ESS 7
Lectures 21 and 22
May 24 and 26, 2010
The Planets
Exploration Initiative

- Moon in 2015
- Stepping Stone to Mars

George W. Bush’s January 2004 initiative died on Feb. 1 2010

Ares I-X test 28 Oct 2009

- Bush plan had a return of men to the Moon by 2020, Mars later

- Pres. Obama cancelled the program on Feb. 1, 2010 and put forward a five-point plan:
  1. ISS use to 2020 and beyond with commercial launchers
  2. Technology development and test program (includes heavy lift)
  3. Steady stream of new robotic missions (Moon, near-Earth asteroids, Mars)
  4. Earth science and aviation
  5. Inspiring young people

$6 Billion increase in NASA budget
Apollo 8 Christmas 1968 Earthrise and Apollo 17 Dec. 1972 “Blue Marble” galvanized the peace and environmental movements.

Apollo 17 was the only mission to place a scientist on the Moon. The Moon Rocks did enable a revolution in our view of Moon formation.
Scientists' Views of Manned Space Flight

“The manned space flight program often masquerades as science, but it actually crowds out real science at NASA, which is all done on unmanned missions...All of the brilliant discoveries in astronomy for which NASA can take credit have been made by unmanned satellite-borne observatories...”

“The cost of all those projects would be a few billion dollars — not cheap, but nothing like $100 billion needed for a manned return to the moon, or the many hundreds of billions of dollars for a manned mission to Mars.”

Steven Weinberg, US Nobel Prize Winner, quoted from statesman.com
The Moon

- A body like our moon composed of insulating material and embedded in a flowing plasma absorbs the plasma particles that hit it.

- The lunar soil contains a record of the solar wind.

- There is no bow shock at the moon because there is no obstacle to the flow.

- The magnetic field diffuses into the outer layers of the moon quickly.
The Magnetic Field and Plasma at the Moon

• If the flow is slow compared to the thermal speed a short wake forms behind the obstacle.
• If there is no magnetic field (or the flow is parallel to the magnetic field) and the flow speed is large compared to the thermal velocity a wake will persist to large distances.
• For perpendicular flow the wake will be shorter.
Planetary Magnetospheres

• In addition to the direct space weather applications to astronaut and equipment safety investigating other planets helps us test the concepts we are using to study space weather at Earth.

• Fortunately planetary magnetospheres cover a wide variety of parameters.

• Mercury, Jupiter, Saturn, Uranus and Neptune have an interaction similar to that at Earth - a supersonic solar wind interacts with a magnetic field to form a magnetospheric cavity but the nature of the obstacle differs greatly as do the solar wind parameters.
Interaction of the Solar Wind with Planets

- Jupiter’s moon Ganymede has an intrinsic magnetic field however it interacts with a plasma wind within Jupiter’s vast magnetosphere rather than the solar wind.

- Jupiter’s moon Io provides the main source of plasma for Jupiter’s magnetosphere. Saturn’s moon Enceladus is the major source for Saturn’s magnetosphere.

- Europa and Callisto have induced magnetospheres possibly related to a subsurface ocean. (Ganymede too may have an induced field but it is small compared to the intrinsic magnetic field.)
Interaction Between Solar Wind and Planets

- The ionospheres of Venus and Titan (when outside Saturn’s magnetosphere) interact with the solar wind flow to form an induced magnetospheric cavity.

- The small size and large amount of gas that evaporates from a comet make its interaction with the solar wind unique.
Some planets are magnetic, some are not (oh, and some are not planets any more)

- Magnetic:
  - Mercury
  - Earth
  - Jupiter
  - Saturn
  - Uranus
  - Neptune
- Non-magnetic
  - Venus
  - Mars
  - Pluto (probably but we won’t know – New Horizons does not have a magnetometer)

Why? We are not entirely sure!
Venus is Earth’s “twin” but has no magnetic field (maybe due to slow rotation)

- Venus is only slightly smaller than Earth. It has a dense CO₂ atmosphere and runaway greenhouse effect.

