Kiruna Mars Workshop: Solar wind interaction and atmospheric evolution

Swedish Institute of Space Physics, IRF
Kiruna, Sweden

27 February – 1 March 2006

Abstract Booklet

Editors: S. Barabash, E. Carlsson, and H. Gunell

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Preface

The Kiruna Mars Workshop is being organised at the Swedish Institute of Space Physics in Kiruna 27 February - 1 March 2006.

The objective of the meeting is twofold. The first is to review the modern views of the solar wind interaction with Mars and its impact on the Martian atmosphere. The second is to bring together teams working with data from plasma instruments now operational at Mars, i.e., the particle and field sensors aboard MGS and MEX.

The workshop will follow the Kiruna style. Invited speakers will give oral presentations with plenty of time for discussions. Each talk is one hour with approximately 40 min for presentation and 20 minutes for discussions. Questions and discussions during the presentation are welcome. All contributed papers will be presented as posters. The 3-day workshop includes 17 invited talks and 2 poster sessions. A special issue of Space Science Reviews will be dedicated to papers presented at this workshop.

Kiruna, 17 February 2006

Stas Barabash, Ella Carlsson, and Herbert Gunell

Programme

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Poster session 2: Wednesday 1 March 16:00 - 17:30

Oral session 1
Monday 27 February

The Magnetic Field of Mars: Past, Present and Future

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Presently, Mars possesses no intrinsic global magnetic field but experimental evidence from Mars Global Surveyor suggests that one similar to that of Earth's once existed in its distant past. This evidence is based on the existence of strong crustal magnetization in the ancient terrain of the highlands south of the dichotomy boundary. The deficiency in magnetization in surrounding volcanic provinces and impact basins suggests that the crust gained its magnetic remanence early on via an internal dynamo that became dormant by the time of the last major impacts. This unique timing of the epoch of dynamo cessation has important implications for the history of Mars atmosphere, ionosphere and volatiles. Ion pick-up becomes a significant atmospheric loss mechanism operating for billions of years, enhanced by the low gravity environment and corresponding large scale height that allow the solar wind to interact with exospheric neutrals over an extended volume of space. The MGS magnetic field measurements explored $< 20\%$ of the surface at periapses ranging from 100 km to 400 km during the aerobraking and mapping orbits. A major question raised by the observations is what is the true spatial scale of the intense magnetic anomalies and missions such as ARES (Mars airplane) as well as others using balloons are being proposed to resolve this major puzzle from low altitude platforms. Although Mars Express does not measure magnetic fields directly, the activation of the MARSIS experiment has revealed an unexpected source of scalar in-situ magnetic field data that coupled to the complementary data acquired by the ASPERA and other MEX investigations will allow a significant extension of the MGS and PHOBOS results.

Mars Ion Boundaries - ASPERA-3 Observations

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and the ASPERA-3 team

The plasma boundaries caused by the interaction of the solar wind and the ionosphere of Mars have so far only been determined by magnetic field observations of the MAG-ER-experiment on board Mars Global Surveyor - apart from some earlier measurements by the Phobos mission. The Aspera-3 experiment on board Mars Express measures electrons, protons and heavy ions at thermal and at higher energies. We exploit this capability to investigate the build-up of ion boundaries related to the magnetic pile-up boundary and the penetration of different ion species into the Martian ionosphere. Specifically we discuss the impact of the He^{++}- penetration on the ionospheric erosion.

Martian Tail

A. Fedorov[1] and ASPERA team

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According to the first theoretical model of cometary tails by Alfvén (1957) the region behind the gaseous non-magnetic planet looks like a long wake filled by draped magnetic field with the large B_X component. The first *in situ* measurements performed by Mars-5 mission has shown that the martian magnetotail exists and is filled by low energy ions of probably planetary origin. Moreover it was shown that magnetotail boundary confines of the heavy ions domain. The next important step in the understanding of the martian tail structure was made after the PHOBOS mission. ASPERA and TAUS experiments have shown the composition, dynamics and structure of the planetary wake. It was shown that picked-up high energy ions lose their energy closer to the tail center. But at the same time another intense and almost monoenergetic plasma flow called "plasma sheet" appearers in the current sheet region between the magnetic lobes. The mechanism of ion acceleration in the plasma sheet is not clear up to now. The last data obtained from ASPERA-3 experiment onboard the Mars Express mission allows to clarify the view on the martian wake problem. Extremely good epoch superposition statistics and rather good mass resolution give the chance to see the tail structure in details. Present work shows the last statistical data obtained from ASPERA-3 experiment and discusses the different mechanisms of creation of such a structure. The paper also discusses the role of magnetic anomalies in the formation of the plasma sheet.

Submitted on 2006.01.13

Abstract for the 'Mars-solar wind interaction and atmosphere evolution' conference in Kiruna.

MARSIS ionosphere sounder results

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MARSIS (= Mars Advanced Radar for Subsurface and Ionosphere Soundings) on board the Mars Express orbiter is a low frequency radar used to sound the top side ionosphere in the range from 0.1 to 5.4 MHz. The planet's atmosphere and solar radiation interacts to form an ionosphere, which typically gives rise to radar echoes from nadir caused by specular reflections from the horizontally stratified electron densities. The characteristics of this dominant electron density peak are as predicted for a Chapman layer. Occasionally the echo traces are diffuse in the low frequencies indicating a 'broken up' top side ionosphere. Off nadir echoes mainly arise from stationary ionosphere structures. These are likely caused by spatially varying precipitation of solar wind energy into the ionosphere controlled by the inclination of the magnetic field lines. Exploiting observations for varying nadir angles and considering the spacecraft dynamics, the locations of reflecting structures can be identified. Some nighttime observations suggest the presence of 'holes' in the ionosphere. During nighttime the ground reflected signal is usually observed, but on occasions it disappears for long times indicating extraordinary long lasting radio wave absorption. In case of non-propagation of the transmitted radar signal electron plasma oscillations are excited with a frequency determined by the local electron density. When the spacecraft is in a region of magnetic fields of more than ~10nT periodicities in the received signal indicates excitation of the electron cyclotron period. This implies that the radar can measure the magnitude of the local magnetic field in the ionosphere. Where there are different spatial scales of the crustal magnetic field (short) and the sun induced field (large) the components may be separated and the components estimated.

Poster session 1
Monday 27 February

The role of plasma waves in Mars' atmospheric loss

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Abstract

An analysis of recent observations of plasma waves, electron fluxes, and ion fluxes in Mars' ionosphere indicates that ion heating may have had a considerable impact on Mars' atmospheric loss. We discuss two energy sources of plasma waves: the solar wind interaction with Mars and field-aligned currents in the cusps of the crustal magnetic fields. These plasma waves can damp through cyclotron resonance with the O^+ population in the ionosphere leading to substantial heating and subsequent O^+ escape. These mechanisms can support $\sim 10^{25}$ atoms s^{-1} (~0.4 kg/s) O^+ outflow indicated by observations. We suggest that a stronger source of O^+ ~4 Gyr ago could support losses on the order of 100 kg/s, enough to strip Mars atmosphere or 10 m of water in a ~0.3 Gyr period. The observational evidence for ion heating is, with current data sets, largely circumstantial so we suggest needed observations.

Investigation of the Signal from the Limb Obtained by the Neutral Particle Imager and Possible Implications

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We report on the progress of our study using the data obtained from the Neutral Particle Imager (NPI) on board ASPERA-3. NPI has observed a signal coming from the direction of the limb with varying intensity and distribution. While the scanning motion of the instrument is currently disabled, preventing instantaneous sampling of the global limb distribution, we use several eclipse passes of the Mars Express (MEX) spacecraft to determine the statistical distribution of the signal. Milillo and Mura have indicated in previous studies a higher intensity when MEX is located in the northern ecliptic portion of the umbra. Brinkfeldt et al. showed that the limb signal displayed high intensity variation that they hypothesized could be temporal. We investigate three different source mechanisms for the signal:

(1) Photons scattered (or resonantly reradiated) in the upper atmosphere;
(2) Solar-wind hydrogen ENAs scattered in the upper atmosphere;
(3) Atmospheric ENAs produced by charge exchange between outflowing heavy ions such as O^+ and the exosphere.

