Interplanetary Space Weather & Climate: A New Paradigm

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Comparative Climatology
May 7, 2013
Nature of the Challenge
This is a complex system with many different temporal and spatial scales

- A quantitative, predictive understanding of a complex system
- Microphysical processes regulate global & interplanetary structures
- Multi-constituent plasmas and complex photochemistry
- Non-linear dynamic responses

- Integration and synthesis of multi-point observations
- Data assimilative models & theory
- Interdisciplinary communities and tools
System is Multi-Scale & Couples between Scales

Processes operating at one scale can influence phenomena at other scales.

Image credit: T. Gombosi, CSEM, U of Mich
The need for interplanetary space weather forecasting may be divided into three main areas of interest:

1. Human Safety
2. Spacecraft Operations

Space Weather is not always a problem, sometimes it is an opportunity.
**Ion-Neutral Coupling**

- Strength of the interaction proportional to $Ne$ which is controlled by auroral precipitation, solar EUV, chemistry, and transport.
- Neutral winds spread local heating globally.
- Heating produces waves that propagate vertically and horizontally.
- Neutral winds:
  - alter the chemistry of the ITM by advecting chemical constituents
  - drag the ions across field lines at low altitudes creating E fields, which alter winds at high altitudes.
  - Seed instabilities at low latitudes.
Interplanetary Space Weather & Climate

NASA and other space agencies have begun to expand their research into the solar system. Probes are now orbiting or en route to Mercury, Venus, the Moon, Mars, Ceres, Saturn, and Pluto—and it is only a matter of time before astronauts are out there too. Each mission has a unique need to know when a solar storm will pass through its corner of space.

An intense episode of solar activity in March 2012 drove this point home. It began on 2 March with the emergence of sunspot AR1429. For the next 2 weeks, the angry-looking active region rotated across the solar disk and fired off more than 50 flares, 3 of which were X-class flares, the most powerful type of flare. The Sun’s rotation carried AR1429 around to the far side of the Sun, where the explosions continued. By the time the sunspot finally decayed in April 2012, it had done a 360-degree pirouette in heliographic longitude, hitting every spacecraft and planet in the solar system at least once with either a coronal mass ejection or a burst of radiation. This extraordinary series of solar storms, referred to as the “St. Patrick’s Day storms” caused reboots and data outages on as many as 15 NASA spacecraft.

This highlighted NASA’s need for interplanetary space weather forecasting.
Until recently, forecasters could scarcely predict space weather in the limited vicinity of Earth. Interplanetary forecasting was even more challenging. This began to change in 2006 with the launch of the twin STEREO probes followed almost four years later by the Solar Dynamics Observatory. Together with SOHO, these spacecraft now surround the sun, monitoring active regions, flares, and coronal mass ejections around the full circumference of the star. No matter which way a solar storm travels, the STEREO-SDO-SOHO fleet can track it.

Reasons for developing this predictive capability may be divided into three pressing areas: Human Safety, Spacecraft Operations, and Science Opportunities.
Happy Birthday, Interplanetary Space Weather Forecasting: February 6, 2011

The STEREO spacecraft reached opposition, prompting NASA to release this almost-complete image of the sun:
This development is akin to the first satellite images of hurricanes on Earth.
The Space Environment of Planets

**Ganymede, Mercury**
- what a magnetic field says about a core
- magnetosphere within a magnetosphere

**Mars**
- surface magnetization
- atmospheric loss

**Europa, Callisto**
- radiation of surfaces
- induction in conducting shell -> water

**Io**
- volcanism, patchy atmosphere
  - aurora

**Comets + Pluto**
**Planetary Dynamos**

Volume of electrically conducting fluid $\text{1}$

... which is convecting $\text{2}$

... and rotating

All planetary objects probably have enough rotation - the presence (or not) of a global magnetic field tells us about $\text{1 and 2}$

**Magnetospheres of the Giant Planets**

Rotating with planet

Jupiter + Saturn:
  - dipole with small tilt
dynamo in metallic hydrogen

Uranus + Neptune:
  - multipole, large tilt
dynamo in water/ammonia/methane layer
Space Weather on Mercury

The most ferocious space weather in the solar system is felt on Mercury, the closest planet to the Sun. MESSENGER has observed a highly dynamic magnetosphere with magnetic reconnection events taking place at a rate 10 times greater than what is observed at Earth during its most active intervals.
A CME impact on Mercury

Exactly what we would see is not known. Even garden-variety CMEs may be strong enough to overwhelm Mercury’s weak magnetic field and strip atoms right off the planet’s surface. Mercury’s comet-like tail of sulfur is likely populated by this process.

