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Energetic particle showers over Mars from comet Siding-Spring

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Abstract

On October 19th 2014, Mars experienced a close encounter with Comet C/2013 A1 (Siding Spring), at a distance of only 141,000 km, or one third the Earth Moon distance. The gaseous coma washed over Mars and Mars passed directly through the cometary debris stream [1]. As a close encounter of this type is predicted only once in 100,000 years, this is likely the only opportunity for measurements associated with planetary/cometary encounters. Additionally, the encounter was masked by the transit of a powerful Coronal Mass Ejection (CME) 44 hours before [2]. Thus, the comet flyby took place when the Martian plasma system was still recovering from the CME impact, whilst the solar wind passing Mars remained significantly disturbed. In this study, we investigate the interaction of the comet with the solar wind, and their effects on the shock-accelerated energetic particles that precipitate into the Mars' atmosphere. The study is based on data from MAVEN, Mars Odyssey, MSL and Mars Express missions.

1. Space weather context

This unique event allows us to investigate the response of Mars' upper atmosphere to such a rare encounter, as this may have implications for overall atmospheric evolution. However, the conditions were very complex due to the significant space weather variability, which makes discerning between space weather and cometary effects on the Martian plasma system difficult.

Numerous solar flares occurred on the Mars-facing side of the sun [e.g. 3], and two CMEs were launched. In particular, the second CME was one the largest of the current solar cycle and hit Mars ~44 hours before the comet flyby, creating a strong perturbation in the plasma system [2]. Although this perturbation somewhat diminished over the following hours, effects were still present during the comet passage. In addition, the encounter occurred while a fast solar wind stream was transiting Mars as observed by Mars Express and by solar wind simulations [2].

2. Comet encounter ephemerides

The Mars closest approach with Comet Siding Spring took place at 141,000 km, on 19 October 2014 at 18:30 UT. The comet passed Mars at a relative speed of 56 km/s, moving from below to above the ecliptic due to its high inclination orbit angle [4].

3. Energetic particle observations

In this work, the influence of the CME and of the comet's coma on the high-energy particles that reached Mars during the 10 hours of encounter is assessed with datasets from MAVEN-SEP, MSL-RAD and Mars Odyssey-HEND (an example is shown in Figure 1).

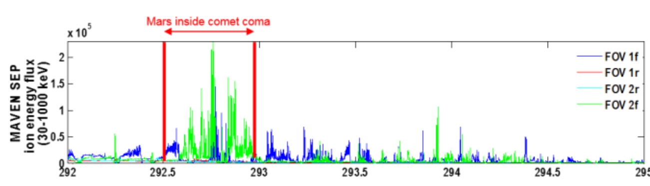

Figure 1: MAVEN-SEP ion energy flux measured during the comet encounter.

Also, the oxygen pick-up ions created and deposited in the Martian atmosphere during the following days are analysed. The study is supported with a pickup ion simulation based mainly on observations [5].

Results are compared with previous estimations pre-comet flyby [4, 6], and energy deposition in the atmosphere is assessed [see also 7 for its effects on the Mars ionosphere]. Finally, neutral sputtering from the comet tail up to a day and half after the closest approach is evaluated by using Mars Odyssey-HEND observations.

4. Conclusions

We investigate whether is possible to separate the effects of the comet coma and the space weather activity on the shower of energetic particles and pick-up ions observed at Mars by MAVEN, Mars Odyssey and MSL, or if these observations come from a mixed source of both phenomena. This is important in order to better understand the ionospheric variability detected during the comet flyby (possible energy deposition), as well as may have implications for overall atmospheric evolution.

Acknowledgements

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Comet Siding Spring's influence on the Mars' ionosphere

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Abstract

On October 19th 2014, Mars experienced a close encounter with Comet C/2013 A1 (Siding Spring), at a distance of ~138,000 km. The coma washed over Mars and the planet passed directly through the cometary debris stream, producing significant effects in Mars' upper atmosphere. We present here an overview of ionospheric measurements performed during the comet encounter with Mars Express, MAVEN, and Mars Reconnaissance Orbiter. We discuss the comet's influence on the ionosphere through different processes that work at different altitudes: magnetospheric disturbances, impact of cometary pick-up ions, and deposition of cometary dust.

1. Geometry and timing of the comet encounter

The closest approach with comet Siding Spring took place at a distance of ~138,000 km from the center of Mars, on 19 October 2014 at 18:28 UT (Solar longitude Ls 217, Martian Year 32). It flew by Mars at a relative velocity of ~56 km/s, moving from South to North (retrograde orbit, 129 degrees inclination).

2. Context of the comet encounter

The context is essential to properly analyse the data taken during this unique event. Since we are dealing here with dust and upper atmosphere, it is important to characterise the space weather and the seasonal dust contexts.

The space weather conditions are peculiar: a large interplanetary coronal mass ejection hit Mars about 44 hours before the comet closest approach, disturbing the Mars' plasma environment [1]. Many solar flares also occur in this period, some of them could have hit Mars. Moreover, this cometary flyby took place at the start of a dust season, as indicated by Mars Express PFS dust opacity measurements and data assimilation [13,14].

Obviously, this context implies that the data analysis is not trivial.

3. Measurements and data sets

The following data sets are used in this study: Data recorded by the MARSIS radar aboard Mars Express in the active ionospheric mode [2] give access to local electron densities at the spacecraft altitude, electron density profiles and an indication of the signal attenuation (due to electrons present at low altitudes [3]). The data recorded by the SHARAD radar aboard Mars Reconnaissance Orbiter give access to the Total Electron Content [4]. The data recorded by the MAVEN orbiter include information on the magnetic field [5], the metallic ions originating from the comet [6,7], and energetic particles possibly identified as pick-up ions [8].

4. Effects on the Mars' ionosphere

The interaction of the Siding Spring coma and the Mars' ionosphere can be characterized by several processes. First, the magnetosphere was severely distorted during the comet's passage [5]. As a consequence, we can expect some disturbances in the topside ionosphere. A second effect is the flux of pickup O^+ ions originating from the coma interacting with the solar wind. These pickup ions precipitate primarily on the dayside hemisphere and can increase ionospheric densities around 110-120 km altitude [9,10]. Finally, the cometary dust is deposited in the atmosphere, mainly below 100 km altitude, and is responsible for the formation of a low altitude ionospheric layer [2,6,7,11].

These mechanisms and effects are discussed and compared, with the support of modeling and data analysis. In particular, we propose some explanations to understand those ionospheric compressions and bulges observed in the Mars Express data set (see Figure 1), and explore the complex interaction dust-ionosphere.

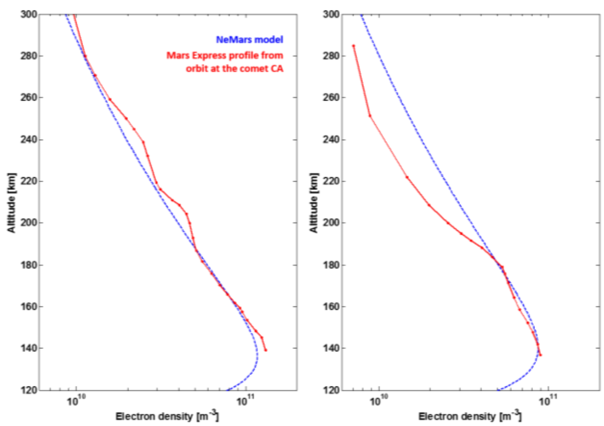

Figure 1: Mars Express MARSIS electron density profiles obtained within 5 minutes of difference from the orbit at the time of the comet closest approach, on the dayside hemisphere. Left panel: electron density profile showing two bulges centered around 200 and 240 km. The solar zenith angle is 71 degrees. Right panel: electron density profile where a clear compression of the ionosphere is found above 180 km. The solar zenith angle is 80 degrees. In both panels, the NeMars model [12] was plotted to compare with a predicted and undisturbed ionosphere.