Specifically we assemble statistical distributions ordered in inertial directions (e.g. sunward). While no quantitative conclusions can be made at this stage we assess the physical implications for these mechanisms. Mechanism (2) provides a method for investigating the solar-wind ENA precipitation onto the dayside upper atmosphere. We use this method to estimate the energy input to the dayside and compare it to the energy input given by the solar photon flux. The relative importance of neutral particle precipitation at Mars is compared to the conditions at Titan using recent ENA observations obtained by the Ion and Neutral Camera (INCA) on board the Cassini spacecraft. The atmospheric effects are investigated using a data-driven atmospheric circulation model applied to Titan. We aim at investigating mechanism (3) further by comparing the distribution of the NPI signal with ion observations from the Ion and Mass Analyzer (IMA).

PLASMA MORPHOLOGY AT MARS. ASPERA-3 OBSERVATIONS

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The ASPERA-3 experiment on the MEX spacecraft provided us with a wealth of data on the plasma environment of Mars. The environment is controlled by the direct interaction between the solar wind and planetary atmosphere/ionosphere which results in the formation of a magnetospheric cavity. In this paper we analyze morphological features of the main magnetospheric regions. The ionospheric plasma is well traced by the characteristic 'spectral lines' of the photoelectrons. Plasma of solar wind and planetary origin is diagnosed by ion mass spectrometry. It is observed that the momentum of the solar wind is effectively transferred into the magnetosphere driving the motion of planetary 'photo-ions' and ionospheric plasma. Photo-ions gain significant energy and occupy two main reservoirs, the boundary layer/mantle adjacent to the magnetospheric boundary and the plasma sheet. Photo-electrons are also recorded far above nominal ionosphere altitudes. Maps of these regions are built on the base of a statistical study. Their morphology and dynamics are controlled by several factors. Among them are solar wind dynamic pressure, interplanetary electric field (determined as proxy products from the MGS measurements) and local crustal magnetizations.

TIME VARIABILITY IN THE PLASMA AND ENERGETIC NEUTRAL ATOMS NEAR THE MARTIAN SUBSOLAR POINT

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Observations of oscillations in the plasma near the subsolar point of the induced Martian magnetosphere have been detected by several instruments, including the magnetometer on Phobos-2, [1], the magnetometer and electron reflectometer on Mars Global Surveyor [2-4], and the electron reflectometer onboard Mars Express [5]. Recently, oscillations in the energetic neutral atom (ENA) flux have been reported in the same region [6,7]. It seems plausible that these observations are related and several different physical interpretations have been given for the observations.

In my presentation I review the observations made so far and compare the physical interpretations. These interpretations include mirror mode instabilities [3,4] bi-ion instabilities [8], plasma reflections into the foreshock [1,2], and ENA jets [6,7].

References: [1] Russell, C. T., et al., *GRL*, *17,* 897-900, 1990. [2] Brain, D. A., et al., *JGR,* doi:10.1029/2002JA009482, 2003. [3] Bertucci, C. et al., *AdSR*, *33,* 1938-1944, 2003. [4] Espley, J. R., et al., *JGR*, doi:10.1029/2003JA010193, 2004. [5] Winningham, D., et al., *Icarus,* in press, 2006. [6] Grigoriev, A. et al., Fall AGU, 2005. [7] Grigoriev, A., et al., this workshop, [8] Sauer, K., et al., *Earth Planets Space, 50,* 793-801, 1998.

Locations of Atmospheric Photoelectron Energy Peaks Relative to the Sun

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The solar photon spectrum contains both discrete spectral lines and continuua. These emissions interact with the Martian atmosphere, generating photoelectrons. One of the discrete lines generated by the Sun is the HeII emission at 30.4 nm, which ionizes carbon dioxide and atomic oxygen to form distinct electron peaks. Direct ionization produces electrons with an energy peak of about 27 eV while direct ionization coupled with molecular vibration and rotation produces electrons with energy peaks in the range of 21-24 eV.

At Mars, the photoelectron energy peaks are mainly generated near the exobase. Once photoionization occurs, the photoelectrons are confined to move along the local remanent magnetic field. Sometimes the direction of electron motion causes them to precipitate into the atmosphere; however, it is also probable that the photoelectrons are transported away from the planet.

Interactions of these electrons in the altitude range from just above the exobase to about three Mars radii (the Mars Express apoapsis) are infrequent, remaining intact until dispersed by interaction. Thus, the photoelectron energy peaks from HeII photoionization may be used as a tracer, providing important information on the morphology of the atmospherically generated photoelectron population. Example data from the ELectron Spectrometer (ELS) of the Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) experiment on the Mars Express (MEX) spacecraft show the robustness of these spectral tracers and emphasizes the role played by both the solar wind and the crustal magnetic field in determining the distribution of the photoelectron population in the Mars environment.

ENA observations at Mars (1): ENA emission from the global Martian upper atmosphere

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The ASPERA-3 team

The Neutral Particle Detector (NPD) on board Mars Express has observed energetic neutral atoms (ENAs) from a broad region on the dayside of the Martian upper atmosphere. We show one such example for which the observation was conducted at an altitude of 570 km, just above the Induced Magnetosphere Boundary (IMB). The time of flight spectra of these ENAs show that they had energies of 0.2-2 keV/amu, with an average energy of ~1.1 keV/amu. This is the first observation of global ENA emissions from the Martian upper atmosphere. While the energy distributions of these ENAs were consistent with theories of the backscattered ENAs of the precipitation of the solar wind ENAs, the observed flux was 3-4 times higher than the expected value. One possible explanation is that there exist contributions of direct precipitation of the solar wind proton to the exobase.

We also made a global map of the flux of the ENA at the height of the upper atmosphere. This map was made by an inversion method with a two-month long data by the NPD instruments. Since the ENA generation is considered to be proportional to the precipitation of the solar wind protons/ENAs, the map is fundamentally converted to the flux of the precipitating particle map. The map exhibits clear solar zenith angle dependence in the backscattered ENA generations. This result is also consistent with theories.

ENA observations at Mars (2):
Response of the subsolar ENA jet flux caused by an interplanetary shock

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The ASPERA-3 team

The neutral particle detector (NPD) of the ASPERA-3 experiment on board the Mars Express spacecraft provides a survey of the Martian Energetic Neutral Atom (ENA) environment for the first time. Futaana et al.[2005] confirmed that the subsolar region is a very intensive ENA production region, and the observed ENA fluxes sometimes exhibit very sharp boundaries in their outer edges. The signature implies that the sub-solar ENAs are emitted anisotropically, and then the ENA flux forms a jet-like (or cone-line) structure. Since the solar wind can penetrate deeply into the exosphere at the sub-solar region, the charge-exchange is expected to occur more frequently than at other places. The streamlines above the induced magnetosphere boundary (IMB) are highly deflected at the subsolar region and ENA produced in this region move along tangentially to them forming a jet / cone as observed.

The sub-solar ENA jet can be seen in almost all orbits with suitable geometry. In one third of the observations, the sharp boundaries at the outer edge of the jet were observed. However, the data obtained on June 7, 2004 shows the sharpest boundary of the sub-solar ENA jet ever. The observed ENA jet flux was 3-4 times higher than the typical flux and abruptly decreases over a very short time of less than 10s when the spacecraft crossed jet's outer boundary. (Typically the spacecraft crossed the boundary approximately 1 min.) This unusual sharp decrease could be interpreted as a spacial feature related to the spacecraft crossing the jet boundary. However, the simultaneous in situ ion and electron observations show that the structure of the interplanetary medium suddenly changed at approximately the same time when the spacecraft crossed the ENA jet boundary. The change in interplanetary medium is most likely due to an interplanetary shock (IS) related to a co-rotational interaction region (CIR). Therefore, there is another interpretation that the sudden ENA jet decrease was caused by the interaction between Mars and the IS. When the IS pushed the IMB toward the planet, the emission region of ENA jet also moved toward Mars. In addition, the direction of the jet would be changed due to changes in the shape of the IMB. These global changes of the ENA jet geometry can result in the sudden change of the ENA jet at the spacecraft location.

