is in progress.

We plan to produce two peer-reviewed papers during the course of this project, one on a scientific survey of the Mariner 9 electron density profiles and one on the comparison of MARSIS (local and remotely sensed) and radio occultation (Mariner 9 and MGS) electron densities. It is also plausible that aspects of our Mariner 9 results could contribute to publications primarily associated with our other ongoing projects and also that aspects of our MARSIS validation findings could be included in publications led by the MARSIS team.

11 – Relevance to NASA

"The objective of the Mars Data Analysis Program (MDAP) is to enhance the scientific return from missions to Mars." We will do so by making a long-lost dataset with unique strengths widely available and by determining the reliability of MARSIS ionospheric data. This proposed research is aligned with MEPAG Investigation II.A.1, which emphasizes determination of the present state of the upper atmosphere (neutral/plasma) structure and dynamics and quantification of the processes that link the Mars lower and upper atmospheres. Escape and climate evolution are always part of the rationale for studies of the upper atmosphere and ionosphere of Mars, and this proposal is no exception. Ionospheric plasma above the 200 km exobase, which the Mariner 9 data probe well, is a major reservoir from which escape occurs. The MAVEN mission was selected to make extensive measurements of the structure of the ionosphere of Mars for the same reasons that justify the work proposed here. Trends and features identified in this work will help develop scientific questions for MAVEN data users to address.

"MDAP supports investigations that use only publicly available and released data." The Mariner 9 data were deposited at the NSSDC decades ago. The MGS electron density data are archived at the PDS. The MARSIS data products to be used in this project are the synthesized representations published by Duru et al. (2008) and Nemec et al. (2011). We do not propose to use any unreleased MARSIS electron density measurements. Instead, we follow the MDAP announcement's explicit encouragement of proposers to archive data products with the PDS.

12 – Personnel

This investigation will be carried out by PI Paul Withers, Boston University students, Collaborator Dave Morgan (University of Iowa), Collaborator Dave Hinson (SETI Institute), and Collaborator Steve Joy (UCLA).

Paul Withers, Professor in the Astronomy Department of Boston University, will be responsible for the success of this investigation and for compliance with all reporting requirements. He has completed a range of studies on the ionosphere of Mars, including the effects of solar energetic particle events, meteoroid influx, crustal fields (both observational and theoretical), solar flares, and other solar variations (Withers and Mendillo, 2005; Withers et al., 2005, 2008; Withers, 2008, 2009, 2011; Mendillo et al., 2006; Opgenoorth et al., 2010; Lillis et al., 2010).

Boston University graduate student Katy Fallows has worked with Paul Withers on analysis of radio occultation electron density profiles at Mars since starting her PhD program in fall 2010 (Fallows et al., 2011). She is available to work on this project. Undergraduate Nick Ferreri will complete processing the Mariner 9 profiles (supported by other funds).

Dave Morgan, MARSIS Project Manager at the University of Iowa, plays a leading role in the reduction of MARSIS ionospheric observations and in their scientific interpretation. He has authored 19 publications concerning MARSIS observations of the ionosphere and his main scientific interests lie in the interaction of the solar wind and space environment with Mars.

Dave Hinson, Principal Investigator at the SETI Institute, led the radio occultation component of the MGS radio science instrument and produced the MGS electron density profiles we will use in this project. He has conducted radio occultation studies of every atmosphere in the solar system and has participated in the radio occultation experiments of six spacecraft.

Steve Joy, Operations Manager of UCLA's PPI Node of the PDS, handles the ingestion of data deliveries to this Node. He worked with Paul Withers during the delicate process of obtaining Venera 15 and 16 radio occultation electron density profiles of the ionosphere of Venus from a Russian investigator and preparing them for archiving.

13 – Work plan ("If we knew what we were doing, it would not be called research" – Einstein)

This investigation will be carried out by Professor Withers and a Boston University graduate student. It will also be supported by a network of collaborators. Professor Withers will be responsible for the success of this investigation and for compliance with all reporting requirements. He will mentor the graduate student and direct their activities. His funded effort is 0.5 months, but 40% of his time during the 9-month academic year is nominally available for research projects such as this one. Collaborator Morgan will advise us on the use of MARSIS data. Collaborator Hinson will advise us on the reliability of radio occultation data. Collaborator Joy will manage the archiving of the Mariner 9 profiles. Interactions with Collaborators will occur via phone and email as needed, plus anticipated face-to-face meetings at conferences.

