Pergamon
www.elsevier.com/locate/asr

Adv. Space Res. Vol. 27, No. 11, pp. 1851–1860, 2001
© 2001 COSPAR. Published by Elsevier Science Ltd. All rights reserved
Printed in Great Britain
0273-1177/01 $20.00 + 0.00
PII: S0273-1177(01)00338-6

SCIENTIFIC OBJECTIVES OF THE DYNAMO MISSION

E. Chassefière, F. Forget, F. Hourdin, F. Vial[1], H. Rème, C. Mazelle, D. Vignes, J.-A. Sauvaud, P.-L. Blelly, D. Toublanc[2], J.-J. Berthelier, J.-C. Cerisier, G. Chanteur, L. Duvet, M. Menvielle[3], J. Lilensten, O. Witasse[4], P. Touboul[5], E. Quèmerais, J.-L. Bertaux[6], G. Hulot, Y. Cohen, P. Lognonné[7], J.P. Barriot, G. Balmino, M. Blanc, P. Pinet[8], M. Parrot, J.-G. Trotignon[9], M. Moncuquet, J.-L. Bougeret, K. Issautier, E. Lellouch, N. Meyer[10], C. Sotin, O. Grasset[11], F. Barlier, C. Berger[12], P. Tarits, J. Dyment[13], D. Breuer, T. Spohn[14], M. Pätzold, K. Sperveslage[15], P. Gough, A. Buckley[16], K. Szego[17], S. Sasaki[18], S. Smrekar, D. Lyons[19], M. Acuna, J. Connerney, M. Purucker[20], R. Lin, J. Luhmann, D. Mitchell[21], F. Leblanc, R. Johnson[22], J. Clarke, A. Nagy, D. Young[23], S. Bougher[24], G. Keating[25], R. Haberle[26], B. Jakosky[27], R. Hodges[28], M. Parmentier[29], H. Waite, D. Bass[30]

[1] *Laboratoire de Météorologie Dynamique (IPSL), Université P. & M. Curie, 4 Place Jussieu, BP 99, 75252 Paris Cedex 05, France*
[2] *Centre d'Etude Spatiale des Rayonnements, Toulouse, France*
[3] *Centre d'Etude des Environnements Terrestre et Planétaires (IPSL), Paris, France*
[4] *Laboratoire de Planétologie de Grenoble , Grenoble, France*
[5] *Office National d'Etudes et de Recherches Aérospatiales, Paris, France*
[6] *Service d'Aéronomie (IPSL), Paris, France*
[7] *Institut de Physique du Globe, Paris, France*
[8] *Observatoire Midi-Pyrénées, Toulouse, France*
[9] *Laboratoire de Physique et Chimie de l'Environnement, Orléans, France*
[10] *Département d'Etudes Spatiales, Observatoire de Paris-Meudon, Paris, France*
[11] *Laboratoire de Planétologie et Géodynamique, Nantes, France*
[12] *CERGA, Observatoire de la Côte d'Azur, Grasse, France*
[13] *Université de Bretagne occidentale, Plouzane, France*
[14] *Institute für Planetologie, Münster, Germany*
[15] *Institute für Geophysik und Meteorologie, Köln, Germany*
[16] *University of Sussex, Brighton, U.K.*
[17] *Hungarian Academy of Sciences, Budapest, Hungary*
[18] *Geological Institute, University of Tokyo, Japan*
[19] *Jet Propulsion Laboratory, Pasadena, USA*
[20] *Goddard Space Flight Center, Greenbelt, USA*
[21] *Space Science Laboratory, Berkeley, USA*
[22] *University of Virginia, Charlottesville, USA*
[23] *University of Michigan, Ann Arbor, USA*
[24] *University of Arizona, Tucson, USA*
[25] *George Washington University, Hampton, USA*
[26] *NASA/AMES Research Center, Moffett Field, USA*
[27] *University of Colorado, Boulder, USA*
[28] *Univesrity of Texas, Dallas, USA*
[29] *Brown University , USA*
[30] *Southwest Research Institute, San Antonio, USA*

ABSTRACT

DYNAMO is a small Mars orbiter planned to be launched in 2005 or 2007, in the frame of the NASA/ CNES Mars exploration program. It is aimed at improving gravity and magnetic field resolution, in order to better understand the magnetic, geologic and thermal history of Mars, and at characterizing current atmospheric escape, which is still poorly constrained. These objectives are achieved by using a low periapsis orbit, similar to the one used by the Mars Global Surveyor spacecraft during its aerobraking phases. The proposed periapsis altitude for DYNAMO of 120-130 km, coupled with the global distribution of periapses to be obtained during one Martian year of operation, through about 5000 low passes, will produce a magnetic/gravity field data set with approximately five times the spatial resolution of MGS. Additional data on the internal structure will be obtained by mapping the electric conductivity. Low periapsis provides a unique opportunity to investigate the chemical and dynamical properties of the deep ionosphere, thermosphere, and the interaction between the atmosphere and the solar wind, therefore atmospheric escape, which may have played a crucial role in removing atmosphere and water from the planet.

INTRODUCTION

There is much room for debate on the importance of current atmosphere escape processes in the evolution of the Martian atmosphere, as early "exotic" processes including hydrodynamic escape and impact erosion are traditionally invoked to explain the apparent sparse inventory of present-day volatiles. Yet, the combination of low surface gravity and the absence of a substantial internally generated magnetic field have undeniable effects on what we observe today. In addition to the current losses in the forms of Jeans and photochemical escape of neutrals, there are solar wind interaction-related erosion mechanisms because the upper atmosphere is directly exposed to the solar wind. The solar wind related loss rates, while now comparable to those of a modest comet, nonetheless occur continuously, with the intriguing possibility of important cumulative and/or enhanced effects over the several billion years of the solar system's life. It is now well established that the Mars internal field ceased to operate less than 500 Myr after accretion, because no crustal magnetization is found in the Hellas and Argyre basins which are very old (Acuna *et al.*, 1998). Prior to this time, Mars atmosphere was protected against direct solar wind interaction, which could have strongly influenced the history of the young Mars by favouring the retention of volatiles (greenhouse gases, water), despite the weak gravitational field of the planet.