- Mars is much smaller than Earth. It has a thin CO₂ atmosphere. It is colder, now, and not much magnetism.

- Strangely, Mercury has the most Earth-like magnetosphere, however, no ionosphere.
Mercury

- Visited twice by Mariner 10
- In September 2009, Messenger flew a third time by Mercury – will go into orbit around Mercury March 2011.

Messenger False Color Image - NASA
**Mercury’s Magnetosphere**

- Mercury has an intrinsic magnetic field with a dipole moment of $\sim 300 \, \text{nT} \, R_M^3 \left(3 \times 10^{12} \, \text{T} \, \text{m}^3\right)$ and a dipole tilt of $\sim 10^0$.

- The magnetic field is strong enough to stand off the solar wind at a radial distance of about $2R_M$.

- Mercury’s magnetosphere contrasts that at the Earth because it has no significant atmosphere or ionosphere.
Substorms at Mercury?

- Mariner 10 flew through the tail of Mercury’s magnetosphere and found evidence of substorm activity although this is controversial. MESSENGER will probe the magnetosphere from orbit.

- Magnetic field changes consistent with field aligned currents have been reported.
Planetary Ionospheres

- To be an obstacle to the solar wind a body must be conducting.
- Imagine a planet with an atmosphere.
  - In sunlight some of the neutral atoms and molecules can be ionized.
  - If the solar wind is magnetized currents can be generated in the ionosphere that will keep the magnetic field from penetrating the planet.
  - This condition will persist as long as the magnetic field keeps changing (otherwise it will eventually diffuse into the planet).
Venus
**Venus' Atmosphere**

- The main constituent of the Venus' atmosphere is carbon dioxide.
- Venus' lower atmosphere is warmer than Earth’s because of the greenhouse effect, the upper atmosphere is much colder because of the absence of heating by the magnetosphere.
- Scale height of Venus’ atmosphere is small being only a few kilometers on the night (cold) side.
  - Atmospheric density falls off with height according to the equation of hydrostatic equilibrium that balances the upward pressure gradient with the downward force of gravity.
    \[ nmg = -\frac{d(nkT)}{dh} \]
    where \( n \) is the number density of molecules, \( m \) is their mass, \( g \) is the force of gravity, \( k \) is Boltzman’s constant, \( T \) is the temperature of the gas and \( h \) is the height.
  - For an isothermal atmosphere the density decreases as
    \[ n = n_0 \exp(-h/H_n) \]
    where \( H_n = kT/mg \).
Venus' Ionosphere

- The upper atmosphere is partially ionized by solar ultraviolet radiation.

- The rate of ionization decreases rapidly with decreasing altitude at low altitudes where ionizing radiation is absorbed.

- The rate of ionization decreases with increasing altitude at high altitudes where the number of neutral particles decreases.

- There is a maximum ion production rate at some altitude $h_m$. 
The Chapman Layer Ionosphere at Venus

- Top – UV radiation drops as it is absorbed in the photoionization process.
- Middle – The rate of electron production versus altitude.
- Bottom - The electron density profile.
- The high altitude electron temperature is about 5000K.
- The peak of the density is at about ~140 km and the density is ~$10^6$ cm$^{-3}$. At 400 km the density is ~20000 cm$^{-3}$ under solar maximum conditions.
- In general the solar wind plasma doesn’t penetrate below about 400 km.
Venus' "Magnetosphere"

- A bow shock forms upstream of Venus.
  - At solar maximum the shock front is about 2000 km above the subsolar point.
  - At solar minimum the typical ionosphere doesn’t completely hold off the solar wind.

- Downstream of the shock the velocity of the solar wind drops drastically.