The **Tasks** will be completed sequentially, with 6 months of graduate student effort devoted to **Task A**, 12 months to **Task B**, and 9 months to **Task C**. Approximately equal effort will be devoted to each **Investigation** within a **Task**. The graduate student will lead the preparation of both manuscripts and also report results at a conference annually, which is essential for their professional development and for receiving critical feedback on work in progress.

References

Barabash, S., and Lundin, R., (2006) ASPERA-3 on Mars Express (Introduction to special issue), Icarus, 182, 301-307

Barth, C., Stewart, A., Bougher, S., Hunten, D., Bauer, S., and Nagy, A. (1992) Aeronomy of the current martian atmosphere, in Mars, eds. Kieffer, H., Jakosky, B., Snyder, C., and Matthews, M., pp. 1054-1089, University of Arizona Press.

Bauer, S., and Hantsch, M. (1989) Solar cycle variation of the upper atmosphere temperature of Mars, Geophys. Res. Lett., 16, 373-376

Bougher, S. (1995) Comparative thermospheres: Venus and Mars, Adv. Space Res., 15, 21-25

Bougher, S., Engel, S., Hinson, D., and Forbes, J. (2001) Mars Global Surveyor radio science electron density profiles: Neutral atmosphere implications, Geophys. Res. Lett., 28, 3091-3094

Bougher, S., Roble, R., and Fuller-Rowell, T. (2002) Simulations of the upper atmospheres of the terrestrial planets. In Atmospheres in the solar system: Comparative aeronomy, eds. Mendillo, M., Nagy, A., and Waite, J., pp. 261-288, AGU Press

Bougher, S. (2005) Comparative thermospheres: Venus and Mars, Adv. Sp. Res., 15, 21-25

Bougher, S., Valeille, A., Combi, M., and Tenishev, V. (2009) Solar cycle and seasonal variability of the martian thermosphere-ionosphere system and associated impacts upon atmospheric escape, SAE Technical Paper 2009-01-2396, SAE International.

Bougher, S., Brain, D., Fox, J, Gonzalez-Galindo, F., Simon Wedlund, C., and Withers, P (2011) Upper atmosphere and ionosphere. In Mars, eds. Clancy, R., Forget, F., Haberle, R., Smith, M., and Zurek, R., chapter submitted to Cambridge University Press in March 2011.

Brain, D., and 26 colleagues (2010) A comparison of global models for the solar wind interaction with Mars, Icarus, 206, 139-151

Chassefiere, E, and Leblanc, F. (2004) Mars atmosphere escape and evolution: Interaction with the solar wind, Planet. Space Sci., 52, 1039-1058

Dubinin, E., and 13 colleagues (2008) Plasma environment of Mars as observed by simultaneous MEX-ASPERA-3 and MEX-MARSIS observations, J. Geophys. Res., 113, A10217, doi:10.1029/2008JA013355

Duru, F., and 7 colleagues (2006) Magnetically controlled structures in the ionosphere of Mars, J. Geophys. Res., A12204, doi:10.1029/2006JA011975.

Duru, F., Gurnett, D., Morgan, D., Modolo, R., Nagy, A., Najib, D. (2008) Electron densities in the upper ionosphere of Mars from the excitation of electron plasma oscillations, J. Geophys. Res., 113, A07302, doi:10.1029/2008JA013073

Fallows, K., Withers, P., and Girazian, Z. (2011) The lower layer of the ionosphere of Mars, Fall AGU meeting, abstract number pending

Fillingim, M., Peticolas, L., Lillis, R., Brain, D., Halekas, J., Lummerzheim, D., and Bougher, S. (2010) Localized ionization patches in the nighttime ionosphere of Mars and their electrodynamic consequences, Icarus, 206, 112-119

Fox, J. (2004) Response of the martian thermosphere/ionosphere to enhanced fluxes of solar soft X-rays, J. Geophys. Res., 109, A11310, doi:10.1029/2004JA010380.