Planetary Hydrogen and Oxygen on the Nightside of Mars

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We present an overview of energetic neutral particle data that were measured on the nightside of Mars during ESA's Mars Express mission in spring 2004. We measured on several occasions an intense tailward flow of accelerated hydrogen atoms, which we identified as planetary particles or neutralized solar wind protons. Energetic oxygen atoms, on the other hand, were never detected above the uncertainty level of 10^4 cm^{-2} sr^{-1} s^{-1}, in contradiction to theoretical predictions.
To interpret our measurements, we study the temporal variation and the spatial distribution of the energetic hydrogen fluxes, and we compare the energy spectrum and the flux intensity with theoretical predictions. The absence of a detectable tailward flow of energetic oxygen can be explained by low exospheric densities. If true, this suggests low atmospheric loss rates.

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ENA observations at Mars (3): Oscillations of the ENA Flux From the Subsolar Region at Mars

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The ASPERA-3 team

Neutral Particle Detector (NPD) of the ASPERA-3 experiment (Analyser of Space Plasmas and Energetic Atoms) onboard Mars-Express mission is designed to measure Energetic Neutral Atoms (ENA) in the energy range 0.1 - 10 KeV with an energy resolution of 80% and a mass resolution sufficient to separate H and O. During the first year of observations around Mars under suitable observation geometry NPD detected an ENA flux emitted anisotropically from the subsolar region. Time-of-Flight analysis shows that the detected ENAs are hydrogen atoms with an energy of 1.4 KeV.

In several cases the ENA flux has very evident short-time scale variations as the spacecraft moves outward the planet but sustains the NPD pointing toward the subsolar region. Several tens of orbits have been analysed and 19 cases have been found to have strong signatures of the oscillations. The oscillation period varies from orbit to orbit and is about 130 to 240 sec on average. The drops in the ENA flux reached 30% - 60% of the maximum value. In situ observations by an electron instrument of ASPERA-3 show signatures of electron flux variations. We discuss possible interpretations of the detected oscillations which can be either temporal variations in the generation region caused by an instability at the induced magnetosphere boundary, or spacial variations of the ENA flux.

The Martian Induced Magnetosphere Boundary from the Proton and Alpha particle observation

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Abstract

The Martian ionospheric plasma directly interact with the solar wind due to the lack of the strong intrinsic magnetic field. The recent observations by Mars Express (MEX) revealed that there are three plasma boundaries in the interaction region; the bow shock, the induced magnetic boundary (IMB), and the photoelectron boundary [Lundin et al., 2004]. The IMB is defined as the envelope of the induced magnetosphere which means that the IMB is the stopping boundary for the solar wind. On the other hand, Mars Global Surveyor defined another boundary called the magnetic pileup boundary (MPB). The characteristics of the IMB are not yet well known, especially the relationship between the MPB and the IMB is still an open question.

We searched 300 orbits, (Jun.7-Jul.4 2004 and Jan.17-Mar.13 2005), and identified 132 IMB crossings. Because the IMB have large thickness, we used two definitions of the IMBs; Top of the IMB (IMB_T) and Bottom of the IMB (IMB_B). The IMB_T is the point where the solar wind ions begin to decrease. The IMB_B is the position where the solar wind proton or alpha particles disappear. We obtained the average locations and the distributions of the IMBs by plotting those boundary crossings on three-dimensional maps to investigate the difference and similarity between the IMB and the MPB.

We also investigated the dependence of the IMB positions for different solar wind species. By the identification of the IMBs for the proton and alpha particle independently, and found that the observed alpha boundaries are occasionally higher than the proton boundaries. This tendency conflicts with Mars-solar wind interaction theories considering gyromotion. In those theories, the proton boundary should be higher than the alpha boundary because the Larmor radius of the protons is smaller than that of alpha particles. We would discuss possible physical processes that explain the tendency of the IMB locations for different species.

Abstract

Plasma boundaries at Mars and Venus

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The Aspera-3 experiment on Mars Express and the Aspera-4 experiment on Venus Express have the capability to determine ion boundaries for electrons, protons and heavy ions. We investigate whether the different ion species have different boundary locations at Mars and whether these locations are different from the magnetic pile-up boundary. Then we discuss what is known about the boundary build-up at Venus and what we can expect from the respective measurements of the Aspera-4 experiment.

The Magnetic Pile-up Boundary: a characteristic feature of the interaction of a fast-flowing plasma with a non-magnetized atmospheric body

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Among solar system bodies, planets like Mars and Venus, active comets or Titan share the lack of any measurable large-scale magnetic field and the existence of a dense expanding neutral atmosphere. Therefore, it is not surprising that, despite their obvious different physical nature and different characteristic scales, their interaction with the solar wind or the ambient plasma flow exhibits many similarities. The most important are the formation of a magnetic barrier in front of the highly conducting ionosphere and an induced magnetic tail. The observations at comets first have also revealed the existence of an unexpected sharp plasma boundary, the Magnetic Pileup Boundary (MPB), representing the outer edge of the magnetic barrier on the dayside. It has been identified by very well defined signatures both on particles and fields. They have also been reported around Mars, leading to using the same terminology for the Martian boundary after getting rid of the previous ambiguity on a putative planetary magnetic dipole. Data analysis also helped to reveal identical local boundary properties, e.g., a clear change of the 3D magnetic field topology; this feature has also been recently revealed at Venus, although the MPB itself had never been reported previously at this planet. More recently, the signature of a MPB at Titan has also been clearly demonstrated. We compare the particle, magnetic field and wave characteristics at the MPB as derived from the observations at comets, Mars and Venus and discuss the physical nature of this characteristic feature of the plasma environment of all these solar system objects. Recent analysis of the local properties of the boundary and recent observations as well as simulation results will also be discussed.

A survey of the possible influence of magnetic anomalies on ions near Mars

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We present a survey of the possible influence of magnetic anomalies on ions near Mars. The presence and characteristics of ions are investigated for cases where the electron data indicates magnetic anomalies. The location of heavy ion beam events and other ion signatures are compared with the expected location of magnetic anomalies based on the Cain Mars crustal magnetic field model. This is done both as case studies and in a statistical study. We also extend studies of heavy ion beams observed in the vicinity of Mars by the Mars Express ASPERA-3 ion mass analyzer by investigating the direction of the ion flow. It is discussed whether any of the spatial characteristics including the flow direction indicate an influence of magnetic anomalies. The ion events concern heated/accelerated ions with energies above 300 eV so the gyro radii of the ions are mostly large compared to the size of magnetic anomalies. Therefore phenomena such as bending of the ion path or heating up to some threshold energy after which the ions are lost from the anomaly due to gyro radii effects are good candidates for observable effects.

Altitude Dependence of Magnetic Anomaly Signatures in Mars Express ASPERA-3 ELS Data

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We use data from Mars Express (MEX) Analyzer of Space Plasmas and Energetic Atoms (ASPERA-3) Electron Spectrometer (ELS), to observe the behaviour with altitude and angular distribution of electrons around magnetic `anomaly' regions on Mars, and to examine differences between observations on the day-side and night-side. Results show the arrival of electrons at the cusps of magnetic anomalies and electrons from intensified events reaching low altitudes.