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Signature of Metallic ion in the upper atmosphere of Mars following the passage of comet C/2013 A1 (Siding Spring)

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Abstract

The Mars Atmosphere and Volatile EvolutioN (MAVEN) mission made the first in situ detection of metal ions in the upper atmosphere of Mars. These ions result from the ablation of dust particles from comet Siding Spring. This detection was carried out by the Neutral Gas and Ion Mass Spectrometer (NGIMS) on board the MAVEN spacecraft. Metal ions of Na, Mg, Al, K, Ti, Cr, Mn, Fe, Co, Ni, Cu, and Zn, and possibly of Si, and Ca, were identified in the ion spectra collected at altitudes of ~185 km. The measurements revealed that Na^+ was the most abundant species, and that the remaining metals were depleted with respect to the CI (type 1 carbonaceous Chondrites) abundance of Na^+.

1. Introduction

The close passage of comet Siding Spring (C/2013 A1, CSS) provided a unique opportunity to observe the close interaction between the dusty coma of a comet and a dense planetary atmosphere. During this event, the MAVEN spacecraft was ideally located and equipped to measure the response of the upper atmosphere of Mars to a strong and rapid cometary mass and energy disposition, and to assess the mechanisms by which the atmospheric system returns to equilibrium. It also offered the rare opportunity for direct characterization of cometary material being freshly delivered into the upper atmosphere and ionosphere of Mars.

2. Observations

Data of neutrals and ions were collected by NGIMS from 18 October to 22 October 2014 as part of the MAVEN Siding Spring observation campaign that took place immediately before and after the comet's encounter with the planet. During this campaign, NGIMS carried out 19 sets of special observations. This special observation sequence devoted the majority of the instrument's observing time to a select set of atmospheric neutrals and ions but included 10 ion "survey" scans that were conducted at various altitudes. Each survey scan covered the full 2–90 Da mass range at a unit mass resolution. The NGIMS activities were conducted at regularly spaced intervals (orbits #108-128), interrupted only by a 10 h period at the peak of the cometary dust flux, when the instrument was temporarily turned off to minimize risk to the hardware.

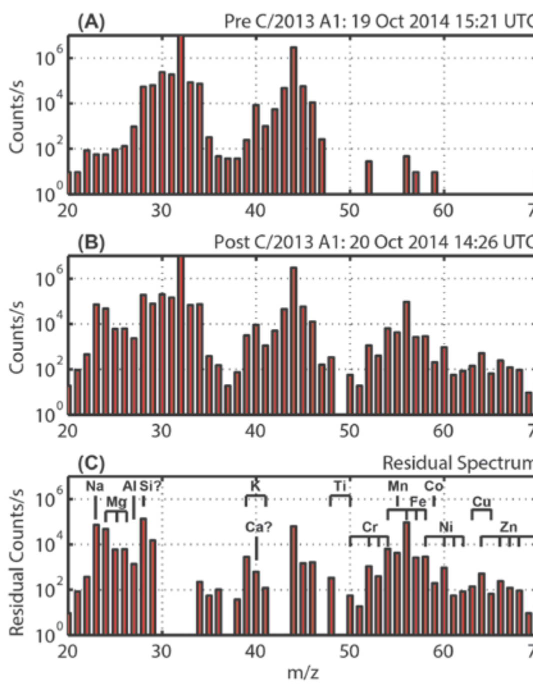

Figure 1: Comparison between two spectra collected (a) 5 h prior to and (b) 19 h following the time of maximum dust flux of CSS. (c) The residual spectrum reveals the emergence of 14 spectral lines characteristic of metal ions.

Figure 1 depicts the spectral signatures of ions before and after the passage of CSS in two ion survey spectra collected at the same altitude (185–189 km). The difference between these two spectra reveals the emergence of several mass peaks that are characteristic of metal ions in the few hours that followed the CSS encounter. These ions were identified as Na^+, Mg^+, Al^+, K^+, Ti^+, Cr^+, Mn^+, Fe^+, Co^+, Ni^+, Cu^+, and Zn^+, and possibly Si^+, and Ca^+. The identity of most of these species was established unambiguously by comparing measured isotope ratios to their relevant natural relative abundances.

3. Inferred abundances

Figure 2 shows that the relative NGIMS ion abundances are depleted with respect to Na^+ in primitive CI carbonaceous chondrites [1]. As an example, Fe^+ and Mg^+ are depleted by factors of 44 and 24, respectively. There are three reasons to why Fe^+ and Mg^+ could be depleted relative to Na^+ at 185 km.

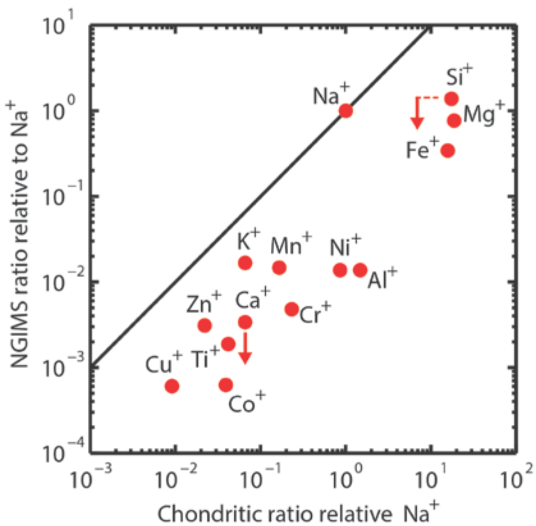

Figure 2: Comparison between relative NGIMS ion abundances and those of primitive CI carbonaceous chondrites. All abundances are normalized to that of Na^+. The relative abundances of Si^+ and Ca^+ reflect upper limit values.

First, a significant fraction of the ablating elements would have been ionized by hyperthermal collisions with CO_2 molecules on entry. At the speed of incoming meteoroids, Na is more than twice likely to be ionized than Fe or Mg. Second, during transport from the ablation region below 120 km up to the height of the NGIMS measurements, neutral metal atoms will be ionized by charge transfer with ambient O_2^+ ions. The rate coefficient for charge transfer with Na is about 2.5 times faster than for Fe or Mg [2, 3] leading to an excess in relative abundance of Na^+. Third, neutralization of the metal ions involves clustering with CO_2, followed by dissociative recombination with electrons [3]. The rates of these clustering reactions increase by a factor of ~3 from Na to Fe.

4. Summary and Conclusions

The identification of metal ions in the ionosphere of Mars following the passage of CSS is a first-of-its-kind measurement conducted on another planet of the solar system. The characterization of the metal content in the CSS dust particles that ablated in the Martian atmosphere will require untangling the effects of the various mechanisms that interplayed to produce the signatures of metals observed by NGIMS. More importantly, these measurements paved the way to a systematic long term survey of metals in the ionosphere of Mars which led to the detection of a continuous presence of an ablation metal ion layer at lower altitudes [4].

Acknowledgements

The MAVEN mission is supported by NASA through the Mars Scout program. The NGIMS data are available in a readily accessible format on the Planetary Data System at (http://atmos.nmsu.edu/data_and_services/atmospheres_data/MAVEN/ngims.html).