Fox, J., and Yeager, K. (2006) Morphology of the near-terminator martian ionosphere: A comparison of models and data, J. Geophys. Res., 111, A10309, doi:10.1029/2006JA011697

Fox, J. (2009) Morphology of the dayside ionosphere of Mars: Implication for ion outflows, J. Geophys. Res., 114, E12005, doi:10.1029/2009JE003432

Fox, J., and Hac, A. (2010) Isotope fractionation in the photochemical escape of O from Mars, Icarus, 208, 176-191

Girazian, Z., Withers, P., Patzold, M., and Tellmann, S. (2011) The vertical structure of the martian ionosphere, 218th AAS meeting, abstract #224.09

Gurnett, D., and ten colleagues (2005) Radar soundings of the ionosphere of Mars, Science, 310, 1929-1933.

Gurnett, D., and 12 colleagues (2008) An overview of radar soundings of the martian ionosphere from the Mars Express spacecraft, Adv. Space Res., 41, 1335-1346

Hantsch, M., and Bauer, S. (1990) Solar control of the Mars ionosphere, Planet. Space Sci., 38, 539-542

Haider, S., Sheel, V., Singh, V., Maguire, W., and Molina-Cuberos, G. (2008) Model calculations of production rates, ion and electron densities in the evening troposphere of Mars at latitudes 67^{o}N and 62^{o}S: Seasonal variability, J. Geophys. Res., 113, A08320, doi:10.1029/2007JA012980

Haider, S., Abdu, M., Batista, I., Sobral, J., Kallio, E., Maguire, W., and Verigin, M. (2009) On the responses to solar X-ray flare and coronal mass ejection in the ionospheres of Mars and Earth, Geophys. Res., Lett., 36, L13104, doi:10.1029/2009GL038694

Hinson, D., Simpson, R., Twicken, J., Tyler, G., and Flasar, F. (1999) Initial results from radio occultation measurements with Mars Global Surveyor, J. Geophys. Res., 104, 26,997-27,012

Kliore, A., Cain, D., Fjeldbo, G., Seidel, B., Sykes, M., and Rasool, S. (1972) The atmosphere of Mars from Mariner 9 radio occultation measurements, Icarus, 17, 484-516

Kliore, A., Fjeldbo, G., Seidel, B., Sykes, M., and Woiceshyn, P. (1973) S band radio occultation measurements of the atmosphere and topography of Mars with Mariner 9: Extended mission coverage of polar and intermediate latitudes, J. Geophys. Res., 78, 4331-4351

Kliore, A. (1992) Radio occultation observations of the ionospheres of Mars and Venus, in Venus and Mars: Atmospheres, ionospheres, and solar wind interactions, eds. Luhmann, J., Tatrallyay, and Pepin, R., pp. 265-276, AGU Press

Kopf, A., Gurnett, D., Morgan, D., and Kirchner, D. (2008) Transient layers in the topside ionosphere of Mars, Geophys. Res. Lett., 35, L17102, doi:10.1029/2008GL034948

Krymskii, A., and seven colleagues (2002) Structure of the magnetic field fluxes connected with crustal magnetization and topside ionosphere of Mars, J. Geophys. Res., 107, 1245, doi:10.1029/2001JA000239.

Krymskii, A., Breus, T., Ness, N., Hinson, D., and Acuna, M. (2003) Effect of crustal magnetic fields on the near-terminator ionosphere of Mars: Comparison of in situ magnetic field measurements with the data of radio science experiments on board Mars Global Surveyor, J. Geophys. Res., 108, 1431doi:10.1029/2002JA009662.

Krymskii, A., Ness, N., Crider, D., Breus, T., Acuna, M., and Hinson, D. (2004) Solar wind interaction with the atmosphere/ionosphere and crustal fields at Mars: Mars Global Surveyor Magnetoemeter/Electron Reflectometer, radio science, and accelerometer data, J. Geophys. Res., 109, A11306, doi:10.1029/20034JA010420.

Lillis, R., Brain, D., England, S., Withers, P., Fillingim, M., and Safaeinili, A. (2010) Total electron content in the Mars ionosphere: Temporal studies and dependence on solar EUV flux, Geophysical Research Letters, 115, A11314, doi:10.1029/2010JA015698.