Positions and Shapes of Martian Plasma Boundaries from Phobos 2 and Mars Global Surveyor Observations

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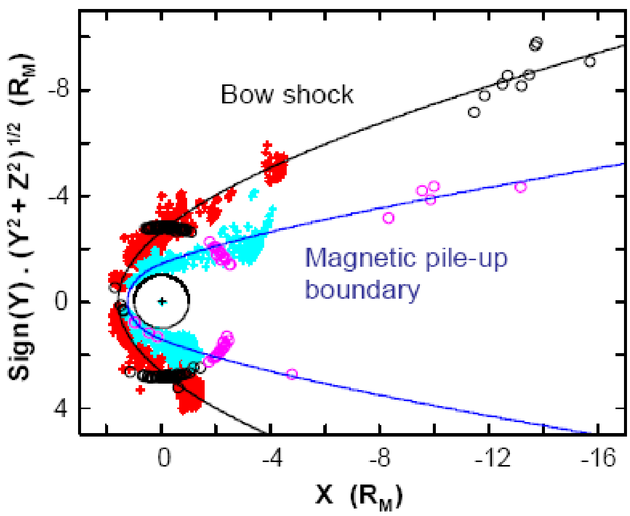
A great many Martian bow shock and magnetic pile-up boundary crossings have been identified in the Phobos 2 and Mars Global Surveyor, MGS, data. From these observations the positions and shapes of the bow shock and magnetic pile-up boundary, MPB, have been derived and modelled, using curve-fitting techniques. The models thus derived separately from the Phobos-2 and MGS data sets do not differ drastically, despite the different time and space data coverages. The purpose of the paper is therefore to show the results obtained from the mixing of the Phobos-2 and MGS data bases and to compare the derived bow shock and MPB models with the ones obtained previously. The underlying objective was to see whether it was possible to determine improved bow shock and MPB models or not. The answer is definitely yes, and particularly for the MPB, thanks to the complementary nature of the observations. The boundaries crossed close to the subsolar direction or mostly far downstream by Phobos 2 indeed allow a better coverage of the Martian space environment to be considered. Nevertheless, in order to reduce the domination of the overabundant MGS data set and/or the crossings that are close to Mars ($x > -4\ R_M$, i.e. $x > -13\ 562$ km) weighting factors have been introduced.



Martian bow shock (black line) and Magnetic Pile-up Boundary (blue line) models that best fit the observations made by both the plasma wave system of the Phobos 2 mission (black rings for the shock and purple rings for the MPB) and the MAG/ER experiment aboard the MGS spacecraft (red crosses for the shock and blue crosses for the MPB). Negative and positive ordinate values correspond with crossings in respectively the dawn and dusk hemispheres.

Oral session 2
Tuesday 28 February

Ion Escape Processes from Mars

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Without a significant, global magnetic field at Mars, the solar wind comes into direct contact with the Martian exosphere. Through electron impact ionization, charge exchange, and photoionization, new ions are created in the solar wind. They are subsequently accelerated by the solar wind and are lost from Mars at a rate of a few 10^{25} O^+ per second. We review data from PHOBOS-2, Mars Global Surveyor and Mars Express that directly and indirectly detect the ion escape processes in action at Mars. We compare those data to models that illuminate the important parameters involved in ion escape at Mars, and therefore, Martian atmospheric loss.

MGS measurements of the Martian solar wind interaction

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The arrival of Mars Global Surevyor (MGS) at Mars in September 1997 was a watershed event in the history of Martian solar wind interaction measurements. First, MGS carried a magnetometer and electron reflectometer eight times closer to the surface than any previous spacecraft. This allowed a more precise determination of the nature of the Martian obstacle to the solar wind and the discovery of strong crustal magnetic fields. Second, MGS remained in a precessing elliptical aerobraking orbit until mid-1999. This orbit resulted in far more extensive coverage of the interaction region than previous missions achieved. Third, continued measurements through the present from a mapping altitude of 400 km cover a small slice of the interaction region. These mapping data provide an opportunity to determine variability in the interaction on many timescales (hourly, interannually and over the course of a solar cycle) and with a variety of external conditions. This presentation will review MGS results relevant to our evolving understanding of the solar wind interaction and highlight new questions and research frontiers made clear by these results.

Martian Aurora: Updates from SPICAM/Mars Express

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During orbit 716 of Mars Express mission, the clear identification of an auroral type emission has been done by SPICAM UV spectrometer [1]. A significant increase of the measured emission has been observed during 7 seconds on the Martian nightside. This increase of the emission is not similar than the already well-identified nightglow emission [2]. It is composed of the CO $A^1\pi$ - $X^1\Sigma^+$ 4+ bands, of the C 156.1 and 165.7 nm, of the CO $a^3\pi$ - $X^1\Sigma^*$ Cameron bands, of the CO_2^+ $B^2\Sigma^u$ - $X^2\pi_g$ doublet and of the O (297.2 nm) emissions which classically composed the Martian dayglow.

Thanks to the property of SPICAM spectrometer we have been able to estimate the position and altitude of this emission along SPICAM field of view. The very high correlation between this position and the presence of the highest crustal magnetic field structures identified at Mars [3] strongly suggests the role of these structures in driving the incident electrons at the origin of these emissions. It is a strong identification of very localized peak of ion density on the Martian nightside in the region of crustal magnetic field and also of the importance of the crustal field in driving the nightside ionosphere.

I will describe the results of a new analysis of the observed emission thanks to a better calibration of SPICAM UV channel and the use of all spectral information obtained during this observation. Several possibilities for the origin of these emissions will be presented and discussed based on the particular geometry of the observation as well as the global present coverage of the Martian nightside by SPICAM UV channel.

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Plasma Acceleration and Aurora above Martian Magnetic Anomalies.

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The ASPERA-3 experiment on ESAs Mars Express have made it possible to study acceleration processes in the nightside/eclipse of Mars. There are strong similarities between accelerated/heated electrons and ions in the deep nightside cavity of Mars and the electron/ion acceleration above Terrestrial discrete aurora. Nearly monoenergetic electrons are observed together with nearly monoenergetic upgoing ions, the classical signature of “inverted V” traversals.
We have analyzed ASPERA-3 data from over 100 Mars Express traversals of the central tail and, using nadir projections, compared with magnetic maps for the crustal magnetization (Brain et al., 2005). We find a close correlation between crustal magnetization regions and the field-aligned acceleration of ions and electrons. The total field-aligned acceleration based on the electron and ion acceleration, is in the kilovolt range. The total downward acceleration should result in intense electron precipitation into the upper atmosphere of Mars. This is therefore evidence for discrete aurora on nightside of Mars. The difference between the Earth´s polar aurora and the Martian aurora is that the latter occur closer to the equator, i.e. where the crustal magnetic field structures are located. Discrete aurora above Mars is expected to form along clefts interfacing crustal magnetization regions, but also along the large scale, halo/oval at the circumference of the largest area of magnetic anomalies at Mars. The precipitating electron flux from the traversals is estimated to be in the range 1 - 50 erg/(cm^{2}s), i.e. energy fluxes similar to those leading to bright discrete aurora above the Earth.

The Solar Wind Interaction with the Martian Ionosphere/Exosphere

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The interaction of the solar wind with the Martian exosphere and ionosphere leads to significant loss of atmosphere from the planet. Data from space craft confirm that this is the case. However, the issue is how much is actually lost. Given that space craft coverage is somewhat sparse, simulation seems to be one of the few ways for these estimates to be made. The spacecraft offer bounding data, but not full coverage necessary because of the asymmetric fashion of the solar wind interaction with Mars.

In this talk the evolution of our attempts to place bounds on this loss rate will be addressed. Using a hybrid particle code the loss rate with respect to solar EUV flux is addressed as well as a variety of numerical and chemical issues. The progress made has been of an evolutionary nature, with one approach tried and tested followed by another as the simulations are improved and better estimates are produced.

This is research still in progress but the discussion of what has worked, what has not worked, and what the rates seem to be sensitive too will be addressed as well as our goals for future research.

X–rays from Mars

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X–ray radiation from Mars was first detected in July 2001 with the satellite Chandra. The main source of this radiation was fluorescent scattering of solar X–rays in its upper atmosphere. In addition, the presence of an extended X–ray halo was indicated, probably resulting from charge exchange interactions between highly charged heavy ions in the solar wind and neutrals in the Martian exosphere. The statistical significance of the X–ray halo, however, was very low.