An attempt has been made (Luhmann *et al.*, 1992) to estimate the evolutionary effect of photochemical escape, pick-up of atmospheric ions by the solar wind fields, and sputtering of neutrals from the atmosphere by impacting pick-up ions. This exercise requires combining a model for the early solar Extreme UltraViolet emission, a model for the history of the solar wind properties, models of the early Martian upper atmosphere, and an assumed history of the planetary magnetic field. The first of these required elements is satisfied to a degree by astronomical observations of Sun-like stars (e.g. Ayres, 1997), while the solar wind history is problematic in that winds of such strength are not generally observable for these stars. Nevertheless, some Lunar implantation studies at least suggest that the early solar wind was stronger by at least a few times in particle flux. For the upper atmosphere, a reasonable first approximation is to adopt the current atmosphere exposed to the hypothetical early solar EUV fluxes. For the global magnetic field, it is simplest to assume that the present conditions of a negligible field prevailed. With this assumption, and the conservative scenarios described above, calculations indicate that important amounts of atmospheric constituents could have been lost due to the absence of planetary magnetic field protection from the solar wind (e.g. Luhmann *et al.*, 1992, Jakosky *et al.*, 1994, Hutchins *et al.*, 1997). It is notable that most of the early solar wind-related losses occur in the first ~1.5 billion years of Mars' history when the solar EUV flux was strongest.

While it can always be argued that some process or processes that we cannot test or prove were responsible for the loss of most of the early Martian atmosphere, we have the possibility of observationally testing a contender that we know continues to operate today. We can exploit the recently discovered Martian remanent magnetic fields (Acuna *et al.*, 1998) by using them to reconstruct, as accurately as possible, the history of the strength of the dynamo generated planetary field. We can also make measurements of the upper atmosphere and solar wind relevant to the escape processes to confirm that they work today in the manner that our models envision. Is Mars as it is today because it was, in effect, a giant comet early in its life? Surely this is as interesting a picture as any invoked to date to explain the fate of the Martian atmosphere, and a question that also happens to be intimately tied to the ongoing geophysical and atmospheric exploration of Mars. The ultimate goal of the DYNAMO mission, in the follow up of the Mars Global Surveyor (MGS) mission, is to improve our understanding of escape processes, therefore indirectly of the history of Martian volatiles, as well as of inner planet evolution (core dynamo, mantle convection, lithospheric morphology), synergistically with other planned international missions (Mars-Express, Nozomi, Netlander, in situ experiments).

DYNAMICS OF THE HIGH ATMOSPHERE AND ESCAPE

Thermospheric Dynamics

Mars Global Surveyor (MGS) recently obtained coordinated lower-atmosphere (thermal and dust) measurements and simultaneous upper atmosphere accelerometer data (densities, scale heights and temperatures) yielding the first quantitative glimpse of the physical processes connecting the Mars lower and upper atmospheres during mildly dusty conditions and during a regional dust storm event (Keating *et al.*, 1998). In particular, measurements from the z-axis accelerometer (ACC) aboard MGS have provided to date more than ≈1000 vertical structures of the Mars thermospheric density and derived temperature and pressure, as compared to only 3 previous in-situ profiles (Keating *et al.*, 1998). These data have been obtained over two distinct Mars seasons : (Phase I) 7-months approaching perihelion from southern Spring to early Summer (Ls = 180 to 300), and (Phase II) 4.5-months near aphelion from northern Spring to early Summer (Ls = 30 to 95). During MGS Phase I aerobraking, the spacecraft periapsis moved from 32N to 61N and from a local time of 6 PM to 11AM, with data acquired from 170 to as low as 110 km. During Phase II, the spacecraft covered similar local times (6PM to 2PM) while traversing a wider latitude (60N to 90S) range. This local time-latitude coverage for minimum to moderate solar conditions (F10.7-cm = 80-150 units) far surpasses the limited spatial and temporal coverage afforded by the previous Viking Landers 1-2 and Mars Pathfinder. Additionally, Phase I CO_2 15-micron band measurements from the Thermal Emission Spectrometer (TES) have yielded temperature maps from the ground to 0.1-mb (about 30 km); corresponding IR dust opacities have also been gleaned from the 9.0-micron silicate band. Independent ground-based microwave measurements (disk-averaged) have routinely obtained temperatures over 0-60 km, generally confirming the TES values when available.

Phase I of MGS aerobreaking witnessed the onset, rise and decay of a regional dust storm event (centered at 20-40S), and the corresponding responses of the lower atmosphere temperatures (TES, microwave), dust opacities (TES), and upper atmosphere densities (ACC) as a function of height. Throughout this "Noachis storm", the ACC density increases (decreases) coincided with the warming (cooling) and hydrostatic expansion (contraction) of the lower atmosphere. ACC densities at 130 km increased by a factor of two to three over 2-3 days (storm onset), in concert with an expansion of the atmosphere by 8 km. Dust opacities also doubled at mid-latitudes, consistent with an increase of TES temperatures in both hemispheres and microwave temperatures (both at ≈30 km) of at least 10-15 K. The gradual decay of this storm occurred over 1-2 months. This observed global response to a regional dust storm, significantly impacting thermospheric densities over the course of 2-4 days, was extraordinary and unexpected.

MGS also confirmed that the Mars lower thermosphere (100-130 km) is a highly variable region on time scales of a day or less. Orbit-to-orbit 2-sigma variability of ACC densities at a constant height was observed to be ≈70% (Keating *et al.*, 1998), in accord with previous Mariner and Viking values (Stewart, 1987). During the onset of the Noachis dust storm, this variability increased to 200%. Longitudinally-fixed thermospheric variations were also observed throughout Phase I that seemed to be correlated with the gross wave#2 features of the topography at Northern mid-latitudes (Keating *et al.*, 1998). Phase II aerobraking witnessed the dominance of wave#1 features throughout Southern mid-latitudes (wave#2 near the equator). This aerobraking experience monitoring the Mars atmosphere near perihelion (Phase I) and near aphelion (Phase II) suggests that the coupling of the Mars lower and upper atmospheres is drived by: (1) inflation/contraction of the atmosphere, and (2) dynamical forcing (tides, planetary waves, gravity waves) connected to the unexplored middle atmosphere (50-100 km) (Keating *et al.*, 1998 ; Bougher *et al.*, 1999).

