Satellites of the Solar System

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Outline

1. Diversity of Satellites (main characteristics of selected satellites)

2. Overview on Outer Planet Satellite Systems

3. Orbital Evolution (Tides, Oceans, Resonances)

4. Stability of Orbits (example of an extrasolar system)
Sizes of Planets and Satellites

- Ganymede: 5262 km
- Titan: 5150 km
- Mercury: 4880 km
- Callisto: 4806 km
- Io: 3642 km
- Moon: 3476 km
- Europa: 3138 km
- Triton: 2706 km
- Pluto: 2300 km
- Titania: 1580 km

The Largest Moons and Smallest Planets © Copyright 1999 by Calvin J. Hamilton
- geologically most active body in the Solar System
- continuous surface alteration
- silicate volcanism
- enormous surface heat flux (several watts per m²)
- subject to extreme tidal forces
Europa

- surface of water ice
- lots of evidence for past (maybe ongoing) geologic activity
- complex geology
- young surface age (~ 30 – 150 Ma)
- subsurface ocean
Ganymede

- largest satellite
- highly differentiated
- intrinsic magnetic field
- past intense geologic activity
- surface modified by tectonism
- two different types of terrain (dark, heavily cratered, bright grooved terrain)
- subsurface ocean
Callisto

- similar in size, mass and bulk composition to Ganymede
- old cratered surface
- almost no geologic activity
- not fully differentiated
- subsurface ocean
Saturn: Titan

Dense Atmosphere

Geologic Activity

Methane Cycle

(see lecture by R. Jaumann)
Saturn: Enceladus

Active Cryovolcanism
Young and old surface terrain
Thermal Activity
Tidal heating as a driver?
Source of Saturn’s E-ring
Saturn: Iapetus

- Two hemispheres with different albedo
- Shape consistent with hydrostatic equilibrium of an early rotation state
- Shape was ‘frozen’ during de-spinning
- Huge equatorial ridge
Saturn: Small Satellites

Hyperion

Phoebe
Uranus

Miranda             Ariel                 Umbriel                Titania                  Oberon
Neptune: Triton

- Captured satellite
- former KBO
- Retrograde rotation
- Active surface
Planetary Satellites

Satellite systems, compared

<table>
<thead>
<tr>
<th>System</th>
<th>total</th>
<th>R&gt;190km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jupiter</td>
<td>63</td>
<td>4</td>
</tr>
<tr>
<td>Saturn</td>
<td>59</td>
<td>7</td>
</tr>
<tr>
<td>Uranus</td>
<td>27</td>
<td>5</td>
</tr>
<tr>
<td>Neptun</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>Pluto</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

![Schematic of Jupiter’s Outer Satellites](image)

44 New satellite orbits are shown in red

Retrograde satellites

Prograde satellites

Callisto’s orbit

May 15, 2005

May 18, 2005

NASA, ESA, H. Weaver (JHU/APL), A. Stern (SwRI), and the HST Pluto Companion Search Team

STScI-PRC05-19a
Satellite Systems

Orbits scaled to Jupiter's radius

Jupiter
- Io
- Europa
- Ganymede
- Callisto

Saturn
- Mimas
- Enceladus
- Tethys
- Dione
- Rhea
- Titan
- Hyperion
- Iapetus

Uranus
- Miranda
- Ariel
- Umbriel
- Titania
- Oberon

Neptune
- Proteus
- Triton
Satellite Systems

Inner satellites, scaled to the respective planet radius.

Jupiter
- Metis
- Adrastea
- Amalthea
- Thebe

Uranus
- Cordelia
- Ophelia
- Bianca
- Cressida
- Desdemona
- Juliet
- Portia
- Rosalind
- Belinda
- Puck

Saturn
- Pan
- Atlas
- Prometheus
- Pandora
- Epimetheus
- Janus
- (Mimas)

Neptune
- Naiad
- Thalassa
- Despina
- Galatea
- Larissa
- (Proteus)
Satellite Systems

Irregular satellites (radii of a few up to 10's of km))

Jupiter

Saturn

The irregular satellites have high inclinations and large eccentricities. Their orbits are often retrograde indicating that these are captured objects.
The number of satellites is smaller at Uranus and Neptune due to an observational bias.
Outer Solar System Satellites

- Jupiter
  - Io
  - Europa
  - Ganymede
  - Callisto

- Saturn
  - Mimas
  - Enceladus
  - Tethys
  - Dione
  - Rhea
  - Titan
  - Iapetus

- Uranus
  - Miranda
  - Ariel
  - Umbriel
  - Titania
  - Oberon

- Neptune
  - Proteus
  - Triton
  - Nereid

- Pluto-Charon
  - Pluto
  - Charon
Ice is a major component in the interior of outer planet satellites:

- Rocky Moons: Io, Earth's Moon, (Europa)
- Large Icy Satellites: Ganymede Callisto, Titan
- mid-sized satellites: Saturn's moons (without Titan), the moons of Uranus
- Trans-Neptunian Objects and Triton
Temperature gradient in the Solar Nebula

Volatile components can condense in the outer solar system. Outer planet satellites contain large fractions of water-ice.
Comparative Study of the Galilean Satellites

Greeley, 2004
Density Gradient in the Jovian System

Density gradient of the Galilean satellites

- Io: 0% ice
- Europa: 10% ice
- Ganymede: 50% ice
- Callisto: 50% ice
Lack of density gradient in the Saturnian system.
Orbital Elements

To define a state of a point-mass in space at a time t, 6 quantities, e.g. 3 spatial coordinates and 3 velocities $x$, $y$, $z$, $v_x$, $v_y$, $v_z$ must be specified. The 6-dimensional vector $(x, y, z, v_x, v_y, v_z)$ is called the state vector.