If operators know when a CME is coming, special preparations can be made e.g., instructing their sensors to collect data at the highest rates during CME passages.
Opportunities at Mars

In 1998, MGS discovered that Mars has a very strange magnetic field. Instead of a global bubble, like Earth's, the Martian field is in the form of magnetic umbrellas that sprout out of the ground and reach beyond the top of Mars' atmosphere. These umbrellas number in the dozens and they cover about 40% of the planet's surface, mainly in the southern hemisphere.

When Mars gets hit by a CME, the resulting magnetic storms take place not at the planet's poles but rather in the umbrellas.
For years, researchers thought the umbrellas protected the Martian atmosphere, shielding pockets of air beneath them from erosion by the solar wind. Surprisingly, David Brain finds that the opposite can be true as well: "The umbrellas are where coherent chunks of air are torn away."

[Diagram of Plasmoid Interpretation]

Most likely scenario: Ionospheric plasma escapes from Mars in a bulk removal process.

Formed via surface instability.

Formed via reconnection.
Timely interplanetary alerts would allow us to make specialized observations.

For example, orbiting sensors could make more frequent (higher time resolution) observations of escaping atmospheric particles, and monitor the density and temperature of the upper atmosphere during solar storms. **Spacecraft (MAVEN) or surface rovers (MSL) could look for Martian auroras during solar storm periods.**

MAVEN (Mars Atmosphere and Volatile Evolution) (launch in Nov. 2013)

One important focus of MAVEN is to determine how CMEs and solar energetic particles alter the upper atmosphere and escape rates. Space weather alerts would certainly advance the goals of this mission.
Lunar Space Weather (it's visible to the human eye)

In 1968, on many occasions, NASA's Surveyor 7 moon lander photographed a strange "horizon glow" after dark. Researchers now believe the glow is sunlight scattered from electrically-charged moondust floating just above the lunar surface.

What is going on?
Moondust becomes charged by point-blank exposure to the solar wind and irradiation by solar EUV.
Like charges repel ==> charged moondust floats
Variety of Lunar Space Weather

Solar and Geomagnetic Storms

-- help populate the Moon’s thin atmosphere (mainly argon and helium with trace amounts of sodium), remember Mercury!

--boost the charge-density of the lunar ionosphere (yes, the Moon has an ionosphere)

--play a role in driving gossamer winds of electrified dust across the day-night terminator
NASA already has one mission (ARTEMIS) in orbit to measure the plasma environment of the Moon and another (LADEE, Lunar Atmosphere and Dust Environment Explorer) in the works to monitor the lunar exosphere. Both would benefit from accurate storm forecasting.

If scientists could be forewarned of a space weather event at the Moon, then they could better prepare their experiments to observe its impact. This could involve making sure that a space plasma observing mission (e.g., ARTEMIS) is set to ‘burst mode’ in order to collect the highest time resolution data it can when the CME reaches the Moon. Meanwhile, missions that have specific look directions, such as LADEE, could adjust their viewing geometry to make sure they're looking where something interesting is expected to happen.
The Solar-Stellar Connection

Tools originally developed for the Sun are now becoming broadly applicable to stars.

Technical breakthroughs in stellar astrophysics now permit us to place solar questions in a broad astrophysical context.

- Seismology is now a powerful tool for both the Sun and stars.
- Deep time-domain studies are placing the Sun in context.
  - Future prospects: butterfly diagrams, rotation-age diagnostics.
- Differential rotation measurements indicate that the solar pattern is not universal.
- New stellar capability: magnetic topology reconstruction.
Sun-Climate Connection

• As the scope of space weather forecasting expands to other planets, it is also expanding in directions traditionally connected to climate research. Climate refers to changes in planetary atmospheres and surfaces that unfold much more slowly than individual storms. There is no question that solar activity is pertinent to climate time scales.

