13. Jupiter’s Four Galilean Satellites

- The 4 Galilean satellites are easily seen
- Spacecraft reveal unique properties
- Galilean satellites mimic a planetary system
- Io has abundant volcanic sulfur compounds
- Io is internally heated by Jupiter
- Europa is covered with smooth ice
- Ganymede is covered with cratered ice
- Callisto is covered with cratered ice
- Voyager found tiny moons & a dark ring system
- Titan is Saturn’s only large moon

Galilean Satellites: A Family Portrait

Galilean Satellite Comparisons

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Distance from Jupiter (km)</th>
<th>Orbital period (Earth days)</th>
<th>Mass (kg)</th>
<th>Average density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Io</td>
<td>417,000</td>
<td>1.769</td>
<td>8.792 × 10²⁴</td>
<td>1.22 1320 0.03</td>
</tr>
<tr>
<td>Europa</td>
<td>670,000</td>
<td>3.551</td>
<td>1.451 × 10²⁴</td>
<td>4.78 3790 0.06</td>
</tr>
<tr>
<td>Ganymede</td>
<td>1.107,000</td>
<td>2.780</td>
<td>4.893 × 10²⁴</td>
<td>1.94 3530 0.12</td>
</tr>
<tr>
<td>Callisto</td>
<td>1.878,000</td>
<td>16.689</td>
<td>1.723 × 10²⁴</td>
<td>3.02 9910 0.07</td>
</tr>
</tbody>
</table>

Galilean Satellites are Easily Seen

- It takes binoculars or a telescope...
  - All Galilean satellites are bright enough to be seen
  - All Galilean satellites are very close to Jupiter
  - All Galilean satellites are lost in Jupiter's glare
  - Even small binoculars easily separate the moons

- Orbits of the Galileans satellites
  - Some numbers
    - Io 1.769 days
    - Europa 3.551 days ~ 2 times that of Io
    - Ganymede 7.155 days ~ 4 times that of Io
    - Callisto 16.689 days
  - Some implications
    - Io's orbital motion is easily seen in 2 hours
    - The moons are in different locations on successive nights

Galileans Seen Through Binoculars

- The observations
  - Galilean transits
    - Each Galilean satellite crosses in front of Jupiter
      - A satellite’s shadow is often obvious on Jupiter
  - Galilean occultations
    - Each Galilean satellite crosses behind Jupiter
  - Galilean eclipses
    - Each Galilean satellite crosses into Jupiter's shadow

- The deductions
  - The size of each Galilean moon can be determined
10/6/14

Spacecraft Show Unique Properties
- **Pioneer 10 & Pioneer 11** 1973 & 1974
  - Few images & all of relatively low resolution
- **Voyager 1 & Voyager 2** 1979
  - Many more images with much higher resolution
- **Galileo** 1995
  - Orbit Jupiter for nearly 8 years
  - Had numerous close fly-bys of Galilean satellites
- **Cassini** 2000
  - Did limited imaging on the way to Saturn
- **New Horizons** 2007
  - Did extensive imaging on the way to Pluto
    - Life cycle of fresh ammonia clouds
    - Structure inside volcanic eruptions on Jupiter's moon Io
    - Charged particles in Jupiter's long magnetic tail

Galileo's Non-Imaging Mission
- Determine the density of the Galilean satellites
  - Measure gravitational deflection by each satellite
    - Doppler effect on the radio signals transmitted to Earth
  - Measure diameter of each satellite
- Two classes of Galilean satellites
  - High density: Mostly rock & metal
    - Io: 3.529 g·cm⁻³, No known ices
    - Earth's Moon: 3.344 g·cm⁻³, Virtually no ices
    - Europa: 3.018 g·cm⁻³, Small amount of ices
  - Low density: Mostly ices
    - Ganymede: 1.936 g·cm⁻³
    - Callisto: 1.851 g·cm⁻³

Galileans Mimic a Planetary System
- Orbital dynamics
  - All 4 Galilean satellites orbit in the same plane
    - Jupiter's equatorial plane
  - All 4 Galilean satellites are in prograde orbits
    - Same as all planets
- Formation process
  - Solar system condensation temperature
    - Continuing abundant energy production
      - Core fusion of hydrogen into helium
    - Condensation temperature almost to Jupiter
  - Jovian system condensation temperature
    - Initial moderate energy production
      - Kelvin-Helmholtz [gravitational] contraction
    - Condensation temperature almost to Ganymede