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Constraining the Water Production Rate and Impact on Mars' Ionosphere of Comet Siding Spring

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Abstract

The approach of comet C/2013 A1 (Siding Spring) provided Mars with a unique opportunity for investigating how an Oort cloud comet coma interacts with a planet's atmosphere. Studies predicted a water production rate of ~10^{28} molecules/s [e.g., 1]. Here we present comet Hydrogen Lyman-α spectra measured with the high-resolution echelle mode of the Imaging Ultraviolet Spectrometer (IUVS) instrument on board the Mars Atmosphere and Volatile Evolution (MAVEN) mission. The comet H Lyman-α emissions are resolved from Mars H Lyman-α and so are used to calculate a water production rate using emissions exclusively from comet coma. These observations as well as those made by the Hubble Space Telescope (HST) of the extended Mars corona are used to constrain the amount of cometary water and subsequent atomic H flux on the ionosphere of Mars. The effects of H influx on the upper atmosphere and ionosphere of Mars are assessed using a fluid ionospheric model. Model results are compared with *in situ* ion density measurements made by the MAVEN Neutral Gas and Ion Mass Spectrometer (NGIMS) instrument.

1. Introduction

The MAVEN IUVS instrument obtained hydrogen Lyman-α spectra of comet Siding Spring and Mars' extended H corona. Low-resolution images were used to determine the water production rate of the comet [2]. These data were unable to resolve the combined contribution of H Lyman-α emissions from the Mars extended coma, interplanetary hydrogen (IPH), as well as cometary hydrogen. A recent analysis of high-resolution spectra, using calibrated data [3], measured by IUVS have shown that these three contributions can be separated, as shown in Figure 1, to determine a more accurate estimate of the observed water production rate, as well as to provide constraints on the H-producing photochemical reactions near the comet nucleus [4, 5].

A refined comet water production rate is derived using a Direct Simulation Monte Carlo Model [6, 7] that will be used to derive the H influx into the upper atmosphere of Mars, together with upper limits of this flux, derived from HST observations of the extended Mars corona and a Radiative Transfer model [8]. The perturbations due to increased concentration of neutral hydrogen in the martian atmosphere affect the chemical balance of the ionosphere [9]. These effects are simulated, as shown in Figure 2, to produce ionospheric density enhancements that are compared with NGIMS *in situ* measurements taken at the time of the comet closest approach to Mars.

2. Figures

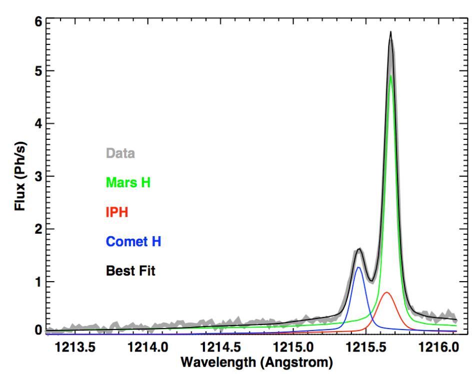

Figure 1: MAVEN IUVS echelle spectrum obtained by averaging over 70 high-resolution observations.

The spectrum (grey) shows separate contributions of Mars H (green), IPH (red), and comet H (blue) that are separated by Doppler shifts. A model based on Solar Wind Anisotropies (SWAN) instrument observations is used to optimize the fit to the IPH and remaining H contributions (black).

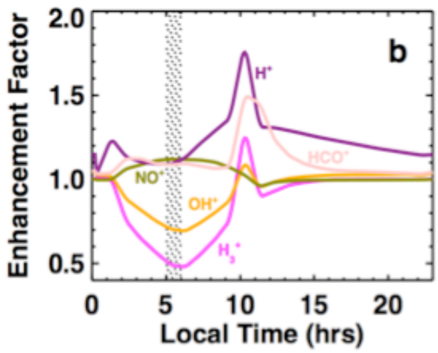

Figure 2: Preliminary estimates of the enhancement of ionospheric ions at Mars due to the influx of cometary hydrogen as a function of local time. The shaded vertical region indicates the time of closest approach of the comet to Mars. Enhancements and depletions of a few key hydrogenated ions are simulated using a fluid ionospheric model [10].

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The precipitation of keV energetic oxygen ions at Mars and their effects during the comet Siding Spring approach

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Abstract

On October 19, 2014, the Siding Spring C/2013 A1 comet passed in the vicinity of Mars with a closest approach of ~130,000 km with a heliocentric distance of 1.38 AU. The coma of the comet interacted with Mars, leading to the precipitation of molecules, ions, and dust particles. The most important atmospheric effect was the precipitation of atoms/molecules/ions, and especially atomic oxygen atoms and O^+ ions. Although the main gas forming the corona of comets is H_2O, the cometary coronal gas is partially ionized and dissociated by the EUV-XUV solar flux. To understand the atomic and molecular precipitation effects during such an encounter, it is therefore necessary to evaluate the flux of the neutral gas ejected from the comet, and to compute its composition after the dissociation/ionization.

We computed the photodissociation of the cometary gas for different solar conditions, and for the conditions of the comet encounter. In addition, using a pickup ion code, we computed the fluxes of the O^+ ions accelerated by the solar wind at energies greated than a keV. Using the Planetocosmic model, we computed the ionization in the atmosphere of Mars due to these species, and, using the M-GITM model, we computed the associated increase of the ion/electron density.

For the first time, an estimate of the flux of energetic O^+ ions picked up by the solar wind from the cometary coma is shown, with an increase of the O^+ flux above 50 keV by two orders of magnitude. While the ionization of Mars' upper atmosphere by precipitating O^+ ions is expected to be negligible compared to solar EUV-XUV ionization, it is of the same order of magnitude at 110 km altitude during the cometary passage.

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The Metals Delivered by Comet Siding Spring to Mars

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Abstract

On October 19th 2014, comet C/2013 A1 (Siding Spring) had a close encounter with Mars and deposited cometary dust particles into the Martian atmosphere. Dust that impacted Mars was readily identifiable as the meteoric deposition of Mg, Fe, Na, etc. by the Imaging Ultraviolet Spectrograph (IUVS) and Neutral Gas and Ion Mass Spectrometer (NGIMS) on the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft. While Mg^+ from comet Siding Spring and in a persistent layer was identified previously by IUVS, this is the first report on the abundance, spatial distribution and temporal evolution of Mg, Fe, and Fe^+. We compare these observations to the Leeds 1-D Chemical ABlation MODel (CABMOD), and derive constraints on meteoric ablation, which helps to constrain chemistry at high altitudes.

1. Introduction

MAVEN's remote sensing instrument for studying Mars' upper atmosphere is the Imaging Ultraviolet Spectrograph (IUVS) [1]. This instrument observes in the far and middle UV (110-190 nm and 190-340 nm) in separate channels, and measures atmospheric emissions from CO_2, its dissociation and ionization products as well as atomic and molecular species such as O and N_2 [2, 3]. The instrument uses a scan mirror to construct vertical profiles of emergent radiation from the atmosphere at the limb.

We use observations from the periapse segment of each orbit, where IUVS produces limb scans over the altitude range 75-250 km. During each orbit, IUVS takes up to 12 limb scans in a ~22 minute observation period spanning ~45 degrees around the planet. MAVEN's elliptical orbit precesses about Mars on timescales of months to provide complete coverage of the planet. Data processing techniques are outlined in detail in previous MAVEN/IUVS papers [2, 3, 4, 5, 6].