Initial model studies have been conducted to simulate the Mars lower to upper atmosphere coupling observed by these MGS measurements (Bougher *et al.*, 1999). The Mars Thermospheric General Circulation Model (MTGCM) (70-300 km) and the NASA Ames Mars General Circulation Model (MGCM) (0-90 km) have been crudely coupled for this purpose. Preliminary simulations suggest that the mean solar cycle, seasonal-orbital, latitude, and diurnal variations of the Mars lower thermosphere (aerobraking altitudes) are generally reproduced. However, observed day-to-day variations over 100 to 130 km (70-200%) (especially during the Noachis dust storm period) are not well modeled, owing to missing dynamical processes. It is clear that longitudinally-fixed planetary waves must be properly addressed in 3-D model simulations in order to explain the wave#1, 2 or 3 thermospheric variations monitored throughout Phase I and II. Furthermore, coupled 3-D model simulations have thusfar not been able to reproduce the rapid thermal expansion or the global response of the Mars atmosphere to the Noachis dust event. These model shortcomings point to our present lack of understanding regarding dynamical processes connecting the Mars lower and upper atmospheres. DYNAMO remote/in-situ measurements of the Mars mesosphere and thermosphere will provide global dynamical constraints, enabling a comprehensive characterization of this atmospheric coupling to be obtained. Global monitoring throughout the Mars year and throughout the solar cycle (F10.7-cm = 70-220 units) is critically needed, and will be partially accomplished by DYNAMO.

Plasma Environment

The first in-situ observations of the ionosphere of Mars came from the Retarding Potential Analyzers RPA carried by the Viking landers which provided the first, and so far the only, altitude profiles of the ion composition, density and temperature (Hanson *et al.*, 1977). The subsequent observations made by the Russian Phobos 2 spacecraft launched in 1988 did not make measurements at altitudes below about 850 km on the dayside during the initial phase of operation when the orbit was still elliptical; later when the spacecraft went in a circular orbit, data were acquired at a somewhat lower altitude on the nightside. The data from Phobos 2 which form the most important set of measurements on the Mars ionized environment due to its very complete plasma payload, cover only the outermost regions of the ionosphere and are essentially related to the boundary regions filled with shocked solar wind and pick-up accelerated ions of planetary origin. Unfortunately the relatively short life of this mission, providing only a few elliptic orbits with dayside pericenter and then two months in a circular orbit with active sequences on the nightside, resulted in a very limited spatial coverage. Radio occultation measurements (Kliore, 1992) revealed the existence of a robust dayside ionosphere with a peak electron densities of a few times 10^5 cm^{-3} with seemingly relatively little dependency upon the solar zenith angle on the dayside although the spatial averaging inherent to this technique of observation precludes any firm conclusion. These electron density profiles are in good agreement with the results of Hanson *et al.* (1977). The Viking 1 and 2 RPAs established the existence of significantly enhanced dayside ion temperatures reaching on the order of 3000°K at ~300 km. These high temperatures imply either a modification of thermal conductivities and/or intense heating of the ion gas from above, a situation totally analogous to that at Venus which has remained unresolved. It has been suggested that a high altitude energy input from the solar wind to the planetary plasma, caused by the growth and dissipation of waves due to plasma instabilities, is responsible for this (Taylor *et al.*, 1979; Szego *et al.*, 1991; Shapiro *et al.*, 1995). At larger distances from the planet, Phobos 2 observations revealed the existence of islands of cold plasma in an otherwise low density warmer plasma (Trotignon *et al.*, 1996) and also, in the nocturnal tail of the planet itself, of outflowing low energy suprathermal ions seemingly accelerated at lower altitudes (Lundin *et al.*, 1989). The existence of an induced magnetic field in the tail and its strong dependance on the interplanetary magnetic field (IMF) may be related to such phenomena which thus make the nightside ionosphere very responsive to interplanetary conditions.

One of the important observed features of the Earth ionosphere is the large scale day to night plasma transport around the planet which is expected to be also present on Mars, as in the case of Venus, and which may have important consequences both for the ionosphere itself and for the atmosphere. The ion flows along the flanks of the ionosphere and in the tail is a possibly efficient loss mechanism. Losses can be caused simply by the direct escape of ions towards the interplanetary medium or by the presence of certain instabilities at the ionospheric boundary. An example of the latters is the Kelvin-Helmotz instability, which can lead to the formation of distached plasma blobs which ultimately are dragged by the solar wind. Similar processes have been for example observed on the Earth at the plasmapause where dense plasma clouds from the plasmasphere are distached and dragged away by convection in the outer magnetosphere.

The dayside magnetosphere and boundary layers of Mars were unexplored before the Phobos 2 mission. Phobos 2 carried a very complete plasma payload with a magnetometer, a wave experiment and several particle detectors such as the HARP experiment (Shutte *et al.*, 1989) for both ions and electrons up to 550 eV, the TAUS instrument (Rosenbauer *et al.*, 1989) to measure protons and heavy ions in the 30 eV to 6 keV range and ASPERA, a plasma composition spectrometer that measured the composition, energy and angular distribution of ions up to 24 keV and electrons up to 50 keV (Lundin *et al.*, 1989). The plasma instruments carried onboard of Phobos 2 have identified several plasma boundaries on the dayside of Mars. Several boundaries appear to be located closely to each other, but they exhibit different plasma features (Grard, 1994). Szego *et al.* (1998) concluded that there exists a dayside region at Mars with the following characteristics: (i) the bulk of the shocked solar wind protons is deflected, (ii) the total magnetic field increases, (iii) a plasma depletion region is formed, (iv) both shocked solar wind and planetary plasma are present, (v) accelerated electrons and heavy ions are also present, ions flowing tailward with a velocity of about 50 to 100 km/s corresponding to energies up to 300 eV while the electrons reach even higher energies up to 600 eV, (vi) intensive wave activity is seen in the 5 to 150 Hz frequency interval, and (vii) a current layer and associated magnetic shears can be identified.

The recent MAG/ER observations on the MGS mission have proved the permanent existence of a quite specific plasma boundary : the Magnetic Pile-up Boundary between the Bow Shock and the ionopause. The solar wind interaction with Mars displays both Venus-like (Cloutier *et al.*, 1999) and comet-like (Mazelle *et al.*, 1999) features. The solar wind plasma with its frozen-in interplanetary magnetic field (IMF) perceives the dayside ionosphere as an obstacle. Then, the IMF piles up on the front of the obstacle forming a magnetic barrier. The MPB appears as a sharp and thin plasma boundary marking entry into the magnetic barrier region. Mars' MPB is similar to those detected at comets Halley and Grigg-Skjellerup by the Giotto experiments (Rème *et al.*, 1993 ; Mazelle *et al.*, 1995).