Lundin, R., and 44 colleagues (2004) Solar wind-induced atmospheric erosion at Mars: First results from ASPERA-3 on Mars Express, Science, 305, 1933-1936

Ma, Y., Nagy, A., Sokolov, I., and Hansen, K. (2004) Three-dimensional, multispecies, high spatial resolution MHD studies of the solar wind interaction with Mars, J. Geophys. Res., 109, A07211, doi:10.1029/2003JA010367.

MARSIS (2011) Datasets from Mars Express MARSIS instrument, http://pds-geosciences.wustl.edu/missions/mars_express/marsis.htm

Matta, M., Mendillo, M., and Withers, P. (2011) Hydrogen species in the topside ionosphere of Mars, in preparation for submission to Geophys. Res. Lett.

Mendillo, M, Withers, P., Hinson, D., Rishbeth, H., and Reinisch, B. (2006) Effects of solar flares on the ionosphere of Mars, Science, 311, 1135-1138

Mendillo, M., and five colleagues (2011) Modeling Mars' ionosphere with constraints from same-day observations by Mars Global Surveyor and Mars Express, J. Geophys. Res., in press.

Mitchell, D., and seven colleagues (2001) Probing Mars' crustal magnetic fields and ionosphere with the MGS electron reflectometer, J. Geophys. Res., 106, 23,419-23,428.

Morgan, D., Gurnett, D., Kirchner, D., Fox, J., Nielsen, E., and Plaut, J. (2008) Variation of the martian ionospheric electron density from Mars Express radar soundings, J. Geophys. Res., 113, A09303, doi:10.1029/2008JA013313

Nemec, F., Morgan, D., Gurnett, D., and Duru, F. (2010) Nightside ionosphere of Mars: Radar soundings by the Mars Express spacecraft, J. Geophys. Res., 115, E12009, doi:10.1029/2010JE003663

Nemec, F., Morgan, D., Gurnett, D., Duru, F., and Truhlik, V. (2011) Dayside ionosphere of Mars: Empirical model based on data from the MARSIS instrument, J. Geophys. Res., 116, E07003, doi:10.1029/2010JE003789

Ness, N., and seven colleagues (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, 15,991-16,004.

Nielsen, E., and nine colleagues (2006) Observations of vertical reflections from the topside martian ionosphere, Space Sci. Rev., 126, 373-388

Nielsen, E., and thirteen colleagues (2007a) Local plasma processes and enhanced electron densities in the lower ionosphere in magnetic cusp regions on Mars, Planet. Space Sci., 55, 2164-2172.

Nielsen, E., and eight colleagues (2007b) Vertical sheets of dense plasma in the topside martian ionosphere, J. Geophys. Res., 112, E02003, doi:10.1029/2006JE002723

NSSDC (2011) Reduced and analyzed martian occultation data (tables and plots) on microfilm, NSSDC dataset PSPA-00141

Opgenoorth, H., Dhillon, R., Rosenqvist, L., Lester, M., Edberg, N., Milan, S., Withers, P., and Brain, D. (2010) Dayside ionospheric conductivities at Mars, Planetary and Space Science, 58, 1139-1151.

Patzold, M., and 7 colleagues (2007) The structure of the Mars ionosphere, Fall AGU meeting, abstract #P32A-01

Shinagawa, H., and Cravens, T. (1992) The ionospheric effects of a weak intrinsic magnetic field at Mars, J. Geophys. Res., 97, 1027-1035

Valeille, A., Tenishev, V., Bougher, S., Combi, M., and Nagy, A. (2009a) Three-dimensional study of Mars upper thermosphere/ionosphere and hot oxygen corona: 1. General description and results at equinox for solar low conditions, J. Geophys. Res., 114, E11005, doi:10.1029/2009JE003388

Valeille, A., Combi, M., Bougher, S., Tenishev, V., and Nagy, A. (2009b) Three-dimensional study of Mars upper thermosphere/ionosphere and hot oxygen corona: 2. Solar cycle, seasonal variations, and evolution over history, J. Geophys. Res., 114, E11006, doi:10.1029/2009JE003389

