The Sun’s Influence on Planetary Atmospheres

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Who am I?

Dr. Frank Eparvier

Research Scientist @ LASP

Training in Aeronomy

Aeronomy = study of how energy inputs drive the physics and chemistry of a planetary atmosphere

Experimentalist: I like to measure things

“Experiment is the test of all knowledge.”

Currently work with instruments that measure the solar photonic output of aeronomical importance:

Co-I on TIMED-SEE
Co-I on SDO-EVE
PI on GOES-R EXIS
Lead on MAVEN-EUVM
Storytelling

- Personal Recollection: My first aurora
- Historical Event: The Carrington event
- Here and Now: How space weather affects Earth
- There and Now (and Then): How space weather affects other Planets (Mars in particular)
Personal Story

- Northeast Wisconsin, August 1983
- A young scientist “sees the light”
Thursday, September 1, 1859, 11:18 am
Richard Carrington, a British astronomer, was observing the Sun
Saw a “white light flare” that lasted a few minutes
The Next Day

• All heck broke lose

• Telegraph operators around Europe & US had problems:
  • Could transmit without turning on their power
  • Sparks flew from equipment
  • Fires broke out and burned down stations

• Aurora were seen far to the south of normal
  • Cuba, Bahamas, Jamaica, Hawaii, Rome, Hong Kong

• Carrington speculated the solar and terrestrial events were connected
  • Many scientists poo-pooed the idea that what happened on the Sun could affect the Earth
The Present Day

- We understand that the Sun and Earth are a complex, connected system.
- We call this system "Space Weather."
The Story Starts at the Sun

- Gives off energy of many forms
  - Light
    - of all wavelengths
  - Solar Wind
    - Charged particles
    - Magnetic fields
- The Sun is constantly changing
  - On all time scales from seconds to centuries
  - On all size scales from millimeters to megameters
Solar Cycles

• The Sun goes through activity cycles
Photon Effects

• Increased light from Sun (especially UV and X-Rays) means:
  • Heating of the upper atmosphere
    • Temperatures at 200 km can range from 500 to 1500 K
    • Results in expansion of atmosphere
    • Density at a particular altitude can change by an order of magnitude
  • Ionization of the upper atmosphere
    • The ionosphere exists because of solar EUV
    • Large day/night changes and solar activity changes
  • Dissociation of molecules
    • Changes the chemistry and constituents of atmosphere
Irradiance Spectrum and Variability

![Graph showing solar irradiance spectrum and variability over different wavelength ranges.](image)
How Does all this Affect the Earth?

- Sunlight in the ultraviolet and X-rays is absorbed in the Earth’s upper atmosphere
  - Heating to make the thermosphere
  - Ionizing to make the ionosphere
- Changes in the amount of UV from the Sun cause changes in the upper atmosphere
Earth’s Atmosphere Composition & Density

![Diagram showing the composition and density of Earth's atmosphere at different altitudes. The graph plots altitude (km) on the y-axis and number density on the x-axis. Key reactions include:
- \( O_2 + h\nu \rightarrow O + O \)
- \( O + O + M \rightarrow O_2 + M \)
- \( O_2 + h\nu \rightarrow O + O_2 \)
**Typical Atmospheric Temperature Profile**

EUV, FUV, Soft X-rays absorption and ionization heating

Primarily IR radiating to space cooling, Some FUV absorption heating

MUV Sunlight absorption by O₃ heating

Visible, NIR, NUV absorption of sunlight by air and surface, surface heats from below
Ionosphere Reaction to Solar Variability
Ionosphere in Itself is Complex System

Ionospheric Electrodynamics
The Earth’s Radiative Energy Balance
Particles and Fields Effects

• The Solar Wind, IMF, and CMEs all have impacts at Earth:
  • Magnetic fields from Sun interact with Earth’s magnetic field and depending on orientation and strength can shake, rattle, and compress it.
  • Energetic particles can either penetrate the Earth’s magnetic shield, or be diverted by it and get trapped in the radiation belts or magnetotail
    • Trapped particles can follow field lines down to impact the upper atmosphere at high latitudes and ionize it and make the aurora.
    • If the magnetic field is disrupted, particle effects can extend down to mid-latitudes.
Spirals for SW and CMEs
CME Impacting Earth
What About Other Planets?