It should be emphasized that the physical processes inside the dayside mantle differs substantially from the processes inside the mantle behind the terminator line. The plasma which populates the dayside region consists essentially of the hot shocked solar wind and colder planetary plasma, both components being equally important. Tailward in the mantle, the "mature plasma" is the result of the dayside interaction, and possesses many of the features observed on the dayside, but it is a distinct plasma region with different plasma populations. The mantle is much broader in the tail than on the dayside. In the tail region both ASPERA and TAUS measured significant fluxes of ions leaving the planet tailward. However, from the limited amount of data the experimenters of the two instruments came to different conclusions whether the ions are leaving the planet in a form of a cylinder, that is more or less independently of the clock angle perpendicular to the Sun-Mars line, or whether the ions leave the planet along a plane close to the ecliptic. Depending on the scenario, the amount of ions leaving the planet is different. The effect of ion pick-up by **E** x **B** in the tail at Mars was studied by Kallio *et al.* (1998) in depth; the conclusion of the study was to stress the importance of these ions as is the case for Venus. Several ion and electron acceleration mechanisms were suggested to account for the various observations of the Phobos 2 particle instrument. These mechanisms, however, need further observations, which must be done with a complete coverage of the energy range, from the deep ionosphere to topside layers, as proposed on DYNAMO.

Exosphere and Escape Processes

Most of our knowledge concerning the high neutral atmosphere of Mars comes from the data acquired during the descent of the Viking landers by the mass spectrometer measurement of Nier and Mc Elroy (1977), at altitudes between 200 and 100 km. Besides composition measurements, which was a major goal of this experiment, neutral gas temperature profiles were also obtained. The observed temperatures were colder than anticipated and also large fluctuations were seen, which were tentatively interpreted as vertical structures arising from atmospheric waves generated at lower levels. Data are available for the hydrogen corona from the Mariner missions (Anderson and

Hord, 1971) and a summary of the situation was reviewed by Nagy *et al.* (1990). The interaction of the solar wind with a planet like Mars is strongly influenced by the thermosphere, previously described, and exosphere which surround it, and a much better knowledge of these regions and their coupling with the ionosphere is needed to ascertain their roles.

The hot neutral component of the upper atmosphere is believed to play a key role in the solar wind interaction processes and the long term evolution of the atmosphere. The nominal altitude of the pericenter of DYNAMO will allow measurements of the hot neutral gas parameters and escape flux throughout the whole exosphere, down to deep thermospheric levels. The pericenter of DYNAMO will be in the thermosphere, about 100 km below the exobase. The classical view is that exospheric neutrals travel in ballistic trajectories that begin and end with collisions with other neutrals near the exobase. On Earth and Venus the dominant neutral species of the upper thermosphere is atomic oxygen; the terrestrial exosphere is dominated by H while at Venus both O and H are important. On Mars, besides O, CO_2 is also likely to be important at the exobase and, like at Venus, both atomic oxygen and hydrogen make up the exosphere. Essentially all of the escaping oxygen comes indirectly from atmospheric CO_2 that effuses from the interior of the planet as a product of volcanism. On Earth, volcanic CO_2 is dissolved by the oceans. The absence of liquid water on Mars at the present means that the current escape of oxygen is an indication of the loss of primordial carbon, in the form of CO_2, from the planet. The relationship of oxygen and carbon loss is uncertain because carbon may escape as C or CO. The detection of the signature of the escaping carbon in the exosphere and/or ionosphere is an important goal of DYNAMO. This will in turn aid in our understanding of the loss rates of other planetary gases that evolve from the interior of Mars, especially radiogenic He and Ar.

The classical theory of planetary exospheres presumes that the exobase is a surface, that exobase atoms and molecules have thermal velocity distributions, and that these atoms travel over the exobase in ballistic trajectories. In reality, neutrals at the exobase are decidedly non-Maxwellian for a variety of reasons. Even in the simpliest scenario, where upward moving atoms near the exobase have a Maxwellian distribution, the escaping component must be missing among the atoms returning to the exobase (Hodges, 2000). Above the exobase, the transfer of vertical velocity to gravitational potential leads to systematic temperature anisotropies. Neutral species that collide with ions gain kinetic energy by momentum transfer because the ions have much higher temperatures than the neutrals. These interactions produce a hot component of neutrals in the exosphere; they also inject some atoms into quasi-stable satellite orbits (Hodges, 1994 and 1998). The trajectory of a light atom, such as H or He, is a chain of Keplerian orbit segments, interrupted by impulsive velocity changes due to resonant scatter of solar photons. The net effect of resonant scatter can be thought as an antisolar radiation pressure that pushes apocenters of ballistic trajectories toward the Mars-Sun axis.

Another nonthermal processes that is especially important on Mars is the creation of fast neutrals by dissociative recombination of molecular ions and by exothermic ion-neutral reactions. Among the most important are the dissociative recombination of O_2^+ which produces atomic oxygen atoms with energies of 3.1, 5 and 7 eV, the O_2^+/CO_2 or CO_2^+/O reactions which produce CO atoms with energies of 1.3 eV and reactions involving He^+ with O_2, N_2 or O which produce helium atoms with energies of 12.5, 9 and 11 eV respectively. The velocity of a product neutral is equal to the vector sum of the velocities corresponding to the reaction energy in a random direction and the velocity of the center of mass of the reactants. For recombination there are two neutrals that depart from the center of mass in opposite directions. To put the neutral velocities in perspective, the escape velocity at 300 km is 4.8 km/s, the minimum satellite velocity is 4.3 km/s, and the thermal velocities of the parent ions are not negligible at typical ion temperatures. These reactions produce two fast particles, that share the resulting excess energy. Generally, one particle has an upward velocity and may enter the exosphere, while the partner goes downward. The probability that the upward going particle will avoid collision with a thermospheric neutral and reach the exosphere increases with altitude and with the proximity of the velocity vector to the vertical. Upgoing fast particles that do not escape or ionize in the exosphere, and all of the downward going partners, eventually deposit their energy in the thermosphere by collisional processes. Near the exobase, these events create splashes of suprathermal neutrals, some of which enter the exosphere (Nagy *et al.*, 1981; Hodges, 1993).

Primary fast neutrals, and the suprathermal progeny of their collisons with thermal neutrals, that enter the exosphere with speeds in excess of the escape velocity, 4.8 km/s, escape into Mars-crossing orbits around the Sun where they eventually ionize and then escape totally by $\mathbf{v} \times \mathbf{B}$ acceleration in the solar wind. Others with velocities greater than the minimum satellite velocity, 4.3 km/s, may be injected into the quasi-stable satellite orbits. Many of these escape through ionization.