Valeille, A., Combi, M., Tenishev, V., Bougher, S., and Nagy, A. (2010) A study of suprathermal oxygen atoms in Mars upper thermosphere and exosphere over the range of limiting conditions, Icarus, 206, 18-27

Withers, P., and Mendillo, M. (2005) Response of peak electron densities in the martian ionosphere to day-to-day changes in solar flux due to solar rotation, Planetary and Space Science, 53, 1401-1418, doi:10.1016/j.pss.2005.07.010

Withers, P., Mendillo, M., Rishbeth, H., Hinson, D., and Arkani-Hamed, J. (2005) Ionospheric characteristics above martian crustal magnetic anomalies, Geophysical Research Letters, 32, L16204, doi:10.1029/2005GL023483

Withers, P. (2008) Theoretical models of ionospheric electrodynamics and plasma transport, Journal of Geophysical Research, 113, A07301, doi:10.1029/2007JA012918

Withers, P., Mendillo, M., Hinson, D., and Cahoy, K. (2008) Physical characteristics and occurrence rates of meteoric plasma layers detected in the Martian ionosphere by the Mars Global Surveyor Radio Science Experiment, J. Geophys. Res., 113, A12314, doi:10.1029/2008JA013636.

Withers, P. (2009) A review of observed variability in the dayside ionosphere of Mars, Advances in Space Research, 44, 277-307

Withers, P., and Mendillo, M. (2009) The effects of solar flares on planetary ionospheres, AOGS meeting, abstract #PS14-A004, Singapore, 10-14 August 2009

Withers, P., and Murphy, J.R. (2009) Mars Exploration Rover Entry Profiles Data Archive, MER1/MER2-M-IMU-5-EDL-DERIVED-V1.0, NASA Planetary Data System, http://pds-atmospheres.nmsu.edu/PDS/data/merimu_2001/

Withers, P., and 42 colleagues (2009) The ionosphere of Mars and its importance for climate evolution, white paper submitted to Planetary Science Decadal Survey

Withers, P., Catling, D. C., and Murphy, J. R. (2010) Phoenix Lander Atmospheric Stucture Reduced Data Records, version 1.0, PHX-MASE-5-EDL-RDR-V1.0, NASA Planetary Data System, http://pds-atmospheres.nmsu.edu/PDS/data/phxase_0002/

Withers, P. (2011) Attenuation of radio signals by the ionosphere of Mars: Theoretical development and application to MARSIS observations, Radio Science, 46, doi:10:1029/2010RS004450.

Zhang, M., Luhmann, J., Kliore, A., and Kim, J. (1990) A post-Pioneer Venus reassessment of the martian dayside ionosphere as observed by radio occultation methods, J. Geophys. Res., 95, 14,829-14,839

Zou, H., Wang, J.-S., and Nielsen, E. (2005) Effect of the seasonal variations in the lower atmosphere on the altitude of the ionospheric main peak at Mars, J. Geophys. Res., 110, A09311, doi:10.1029/2004JA010963

Zou, H., Wang, J.-S., and Nielsen, E. (2006) Reevaluating the relationship between the martian ionospheric peak density and the solar radiation, J. Geophys. Res., 111, A07305, doi:10.1029/2005JA011580

Zou, H. Nielsen, E., Wang, J.-S., and Wang, X.-D. (2010) Reconstruction of nonmonotonic electron density profiles of the martian topside ionosphere, Planet. Space Sci., 58, 1391-1399

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- PhD, Planetary Science, University of Arizona — 2003
- MS, Physics, Cambridge University, Great Britain — 1998
- BA, Physics, Cambridge University, Great Britain — 1998

Professional Experience

- Assistant Professor, Astronomy Department (Boston Univ.) — 2010-present
- Senior research associate — Dr. Michael Mendillo (Boston Univ.) — 2007 – 2010
  Research associate — Dr. Michael Mendillo (Boston Univ.) — 2003 – 2007
  Analysis of ionospheric data from Venus, Mars and Earth, plus numerical modeling
- Graduate research assistant — Dr. Stephen Bougher (Univ. of Arizona) — 1998 – 2003
  Studied tides in the martian upper atmosphere. Played an advisory role in mission operations for Mars Global Surveyor and Mars Odyssey aerobraking