High-speed collisions with air molecules cause rapid heating of interplanetary dust particles (IDPs), melting and evaporating their constituent minerals [7]. This ablation process deposits a variety of atomic constituents at the ~1 μbar level (80-110 km on Earth). Non-volatile elements such as Mg, Fe and Na act as direct tracers of the ablation process, as no other processes transport these species to these altitudes. In addition to the quasi-steady-state supply from random (or "sporadic") meteors, the ablation of cometary dust during meteor showers can supply additional metals to the upper atmosphere, as shown by comet Siding Spring.

2. Data

We relate the column brightness of these species to their tangent point densities by their scattering efficiencies and an Abel transform. This is a simplification, as these species are generally not optically thin, and future work will use a fully radiative transfer code to determine the true densities. The optically thin approximation (Abel transform) will underestimate the total ion concentration, and distorts the altitude profile below the peak emission altitude (Figure 3).

To determine the total dust deposition, we will relate these observations to a model of 1D Chemical Ablation (CABMOD) [8]. This model uses the speed of comet Siding Spring, assumes the material is deposited uniformly and is of chondritic composition. At these speeds a majority of the Mg+ are produced through the ablation process, in contrast to the persistent layer where the ions are produced through charge exchange with O_2^+ [9].

3. Results

Of the many elements that ablate from interplanetary dust particles, Mg^+ is most readily detectable in ultraviolet (UV) remote sensing, and was observed in a transient layer after the passage of comet Siding Spring [4]. The other dominant species by mass, Fe, is only detected in this time period because the delivered masses are extremely high compared to the persistent layer [10].

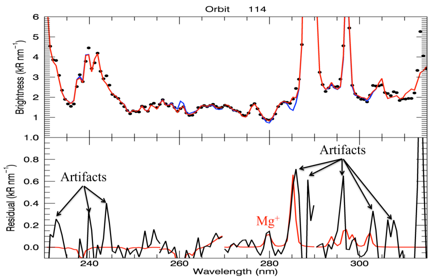

Figure 1: Top: IUVS data from a single scan on Orbit 114 is shown is black. A composite of known airglow emissions is shown in blue, while the red includes Mg, Mg^{+}, Fe and Fe^{+}. Bottom: Residuals, which are consistent with an incomplete knowledge of the shape of the CO Cameron bands, and left shoulder of the CO_2^{+} UV Doublet.

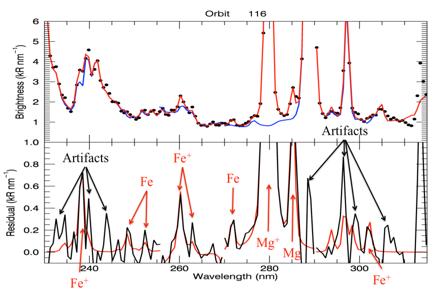

Figure 2: Same colors as Fig. 3. Top: Orbit 116, demonstrating a marked increase in Mg^{+}, Mg, Fe^{+}, and Fe. Bottom: Compared to bottom of Fig. 3 one can see that emissions from these new metal species are identifiable near 239 nm, 245 nm, 260 nm, 272 nm, and perhaps near 295nm.

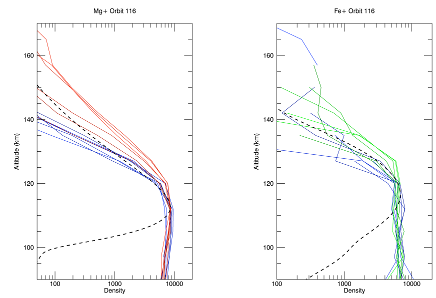

Figure 3: Altitude profiles of Mg^{+} and Fe^{+} shown for orbit 116, directly after dust deposition at Mars. In both profiles, blue represents the beginning of a scan, whereas red or green (Mg^{+} or Fe^{+}, respectively) represents the end of the scan. A model from the Leeds Chemical Ablation Model (CABMOD) is shown as the dotted black line and scaled to match the data.

4. Summary

- We observe metallic species only found at Mars during the meteor shower of comet Siding Spring.
- Using these species we can constrain both the total flux of dust, as well as informing chemical ablation models.
- Spatial evolution of the ions suggest these species are controlled by dynamical processes that require further explanation.
- Temporal evolution indicates lifetimes inconsistent with model expectations.

Acknowledgements

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MAVEN IUVS Observations of the Aftermath of the Comet Siding Spring Meteor Shower on Mars

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Abstract

We report the detection of intense emission from magnesium ions in Mars' atmosphere caused by a meteor shower following Comet Siding Spring's close encounter with Mars. The observations were made with the Imaging Ultraviolet Spectrograph, a remote sensing instrument on the Mars Atmosphere and Volatile EvolutioN spacecraft orbiting Mars. Ionized magnesium caused the brightest emission from the planet's atmosphere for many hours, resulting from resonant scattering of solar ultraviolet light. Modeling suggests a substantial fluence of low-density dust particles 1 – 100 μm in size, with the large amount and small size contrary to predictions. The event created a temporary planet-wide ionospheric layer below Mars' main dayside ionosphere and above the persistent layer that exists due to sporadic meteors. These observations inform our understanding of the meteoric atmospheric chemistry and dynamical processes.

1. Introduction

Shortly after the discovery of comet C/2013 A1 (Siding Spring), orbit determinations identified a very close passage by Mars on 19 October 2014. Motivated by concerns over spacecraft safety, detailed modeling of cometary dust predicted relatively low risk of spacecraft damage from dust impacts [1, 2, 3,4]. The effect of dust on Mars was of particular interest for its potential ionospheric effects [5]. Cometary gas impact was also considered for its potential effects on Mars' upper atmosphere [6], yet no significant enhancements were detected [7]. Accurate predictions were challenging due to the lack of precedent: the interval between such near miss events of the observed distance of 141,000 km has been estimated at 100,000 years [8]. Dust ejected from the comet was expected to remain confined in a stream that lags behind the comet in its orbit and predicted to intercept the planet about 2h after the comet's closest approach.

The Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft entered Mars orbit on 21 September 2014 on a mission to study the behavior of the upper atmosphere and the escape of its constituent gases to space [9]. MAVEN carries one remote sensing instrument for the study of Mars' upper atmosphere, the Imaging UltraViolet Spectrograph (IUVS) [10]. The instrument captures spectra of the planet in the far and mid UV (110 – 340 nm), ideal for recording well-known atmospheric emissions from CO2 and its dissociation and ionization products.

2. Observations

During periapse, IUVS makes observations in a limb viewing geometry and construct vertical profiles of the atmosphere by using a scan mirror inside the instrument.

IUVS repeated its periapse observations from 18 October 16:05 UT (Orbit 109) to 22 October 07:49 UT (Orbit 128), with the exception of Orbit 115 when the spacecraft stood down during maximum predicted dust flux. Data were corrected for detector dark current, scaled according to intensity calibration and binned in altitude above the surface. Cleaned spectra and vertical profiles of individual emissions were obtained through multiple linear regression fits of independent spectral components, accounting for molecular bands, atomic lines and reflected solar spectrum background, as well as instrumental resolution and instrumental offsets [11].

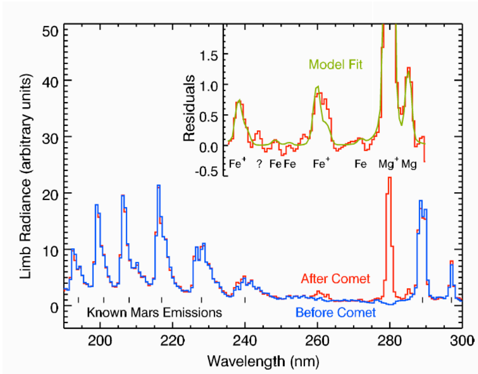

Figure 1: Spectra of Mars' atmosphere immediately before and after the closest approach of Comet Siding Spring. The inset shows a smoothed residual spectrum in red on an expanded vertical scale.