At exospheric altitudes, one of the dominant neutrals should be the exothermic atomic oxygen created by dissociative recombination of O_2^+. Some insight into the distribution of atomic oxygen on Mars can be found in the solution of the analogous problem for Venus studied by Hodges (1993). If Venus is a guide, the velocity distributions on Mars should be similar, but the onset of satellite atoms must be near 3.5 km/s; hence the orbiter population should account for an even greater fraction of the fast atoms than on Venus. This suggests that the fast O density should be increased by a factor between 10 and 100. The non-escaping hot oxygen in the exosphere is of great importance for the interaction of the solar wind with the planet. The creation of high altitude O^+ from hot neutral O is also important from the escape point of view since these ions can escape by being picked-up by the solar wind. Estimates of the ion escape rate are sketchy, in part because the global distribution of O_2^+ has not been measured but also because the effects of these ions on solar wind loading is still speculative. These questions will be addressed by DYNAMO. However, direct escape of fast neutrals is even less understood, and is possibly the most important part of the oxygen escape flux. Owing to the generally oxidized state of the planet, the loss of atmospheric oxygen cannot have a noticeable effect on the total oxygen abundance on Mars. However, when the oxygen escape rate is viewed as an indicator of the rate of photodestruction of CO and CO_2 it takes an obvious significance. Presumably, elemental carbon and/or CO is also escaping and the O escape rate is an indicator of the rate of active degassing of CO_2 from the planet. On the other hand, if no evidence is found for carbon escape, the oxidation path that recycles elemental carbon and/or CO back into CO_2 is all the more interesting. It is important to note that we have no direct measurements of elemental C and O. These elements were seen in the Viking neutral mass spectra but were, to a large degree, the result of dissociation of CO and CO_2 by the energetic electrons in the source. The velocity distributions of parent and progeny C and O obtained near pericenter will certainly help resolving this issue.

The measurement of isotopic ratios, like $^{36}Ar/^{38}Ar$ or $^{18}O/^{16}O$, possibly achieved by DYNAMO, will provide a diagnostic of cumulative past escape, because escape results in isotopic fractionation.

Solar Wind Absorption as an Atmospheric Source

Most work to date has focused on the atmospheric losses associated with the Mars-solar wind interaction. However, as long as the Martian magnetic field has ceased to deflect the solar wind well above the upper atmosphere, there has certainly been some absorption of solar wind ions as well. Solar wind ions can be absorbed in the classical sense, when the ion trajectories close to the planet cross over the exobase where collisions retain the particles. They can also be absorbed in a way that effectively switches an atmospheric particle for a solar wind particle. In the charge exchange process, the solar wind ion (usually a proton) adopts an electron from an upper atmosphere neutral, leaving behind an atmospheric ion that is then subject to solar wind pickup and removal. In the latter case, the neutral produced above the exobase must be on a trajectory that allows it to either cross the exobase, or to be trapped in orbit around the planet. Only a few calculations have attempted to address absorption processes, and these have focused on the modern era. In one recent analysis (Brecht, 1997), Brecht performs a numerical simulation of the Mars-solar wind interaction using a particle description of the solar wind protons, and examines the proton flux that enters the atmosphere. In this case the physics underlying the absorption is related to the small size of the weakly magnetized Martian obstacle to the solar wind, compared with the gyroradius of the solar wind ions in the interplanetary magnetic field piled up against the obstacle. In the other relevant study by Kallio et al. (1997), the deposition in the atmosphere of neutralized solar wind protons born in the charge exchange collisions is estimated. As even the modern cases require many assumptions to model solar wind absorption, the prospect of a historical study is daunting. Nonetheless, it would be possible to use the techniques developed by the above authors to model solar wind absorption through time if the nature of the obstacle (magnetospheric or ionospheric, in particular), and the solar wind history, were known.

HIGH-RESOLUTION MAPPING OF MARTIAN FIELDS : GENERAL OBJECTIVES

Toward an Integrated View of the Mars System

The scientific investigations of the DYNAMO mission will provide new and improved insights into the evolution and the present state of the Martian mantle and crust. In this respect, the global mapping of magnetic anomalies and of the electric structure down to a few hundred kilometers and the measurement of gravity profiles will be of greatest interest. However, due to the interactions between the core, mantle, crust and atmosphere reservoirs, the determination of the magnetic field history in the core and the evolution of the atmosphere also planned by DYNAMO will allow further constraints to be placed on mantle and crust structure and evolution models. The recent finding by Mars Global Surveyor of a crustal magnetic field on Mars, while a strong dipole field is lacking, suggests that Mars had an early self-generated magnetic field. But the surface coverage of about 20 % is not sufficient to allow detailed modeling of the history of the magnetic field generation and the sources of these anomalies. Instead a global mapping of the magnetic anomalies by DYNAMO together with a determination of the age distribution of the surface by crater counting is required.

Through a study of the evolution of the magnetic field, one can derive constraints on the thermal evolution of the mantle: magnetic field generation in the core is strongly influenced by the overlying mantle. Convection in the core depends on the heat transfer rate in the mantle since the core can only cool at a rate that is dictated by the mantle. If the vertical heat flow in the lower mantle can be balanced by heat conduction down the core adiabat, the core becomes stably stratified with respect to convection and the dynamo ceases to operate. For larger values of core to mantle heat flow, heat is transferred in the core by convection and the dynamo is likely to be active. It has been shown that phase transitions in the lower mantle may interact with the convective flow and may seriously influence the heat transfer rate in the mantle. In particular the spinel to perovskite phase transition, the presence of which depends on the core size and the lower mantle temperature, may act as a barrier to the heat flow from the core thereby reducing the available power for generating a magnetic field. It is possible that various paths of evolution of the dynamo action could explain the data. However, a determination of the present state and the size of the core from seismic data by NetLander together with the data from DYNAMO would strongly constrain the evolution models of the core and the mantle.