In November 2003, Mars was observed again in X–rays, this time with the satellite XMM–Newton. This observation, characterized by a considerably higher sensitivity, confirms the presence of the X–ray halo. It also proofs that charge exchange is indeed the origin of the emission. This is the first definite detection of charge exchange induced X–ray emission from the exosphere of another planet.

During the XMM–Newton observation, Mars was a highly variable X–ray source. The X–ray flux observed from close to the planet was clearly correlated with solar flares. However, X–rays from the halo exhibited variations on independent time scales. X–ray spectroscopy reveals that close to the planet the radiation is caused by fluorescence of neutral molecules, while the halo emission results from de-excitation of highly charged ions. Spectral fine structure observed in the O^{6+} emission rules out that the high ionization occurs in the Mars environment.

All these findings are fully consistent with the idea that the X–ray halo is the direct result of charge exchange interactions between atmospheric constituents and solar wind ions. Since this process is considered as an important nonthermal escape mechanism, probably responsible for a significant loss of the Martian atmosphere, X–ray observatins may lead to a better understanding of the present state of the Martian atmosphere and its evolution.

X–ray images of the Martian exosphere in individual emission lines exhibit a highly anisotropic morphology. Most of the emission is observed several 1000 km above the Martian poles. The detailed morphology, however, is different between individual ions and ionization states. With its capability to trace the X–ray emission out to at least 8 Mars radii, XMM–Newton proceeds into exospheric regions far beyond those that have been observationally explored to date. Thus, X–ray observations provide a novel method for studying processes in the Martian exosphere on a global scale.

Atmospheric Sputtering

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The flow of solar wind and local pick-up ions onto the Martian exobase can affect the long-term evolution of the atmosphere, a process often referred to as atmospheric sputtering (*Johnson* 1990, 1994). Solar forcing via both atmospheric sputtering and UV absorption forms a hot oxygen corona. This corona, in turn, alters the incoming solar plasma by *mass loading* the solar wind with newly created ions and by *charge exchange* collisions. Mars-Express observations (*Lundin et al*. 2004) show that the incident plasma penetrates deeply into the Mars atmosphere: e.g., keV O^+ found at 300 km are of exospheric origin accelerated by the interplanetary magnetic fields. Therefore, acceleration processes might also occur deep into the ionosphere with the planetary wind from the dayside region sweeping tailward at altitudes as low as 270 km. Pick-up ions following the field lines that are draped across Mars can either be swept away or re-impact the atmosphere with energies up to ~1 keV. Through momentum transfer collisions they can energize other atoms and molecules enhancing escape and populating the hot corona (*Luhmann and Kozyra* 1991; *Luhmann et al*. 1992; *Johnson and Luhmann* 1998). Unlike dissociative recombination, sputtering is non-selective and can, in principle, eject all particles that are present at the Martian exobase: C, O, CO, N, N_2 and CO_2 (*Leblanc and Johnson* 2002). In the present epoch, the sputter loss rate of O and CO_2 has been estimated to range from 3×10^{23} to 4.7×10^{24} atoms/s (*Chassefiere and Leblanc* 2004). This is smaller than the nonthermal escape of oxygen due to exothermic chemistry but may dominate the carbon loss. Modeling also suggests that atmospheric sputtering could have dominated in earlier epochs (*Leblanc and Johnson* 2001, 2002).

The physical and chemical processes leading to the formation, kinetics, and transport of suprathermal O atoms in the corona will be described. This is a computationally challenging non-linear problem. On one hand, the chemistry induced by the UV and the atmospheric sputtering cause the formation of an extended corona (*Krestyanikova and Shematovich* 2005, 2006). On the other hand, pick-up-ion formation in this corona leads to escape and enhanced atmospheric loss. This feedback process is critical in determining atmospheric loss in earlier epochs (*Johnson and Luhmann* 1998). The affect on the loss rate of the uncertainties in the energy spectra of ionospheric pick-up ions and our knowledge of the differential energy transfer cross sections will be discussed.

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Oral session 3
Wednesday 1 March

Long-term planetary evolution: Solar radiation and particle induced effects on the early Martian atmosphere and loss

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The evolution of the Martian atmosphere with regard to its H_2O inventory is influenced by thermal loss and non-thermal atmospheric loss processes of H, H_2, O, N, C, CO, CO_2, H^+, O^+, H_2^+, $N2^+$, CO^+, CO_2^+, and O_2^+ into space, as well as by chemical weathering of the surface soil. The epochs related to escape of the atmosphere and water from Mars over long-term periods can be divided into 3 epochs, the present Mars, the period between the present and 3.5 Gyr ago and the first billion years. The evolution of all escape processes depend on the history of the intensity of the solar X-ray and EUV (XUV)radiation and the solar wind density. Thus, we use actual data from the observation of solar proxies with different ages from the Sun in Time program for reconstructing the Sun's radiation and particle environment from the present to 4.6 Gyr ago. We compare different model investigations for the non-thermal escape processes (ion pick up, sputtering, ionospheric clouds triggered by the Kelvin Helmholtz plasma instability) of the Martian atmosphere over long-time periods and discuss the effect on the total loss to the Martian CO_2 and/or H_2O inventory. We apply a thermospheric model to the CO_2-rich atmosphere of Mars that have been modified to high XUV flux values expected during the Sun's evolution. During the first Gyr after the Sun arrived at the Zero-Age-Main-Sequence high XUV fluxes between 10 - 100 times that of the present Sun were responsible for much higher temperatures in the thermosphere-exosphere environments on both planets. By applying a diffusive-gravitational equilibrium and thermal balance model for investigating radiation impact on the early thermospheres by photodissociation and ionization processes, due to exothermic chemical reactions and cooling by CO_2 IR emission in the 15 μm band we found expanded thermospheres with exobase levels between about 200 (present) to 2000 km (4.5 Gyr ago). Our model results indicate that the high temperature in the thermosphere-exosphere environment on early Mars could reach "blow-off" conditions for H atoms even at high CO_2 mixing ratios of 96 %. Furthermore, we show that lower CO_2 / N_2 or CO_2 mixing ratios in general, or higher contents of H_2O-vapor in the early Martian atmosphere could have had a dramatic impact on the loss of atmosphere and water on early Mars. The duration of this phase of high thermal loss rates essentially depended on the mixing ratios of CO_2, N_2 and H_2O in the early atmosphere. Lower CO_2 mixing ratios on early Mars shortly after its volatile out-gassing could have had a major impact on the thermal loss of the main atomic atmospheric species (O, N, C) combined with impact erosion and loss of O due to dissociative recombination in the dense solar XUV-produced early Martian ionosphere. One should note that thermal and photochemical loss process are independent from an early Martian magnetosphere because these atomic species escape as neutrals. Furthermore, a combination between an expanded thermosphere-exosphere region and a stronger early solar wind could have also enhanced ion pick up loss during the period where the Martian magnetic dynamo decreased.

Mars long-term planetary evolution: the MEx / OMEGA view

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OMEGA is a hyperspectral imaging spectrometer operating in the VIS/NIR range (0.35 to 5.1 µm). Its spatial sampling varies from 300 m when observing close to the orbital periapsis, up to 5 km. Along the Mars Express nominal mission, OMEGA has covered almost the entire surface of Mars with a footprint of 2 to 5 km, and some 5 % at high resolution. From the spectra acquired, it is possible to retrieve the composition of surface (minerals and ices) and atmospheric (gas and grains) major constituents. In particular, OMEGA has identified and mapped the mafic minerals and their alteration products, in the form of three distinct families: phyllosilicates, found in oldest Noachian terrains; sulfates, in deposits within Valles Marineris, Terra Meridiani and the northern polar cap; anhydrous ferric oxides within the bright soil covering extended areas. Each of these families requires distinct climatic and environmental conditions to form. Consequently, these identifications suggest a long-term planetary evolution, with major and global changes, that will be presented and discussed.