• The radiative output of the Sun, the size and polarity of the Sun’s magnetic field, the number of sunspots, and the shielding power of the Sun’s magnetosphere against cosmic rays all change over decades, centuries, and millennia.

• The sun-climate connection is a matter of cutting-edge research on Earth as described in a recent NRC report on Solar Variability and the Earth’s climate.

• The new paradigm of interplanetary space weather sets the stage for it to be cutting-edge research on other planets, too.

- How do magnetic storms affect the density of the Martian atmosphere?
- How do cosmic rays and solar energetic particles influence cloud cover on Titan?
- How do long-term changes in total solar irradiance alter surface temperatures of any rocky planet?

• These are questions that can be answered as we learn more about space weather conditions throughout the solar system. Moreover, comparative planetologists would tell us that we must answer these questions to get to the bottom of what’s happening on Earth.
Sun-Climate Research Needs (from NRC Report)

- Understanding of apparently significant long-term Sun-climate couplings and current regional impacts requires
  - improved absolute calibration of the observed total solar irradiance, and
  - establishment of multi-decade records of the solar spectral irradiance, leading to
  - extension of the TSI and SSI components into to pre-instrumentation past by:
    - utilization the solar-stellar connection to expand the knowledgebase for possible solar variability patterns on time scales of years to decades.
    - improved understanding of the various climate proxies to create a uniform global climate history.
    - understanding how to translate empirical proxies of solar activity (such as cosmogenic radionuclides and historically-recorded sunspot numbers) into solar spectral irradiance (via heliospheric modulation of galactic cosmic rays and photospheric flux distributions of spots and faculae).
    - understanding differential impact of distinct parts of the solar spectral irradiance on different parts of the Earth’s regional climates and ocean circulation system.
  - With multi-century TSI and SSI data and heliospheric wind and field models in hand, attribution studies can be performed
    - to differentiate between irradiance and cosmic-ray effects, and
    - to establish the relative roles and couplings of top-down and bottom-up mechanisms compared to ‘internal’ drivers (such as volcanic eruptions).
Solar Cycle in Total and Spectral Solar Irradiance

Total Solar Irradiance (TSI)

Spectral Solar Irradiance (SSI): SMax vs. SMin

Small variations in the visible (0.1%), but big changes in the UV.
Solar EUV Temporal Variability

Solar Cycle - months to years
Evolution of solar dynamo with 22-year magnetic cycle, 11-year intensity (sunspot) cycle
Long-term H I Lyman-α time series has been extended with TIMED SEE measurements

Solar Rotation - days to months
Beacon effect of active regions rotating with the Sun (27-days)

Flares - seconds to hours
Related to solar storms (such as CMEs) due to the interaction of magnetic fields on Sun
Just When You Thought it was Safe to Predict the Solar Cycle....
The Sun is never boring

**Solar La Niña**
(low sunspot number)

- extreme galactic cosmic rays
- rapid accumulation of space junk
- sharp contraction of the heliosphere
- collapse of the upper atmosphere
- total solar irradiance changes

**Solar El Niño**
(high sunspot number)

- super solar flares
- extreme solar "cosmic rays" (energetic particles)
- radio blackouts
- extreme geomagnetic storms
- melted power grid transformers – power blackouts
- solar wind streams hit Earth

Illustration shows smoothed monthly sunspot counts from the past six solar cycles plotted horizontally instead of vertically. High sunspot numbers are in red and on the right; low sunspot numbers are in blue and on the left. Associated with each high and low sunspot numbers are different space weather impacts experienced at Earth (doi: 10.1002/swe.20039).
Future Vision

Think of a virtual interdisciplinary consortium of experts scattered across many universities and agencies. If a probe is sent to Titan, other experts would come to the fore---e.g., a planetary scientist at Brown University who predicts tropospheric weather on Titan; a CME modeler at Goddard/CCMC who predicts the onset of geomagnetic storms at Saturn; an EUV expert at the University of Colorado who estimates the solar ultraviolet flux impinging on the giant satellite. An approaching Titan probe could get a genuine weather forecast for its target body. Whether the forecast is for Earth or Titan or some other body, what is needed is an interdisciplinary consortium.
The END