The global mapping of magnetic anomalies may also provide information about their sources and the tectonic activity on Mars. Because the anomalies are observed from high altitude, satellite data can be used to detect anomalies only of large spatial scale and large magnetization contrast. To resolve the source of the anomalies measured at an altitude of about 120-130 km, their extent must exceed approximately the altitude of the orbiter. The cause can be a wide variety of factors, for instance by large ore deposits, lateral thickness variations in the crust or lithosphere or spatial variations in the magnetization of the material. Differences in the crust and lithosphere thicknesses are expected between the southern and northern hemisphere along the crustal dichotomy. The border of these hemispheres could be a source for a detectable anomaly. An analysis may provide some explanations for the unknown origin of the dichotomy. Anomalies may also be relicts of an incomplete core differentiation with iron or iron-rich blocks magnetized in an early Martian field which are stuck in the crust or upper lithosphere. There is some evidence that the inner terrestrial planets have been formed at least partly by planet embryos which had been already differentiated into core, mantle and crust. If there was no deep magma ocean at the end of the accretion it would be possible that some of these iron cores did not sink through the relatively stiff upper layer into the convecting mantle and from there to the Martian core. The magnetized iron cores of these planet embryos would result in relatively strong anomalies due to the high susceptibility of iron. In addition, tectonic features may be the source of anomalies. For instance, it would be possible to examine the hypothesis of early plate tectonic. In the region of ancient subduction zones, anomalies result from the changing direction of the remnant magnetic field. If plate tectonics existed on early Mars this would play an important role for the heat transport mechanism of the mantle and for the thermo-chemical evolution in general. It is likely that the anomalies are caused by a combination of different sources. The precise sources of the anomalies are difficult to derive from the anomalies alone. But in combination with other geophysical and geological data such as seismic, gravity, electric conductivity and surface geology data, it would be possible to better understand the nature and evolution of the Martian crust and lithosphere.

The thickness of the crust and its variation over the entire planet can be constrained by the gravity data obtained from DYNAMO. With the seismic stations of NetLander an independent assessment of the crust thickness at least in some places of the planet is possible and may serve as anchoring points for models based on the global gravity field. Together with topography data, it will be possible to analyze the compensation depths of geological structures and the lateral temperature variation in the mantle. Here, the Tharsis region is of particular interest because a hot plume is expected to be located underneath. NetLander stations in that area will provide the crust thickness to strongly constrain the models. Additional data on the internal structure and the thermodynamics will be obtained by mapping the electric conductivity from the uppermost layers down into the upper mantle to about 400 km. At depth deeper than the crust, the electric conductivity depends strongly on the temperature, therefore lateral temperature variations in the upper mantle might be detected. Comparing these models with the gravity and tomographic inversion models, one can be able to constrain the convection and thermal evolution models. Moreover, an interesting goal of this study is to find liquid water in the subsurface layers.

The crust thickness is an important piece of information for models of mantle dynamics. Crust formation through mantle differentiation depletes the mantle in incompatible elements which are important heat sources for the mantle dynamics. The redistribution of the radioactive elements from the mantle into the crust with time influences, therefore, the convection flow and the heat transport rate. The crust production rate depends on the temperature distribution and the solidus of the mantle material. Simple scaling laws relate the crust production rate to the vigor of mantle convection, the potential crustal components in the mantle and the lithosphere thickness. Knowing the crust thickness together with the age distribution of the crustal regions, the mantle differentiation process will be better understood.

Improvement of Gravity and Magnetic Field Resolution for Tectonic Problems

The DYNAMO mission should provide a great improvement over Mars Global Surveyor (MGS) in resolution and coverage for magnetic and gravity field data. The proposed periapsis altitude for DYNAMO of 120-130 km, coupled with the global distribution of periapses to be obtained during one Martian year of operation, will produce a magnetic field data set with approximately five times the spatial resolution of MGS. Some gravity data were acquired at low altitude in the northern hemisphere (Smith *et al.*, 1998). The gravity field data for MGS are now obtained at an altitude of 360-400 km, from the nominal circular orbit.

The increased coverage and resolution of DYNAMO will allow for better definition of the crustal magnetic anomaly sources and elastic lithospheric thickesses for smaller geologic features. These data will extend the reconnaissance-oriented analyses of MGS data and enable systematic process-oriented studies to be undertaken. In addition to enhanced resolution of the magnetic anomalies, comparison of DYNAMO data with spatially coincident MGS data will allow an assessment of noise in the magnetic data due to spacecraft fields and time-varying external (ionospheric) fields of Mars. The increase in resolution will allow identification of discrete sources at a scale of hundreds of km, providing information on the three-dimensional distribution of sources. This will be very useful for placing the sources in a stratigraphic context and understanding the origin of the magnetic remanence. Magnetic anomalies of features such as Valles Marineris should be well-resolved, allowing an assessment of the presence of linear, age-progressive anomalies such as might be expected if a rifting had occurred during reversals of the magnetic field. Structures at high latitudes will be well-resolved, allowing detailed studies of their origin. Assuming that a relative age relationship between possible magnetic reversals can be determined, regional studies can be placed into a global context to understand the magnetic field history, and thus by inference, the thermal evolution of the planet.

Assuming that the gravity field can be obtained at the periapsis altitude, the enhanced resolution has a very great impact on the types of problems that can be addressed. In particular, the elastic thickness and loading structure of a variety of geologic features and provinces can be better determined. For MGS, the wavelength of features that can be well resolved is approximately 700-800 km. Thus the hemispheric dichotomy, many volcanoes, and other regional scale features can not be well resolved. Elastic thicknesses are best estimated using coherence techniques (Forsyth, 1985) as the uncertainties introduced by the position of the load flexing the lithosphere (top-loads or bottom-loads) can be eliminated and used to better understand the loading history of a given geologic feature. For a DYNAMO periapsis of 120 km and a wavelength of ~250 km, elastic thicknesses of approximately 25 km can be well resolved. In contrast, for the resolution from MGS, elastic thicknesses of approximately 75 km can be determined from coherence methods. The global gravity resolution of MGS will be very similar to that of the Magellan data for Venus. Although smaller values of elastic thickness can be determined from admittance techniques for Venus, they contain considerable uncertainties (e.g. Simons *et al.*, 1994; Smrekar and Stofan, 1999). The typical range of estimated elastic thicknesses from modeling topographic profiles on Mars is 10-110 km (Solomon and Head, 1990). Given this range, it is clear that the ability to determine small values of elastic thickness with certainty is important both for understanding the formation of individual features and for determining globally how the elastic lithosphere has evolved over time.