The Geological Evolution of Mars as Seen through the Mars Express High Resolution Stereo Camera (HRSC)

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After two years of orbital acquisition of high-res stereo and color data by the HRSC experiment on the ESA Mars Express Mission and nearly 30% coverage of the martian surface at a resolution of better than 20m/pixel, we are beginning to understand the geological evolution of Mars at different scales (globally, regionally, and locally) considerably better. The combination of the new HRSC data with MOC data where high-res context information can be merged with detailed local information, and the combination with color data giving the distribution of different materials as well as stereo viewing capability open up a new domain of photogeological high-precision interpretation.
We can demonstrate that there has been episodic volcanic, hydrothermal, fluvial, and glacial activity throughout the whole history of Mars though declining in magnitude through time and peaking at certain periods in the past, becoming confined more and more to certain regions or locales, such as the poles, the highland-lowland boundary and in particular the Tharsis and Elysium regions and vicinities. What is becoming much clearer now is that in parallel to the cessation of the martian highland volcanism ~3.5 Ga ago and probably the rapid loss of the martian atmosphere within a few 100 Ma by that time, Mars fell dry on a global scale.
It is now very clear on the basis of our analysis of HRSC data the early “wet and warm” Mars as put forward after Viking, is more of a fiction than reality. Whether a global large ocean in the north ever existed is less clear than ever, the odds seem to be against it. At least by 3.5 Ga ago, probably already around 3.8 Ga ago, our data tell us, it was gone if it was there before and Mars fell dry rapidly on a global scale.
Nevertheless, from time to time through the Aeons until today Mars has been volcanically active in periods, and largely through this activity water seems to have been released from ice-rich layers on the surface or sub-surface or from aquifers which formed fresh small-channel systems locally and triggered glacial processes through the freezing water.

Long-term planetary evolution. Does plasma matter?

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An atmosphere/ionosphere of a non-magnetized atmospheric body interact directly with the solar wind flow. Through the interface boundary, which I call for the Martian case induced magnetosphere boundary, the constant exchange of matter, energy, and momentum occurs. The electrodynamical coupling via induced ionospheric currents and fields also takes place. Through the cross section corresponding to the size of the induced magnetosphere boundary ($1.47R_m$) at the terminator region, the typical solar wind at Mars with a density of 2 cm^{-3} and velocity of 420 km/s carrying a frozen-in magnetic field of 4 nT transports the $6.6x10^{25}$ protons/s or $2x10^{42}$ protons/1Gy. The solar wind also carries an energy of $1.3x10^{-8}$ W/cm^2 related to the plasma (proton) motion. By comparing these numbers with the current total amount of particles (CO_2) in the Martian atmosphere $3.6x10^{41}$ particle and the solar radiation energy flux 568 W/m^2, it is natural to suggest that the effect of the solar wind interaction on the current state of the atmosphere is not significant. The solar wind influence may be important only over periods of few Gy. I will attempt to evaluate (as unbiased as I can having plasma physics background) the importance and significance of the different mechanisms and processes through which the solar wind may impact the Martian atmosphere and its evolution and compare them with the other factors influencing the atmosphere evolution.

The Solar Wind and the Sun in the Past

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Exposure to the solar wind can have significant consequences for planetary atmospheres, especially for planets such as Mars that are not protected by global magnetospheres. Estimating the long term effects of solar wind exposure requires knowledge of the history of the solar wind. Much of what we know about the Sun's past behavior is based on inferences from observations of young solar-like stars. Stellar winds analogous to that of the Sun cannot be detected directly, but the interaction regions between these winds and the interstellar medium have been detected and used to estimate wind properties. I here review these observations, with emphasis on what they suggest about the history of the solar wind.

Poster session 2
Wednesday 1 March

Evidence for a Magnetic Pileup Boundary at Titan: New elements for the interpretation of the observations at Mars.

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Abstract:
The measurements obtained by the Cassini magnetometer and plasma instruments during the first flybys of Titan are providing invaluable information on its interaction with Saturn's co-rotating magnetosphere. On one hand, the virtual absence of a significant global magnetic field and the presence of a dense atmosphere make Titan's interaction very similar to the solar wind interaction with Mars, Venus and comets with a magnetic barrier above Titan's ionosphere and a magnetic tail generated from the draping of Saturn's magnetic field, as it passes by the satellite frozen into the co-rotational flow. On the other hand, the diversity of the upstream conditions (especially the variation in the angle between the incoming plasma flow and the solar EUV flux) as Titan moves on its orbit makes it one of the most outstanding laboratories to study the variability of the plasma structures generated by this interaction.
In particular, previous and current studies on the solar wind interaction with Mars, Venus and comets reveal the occurrence a sharp plasma boundary marking the entry into the magnetic barrier and tail lobes: the Magnetic Pileup Boundary (MPB). At these objects, the MPB has been identified from a series of very clear observational signatures including: an increase in the magnetic field magnitude, the enhancement of the magnetic field draping, and strong changes in the local electron distribution and in the dominant ion population, which are attributed to the increasing influence of the body's exosphere. Based in the mentioned signatures, we present evidence in favour of a magnetic pileup boundary at Titan as implied by Cassini magnetic field and plasma data. In addition, we study the structure of this boundary with the intention of providing new elements for the interpretation of past and future observations by MGS, Phobos-2, Mars Express and Rosetta at the Martian MPB.

Analysis of the composition of the escaping plasma at Mars

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Results from Mars Express, Mars Exploration Rovers and Mars Global Surveyor indicate that Mars harboured large amounts of liquid water on the surface in the past. In order for the water-associated geomorphologic features to form, the pressure in the atmosphere must have been at least a hundred times higher to produce the necessary greenhouse effect required to hold liquid water stable. The present atmospheric pressure is only 6-9 mbar and moreover, the spectral imaging of Mars suggests that the amount of carbonates stored in the surface is too low in order to explain the denser atmosphere in the past. This controversy led us to investigate the escaping plasma by analyzing the data from the IMA sensor (Ion Mass Analyzer) of the ASPERA-3 instrument suite onboard Mars Express. The IMA sensor measures the differential flow of ion components in the energy range of 0.01-30 keV/q.

Since the instrument design was optimized for studies of plasma dynamics, the mass resolution is not adequate enough to directly resolve CO_2^+ from O_2^+, which is the main molecular ion composing the Mars ionosphere according to theoretical models. Therefore, a special multi-species fitting technique, using calibration and in-flight data, was developed to resolve the CO_2^+ peak from the neighbouring and much more intense O_2^+ peak. This technique was applied to the observations covering the period from April 4, 2004 to October 3, 2005. The events of heavy ion escape were identified inside the induced magnetosphere boundary and the Martian eclipse. We report the results of statistical studies of these ion-beam events which permitted to determine CO_2^+/ O^+ and the O_2^+/ O^+ ratio of the escaping plasma at Mars.

Electrons at Mars: similarities and differences to Titan

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Mars is an unmagnetized (on the large scale) body with an atmosphere immersed in the supersonic solar wind. Titan is a similar type of body immersed in subsonic plasma flow in Saturn's corotating magnetosphere. We compare some Mars Express ASPERA-3 ELS measurements at Mars with Cassini-Huygens CAPS-ELS measurements at Titan. We find several similarities including ionospheric photoelectrons on the day side, and relatively sharp plasma boundaries. Differences include the upstream conditions, the nature of the plasma boundaries and the source of the photoelectrons. We present a preliminary comparison of the electron results at each body.

Nonlinear evolution of modified two stream instability above ionosphere of Titan: comparison with the data of the Cassini Plasma Spectrometer. and application to Mars and Venus.

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Abstract. The ionosphere of Titan, moon of Saturn is directly exposed to the streaming plasma either of magnetospheric or solar wind origin. A turbulent interaction region between the two different plasma types is formed, called here flowside plasma mantle, where both ionospheric and hot streaming plasma are present at comparable densities. In order to study the microphysics of the collective plasma phenomena taking place within the flowside plasma mantle of Titan, a one dimensional electromagnetic hybrid simulation was constructed, retaining the inertia of the electrons. Within the framework of this model we study the wave particle interaction created by the relative drift between the streaming ion flow and the ionospheric ions.