- The IMF is compressed near the stagnation point and the field drapes around the obstacle.
Venus' Ionopause

- The magnetic barrier has the effect of confining the ionosphere to regions close to Venus.
- The boundary is called the ionopause.
  - Ionospheric plasma is not detected above the barrier because the ions produced there are immediately removed by the interplanetary magnetic field.
  - The ionopause nominally forms where solar wind dynamic pressure ($\rho v^2$) equals the ionospheric thermal pressure ($nkT$).
Mars Showing Polar Ice Cap
Maps of Magnetic Signatures at Mars

a. 

b. 

c. 

d.
Mars

- Mars does not have a global magnetic field but is thought to have had one in the distant past.

- Mars Global Surveyor found evidence of crustal magnetization mainly in ancient cratered Martian highlands.

- The magnetic signatures are thought to be caused by remanent magnetism (when a hot body cools below the Curie temperature in the presence of a strong magnetic field the body can become magnetized).

- The surface magnetic field is organized in a series of quasi-parallel linear features of opposite polarity.

- One explanation of this is tectonic activity similar to sea floor spreading and crustal genesis at Earth. The field reversals result from reversals in Mar’s magnetic field.

- The north-south dichotomy is not understood.
Jupiter
Jupiter’s Magnetic Field

- Jupiter has a magnetic moment of $1.53 \times 10^{20} \text{Tm}^3$ which is tilted by 9.7°
- Jupiter’s rotation period is 9h 55m 29.7s

Left: ENA image from Cassini spacecraft. Jupiter’s magnetosphere is the largest structure inside the heliosphere.
Jupiter’s Magnetosphere

- The first spacecraft to probe Jupiter’s magnetosphere was Pioneer 10.

- The outer magnetosphere ($r > 60R_J$) is extremely variable with a more dipolar structure than the middle magnetosphere.

- The middle magnetosphere ($60R_J < r < 20R_J$) has a strong equatorial current sheet. The field is magnetotail like.

- The main source of plasma for this plasma sheet is the moon Io in the inner magnetosphere.

- Near Jupiter there are strong radiation belts.
Jupiter’s Equatorial Current Sheet

- An equatorial current sheet that is rotating and a few $R_J$ thick dominates the region between roughly $20R_J$ and $60R_J$.

- The rotating flow carries an azimuthal current that stretches the magnetic field into a tail-like configuration.
Jovian Aurora

- Jovian aurora are as bright as the brightest seen on Earth.

- Aurora are best observed in the far ultra-violet (UV) where hydrogen atoms and molecules radiate but they also are observed in the near-infrared, visible and X-ray wavelengths.

- At high northern and southern latitudes an auroral oval analogous to the Earth’s auroral oval can be found.

- At lower latitudes three lines of auroral emissions are evident. This aurora is the ionospheric signature of the interaction between Jovian plasma and the moons, Ganymede, Europa and Io.
The Galilean Satellites

Ganymede  Callisto  Io  Europa
Moon Interactions with Jupiter’s Magnetosphere

• Jupiter’s moon Ganymede has an intrinsic magnetic field however it interacts with a plasma wind within Jupiter’s vast magnetosphere rather than the solar wind.

• Jupiter’s moon Io provides the main source of plasma for Jupiter’s magnetosphere.

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Io

- Io has a strong interaction with the Jovian plasma. Io is known to supply the plasma that fills the Jovian magnetosphere.
- Jovian plasma interacts with the conducting ionosphere of Io.
- The flow is subsonic so that unlike Venus there is no bow shock.
- Large field aligned currents travel between Io and Jupiter forming the aurora along Io’s orbit.
Ganymede’s Mini-magnetosphere

- Ganymede has an internal magnetic field and a magnetosphere.
- The magnetic moment is $1.4 \times 10^{13} \text{Tm}^3$ with an equatorial field strength of $\sim 750 \text{nT}$.
- Ganymede’s magnetic field is strong enough to stand off Jupiter’s magnetic field and plasma. The pressure balance is between Jupiter’s magnetic field ($B^2/2\mu_0$) and Ganymede’s.
The Surface of Europa

Impact craters are rare (young surface age). Ridges and other linear features are common (caused by tidal deformation?)