Using the Magnetic Dynamo data for probing the Electrical Structure of Mars

The magnetic field of a planet may result from two primary sources, convection in a conductive liquid core and interaction between the planet and solar wind plasma, and from two secondary sources, local magnetisation of crustal and lithospheric rocks and electric currents induced in the planet by the transient magnetic fields of external origin. The external natural fluctuations (the primary source) of the magnetic field induce an internal response (the secondary source) that can be used to infer the electrical conductivity structure of the planet. The maximum depth resolved by using this technique is a function of the longest period of variations of the external magnetic sources that may be recovered from the data. The external transient variations result from both the interactions between the planetary environment and the solar wind plasma. For Mars, qualitative considerations show that magnetic field perturbations at the surface are expected to have maximum amplitude ranges between 10 to 20 nT, with typical variation times greater than 30 to 60 seconds. The morphology of the magnetic variations at the surface of Mars is expected to be intermediate between those of the IMF and those observed in auroral and polar magnetic activity on the Earth, since the source (solar wind fluctuations) and the spatial-temporal filter effects of the conducting ionosphere are similar.

Traditionally, induction studies on Earth make use of magnetic data recorded continuously at stations set up at the surface transitionally or permanently (the geomagnetic observatories). The upcoming of several magnetic satellite missions in the next years has triggered the interest of the Electromagnetic Induction community to use satellite data to investigate the electrical conductivity of the Earth. The satellites provide a complete coverage of the planet. Several studies both theoretical and with the 15 years old MAGSAT data have shown that the secondary induced field may be recovered from the satellite magnetic data and that electrical conductivity may be derived from them. These studies also emphasise the advantage to have simultaneously the time and spatially changing magnetic field from satellite and land stations with continuous time series.

There is therefore a great interest to apply a similar approach for the Mars exploration. Measuring the Mars vector magnetic field from a satellite like DYNAMO offers the unique opportunity to investigate at planetary scale the Mars mantle electrical conductivity. This parameter depends strongly on the temperature, partial melting, fluid phase as well as on the mineralogy and may provide strong constraints upon the mantle structure.

EXECUTIVE SUMMARY

Main scientific objectives

Concerning atmosphere and escape processes, the main objectives of DYNAMO are to:

- understand how the whole physical-chemical atmospheric system works, by:

→ extending chemical measurements of Mars-Express up to thermospheric/ionospheric levels in order to model the full atmospheric chemical system and quantify neutral/ion reservoirs available for escape ;

→ monitoring thermospheric dynamics and the way it couples with lower atmosphere ;

→ characterizing ionospheric dynamics and how dynamics couples with chemistry ;

- determine, as a function of solar conditions, the nature and efficiency of the various phenomena involved in the interaction of the upper atmosphere with solar wind by:

→ characterizing the various boundaries, including the exobase, in terms of magnetic, ion, electron and energy distribution discontinuities ;

→ studying fluxes of charged particles and their space/momentum/energy distribution in the ionospheric cavity and magnetotail ;

- study, as a function of solar conditions, the processes by which energy is transferred from the solar wind to the planetary atmosphere and how its dissipation affects its dynamics and its structure by:

→ measuring fluxes and energy distributions of entering solar wind particles, and pick-up ions, in the "sputtering zone" (150-300 km) and above as a function of altitude ;
→ assessing the relative roles of solar UV absorption, electron impact, charge exchange ionization in the energy budget of the upper atmosphere and, by inference, in the global dynamics as well as in the formation rate of pick-up ions ;
→ measuring upward fluxes and energy distribution of escaping neutrals and ions, estimating the total atmospheric loss rate, and its variations with solar wind and UV flux ;
→ assessing the relative weights of sputtering, dissociative recombination and ion escape in atmospheric mass loss ;
→ assessing the relative roles of sputtering and dissociative recombination in populating exospheric levels resulting in possible positive retroaction on escape ;
- analyze the role of the complex structure of the Martian magnetic field on the interaction with the solar wind,
- study, as a function of solar conditions, the nature and the rate of solar wind absorption ;
- evaluate, through physical-chemical modelling of the whole neutral atmosphere/ionosphere/solar wind system, the consequences of atmospheric and ionospheric processes on the escape and long term evolution of the atmosphere, and use measured values of isotopic ratios as a mean of diagnostic.

Objectives related to the solid planet are mainly oriented toward:
- investigate at planetary scale the mantle and crust electrical conductivity ;
- better define crustal magnetic anomaly sources and elastic thicknesses for small geologic features, enabling systematic process-oriented studies ;
- place these sources in the stratigraphic context and understand the origin of magnetic remanence ;
- evidence possible magnetic reversals, understand magnetic field history and, by inference, the thermal evolution of the planet ;
- determine by gravimetry the elastic thickness (3 times better spatial resolution than MGS) and loading structure of a variety of geologic features and provinces ;
- search for traces of ancient tectonism as imprinted on magnetic high resolution maps.

Payload and planned measurements

The nominal payload consists of : a flux gate magnetometer, a Langmuir probe, which may be used as EUV meter (under study), an energetic ion/electron spectrometer, an ion/neutral mass spectrometer, for the different types of thermal and suprathermal populations, a three-axis accelerometer, a system of density gauges, and a UV airglow spectrometer. The X-band transponder required for navigation purpose will be used for gravity measurements. The possibility of including an ultra-stable oscillator, for density profile retrieval, and plasma instruments dedicated to refined electron measurements is also studied. In the present concept, the mass of the core payload is about 10 kg, for a mean power of 15 W, and is increased up to 15 kg by adding optional instruments.

Previous instruments are used for the following purposes :
- planetary magnetic field mapping, full coverage (improving by a factor of 5 the MGS coverage) ;
- electrical structure of Mars through measurement of magnetic variations ;
- planetary gravity field mapping, at high spatial resolution (improving by a factor of 3-5 the MGS resolution) ;
- in situ probing of thermospheric composition, temperature and wind, full vertical/horizontal coverage (follow up of MGS) ;
- in situ probing of deep ionosphere chemical/dynamical structure: vertical, latitudinal and seasonal variations ;
- in situ probing of energetic neutrals/ions/electrons fluxes and energy spectra in the 100-400 km altitude range (in complement of Mars-Express: z≈400 km, and Nozomi: only equatorial regions) ;
- in situ characterization of solar wind/ ionosphere three-dimensional magneto-hydrodynamic interaction.