It is shown that the excited waves are very effective in generating "anomalous viscosity" type interaction between the hot plasma flow and cold ionospheric ions, leading to significant bulk velocity loss of the proton component of the external plasma flow and turbulent heating of the ionospheric ions. The waves are excited due to a modified two-stream instability, the free energy source for the instability is in the streaming ion flow. The stochastic energy transfer from the streaming plasma to the ionospheric ions may also increase the tailward planetary ion escape by collective pick-up mechanism enhancing the rate of erosion of the atmosphere of Titan (sputtering).

We make predictions for the characteristic frequency range and saturation energy level of the excited wave electric field, and the energy range where superthermal charged particles of ionospheic origin can be detected by the charged particle analyzers onboard of Cassini spacecraft near Titan.

Mars and Venus show many similarities with Titan, the model prediction for those planets this will be discussed as well.

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The Rosetta Mars Flyby

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The Rosetta flyby on 25th February 2007 is a good opportunity for studies of the Martian plasma environment from the solar wind and bow shock down to the ionosphere at 250 km altitude. We combine results of hybrid simulations and crustal magnetic field models with the Rosetta trajectory data in order to provide baseline predictions for the Rosetta plasma measurements, useful for planning the operations as well as for comparison to the actual data. We also look at possibilities for Parker spiral conjunctions between Rosetta and Mars.

MHD Simulations of the Solar Wind Interaction with Non-magnetized Planets

Andreas Ekenbäck*, Mats Holmström*, and Herbert Gunell*

The traditional way of making MHD simulations of the interaction between non-magnetized planets and the solar wind is to define an inner spherical boundary. Often a conducting sphere where the ionospheric currents will be induced. Such a curved boundary presents a problem when using a generic MHD solver on a Cartesian grid. It is not easy to modify the solver at the boundary while preserving the accuracy of the numerical scheme.

For a non-magnetized planet such as Venus or Mars, the obstacle to the solar wind flow is the ionosphere, that is created by the photo-ionization of neutrals. Currents are induced in the ionosphere, and these will deflect the incoming solar wind, creating a bow shock in front of the planet, and an ionopause boundary (at Venus), or an induced magnetospheric boundary (at Mars).

Here we propose an approach where we do not have any inner boundary at all. We only specify sources and sinks of ions close to the planet (in the ionosphere). This allows us to use a Cartesian grid MHD solver.

For an initial study of the concept, instead of building a complete ionospheric model with many species, sources, and loss terms, we use a single fluid MHD model with a source of photoions given by the simplified Chapman production function

$$p(h,\chi) = p_0 e^{1-y-\sec\chi e^{-y}}, \qquad y = (h-h_0)/H, \qquad h \geq 0, \quad 0 \leq \chi < \pi/2, \tag{1}$$

where h [m] is the height above the planet surface, χ [rad] is the solar zenith angle, p_0 [$\mathrm{m}^{-3}\mathrm{s}^{-1}$] is the maximum production along the sub-solar line, at height h_0 [m], and H [m] is the scale height. Here all model parameters are chosen to be relevant for the Mars–solar wind interaction.

A future extension of the code to the more realistic multi-fluid setting should not present a problem since the MHD solver used can handle that. The code that we have adapted (FLASH from University of Chicago) is an open source application capable of handling general compressible flow problems. The modularity of the code permits users to solve flow problems using only the appropriate modules. Written mainly in Fortran 90, the FLASH code contains different solvers for flow problems along with a version of the PARAMESH library that handles an adaptive computational grid. FLASH is portable, and uses the Message-Passing Interface (MPI) for inter-processor communication. By using this existing code we benefit from the extensive testing and optimization of the code that has been done.

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Asymmetries in Mars' Exosphere: Implications for X-ray and ENA Imaging

Mats Holmström*

Traditionally, exospheric densities and velocity distributions are modelled by spherical symmetric analytical Chamberlain functions, assuming gravity is the only force acting on the neutrals. Planetary exospheres are however not spherical symmetric to any good approximation, as evident from observations, due to non-uniform exobase conditions and effects such as photoionization, radiation pressure, charge exchange, recombination and planetary rotation. To account for these effects numerical simulations are needed. Using Monte Carlo test particle simulations it is possible to account for the above effects (if ion distributions are assumed).

Even though neutrals in the exospheres by definition do not collide often, collisions occur. Especially near the exobase the transition is gradual from collision dominated regions at lower heights (with Maxwellian velocity distributions) to essentially collisionless regions at greater heights.

We present exospheric simulations that include collisions self consistently using the direct simulation Monte Carlo (DSMC) approach. The code is three dimensional, parallel and uses an adaptive grid, allowing many particles to be included in the simulations, leading to accurate results. In particular, we here study Mars' hydrogen exosphere and the effects of the above processes, including thermal escape rates.

Accurate exosphere models are also important for analysis of X-ray and energetic neutral atom (ENA) images, since the measured fluxes are line of sight convolutions of ion fluxes and neutral densities, and asymmetries in the exospheric profiles will directly affect the images. We present the implications for observations of solar wind charge exchange X-rays and for observations of ENAs at Mars.

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Ion escape at Mars: IMA/ASPERA-3 observations and QNH model simulations

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Mars does not have a strong global intrinsic magnetic field and therefore the solar wind can flow close to the planets in high neutral density regions. Because of the formed direct interaction between the atmosphere/exosphere and the solar wind, the ionized atmospheric contents can be picked up and accelerated by the solar wind. Charge exchange between solar wind protons and planetary neutrals, instead, produce energetic neutral hydrogen atoms which are the manifestation of the direct interaction between the solar wind and planetary neutrals. Picked-up planetary ions in turn form energetic neutral atoms via charge exchange process. The ion and energized neutral escape forms the total loss flow from the planet.

In this work we are concentrating on the ion losses which are measured by ion mass analyzer IMA (ASPERA-3 experiment) onboard of Mars Express. This sensor provides 3-D measurements of both solar wind and planetary ions from the beginning of 2004. We continue the preliminary comparison [Kallio et al., Icarus, 2006] between the self-consistent 3-D quasi neutral hybrid (QNH) model (electrons a fluid, ions are particles) and IMA observations and study: 1) similarities/differences between the properties of escaping planetary O^+, $O_2{}^+$ and $C0_2{}^+$ ions, and 2) the 3-D velocity distribution function of escaping planetary ions.

Hot Oxygen Corona at Mars

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Solar forcing via both UV absorption and atmospheric sputtering forms an oxygen corona populated by the suprathermal (hot) atoms (*Nagy and Cravens*, 1988; *Lammer and Bauer* 1991; *Kim et al*. 1988; *Hodges* 2000). The hot corona, in turn, is altered by the inflow of solar wind and local pick-up ions onto the Martian exobase which can affect the long-term evolution of the atmosphere (*Johnson and Luhmann* 1998).

