Mars plasma system response to space weather variability with solar cycle

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Credits: MEX VMC image
Outline

1. General description of the Mars’ plasma system

2. Long-term solar cycle variability effects on Mars’ ionosphere
   - Ionosphere modelling

3. Short-term solar cycle variability effects on Mars’ ionosphere
   - Ionosphere modelling
   - ICME propagation throughout the solar system
   - ICME effects on Mars at high and low solar cycle phases
General description
Since Mars does not have a global intrinsic magnetic field, the Mars’ upper atmosphere and ionosphere are the main obstacles that the solar wind finds at Mars.

Therefore, the “strength” of this obstacle is a determining factor to assess the behaviour of the Martian plasma with solar wind variability.
MARSIS-Mars Express radar

MARSIS in its Active Ionospheric Sounding mode

max \( fp = max \text{ Ne} \)
Long-term variability
EUV and soft X-ray play the major role in the formation of the ionosphere of Mars, and therefore, in the “strength” of the Martian obstacle to the solar wind.
Solar cycle variations in the Martian ionosphere

Total Electron Content (TEC) of the full atmosphere gives us an idea of the strength of the Martian plasma obstacle that acts to deflect the solar wind flow.

Data extended from Sanchez-Cano et al., 2016
Ionospheric modelling: TRANSPLANET

In order to study the space weather variability effect on the ionosphere of Mars, we have used the IPIM model in several studies

http://transplanet.irap.omp.eu/

IPIM is a one dimensional coupled kinetical model, which has been built in a modular way, leading to a core model that is independent from the planet.

The interment interface is very convenient because the model is very complex to run.
Case study I: solar cycle effect

Since the ionosphere was much weaker during the low solar activity phase, the thermal pressure of the ionosphere was very close to the magnitude of the dynamic pressure of the solar wind.

To evaluate the effect of this pressure relationship on the ionosphere, we selected profiles with similar conditions from 2 Mars Express orbits, a case study and made an ionospheric simulation.
Case study I: solar cycle effect

We made a numerical simulation with the IPIM model to analyze the shape of the profiles with similar conditions, but at different phases of the solar cycle.

The low solar activity phase of the solar cycle leads to a general reduction of the topside ionosphere of Mars, which is mainly produced by a small and constant induced magnetic field in the dayside ionosphere of Mars.

For the same conditions:
- SZA= 45-55 [deg]
- Heliocentric distance= 1.40 [AU]
- Ls=220 and 213 [deg]
- F10.7=69 [sfu]
- EUV= $1.5 \times 10^{-4}$ [W/m$^2$]
- LAT=-40 and -63 [deg]
- LON=73 and 327 [East deg]
Short-term variability (I)
Case study II: effect of a solar event

It is well-known that the presence of an induced magnetic field in the top of the ionosphere creates a large reduction on the topside electron density profile. However, at Mars (before MAVEN), this was not possible to directly assess due to the lack of magnetometer on board Mars Express.

For the Mars case

MEX obs

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Case study II: effect of a solar event

We selected 5 consecutive Mars Express orbits over the same region of the planet, from June 2006 in which the radar MARSIS was working.

3 of the orbits were affected by a solar event (possible CIR), and MARSIS recorded some induced magnetic field at the spacecraft altitude.

As a result, the vertical electron density profiles during the solar event, were notably affected.

Ramirez-Nicolas et al., PSS, 2016
Case study II: effect of a solar event

Using some plasma properties from the electron density profiles (plasma scale height, transition altitude from photochemical to diffusive region, pressure balance…), we could estimated the B field magnitude at the transition altitude.

Finally, we performed an independent IPIM simulation, which confirmed our results.

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Ramirez-Nicolas et al., PSS, 2016
Short-term variability (II)
ICMEs effect at Mars. (I) propagation

To evaluate the reaction of the Mars’ plasma system, a good knowledge of the solar event that hit the planet is absolutely needed. Solar wind propagation modelling is many times a crucial factor.