REFERENCES

Acuna, M.H. et al., Magnetic field and plasma observations at Mars: Initial results of the Mars Global Surveyor Mission, *Science*, **279**,1676-1680, 1998.
Anderson, D.E. and C.W. Hord, Mariner 6 an 7 ultraviolet spectromemter experiment: Analysis of hydrogen Lyman alpha data, *J. Geophys. Res.*, **76**, 6666, 1971.
Ayres, T.R., Evolution of the solar ionizing flux, *J. Geophys. Res.*, **102**, 1641, 1997.
Brecht, S.H., Solar wind proton deposition into the Martian atmosphere, *J. Geophys. Res.*, **102**, 11,287, 1997.
Bougher, S. W. et al., Mars Global Surveyor aerobraking : atmospheric trends and model interpretation, *Adv. Space Res.*, **23**, 11, 1887-1897, 1999.
Cloutier, P.A., et al., Venus-like interaction of the solar wind with Mars, *Geophys. Res. Lett.*, **26**, 17, 2685, 1999.
Forsyth, D. L., Subsurface loading and estimates of the flexural rigidity of continental lithosphere, *J. Geophys. Res.*, **90**, 12,623-12,632, 1985.
Grard, R., The wave and plasma environment of Mars, *Current Science*, **66**, 562, 1994.
Hanson, W. B., S. Satani, and D. R. Zuccaro, The Martian ionosphere as observed by the Viking retarding potential analyzers, *J. Geophys. Res.*, **82**, 4351, 1977.

Hodges, R.R., Isotopic fractionation of hydrogen in planetary exospheres due to ionosphere-exosphere coupling : implications for Venus, *J. Geophys. Res.*, **98**, 10833-10838, 1993.

Hodges, R.R., Monte Carlo simulation of the terrestrial exosphere, *J. Geophys. Res.*, **99**, 23229-23247, 1994.

Hodges, R.R., Exospheric dynamics of hydrogen and deuterium at solar minimum, *J. Geophys. Res.*, **103**, 2155-2162, 1998.

Hodges, R.R., Distributions of hot oxygen for Venus and Mars, *J. Geophys. Res.*, **105**, 6971-6981, 2000.

Hutchins, K.S., B.M Jakosky and J.G. Luhmann, Impact of a paleomagnetic field on sputtering loss of Martian atmospheric argon and neon, *J. Geophys. Res.*, **102**, 9183, 1997.

Jakosky, B.M., R.O. Pepin, R.E. Johnson and J.L. Fox, Mars atmospheric loss and isotopic fractionation by solar wind-induced sputtering and photochemical escape, *Icarus*, **111**, 271, 1994.

Kallio, E., J.G. Luhmann and S. Barabash, Charge exchange near Mars: The solar wind absorption and energetic neutral atom production, *J. Geophys. Res.*, **102**, 22,183, 1997.

Kallio, E., J.G. Luhmann and J.G. Lyon, Magnetic field near Venus- a comparison between Pioneer Venus Orbiter magnetic field observations and an MHD simulation, *J. Geophys. Res.*, **103**, 4723, 1998.

Keating, G. M. et al., The Structure of the Upper Atmosphere of Mars : In Situ Accelerometer Measurements from Mars Global Surveyor, *Science*, **279**, 1672-1676, 1998.

Kliore, A. J., Radio Occultation Observation of the Ionospheres of Mars and Venus, in: AGU Monograph 66, p. 265, 1992.

Luhmann, J.G., R.E. Johnson and M.H.G. Zhang, Evolutionary impact of sputtering of the Martian atmosphere by O^+ pick-up ions, *Geophys. Res. Lett.*, **19**, 2151, 1992.

Lundin et al., First measurements of the ionospheric plasma escape from Mars, *Nature*, **341**, 609, 1989.

Mazelle, C., et al., Comparison of the main magnetic and plasma features in the environments of comets Grigg-Skjellerup and Halley, *Adv. Space Res.* , **16**, (4)41-(4)45, 1995.

Mazelle, C., et al., Comet-like features in the interaction of the solar wind with Mars, *Geophys. Res. Lett.*, 1999, in press.

Nagy, A.F., T.E. Cravens, J.H. Yee and A.I. Stewart, Hot oxygen atoms in the atmosphere of Venus, *Geophysic. Res. Lett.*, **8**, 629, 1981.

Nagy, A. F., *et al.* , Venus Mantle - Mars Planetosphere: What are the Similarities and Differences? *Geophys. Res. Lett.*, **17**, 865-868, 1990.

Nier, A.O. and M.B. McElroy, Composition and structure of Mars' upper atmosphere : results from the neutral mass spectrometers on Viking 1 and 2, *J. Geophys. Res.*, **82**, 28, 4341, 1977.

Rème, H., et al., Electron plasma environment at comet Grigg-Skjellerup : General observations and comparison with the environment at comet Halley, *J. Geophys. Res.* , **98**, 20965-20976, 1993.

Rosenbauer et al., Ions of Martian origin and plasma sheet in the Martian magnetosphere: initial results of the TAUS experiment, *Nature*, **341**, 612, 1989.

Shapiro, V. D., *et al.*, On the interaction between the shocked solar wind and the planetary ions in the dayside of Venus, *J. Geophys. Res.*, **100**, 21,289, 1995.

Shutte et al., Observation of electron and ion fluxes in the vicinity of Mars with the HARP spectrometer, *Nature*, **341**, 614, 1989.

Simons, M., B.H. Hager, and S.C. Solomon,Global variations in the geoid/topography admittance of Venus, *Science*, **264**, 798-803, 1994.

Smith, D. E., Zuber, M. T., Lemoine, F. G., Gravity Field Mapping of Mars with MGS (abstract), *Eos, Trans. Am. Geophys. Un*, **79**, F524, 1998.

Smrekar, S.E., and E.R. Stofan, Origin of Corona-Dominated Topographic Rises on Venus, *Icarus*, **139**, 100-115, 1999.

Solomon, S. C., and J. W. Head, Heterogeneities in the thickness of the elastic lithosphere of Mars: Constraints on heat flow and internal dynamics, *J.Geophsy. Res.*, **96**, 11,073-11,083, 1990.

Stewart. A. I. F., LASP-JPL Internal Rep. # NO-802429, JPL, Pasadena, CA., 1987.

Szego K, *et al.* , Physical processes in the plasma mantle of Venus, *Geophys. Res. Lett.*, **18**, 2305-2308, 1991.

Szego K., S. Klimov, G. A. Kotova, S. Livi, H. Rosenbauer, A. Skalsky, and M. I. Verigin, On the dayside region between the shocked solar wind and the ionosphere at Mars, *J. Geophys. Res.*, **103**, 9101-9112, 1998.

Taylor, W.W.L., F.L. Scarf, C.T. Russell and L.H. Brace, Absorption of whistler mode waves in the ionosphere of Venus, *Science*, **205**, 112, 1979.

Trotignon, J. G., *et al.*, Martian planetopause as seen by the plasma wave system onboard Phobos 2, *J. Geophys. Res.*, **101**, 24,965, 1996.