Condensation Temperature: Déjà vu

Io Is Covered With Volcanic Sulfur
- The Voyager 1 fly-by
  - Came within 21,000 km of Io's surface
    - Absolutely no impact craters
    - Extremely colorful surface
    - At least 11 very active geysers / volcanoes
- Remarkable insight
  - Peale, Cassen & Reynolds article in Science
    - Io's heat of formation escaped long ago
      - Io should be "dead" but...
    - Io is flexed by both Jupiter & Europa
      - Its orbit is distorted into an ellipse
    - This generates prodigious amounts of heat
      - More than 40 times more heat than escapes from the Earth
    - This generates prodigious amounts of volcanic activity
      - Io is the most volcanically active body in the Solar System
**Io: Both Hemispheres from Voyager**

- Loki
- Pele
- Ra
- Amirani
- Prometheus

**Io Seen by Voyager 1 & Galileo**

(a) Voyager 1, March 1979

(b) Galileo, November 1997

---

**Io’s Two Types of Volcanic Activity**

- **Geysers**
  - Multiple simultaneous events
  - Matter ejected 70 to 280 km above Io's surface
  - Maximum velocities on Io are ~ 1,000 m·s⁻¹
  - Maximum velocities on Earth are ~ 100 m·s⁻¹
  - Matter ejected is very rich in sulfur & sulfur dioxide
  - Io’s geysers are driven by sulfur dioxide steam
  - Earth’s geysers are driven by water steam
  - Red, orange & yellow are the most common colors

- **Ultramafic lava flows**
  - Occasional isolated events
  - Occasional curtains of lava
  - Matter flows are very poor in sulfur & sulfur dioxide
  - Brown, gray & black are the most common colors

---

**Io: Frequent Volcanic Activity**

- Red ring of sulfur ejected from Pélâ Patera
- White sulfur dioxide “snow”
- Fresh deposits ejected from Pélâ Patera partially cover the red ring from Pélâ

---

**1999 Hawaiian-Style Lava Curtain**

- Lava flows
- Volcanic calderas
- Curtain of lava

---

**Jupiter’s Magnetosphere Affects Io**

- The size of Jupiter’s magnetosphere
  - Io lies well inside Jupiter’s magnetosphere

- The effects of Jupiter’s magnetosphere
  - Powerful electric currents flow inside Io
  - ~ 400,000 volts of electric potential
  - ~ 5,000,000 amperes of electric current
  - A little S & SO₂ enter Jupiter’s magnetosphere
    - The Io torus [donut] is a cloud encircling Jupiter
  - Io generates a weak magnetic field of its own
    - Io clearly has molten material in its interior
The Io Torus As Seen From Earth

Europa Is Covered With Smooth Ice

- Basic characteristics
  - Europa is the smoothest body in the Solar System
  - Some mechanism completely resurfaces Europa
  - Europa does have very few small craters
    - Formed after the period of intense bombardment
  - The dominant feature is a global network of cracks
    - Dominant colors are white, blue & brown
  - Spectroscopy confirms Europa's surface is water ice
    - Some "ice lava" flows are virtually pure water ice
  - Europa's density is relatively high
    - 85% to 90% of Europa's mass must be rocky material
- Basic process
  - Tidal heating by Jupiter, Io & Ganymede
    - Only ~ 25% as much as for Io

The Possibility of Life on Europa

- The evidence
  - Jupiter’s magnetosphere induces currents in Europa
    - These depend entirely on Jupiter’s magnetosphere
  - Europa must have a subsurface conducting liquid
    - Pure water is a poor conductor ⇒ Impurities essential
      - Life on Earth apparently began in saline ocean water
    - Europa’s outer 100 km to 200 km are ice & liquid water
- The implication
  - Organic chemicals are abundant in Solar System
    - Recent analyses of meteorites confirm this conclusion
  - Life may have formed in Europa’s global ocean
    - Life may still exist on Europa ! ! !

Europa: One Hemisphere & Detail

Smooth & Rough Areas on Europa

Ganymede Covered W/Cratered Ice

- Two distinctly different surfaces
  - Dark terrain
    - Rather high density of craters
    - These old craters are dark & none have ray systems
    - Long, deep furrows have partially erased some craters
  - Bright terrain
    - Rather low density of craters
    - These young craters are bright & many have ray systems
    - Long, deep furrows are very prominent in bright terrain
- Prominent feature
  - Galileo Regio
    - Circular dark terrain ~ 1,700 km in diameter
Callisto Is Covered W/Cratered Ice

- Prominent characteristics
  - Callisto is darkest Galilean satellite
    - It is still about twice as reflective as Earth's Moon
  - Callisto is very heavily cratered
    - The most heavily cratered object in the Solar System
    - Total lack of smooth areas on Callisto
    - It became geologically dead very early in its history
- Unusual features
  - Very few craters are less than 1 km in diameter
    - Astronomers cannot explain this fact
  - Callisto has a small induced magnetic field
    - This depends entirely on Jupiter’s magnetosphere
    - Callisto must have a subsurface conducting liquid
  - Valhalla
    - Multi-ringed impact scar ~ 3,000 km in diameter