3. Results

Figure 2a shows a vertical profile of Mg^+ emission from one altitude scan of Orbit 116, peaking around 115 km and falling off rapidly with increasing altitude with an exponential scale height of ~2 km. A profile of the CO_2^+ UV doublet at 289 nm emission is shown as a fiducial for the background atmosphere and ionosphere, with its peak at 130 km and an ~16 km scale height. Together, these profiles demonstrate that the Mg^+ was narrowly confined in a layer 10–20 km below the CO_2^+ UV doublet peak located at a few nanobars pressure.

We will show the spatial distribution and temporal evolution of Mg^+ emission captured with IUVS observations over the course of this campaign. Such observations can then be used to compare to models of chemical ablation, particularly to determine the expected concentration of neutral species, which was not detected in the persistent layer [12].

4. Summary

- IUVS observed the largest meteor shower in modern history.
- Observations of Mg^+ constrain the delivered dust, and call for reexamination of cometary debris models.
- Temporal and spatial evolution constrain our understanding of meteoric chemistry and dynamical transport of these species at Mars.

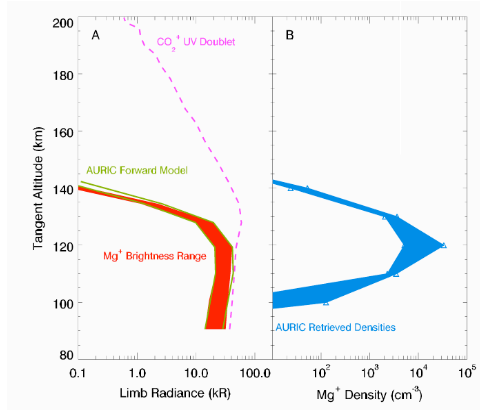

Figure 2: Vertical profiles of metal species and CO_2^+ UVD obtained from the same scan as Figure 1.

Acknowledgements

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Interaction between Mars' induced magnetosphere and the comet Siding Spring

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Abstract

On 19 October 2014 the comet C/2013 A1 (Siding Spring) flew by Mars. This was a unique opportunity to study the interaction between a cometary and a planetary magnetosphere. Here we model the magnetosphere of the comet using a hybrid plasma solver (ions as particles, electrons as a fluid). The undisturbed upstream solar wind conditions are estimated from ion observations by ASPERA-3/IMA on Mars Express, and from magnetic field observations by MAVEN. It is found that Mars probably passed through a solar wind that was disturbed by the comet during the flyby.

1. Introduction

We want to answer two questions. (1) Was the solar wind that Mars encountered disturbed by the comet? (2) What was the precipitation of cometary ions on Mars?

2. Model

To model the interaction of the comet with the solar wind we use a hybrid plasma model. The production rate of ions are analytically computed from a spherical symmetric neutral Haser model [1]. We also need the undisturbed upstream solar wind conditions. The solar wind density, velocity and temperature are estimated from observations by ASPERA-3/IMA on Mars Express [2]. The magnetic field is estimated from MAVEN observations [3].

2.1. Hybrid Model

In the hybrid approximation, ions are treated as particles, and electrons as a massless fluid. The trajectory of the ions is computed from the Lorentz force, given the electric and the magnetic fields. The electric field is

$$\mathbf{E} = \frac{1}{\rho_I}\left(-\mathbf{J}_I \times \mathbf{B} + \mathbf{J} \times \mathbf{B} - \nabla p_e\right) + \eta \mathbf{J}, \qquad (1)$$

where ρ_I is the ion charge density, $\mathbf{J}_I$ is the ion current density, p_e is the electron pressure, and η is the resistivity. The current is computed from, $\mathbf{J} = \mu_0^{-1}\nabla \times \mathbf{B}$, where $\mu_0 = 4\pi \cdot 10^{-7}$ is the magnetic constant.

Then Faraday's law is used to advance the magnetic field in time,

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}.$$

Further details on the hybrid model used here, the discretization, and the handling of vacuum regions can be found in [4].

2.2. Comet Model

The dominant neutral specie produced at the comet is water. For water, the most important loss process is the photodissociation, $H_2O \rightarrow OH+H$.

The water ion production as a function of distance from the origin, r, is

$$q_i(r) = \frac{\nu_i Q}{4\pi r^2 u} e^{-\nu_d r/u} \quad [\mathrm{m}^{-3}\mathrm{s}^{-1}],$$

where the release rate of water molecules is Q at a radial velocity of u. The water is photoionized at a rate of ν_i and the destruction rate is ν_d (including photoionization).

Here we use a water production rate of $Q = 1.1 \pm 0.5 \cdot 10^{28}$ molecules per second [5].

3. Results

As can be seen in Figure 1, a bow shock is formed upstream of the comet. The trajectory of Mars passes through the shock, as seen in the plot of the magnetic field in Figure 2. Mars does however not pass near the region of high density of water ions. Due to the relatively high production rate of the comet, the escape of water ions is mainly not as pick-up ions, but is more fluid like.

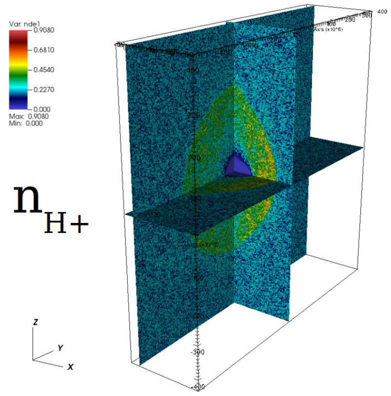

Figure 1: Preliminary simulation results. Solar wind proton number density. The solar wind flows along the $-x$ axis.

4. Summary and Conclusions

We have studied the interaction of the comet Siding Spring with the solar wind on 19 October 2014 using a hybrid plasma model. We conclude that most likely Mars passed through a shocked solar wind that was disturbed by the comet during the flyby. There are uncertainties in the model parameters, but the solar wind interacting with Mars was disturbed for all parameter sets tested. The uncertainty derives from that the size of the disturbed solar wind region in the comet simulation is sensitive to the assumed upstream solar wind conditions, especially the solar wind proton density. The amount of cometary ions precipitating on the planet is small (compared to the solar wind, and to the neutral influx).

Possible further studies are (1) Comparing the model predictions with plasma observations by Mars Express and MAVEN, and (2) Modeling the effects of the time dependent distubed upstream solar wind on Mars.

Acknowledgements

We thank J. Espley (NASA GSFC) for providing an IMF estimate based on MAVEN magnetic field observations. This work used computing resources provided by the Swedish National Infrastructure for Computing (SNIC) at the High Performance Computing Center North (HPC2N), Umeå University, Sweden. The software used in this work was in part developed by the DOE NNSA-ASC OASCR Flash Center at the University of Chicago.