The processes of the kinetics and transport of hot oxygen atoms in the transition region (from thermosphere to exosphere) of the Martian upper atmosphere are discussed. A reaction of dissociative recombination of the main ionospheric ion O_2^+ with thermal electrons in Martian ionosphere is a main photochemical source of hot oxygen atoms. Oxygen atoms are formed in this exothermic reaction with an excess of kinetic energy ~ 0.4—4 eV and their energy is lost in an elastic and inelastic collisions with ambient thermal atmosphere gas. Detailed calculations of formation, collisional kinetics and transport of hot oxygen in transitional region (from thermosphere to exosphere) of upper atmosphere of Mars are presented. These calculations were conducted using the developed by authors method of stochastic modeling of the kinetics and transport of suprathermal atoms. Kinetic energy distribution functions of hot oxygen were calculated using the differential cross sections for collisions of hot O with ambient atmosphere (*Krestyanikova and Shematovich* 2005) and are shown in the Figure. It has been shown that exosphere is populated by substantial amount of hot oxygen atoms with kinetic energies less than escape energy 2 eV, i.e., hot oxygen corona is formed. Comparison with the previous models of hot oxygen corona shows that our model is characterized by higher escape fluxes and higher abundances in the outer regions of oxygen corona at Mars (*Krestyanikova and Shematovich* 2006). The input of exothermic photochemistry (with a dominant role of dissociative recombination of the molecular oxygen ion) into the water loss rate from Mars was estimated and its important role in the evolution of the Martian atmosphere is discussed.
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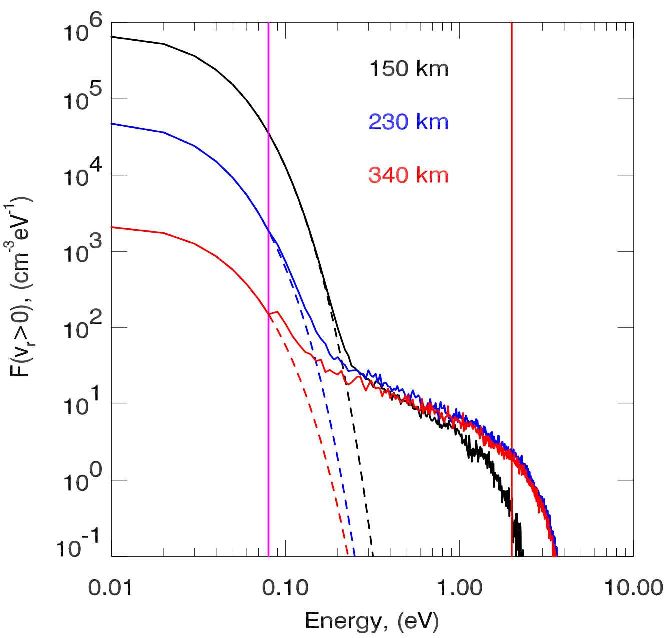

Nonlinear Waves at the Proton Cyclotron Frequency as Signature of Large Distance Escape at Mars

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Low frequency waves at the cyclotron frequency of an ion species in the vicinity of a solar system body surrounded by a neutral atmosphere or exosphere reveals its micro-scale interaction with the solar wind. They are often used to derive constraints on the neutral species density upstream from the body using linear growth rate or quasi-linear theory predictions for the wave saturation level. Quasi-monochromatic low frequency waves at the proton cyclotron frequency are very frequently observed by the MAGER experiment onboard Mars Global Surveyor (MGS) in the plasma environment of Mars. The waves are left-handed circularly polarized in the spacecraft frame. Their wave vectors lie at moderate but oblique angles from the ambient magnetic field. We have solved the Maxwell-Vlasov linear dispersion relation using realistic parameters for the Martian environment and we show that these waves occur when the plasma is linearly unstable with respect to the resonant ion/ion ring-beam instability fed by the planetary pick-up protons. The waves can have large amplitude even at large distance from the planet (at more than 11 R_M) which seem difficult to reach e.g., from the nonlinear saturation of the proton cyclotron instability using realistic pickup ion densities from up-to-date exosphere models. These waves have been also interpreted as nonlinear stationary waves in the bi-ion plasma produced by the existence of the two ion populations (solar wind and planetary). The existence of such waves show the large extension of the pickup process around Mars and its contribution to the general atmospheric escape. We present new results on these Martian waves and discuss their relation with other waves observed upstream from the Martian bow shock, steepened magnetosonic waves and slams (short large amplitude magnetic structures).

Global hybrid simulations of the Solar Wind interaction with the Martian exosphere

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The solar wind interaction with the Martian upper atmosphere and the ionosphere is investigated with global and multi-species hybrid simulations. Ionization of planetary neutrals caused by photons, electron impacts and charge exchange reactions are self-consistently included in the simulation model. The simulation takes into account a fully kinetic description for ions and a fluid description for electrons. The hybrid formalism describes fully and self-consistently the dynamics of four ionic species (H^+,He^{++},O^+ and O_2^+), including all kinetics effects. The Martian neutral environment is described by two coronae of atomic oxygen and hydrogen. The Martian oxygen corona have been calculated for the thermal part using Chamberlain approach, and for the non-thermal part of the corona, from a 3-D Monte Carlo describing the dissociative recombination of O_2^+ in the martian atmosphere. This model allows to propose a whole and realistic image of the coronal 3-D structure. Simulations results are in reasonable agreements with the observations of Phobos-2, Mars Global Surveyor (MGS) and Mars-Express spacecraft. Results of the simulated magnetic field, ions densities and an estimation of the escaping fluxes of planetary ions are presented.

Magnetospheric-Ionosphere interaction and Ionospheric Escape from Titan: What can we learn from Cassini measurements

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We present unique results of the plasma and magnetic environment around Titan from selected events of the first 11 flybys by Cassini (2004-2006). We focus the discussion on the cold ionospheric plasma escape from Titan and its interaction with the streaming magnetospheric plasma of Saturn. We use data primarily obtained from the cold plasma measurements by the RPWS Langmuir probe (LP) sensor, and compare them, where appropriate, with hot plasma (CAPS) and magnetic measurements (MAG).
The ionosphere has been clearly identified and so have the ionopause boundaries, i.e., the regions where the ionospheric thermal pressure balances the magnetospheric pressure (magnetic and dynamic). In the case of Titan, the ionopause boundary is a rather extended and dynamic boundary that depends on magnetospheric conditions. The maximum ionospheric electron number density measured so far is 4000 cm^{-3}. The wake-side electron temperatures increase with altitude, and the altitude profiles there are consistent with electron heat conduction from the hotter Titan wake.
The cold ionospheric related plasma has been observed at times as far out as 9 R_T from Titan, which is interpreted in terms of extensive (and asymmetric) mass loading regions around Titan. The mass loading boundaries (MLB) are identified from the simultaneous decrease of the ion speed, increase of the electron density and sometimes from magnetic pileup (MPB). The simultaneous measurement of the electron density and ion speed by the LP allows a determination of the total ionospheric escape flux along the spacecraft trajectory and together with hybrid model simulations give estimates of the total ionospheric escape flux from Titan. So far preliminary escape fluxes are estimated to a few times 10^{25} ions/s.

The Martian Hydrogen Exospheric Density Profile Measured with ASPERA-3/NPD

P. Wurz, A. Galli, H. Lammer, and the ASPERA-3 team

The NPD sensor has a small susceptibility to UV light for wavelengths below 160 nm. During the analysis of energetic neutral atoms of possible interstellar origin, this UV susceptibility has been calibrated to remove this background from the data [Galli et al., 2005]. Since the Martian UV emission below 160 nm is almost entirely due to Lyman-α radiation this UV background can be used to infer the hydrogen column density inside the NPD field-of-view. On 25 April 2004 there was a favourable observation condition for NPD for such an investigation. From 12:00 UT to 13:10 UT the NPD field-of-view scanned the area close to the Martian limb. The recorded data were interpreted with the help of a Monte-Carlo model of exospheric density profiles [Wurz & Lammer, 2003]. The exospheric hydrogen density is $(6.0\pm1.0)\cdot10^{9}$ m^{-3} and the temperature is about 1000 K. Comparisons with earlier data from the Mariner 6 and Mariner 7 missions will be presented.

IMF direction derivation from pick-up ions

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One weak point with MEX is the lack of the magnetic field data. However, it is in principle possible to derive the IMF direction from the distribution of pick-up ions because its orbit is supposed to be perpendicular to the IMF. For such derivation the ideal operation mode of IMA is highest post acceleration. In 2004, we have such mode during day 54-84, and we present one best example for such study. On 22 March 2004, IMA detected clear pick up ions just upstream of the dayside bow shock at around 1231-1239 UT. The pick up ions are found in azimuth $2 \sim 3$ for polar angle $5 \sim 9$. Solar wind direction is azimuth=3 and polar=8. From the satellite geometry, the y-z place projection of the IMF is nearly north-south aligned. At the same time (12:34$\sim$12:35) we also detected strong beam of proton and alpha particles with $2 \sim 3$ time more energy than the solar wind coming from south (azimuth=0 and polar=7). This phenomena must be related to the IMF direction.

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