Welcome to CDPP/Propagation Tool

Tutorials: video (mov files)
- Introduction to the CDPP Propagation Tool (13M)
- Description of the propagation tool main interface (8M)
- Case 1: Using the tool in the Jmap Carrington/In situ mode (radial) (37M)
- Case 2: Using the tool in the Jmap tool click mode (radial) (39M)

Tutorials: video (mpeg files)
- Introduction to the CDPP Propagation Tool (45M)
- Description of the propagation tool main interface (47M)
- Case 1: Using the tool in the Jmap Carrington/In situ mode (radial) (37M)

Java 8: Mac users: please use Firefox or Safari

A new interactive tool accessible to the solar, heliospheric and planetary science communities to track solar storms, streams and energetic particles in the heliosphere. This tool was defined and developed by IRAP and IAS staff through a subcontract with GFI informatique and CNES financial support. It follows on from and is complementary to the propagation tool developed by the FP7 HELIO project.

The propagation tool allows users:
- to propagate solar eruptions (CMEs) radially sunward or anti-sunward (Radial Propagation),
- to propagate coronating structures (CIRs) in the heliosphere (Corotation),
- to propagate solar energetic particles along magnetic field lines sunward or anti-sunward (SEP Propagation).

http://propagationtool.cdpp.eu/
We studied the propagation of a very large ICME that was ejected on October 14th, 2014 and hit several solar system bodies. One of the solar wind propagation models that we used was the CDPP propagation tool.

Witasse et al., JGR, 2017
ICMEs effect at Mars. (I) propagation

http://3dview.irap.omp.eu/

Witasse et al., JGR, 2017

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ICMEs effect at Mars. (I) propagation

The CDPP predictions were very accurate and help us, together with the observations and a WSA-ENLIL+Cone solar wind simulation, to constrain the velocity, position and structure of the ICME in its journey throughout the full solar system.

Witasse et al., JGR, 2017

Table 1. ICME Propagation Timeline

<table>
<thead>
<tr>
<th>Event</th>
<th>Date and Time (UT)</th>
<th>Heliocentric Distance (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>Launch of the CME</td>
<td>14 Oct 2014 T18:30</td>
</tr>
<tr>
<td>Venus</td>
<td>Putative arrival time from Venus Express housekeeping data</td>
<td>16 Oct 2014 T07:19</td>
</tr>
<tr>
<td></td>
<td>CME associated shock/compression from WSA-ENLIL + Cone</td>
<td>16 Oct 2014 T09:00</td>
</tr>
<tr>
<td></td>
<td>CDPP propagation tool prediction</td>
<td>16 Oct 2014 T07:12</td>
</tr>
<tr>
<td>STEREO-A</td>
<td>STEREO-A shock detection</td>
<td>16 Oct 2014 T20:00</td>
</tr>
<tr>
<td></td>
<td>CME associated shock/compression from WSA-ENLIL + Cone</td>
<td>17 Oct 2014 T00:00</td>
</tr>
<tr>
<td></td>
<td>CDPP propagation tool prediction</td>
<td>16 Oct 2014 T20:57</td>
</tr>
<tr>
<td>Mars</td>
<td>CME detection with Mars Express ASPERA data</td>
<td>17 Oct 2014 T15:45–22:50</td>
</tr>
<tr>
<td></td>
<td>CME detection with MAVEN magnetometer data</td>
<td>17 Oct 2014 T22:53</td>
</tr>
<tr>
<td></td>
<td>FD onset with HEND Mars Odyssey (HDI medium detector)</td>
<td>17 Oct 2014 T18:15</td>
</tr>
<tr>
<td></td>
<td>CME associated shock/compression from WSA-ENLIL + Cone</td>
<td>18 Oct 2014 T00:00</td>
</tr>
<tr>
<td></td>
<td>CDPP propagation tool prediction</td>
<td>17 Oct 2014 T22:51</td>
</tr>
<tr>
<td></td>
<td>CME detection with Rosetta ion data (solar wind proton energy)</td>
<td>22 Oct 2014 T17:24</td>
</tr>
<tr>
<td></td>
<td>FD onset with Rosetta SREM data (Channel 6)</td>
<td>22 Oct 2014 T14:24</td>
</tr>
<tr>
<td></td>
<td>CME associated shock/compression from WSA-ENLIL + Cone</td>
<td>22 Oct 2014 T09:30</td>
</tr>
<tr>
<td></td>
<td>CDPP propagation tool prediction</td>
<td>22 Oct 2014 T17:00</td>
</tr>
<tr>
<td>Saturn</td>
<td>CME detection with Cassini-Huygens magnetometer data</td>
<td>12 Nov 2014 T18:55</td>
</tr>
<tr>
<td></td>
<td>FD onset with Cassini-Huygens MIMI Data</td>
<td>12 Nov 2014 T17:30</td>
</tr>
<tr>
<td></td>
<td>CME associated shock/compression from WSA-ENLIL + Cone</td>
<td>15 Nov 2014 T12:00</td>
</tr>
<tr>
<td></td>
<td>CDPP propagation tool prediction</td>
<td>12 Nov 2014 T16:09</td>
</tr>
<tr>
<td>New Horizons</td>
<td>Time window based on solar wind speed (see text)</td>
<td>18 Jan to 14 Feb 2015</td>
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<tr>
<td></td>
<td>Possible detection of the ICME in the SWAP data</td>
<td>21–29 Jan 2015</td>
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<tr>
<td></td>
<td>CME associated shock/compression from WSA-ENLIL + Cone, prediction for the distance of NH (see text)</td>
<td>8 Feb 2015</td>
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<tr>
<td></td>
<td>CDPP propagation tool prediction for 31.5 AU</td>
<td>24 Jan 2015</td>
</tr>
<tr>
<td>Voyager 2</td>
<td>Possible MIR detection in the dynamic pressure and GCR data sets</td>
<td>Late Mar 2016</td>
</tr>
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Two Interplanetary Coronal Mass ejections (ICME) have been selected, each one from the extremes of the solar cycle. In both cases, Mars Express was transiting the dayside (SZA=40-70 deg) and in the North hemisphere (no crustal fields).