- Space Weather Impacts will vary by:
  - Distance from Sun (photon and particle fluxes “spread out” with distance).
  - Intrinsic Magnetic Field (Jupiter has largest, Venus has only an induce one, Uranus has a complex quadrupole)
  - Atmosphere Size and Composition
    - Outer gas giants have huge atmospheres, Mercury almost none,…
    - Jupiter’ is mostly hydrogen, Venus’ and Mars’ are mostly carbon dioxide
  - Conditions at planets have evolved over history of the solar system.
Distance from Sun Matters

Average Planetary Temperatures

Distance from Sun (Millions of Miles)
Magnetic Fields of Other Planets

- **Earth**:
  - Tilt of rotation axis: 23°
  - Tilt of magnetic axis: 12°
  - Offset of magnetic axis: 8%
  - Field at equator: 31,000 nT
  - Magnetosphere: 10 R_{Earth}

- **Jupiter**:
  - Tilt of rotation axis: 3°
  - Tilt of magnetic axis: -10°
  - Offset of magnetic axis: 10%
  - Field at equator: 428,000 nT
  - Magnetosphere: 65 R_{Jupiter}

- **Saturn**:
  - Tilt of rotation axis: 27°
  - Tilt of magnetic axis: -0°
  - Offset of magnetic axis: 5%
  - Field at equator: 22,000 nT
  - Magnetosphere: 20 R_{Saturn}

- **Uranus**:
  - Tilt of rotation axis: 98°
  - Tilt of magnetic axis: -59°
  - Offset of magnetic axis: 31%
  - Field at equator: 23,000 nT
  - Magnetosphere: 18 R_{Uranus}

- **Neptune**:
  - Tilt of rotation axis: 30°
  - Tilt of magnetic axis: -47°
  - Offset of magnetic axis: 55%
  - Field at equator: 13,000 nT
  - Magnetosphere: 25 R_{Neptune}
Aurora on the Outer Planets
Composition Changes Response

The Atmospheres of the Solar System

The Terrestrial Planets
- **Mercury**: Pressure ~10 atm, O2 42%, CO2 96%
- **Venus**: Pressure ~90 atm, N2 78%
- **Earth**: Pressure ~1 atm, N2 95%
- **Mars**: Pressure ~0.006 atm, CO2 ~10%

The Gas Giants
- **Jupiter**: Pressure ~1000 atm, H2 90%
- **Saturn**: Pressure ~1000 atm, H2 96%
- **Uranus**: Pressure ~1000 atm, CH4 83%
- **Neptune**: Pressure ~1000 atm, CH4 80%

Other Bodies
- **Titan**: Pressure ~1.45 atm, N2 96%
- **Pluto**: Pressure ~3 x 10^-4 atm, CH4 97%

Note: Planet sizes not to scale. Pressures for terrestrial planets are surface pressures. Mercury’s atmosphere is not an atmosphere in the strict sense of the word, being a trillion times thinner than Earth’s.

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Mars Now

Mass: $0.11 \, M_{\text{Earth}}$

Radius: $0.53 \, R_{\text{Earth}}$

Rotational Period: 24.6 hours

Obliquity: $25.2^\circ \rightarrow$ Seasons!

Distance from Sun: $1.38 - 1.67 \, \text{AU}$

(mean: $1.52 \, \text{AU}) \rightarrow$ Eccentric!

Orbital Period: 686 days

Surface Pressure: 6-10 mbar (seasonal)

Surface Temperature: -195°F to 70°F

(mean: -80°F)

Ice Caps: Seasonal CO$_2$ over H$_2$O

Atmospheric Composition:

- CO$_2$ 95.3%
- N$_2$ 2.7%
- Ar 1.6%

Liquid water is not stable on the current Mars surface.
Mars 2 – 3.5 Billion Years Ago (we think)

Early Warm Wet Mars Theory
More Atmosphere: 10 – 30 bar (CO$_2$)
More Water: ~1000 m (Earth has 3000 m worth)
Warmer temperatures (greenhouse)
Liquid Water:
  Oldest flow channels formed 3.5-3.9 Gya
  Other flow features 2.2-3.3 Gya
  Evidence of northern ocean shoreline

What on Mars happened to all that CO$_2$ and H$_2$O?
What causes atmospheric escape?

Transport into Other Reservoirs ("Hiding")
Sequestering in rocks, dissolving in oceans, storage in ice caps, life, ...

Jeans (Thermal) Escape
Atoms at top of atmosphere hot enough to reach escape velocity

Hydrodynamic Escape
Heavier atoms pulled along by flow of escaping lighter ones

Photo-Chemical (Non-Thermal Heating) Escape:
Charge exchange, Dissociative recombination, Impact dissociation, Photo-dissociation, Ion-neutral reactions, Knock-on (heavy – light collisions)

Sputtering/Impact Escape
Impacts by small or large objects “blowing” off atmosphere

Solar Wind Pickup
SW carries ions and electrons away with it
Atmospheric Escape Driven by Space Weather
MAVEN instruments Measure the Energy Inputs to the Atmosphere

Sun, Solar Wind, Solar Storms
- SWEA
- SEP
- EUV
- SWIA

Ion-Related Properties and Processes
- IUVS
- NGIMS
- STATIC
- MAG
- LPW

MAVEN instruments also Measure the Response of the Atmosphere to those Inputs.
Summary

• The Sun is a primary source of energy for the planets (photons, particles, fields)
  • Space Weather!

• How a planet reacts depends on its particulars
  • atmosphere, magnetic field, distance, etc...

• How a planet reacts depends on its particulars
  • atmosphere, magnetic field, distance, etc...
  • The physics is the same, just what processes are important change