Interiors of the Galilean Satellites

Voyager Found Moons & Dark Rings

- Lesser moons
  - At least 63 lesser satellites have been discovered
    - 14 of these are in retrograde orbits
    - Amount to only ~ 0.003 percent of total orbiting mass
  - Many or all may be captured asteroids or comets
- Jupiter’s ring system
  - Ring system is very dark & very narrow
  - Average particle size is ~ 1 μm
    - This is about the size of smoke particles
  - Source may be meteorite impacts with inner moons
**Saturn’s Titan Has an Atmosphere**

- **Titan data**
  - Solar System’s second largest satellite 5,150 km
  - Only satellite with a substantial atmosphere
  - Kuiper detected methane absorption spectrum 1944
  - Overall composition is ~ 90% N₂
  - ~ 1.5 x Earth’s pressure with ~ 10 x Earth’s gas
    - Weaker gravity does not compress gas as much
- **Titan is perpetually cloud covered**
  - Titan’s surface brightness comparable to moonlit Earth
- **Some implications**
  - Hydrocarbon fog obscures visibility
  - Titan’s surface is covered with hydrocarbon “goo”
  - Titan’s surface has liquid hydrocarbon oceans
    * InfraRed EMR penetrates Titan’s clouds to “see” surface

---

**Titan’s North Polar CH₄ Lakes**

![Titan’s North Polar CH₄ Lakes](image)

---

**Saturn’s Six Icy-Surfaced Satellites**

- **Mimas & Enceladus**
  - Small
- **Tethys & Dione**
  - Medium
- **Rhea & Iapetus**
  - Large

---

**Cassini / Huygens on Earth**

![Cassini / Huygens on Earth](image)

---

**Cassini / Huygens at Saturn**

![Cassini / Huygens at Saturn](image)
Rotating Titan

Cassini & Huygens Explore Saturn

- The overall mission
  - Launched 15 Oct. 1997 by a Titan IVB/Centaur
  - Largest, heaviest, most complex interplanetary spacecraft
  - Multiple gravity-assist maneuvers
    - Earth ⇒ Venus ⇒ Venus ⇒ Earth ⇒ Jupiter ⇒ Saturn
- The Cassini orbiter
  - Science observations began 1 Jan 2004
  - Saturn Orbit Insertion 30 Jun 2004
  - Nominal end of science observations 1 Jul 2008
  - Extended mission ??? ???
- The Huygens lander
  - Lander separated from orbiter 25 Dec 2004
  - Lander entered Titan’s atmosphere 14 Jan 2005

The Huygens Scientific Instruments
- Aerosol Collector & Pyrolyser (ACP)
  - Collect aerosols for chemical-composition analyses
- Descent Imager/Spectral Radiometer (DISR)
  - Images & spectral measurements over a wide spectral range
  - A lamp in order to acquire spectra of the surface material
- Doppler Wind Experiment (DWE)
  - Uses radio signals to deduce atmospheric wind properties
- Gas Chromatograph & Mass Spectrometer (GCMS)
  - Identify & quantify various atmospheric constituents
  - High-altitude gas analyses
- Huygens Atmosphere Structure Instrument (HASI)
  - Physical & electrical properties of the atmosphere
- Surface Science Package (SSP)
  - Physical properties & composition of the surface

Huygens "Lake" & Shoreline

Huygens 360° Panorama of Titan

Titan Panorama From ~ 5 Miles Up
Important Concepts

- Some important numbers
  - Galileans are about the Moon's size
  - Two distinct classes of Galileans
    - High density Close to Jupiter
    - Low density Far from Jupiter
  - Ganymede is larger than Mercury
    - It has only ~ 45% of Mercury's mass
  - Io / Europa / Ganymede orbits
    - 1 : 2 : 4 proportion

- A miniature planetary system
  - Orbital dynamics
    - Prograde orbits in the same plane
  - Formation process
    - Condensation temperature again

- Io
  - Most volcanic activity in Solar System
  - Two types of volcanic activity
    - S & SO\textsubscript{2} geysers
    - Ultramafic lava flows

- Europa
  - Icy surface ~ 85% rocky interior
  - Liquid ocean beneath water ice crust
  - Possibilities for life even now

- Ganymede
  - Covered with cratered ice
  - Extensive network of ridges & valleys
  - Dark & bright terrain
  - Old & young respectively

- Callisto
  - Most heavily cratered in Solar System
  - Long dead geologically
  - Vahalla
    - Extremely large multi-ringed impact

- Titan
  - Only moon with an atmosphere
  - Terrain sculpted by flowing liquids
    - Methane (CH\textsubscript{4}) & ethane (C\textsubscript{2}H\textsubscript{6})