More than double difference in TEC

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**Estimated level in 2003**
[Crider et al., 2005]

**Sanchez-Cano et al., 2017**

**Opgenoorth et al., 2013**

**Morgan et al., 2014**

**Jakosky et al., 2015**

**Witasse et al., 2017**

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TEC data extended from Sanchez-Cano et al., 2016
ICMEs effect at Mars. (II) HIGH solar activity

For this event, there were not any satellites between the Sun and Mars.

Consequently, all the in-situ observations come from the vicinity Mars, where Mars Express, MAVEN, Mars Odyssey, and MSL all recorded the event

Witasse et al., JGR, 2017
ICMEs effect at Mars. (II) LOW solar activity

The ICME-like was detected by STEREO B satellite on 6th March, 2008. Just after, the solar wind increases abruptly to almost 700 km/s and lasted for ~15 days.

Mars, both events were observed by Mars Express and Mars Odyssey on 7\textsuperscript{th} and 9\textsuperscript{th} March, 2008 respectively.
Data processing

http://amda.irap.omp.eu/
ICME-like:
• a clear compression of the magnetosheath-ionosphere system is found.
• As in high solar activity, the BS and the IMB are found much lower than expected.
• The ionosphere is found to be more compressed and with a larger induced magnetic field.

Fast stream:
• It also caused a compression in the Martian plasma system, although lower than the first event.
• It led to fast IMB boundary movements.

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**Cold plasma and induced magnetic field at MEX**

**ICME:**
- A clear compression of the magnetosheath-ionosphere system is found.
- The ionosphere is found to be more compressed and with a larger induced magnetic field.

**Fast stream:**
- The plasma system is recovered after few MEX orbits (~15h)
- No apparent effect on the system
To conclude….

Lots of science works can be done (and usually in a much easier way) thanks to the several tools developed at IRAP. I remark:

(1) AMDA is a great tool that helps a lot with the data processing. From the Mars perspective, I think the dataset is very complete, although from other bodies perspective, I think it would be good to have the full Rosetta RPC data set.

(2) The propagation tool is also great and works quite well, even when it was tested in a difficult and extreme case for the tool as in Witasse et al., 2017. My suggestion would be to add New Horizons, and to get as output the speed as a function of the heliocentric distance.

(3) IPIM interface is very convenient because the model is quite complex to run.

(4) 3D view is also an interesting tool to help to visualize events.
Thank you very much for your attention!!

Mars view from Mars Express
Credits: ESA/DLR/FU Berlin (G. Neukum)