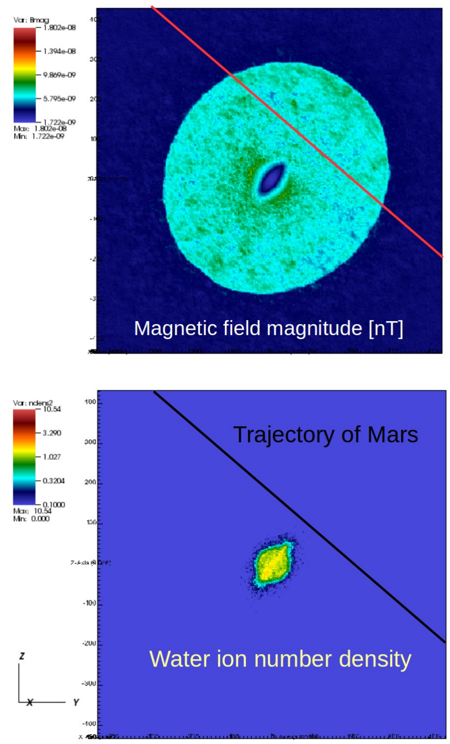

Figure 2: Preliminary simulation results. Magnetic field magnitude (top) and water ion number density (bottom) in a cut at 46 320 km downstream of the nucleus of comet Siding Spring. The lines show the trajectory of Mars (downward). The width and height of the cut is 864 000 km.

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In situ plasma observations of comet Siding Spring encounter to Mars by ASPERA-3

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Abstract

Comet Siding Spring approached Mars with a closest distance of ~140000 km in October 2004. Due to expected enough outgas and dust release, it was expected the space environment of Mars would be disturbed. In situ plasma instrument, ASPERA-3, on board ESA's Mars Express in orbit of Mars during the comet encounter, was operated to detect the changes of plasma environment by the comet encounter. Here we will describe the plasma measurements conducted by ASPERA-3.

1. Introduction

In October 2014, the comet Siding Spring approached Mars with a closest distance of ~140.000 km. Due to enough expected activity including both gas and dust, and a high relative velocity against Mars, it was expected that the space environment of Mars would be disturbed [e.g. 1-3]. Several measurements near Mars report signatures of comet Siding Spring [e.g. 4-8].

2. Instrument

We will present an overview of the plasma measurements of ASPERA-3 during the comet Siding Spring encounter. The ion mass analyzer (IMA) and electron spectrometer (ELS), parts of Analyser of Space Plasma and EneRgetic Atoms (ASPERA-3) on Mars Express, carried out observations during the comet Siding Spring encounter.

3. Observation

At the time of the closest approach of Siding Spring to Mars (18:28 on 19th October, 2014), the Mars Express was nearly at pericenter. The measured plasma environment was highly disturbed in this *Siding Spring pass*. However, two factors complicate the interpretation of this data:1) a slew maneuvour of the spacecraft for the Siding Spring campaign, and 2) more importantly, an interplanetary coronal mass ejection (ICME) traveled through the Mars space environment the day before the Siding Spring pass. The ICME was rather strong, with the maximum velocity of 650 km/s on 18th October observed by IMA. Associated disturbances of the upstream conditions lasted a couple of days, and thus the solar wind near Mars was also disturbed.

4. Summary

In this talk, we will describe the plasma measurement conducted by ASPERA-3 carefully in order to discuss and to identify the sources of the measured disturbed signatures.

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Building a Unique Scenario to Support Cross-Mission Science with SPICE: The Siding-Spring comet encounter with Mars

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Abstract

On October 2014, Mars experienced a close encounter with Comet Siding Spring. This contribution outlines a SPICE scenario built to assist studies combining MEX, MAVEN, Mars Odyssey, MSL, and Siding-Spring data focused on a SPICE-Enhanced Cosmographia 3D scenario.

1. Introduction

On October 19th 2014, Mars experienced a close encounter with Comet C/2013 A1 (Siding Spring), at a distance of only 141,000 km, or one third the Earth Moon distance. The gaseous coma washed over Mars and Mars passed directly through the cometary debris stream [1]. As a close encounter of this type is predicted only once in 100,000 years, this is likely the only opportunity for measurements associated with planetary/cometary encounters. This unique event allows us to investigate the response of the Mars' upper atmosphere to such a rare encounter, as this may have implications for overall atmospheric evolution. Additionally, one of the largest Coronal Mass Ejections (CME) of the current solar cycle hit Mars about 44 hours before the comet flyby, creating a strong perturbation in the system that, although somewhat diminished over the following hours, was still present during the comet passage.

2. Building a unique scenario with SPICE

The ESA SPICE Service (ESS) leads the SPICE [2] operations for ESA missions [3]. The group generates the SPICE Kernel datasets for the Mars Express. The ESS also provides consultancy and support to the Science Ground Segments of the planetary missions, the Instrument Teams and the science community. In this context, a multi-mission SPICE scenario has been built in order to assist the studies of the Siding-Spring comet encounter with Mars. This scenario contains the appropriate SPICE datasets of Mars Express, MAVEN, Mars Odyssey and MSL missions. The particulars of this scenario will be outlined in this contribution.

3. Four Spacecrafts and a Comet at once

The generated scenario has also been implemented in tools provided by ESS to facilitate and support the science data exploitation of this scenario [4].

1.1 SPICE-Enhanced Cosmographia

SPICE-enhanced Cosmographic is an interactive tool used to produce 3D visualizations of planet ephemerides, sizes and shapes; spacecraft trajectories and orientations; and instrument field-of-views and footprints. A scenario has been built that includes Mars Express, MAVEN, Mars Odyssey and MSL information along with comet Siding-Spring and which is also focused on the actual operations that were carried out by Mars Express. This complete operational scenario will be outline in the contribution.

1.2 WebGeocalc

The WebGeocalc tool (WGC) provides a web-based graphical user interface to many of the observation geometry computations available from the "SPICE" system. A WGC user can perform SPICE computations without the need to write a program; the user need have only a computer with a standard web browser. WGC is provided to the ESS by NAIF.

This contribution also presents the WGC instance to support this scenario.

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Preliminary analysis of PFS/MEx observations of Comet Siding Spring

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Abstract

On October 19th 2014, Mars experienced a close encounter with Comet C/2013 A1 (Siding Spring), at a distance of 138,000 km. We analyze observations by the Planetary Fourier Spectrometer (PFS) [1] onboard Mars Express performed between October 13th and October 21st 2014 to search for spectral signatures of the comet and to investigate possible effects of its passage on the suspended dust and ice content in the Martian atmosphere.

1. Measurements and datasets

PFS Observations

PFS observations dedicated to the Siding Spring comet flyby were performed between October 13th and October 21st 2014, and in particular around the closest approach (19 October 2014 at 18:28 UT, Ls 217). Given the large FoV of PFS (1.52° FWHM for the Short-wavelength channel, SWC, and 2.69° FWHM for the Long-wavelength channel, LWC; [2,3]), and the large distance of the target, the spectral signatures of the comet, if any, are expected to be very weak in the PFS spectra, and most likely to be observed only around the closest approach. We used the SPICE-enhanced Cosmographia Mission Visualization Tool v3.0 [4,9] for a 3D visualization of Mars Express, Mars and the comet at closest approach (Figure 1). As the two PFS channels have slightly different boresight directions, we used the WebGeocalc online tool [5] with the latest kernel of the comet to investigate when the comet is expected to be within the PFS SWC and LWC FoV. As a result, for the day of the closest approach, we found four time windows (Table 1).

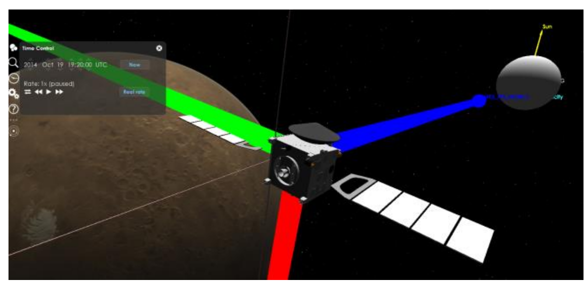

Figure 1: 3D visualization of Mars Express, Mars and the comet at closest approach with the SPICE enhanced Cosmographia Mission Visualization Tool v3.0. The comet is defined with a sphere of 15,000 km (inner coma). The blue vector represents the PFS SWC nadir boresight.