Area of “chaos terrain”, caused by partial melting of surface material? “Icebergs” are 1-10km across.
Water Ice Phase Diagram

Approx. Depth (km)

Pressure (GPa)

-200

0

100 200 300 400

liquid

likely temperature-depth profile

ice I

ice III

ice V

ice I

ρ = 900 kg m⁻³

water

ρ = 1000 kg m⁻³

ice V

ρ = 1200 kg m⁻³

So even a thick ice shell might have an ocean inside
Detecting oceans - induction

- An ocean is a conductor moving through Jupiter’s magnetic field.

- This motion induces electric currents in the ocean.

- The electric currents in turn generate a magnetic field.

... and this magnetic field was detected by Galileo! UCLA scientists are big in this!
Saturn, Uranus and Neptune have Magnetic Fields

<table>
<thead>
<tr>
<th>Planet</th>
<th>Distance (AU)</th>
<th>Magnetic Moment ($M_E$)</th>
<th>Tilt Angle (degrees)</th>
<th>Magnetopause Distance Km</th>
<th>$R_{planet}$</th>
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<tbody>
<tr>
<td>Earth</td>
<td>1.0</td>
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<td>10.8</td>
<td>0.7X10$^5$</td>
<td>11</td>
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<tr>
<td>Jupiter</td>
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<td>20,000</td>
<td>9.7</td>
<td>30-70X10$^5$</td>
<td>45-100</td>
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<tr>
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<td>580</td>
<td>&lt;1</td>
<td>12X10$^5$</td>
<td>21</td>
</tr>
<tr>
<td>Uranus</td>
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<td>49</td>
<td>59</td>
<td>6.9X10$^5$</td>
<td>27</td>
</tr>
<tr>
<td>Neptune</td>
<td>30.1</td>
<td>27</td>
<td>47</td>
<td>6.3X10$^5$</td>
<td>26</td>
</tr>
</tbody>
</table>

- Saturn has an axially symmetric inner magnetosphere while Jupiter’s $10^0$ tilt spreads out the Io torus.

- At present Uranus has an Earth-like magnetosphere since the $60^0$ tilt is from a rotation axis pointing at the Sun.

- At Neptune the dipole axis relative to the solar wind undergoes large variations.
Saturn’s Magnetosphere

- Like Jupiter, Saturn’s magnetosphere has a rotating current sheet.

- Water group ions dominate.

- The biggest source of plasma is the moon Enceladus.

- A large plumb of material can be seen coming from the southern pole of Enceladus.
Uranus and Neptune

- Uranus magnetosphere looks very much like that of Earth.
  - There are two ideas why Uranus’ magnetic axis is so far from the rotation axis.
  - We measured the magnetic field while Uranus was undergoing a field reversal.
  - Uranus dynamo operates in a different location than Earth, Jupiter, Saturn etc.
- During one rotation Neptune’s configuration changes greatly.
  - The spin axis is inclined by 28° with respect to the ecliptic.
  - The inclination of the dipole axis with respect to the plane of the ecliptic varies from 14° to 72°.
  - Neptune has a weak radiation belt near Triton and appears to be the solar system’s least active.
Comparative Sizes of the Planetary Magnetospheres

- Simple pressure balance arguments give the standoff distances at Earth, Saturn, Uranus and Neptune but fail at Jupiter because of the strong internal source of plasma where the balance is between the solar wind dynamic pressure and the dynamic and thermal pressures of Jupiter’s current sheet.
XM Satellite Radio uses geosynchronous satellites to broadcast. Similar to how light spreads out from the Sun so that it is weaker by the square of the distance, radio signals go down too. A much bigger (more expensive) broadcast transmitter is needed at geosynchronous orbit than if the satellite was lower. About how much more power is needed to give the same signal at the ground if the satellite is at geosynchronous rather than at 0.6 $R_E$ height? Why is geosynchronous nonetheless better?

Read Chapter 7
Due May 28, 2010