Selected Fellowships, Honors, and Awards

- NASA Early Career Fellowship — 2009
- CEDAR Postdoctoral Fellowship from NSF for upper atmospheric research — 2003
- Kuiper Memorial Award from the University of Arizona for excellence in academic work and research in planetary science — 2002
- Nominated for the Meteoritical Society/Geological Society of America's Best Student Paper in Planetary Sciences Award — 2002

Membership of Committees and Working Groups

- DPS Nominating Committee — 2008-present
- Mars Exploration Program Analysis Group (MEPAG) Goals Committee member — 2008-present
- Mars Exploration Program Analysis Group (MEPAG) Mars Human Precursor Science Steering Group - Atmospheric Focus Team member — 2004-2005

Selected Peer Reviewed Publications

- **Withers** (2011) Attenuation of radio signals by the ionosphere of Mars: Theoretical development and application to MARSIS observations, Radio Science, 46, RS2004, doi:10:1029/2010RS004450.
- Lillis, Brain, England, **Withers**, Fillingim, and Safaeinili (2010) Total electron content in the Mars ionosphere: Temporal studies and dependence on solar EUV flux, Geophysical Research Letters, 115, A11314, doi:10.1029/2010JA015698
- Opgenoorth, Dhillon, Rosenqvist, Lester, Edberg, Milan, **Withers** and Brain (2010) Dayside ionospheric conductivities at Mars, Planetary and Space Science, 58, 1139-1151
- **Withers** (2010) Prediction of uncertainties in atmospheric properties measured by radio occultation experiments, Advances in Space Research, 46, 58-73
- **Withers** (2009) A review of observed variability in the dayside ionosphere of Mars, Advances in Space Research, 44, 277-307
- Paetzold, Tellmann, Haeusler, Bird, Tyler, Christou and **Withers** (2009) A sporadic layer in the Venus lower ionosphere of meteoric origin, Geophysical Research Letters, 36, L05203, doi:10.1029/2008GL035875
- **Withers**, Mendillo, Hinson, and Cahoy (2008) Physical characteristics and occurrence rates of meteoric plasma layers detected in the martian ionosphere by the Mars Global Surveyor Radio Science Experiment, Journal of Geophysical Research, 113, A12314, doi:10.1029/2008JA013636
- **Withers** (2008) Theoretical models of ionospheric electrodynamics and plasma transport, Journal of Geophysical Research, 113, A07301, doi:10.1029/2007JA012918
- Christou, Vaubaillon, and **Withers** (2007) The dust trail complex of comet 79P/du Toit-Hartley and meteor outbursts at Mars, Astronomy and Astrophysics, 471, 321-329
- Mendillo, **Withers,** Hinson, Rishbeth, and Reinisch (2006) Effects of solar flares on the ionosphere of Mars, Science, 311, 1135-1138
- **Withers** (2006) Mars Global Surveyor and Mars Odyssey Accelerometer observations of the martian upper atmosphere during aerobraking, Geophysical Research Letters, 33, L02201, doi:10.1029/2005GL024447
- Fulchignoni and 42 colleagues, including **Withers** (2005) In situ measurements of the physical characteristics of Titan's environment, Nature, 438, 785-791, doi:10.1038/nature04314
- **Withers** and Mendillo (2005) Response of peak electron densities in the martian ionosphere to day-to-day changes in solar flux due to solar rotation, Planetary and Space Science, 53, 1401-1418, doi:10.1016/j.pss.2005.07.010
- **Withers**, Mendillo, Rishbeth, Hinson, and Arkani-Hamed (2005) Ionospheric characteristics above martian crustal magnetic anomalies, Geophysical Research Letters, 32, L16204, doi:10.1029/2005GL023483
- **Withers**, Bougher, and Keating (2003) The effects of topographically-controlled thermal tides in the martian upper atmosphere as seen by the MGS Accelerometer, Icarus, 164**,** 14-32
- **Withers** and Neumann (2001) Enigmatic northern plains of Mars, Nature, 410, 651
- Lorenz, Lunine, **Withers**, and McKay (2001) Titan, Mars and Earth: Entropy production by latitudinal heat transport, Geophysical Research Letters, 28, 415 – 418