	Start Time	Stop Time	Duration (secs)
1	2014-10-19 15:31:29.430102 UTC	2014-10-19 15:51:53.160819 UTC	1223.73071754
2	2014-10-19 19:20:26.581536 UTC	2014-10-19 19:21:02.702504 UTC	36.12096786
3	2014-10-20 03:26:38.262334 UTC	2014-10-20 03:57:42.493487 UTC	1864.23115331
4	2014-10-20 20:26:33.985109 UTC	2014-10-20 21:01:19.595671 UTC	2085.61056215

	Start Time	Stop Time	Duration (secs)
1	2014-10-19 15:30:05.761012 UTC	2014-10-19 15:56:53.407226 UTC	1607.64621437
2	2014-10-19 19:20:20.371114 UTC	2014-10-19 19:21:09.958563 UTC	49.58744907
3	2014-10-20 03:26:24.454111 UTC	2014-10-20 03:57:59.363859 UTC	1894.90974790
4	2014-10-20 20:26:24.136971 UTC	2014-10-20 21:02:19.138034 UTC	2155.00106317

Table 1: Time windows, for the day of the closest approach, when the Siding Spring comet is expected to be within the PFS SWC (top panel) and LWC (bottom panel) FoVs.

PFS Retrievals

We use PFS retrievals of suspended dust and water ice opacity [6,7,8] to investigate possible effects of

Comet Siding Spring's passage on the suspended dust and ice content in the Martian atmosphere.

2. Preliminary analysis

Clear spectral signals in the PFS data could only be detected for the MEX orbit 13709, which is exactly when PFS observed Siding Spring around its closest approach. Three spectra can be easily distinguished from the others in both the SWC and the LWC, being well above the instrumental noise level. We can also exclude a random/unusual fluctuation of the PFS spectra, because the three spectra correspond in the two channels (same spectrum number in both channels). We confirm that these spectra were acquired within the time window when the Siding Spring comet was inside the PFS SWC and LWC FoV (Table 1). Given the large distance, the comet is only a small percentage of the PFS FoV, but this seems to be enough to measure some signal in the thermal range. Proper calibration and interpretation of these PFS spectra will be challenging. We performed PFS retrievals for the observations recorded during 126 MEX orbits. We separated all observations performed before 19 October 2014 from those performed after this date. We binned data in 1° of latitude. The results are shown in Figure 2.

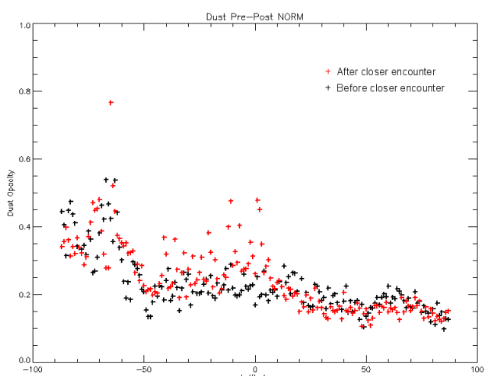

Figure 2: PFS dust opacities retrieved in October 2014 before (black crosses) and after (red crosses) the closest approach

Dust Opacities are normalized to the mean Martian surface pressure (6.1 mbar). Black crosses in Figure 2 are for observations performed before the closest approach, while Red crosses are for subsequent observations. These preliminary results indicate an increase of dust in the Martian atmosphere after the comet's closest approach, especially in the latitude range 40°S-10°N.

Acknowledgements

The PFS experiment has been built at the Istituto di Astrofisica e Planetologia Spaziali (IAPS) of Istituto Nazionale di Astrofisica (INAF), and has been founded by the Italian Space Agency (ASI) in the context of the Italian participation to the ESA’s Mars Express Mission. PFS data are publicly available via the ESA Planetary Science Archive.

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An Ionized Layer in the Upper Atmosphere of Mars Caused by Dust Impacts from Comet Siding Spring

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Abstract

On 19 October 2014, the comet Siding Spring passed within 135,000 km of Mars. This close encounter caused dust from the comet to impact the Martian atmosphere at very high velocities, allowing for major ionization to take place in the upper atmosphere. The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) aboard Mars Express subsequently observed an unusual transient layer of ionization at altitudes of about 80-100 km on the two ensuing spacecraft orbits. This ionized layer was present on both the dayside and nightside of Mars, and contained peak electron densities of 1.5-2.5 x 10^5 cm^{-3}, higher than densities normally observed in the Martian ionosphere. These results have been compared to ionization produced by meteors at Earth and Mars, leading to the conclusion that this layer was directly produced by the cometary dust impacting and ionizing the upper atmosphere of Mars.

1. Mars Express Radar Sounder

The Mars Express spacecraft carries among its instruments the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS). In its ionospheric sounding mode, MARSIS transmits a short pulse at a fixed frequency and then measures the time delay for the pulse to reflect from the ionosphere and return to the spacecraft. For vertical incidence, the ionospheric reflections occur at the point in the ionosphere where the wave frequency is equal to the electron plasma frequency. By stepping the transmitter frequency through a range of frequencies, a vertical profile of the electron density in the ionosphere can be obtained. As a first order approximation, the location of the reflection point can be calculated assuming the radar pulse travels at the speed of light, in which case the altitude of reflection is called the apparent altitude. However, for precise measurements, plasma dispersion effects must be considered. During the period around closest approach of the comet to Mars, the ionospheric radar soundings started at an altitude of about 1200 km over the nightside northern polar region, then proceeded southward across the terminator, through periapsis at about 375 km, and ended at midlatitudes in the southern hemisphere.

2. Observations

The first evidence of anything unusual was on orbit 13710, 7 hours after closest approach. On this pass, strong radar echoes were observed at an apparent altitude of about 100 km over the nightside polar region at frequencies extending as high as 4.6 MHz. The peak plasma frequency corresponds to an electron density of 2.6 x 10^5 cm^{-3}. Densities this high have never been observed on the nightside of Mars. A few minutes later, similar radar echoes were detected on the dayside of Mars at frequencies well above the normal dayside ionospheric echoes. On the next pass, the enhanced ionization over the nightside polar region had completely disappeared, but there was still evidence of an enhanced ionization layer on the dayside of Mars. On the ensuing orbit, there was no evidence of the ionization layer.

The ionograms in Figure 1 show that on orbit 13710 the transient ionization layer extended nearly continuously from the polar region into the dayside midlatitudes. Electron densities were highly variable, ranging from about 1.5-2.5 x 10^5 cm^{-3}, with two well-defined peaks and two brief periods where no echoes were detected. In all cases, the peak densities of the transient layer were well above the peak density of the Martian ionosphere.

The thickness of the ionized layer is also of interest. While no such measurements can be obtained from the topside echoes, the dispersion of the ground echoes gives a direct measurement of the total electron content (TEC). By subtracting the TEC of the ionosphere, the TEC of the transient layer can be determined. Unfortunately, only three ionograms had ground and ionospheric echoes sufficient to yield reliable measurements of the thickness. These ranged from 13.7 to 42.3 km. Patchy ionization may be the cause of this inconsistency.

3. Figures

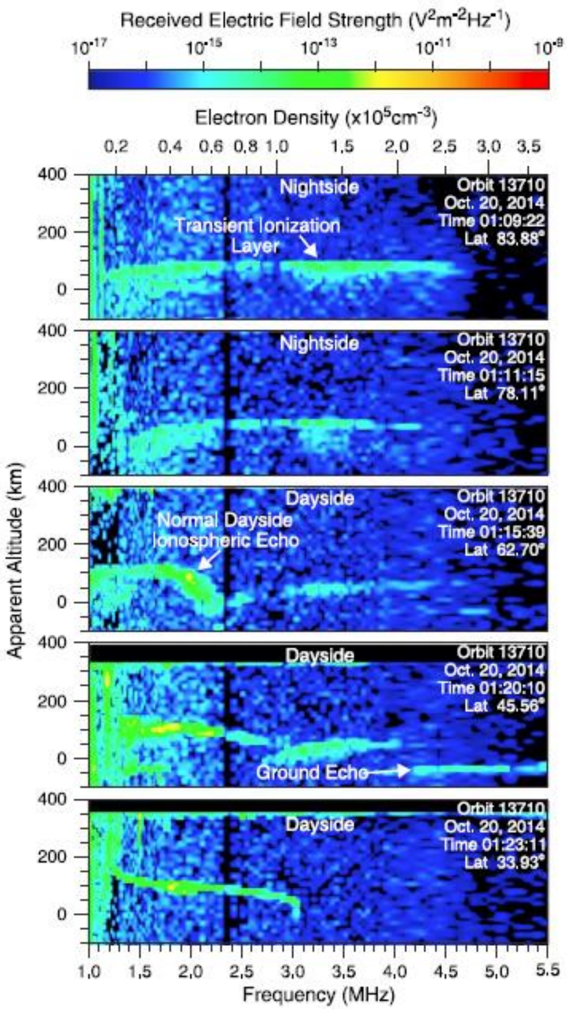

Figure 1: Five ionograms showing the latitudinal variation of radar echoes from the transient ionized layer. The first two ionograms, from the nightside, show the apparent altitude of the reflecting layer to be nearly independent of frequency. Slight dispersion effects below about 2 MHz are due to ionospheric plasma at low densities between the spacecraft and the layer, particularly in the dayside ionograms.

4. Conclusions

Of the two components, gas and dust, released from the comet, only dust can cause this transient layer of ionization. The altitude of this layer is far below the altitudes where the primary interaction with cometary gas was expected. On the other hand, the altitudes are in good agreement with the transient M3 layer in the Martian ionosphere [1]. The M3 layer is believed to be caused by the impact of meteors.

It is interesting to note that the observations obtained here were taken over a local time region that was not exposed to direct impacts of dust from the comet. The main flux of meteoritic particles probably occurred 5-6 hours before our earliest observations [3]. Evidence of the early arrival of the particles is given by the SHARAD radar on the Mars Reconnaissance Orbiter spacecraft, which detected greatly enhanced TECs as early as 3 hours after closest approach [2]. The enhanced TECs lasted almost 10 hours. This means the ionization had to be transported by the rotation of the Martian atmosphere from the main impact region over a period of 10 hours or more, and also in local time.

Acknowledgements

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Dust properties and composition in the coma of Mars-grazing comet C/2013 A1 Siding Spring

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Abstract

Comet C/2013 A1 Siding Spring is a dynamically new comet from the Oort Cloud that crossed the inner solar system in 2014/15. On its way inbound, it passed Mars at a distance of only 140,000 km on 2014 October 19, creating a meteor shower and depositing dust into Mars's atmosphere.

We monitored the development of the coma of C/2013 A1 as it approached the inner solar system during a full year between October 2013 and September 2014, using the Very Large Telescope (VLT) of the European Southern Observatory (ESO) in Chile. We obtained spectra with the ESO/XSHOOTER multi-wavelength medium resolution spectrograph, and broadband images using FORS2.

The composition of the coma is constrained from the spectra. The near-infrared part is of particular interest for assessing the presence and evolution of icy grains in the coma. Dust properties are analyzed from the images. We constrain the dust production rate, size distribution and ejection velocity through numerical simulations.

Our results will contribute to better assess the effects of cometary material on the Martian atmosphere.

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Space Weather Conditions Before, During and After the Comet Siding Spring Encounter with Mars

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Abstract

On October 19th 2014, Comet C/2013 A1 (Siding Spring) passed Mars at a distance of 138,000 km. The resultant interaction as the planet passed through the coma and the cometary debris stream produced significant effects in the Mars' upper atmosphere. However, before, during after the closest approach, there were significant space weather events which make the interpretation of the observations difficult. Here we summarise these events such to aid any subsequent attempts at determining the exact nature of the interaction between comet and Mars' upper atmosphere.

1. Introduction

Comet C/2013 A1 (Siding Spring) approached Mars on the 19th October and closest approach occurred at 18:28 UT that day. The coma entirely engulfed the planet while the tail also washed over the planet. There were a number of spacecraft either in orbit around, or at the surface of Mars during the encounter. These spacecraft included Mars express (MEX), Mars Atmosphere and Volatile Evolution (MAVEN), Mars Reconnaissance Orbiter, Mars Odyssey, and the Curiosity Rover. While not all instruments were switched on during the encounter, there is a substantial data base of observations before during and after the encounter. Here we provide an overview of the space weather events which occurred before, during and after the cometary encounter with Mars, with the aim of providing a general understanding of the background conditions under which the encounter took place. In many respects this interval was one of the most disturbed of the current solar cycle.

2. Timeline of events

We start by providing a simple timeline of events as they occurred at Mars. We divide the background conditions into three separate types of events, a co-rotating interaction region (CIR), coronal mass ejections, and solar flares. Each of these events elicits a different response at Mars.

Based on the observations of solar wind velocity by the ASPERA-3 instrument on MEX, the first CME to impact at Mars was launched on 13th October from the sun, and reached Mars on the 16th October. A larger CME was launched the following day from the sun and arrived on the 17th October. This has proven to be one of the largest CME of the current solar cycle. This second event has in fact been seen at a number of different locations throughout the solar system [1], from Mercury orbit out to possibly New Horizons close to Pluto. At the time of the CME the solar wind velocity at Mars reached 700 km s-1, based on ASPERA data. Multi-spacecraft observations are complemented with a dedicated WSA-ENLIL+Cone (large-scale, physics-based prediction model of the heliosphere) solar wind simulation, in which this CMe has been included. Further, based on the RAD instrument on Mars Science Laboratory on the Curiosity Rover and Mars Odyssey HEND data, the galactic cosmic ray intensity reduced by some 20% of the peak value just after the CME arrival at Mars [1]. Comparison with other CME events at Mars using the same HEND instrument suggests that they typically result in reductions by about 5% of the peak value prior to CME arrival.

Further during the interval of interest, a number of solar flares were detected which would have impacted on Mars. One of the largest of these was an X1.1 flare which impacted at Mars on the 19th October just prior to the cometary encounter [2]. The largest flare, an X1.6 flare, impacted at Mars on 22nd October several days after the cometary encounter, although it is important to understand that the Martian system may at that time have been still recovering from the encounter.

Four M class flares were also launched in the direction of Mars during the interval. An M1.1 class flare was launched at the same time as the second CME on 14th October, while a M1.6 class flare was launched on 18th October, the day before the cometary encounter. Finally, 2 were launched on 22nd October, one a M8.7 class flare and another a M2.7 class flare. There were also some 20 C class events which may have impacted on Mars, but these are not detailed here as their effect is likely to have been smaller, although we will still analyse the effects of these where possible.

3. Summary

In summary the interval before, during and after the Siding Spring encounter with Mars was one of the most disturbed periods of the current solar cycle. Therefore, it is important to understand the impacts of these events in order that we can separate out the cometary effects from space weather effects.

Acknowledgements

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