For the description of elliptical orbits the use of orbital elements is common.

e.g. Keplerian elements:
- $a$: semi-major axis
- $e$: eccentricity
- $I$: inclination (relative to a defined plane)
- $\Omega$: longitude of ascending node
- $\omega$: argument of pericenter
- $f$: true anomaly

The semi-major axis and the eccentricity describe the shape of the orbit; inclination, ascending node and arg. of pericenter describe its orientation in space. The true anomaly gives the position of the object along the orbit at time t.

Several other sets of orbital elements are in use. However, transformation into these systems or into the state vector is always possible.
Orbital Elements

- i Inclination
- Ω longitude of ascending node
- ω argument of pericenter
- a semi-major axis

Not shown here:
- eccentricity
- True anomaly
Two-Body Problem

Newton's law: Force of M on m:

\[ \vec{F} = -G \frac{mM}{r^2} \hat{r} = -G \frac{mM}{r^3} \vec{r}, \quad \hat{r} = \frac{\vec{r}}{r} \]

Equation of motion:

\[ \vec{F} = m\ddot{\vec{r}} \Rightarrow \ddot{\vec{r}} = -\frac{GM}{r^3} \vec{r} \]

(acceleration of m, due to M)

In general: acceleration = gradient of the potential

Special 2-body case: potential of the point-mass M:

\[ U = \frac{GM}{r} \]

\[ \Rightarrow \quad \ddot{\vec{r}} = \nabla U = \frac{\partial U}{\partial r} \hat{r} = \frac{dU}{dr} \hat{r} = -\frac{GM}{r^2} \frac{\vec{r}}{r} = -\frac{GM}{r^3} \vec{r} \]
The Two-Body Problem

Kepler’s Laws:
1. The orbit of every planet is an ellipse with the Sun at a focus.

2. A line joining a planet and the Sun sweeps out equal areas during equal intervals of time.

3. \((a_1/a_2)^3 = (T_1/T_2)^2\), a semi-major axis, T period.

mean motion \( n \)

\[
=> (a_1/a_2)^3 = (n_2/n_1)^2
\]

\[
T = 2\pi \sqrt{\frac{a^3}{G(m_1 + m_2)}} \iff n = \sqrt{\frac{G(m_1 + m_2)}{a^3}}, \quad n = \frac{2\pi}{T}
\]
Tides: the Earth-Moon System

Tidal forces arise due to the gravitational interaction of extended bodies. Example: Tides raised on Earth by the Moon
Tides on Earth are a consequence of the centrifugal force of the Earth’s rotation around the Earth-Moon barycenter combined with the variation of the gravitational attraction of the Moon.

Moon facing hemisphere: gravitational attraction of the Moon dominates
Opposite hemisphere: centrifugal force dominates
The resulting acceleration (black arrows) is only a small fraction of the gravitational acceleration of the Earth itself. However, lateral ocean currents form the tidal bulges in the oceans.
Tides

In an external gravity field planetary bodies can be deformed. Part of the deformation is inelastic. This leads to tidal friction, which can be an internal heat source. A consequence of the dissipation of energy is the decrease of rotation periods.

During this phase of de-spinning stable couplings between rotational and orbital period can occur. Most common for satellites is the 1:1 spin-orbit coupling.
Synchronous Rotation

The synchronous rotation state is a 1:1 coupling between rotation period and orbital period.

All major satellites and all the inner small satellites are locked in a synchronous state.

The central planet decreases the rotation rate of the satellite until the torques reach a minimum. In case of a circular orbit the torques vanish completely.

The time-scale on which satellites get into the synchronous state is significantly smaller than the age of the solar system.

\[
d\Omega/dt = \frac{3k_2}{(2\alpha_s Q_s)} \frac{m_p}{m_s} \left(\frac{R_s}{a}\right)^3 n^2
\]

\(\Omega\) rotational angular velocity

\(k_2\) the satellite’s Love number

\(\alpha\) axial moment of inertia

\(Q\) dissipation factor

\(m\) mass

\(a\) semi-major axis

\(n\) mean motion

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Time (Ga)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moon</td>
<td>20 Ma</td>
</tr>
<tr>
<td>Io</td>
<td>2 ka</td>
</tr>
<tr>
<td>Europa</td>
<td>40 ka</td>
</tr>
<tr>
<td>Hyperion</td>
<td>1 Ga</td>
</tr>
<tr>
<td>Triton</td>
<td>40 ka</td>
</tr>
<tr>
<td>Charon</td>
<td>600 ka</td>
</tr>
<tr>
<td>Pluto</td>
<td>10 Ma</td>
</tr>
</tbody>
</table>
Tides in synchronous rotation

In non-circular orbits gravitational forces are varying with time deforming the planet periodically. The friction due to the tidal flexing is an internal heat source.

$\omega > n$ => librational tides
$\omega = n$ => radial tides
$\omega < n$ => radial tides
Mass and size of Jupiter and the small distance of the satellites cause strong tidal forces. This is an important energy source in the Jupiter system.
Heat sources: tidal heating

Tidal deformation is characterized by
- ... the potential Love number $k_2 = \Phi_i / \Phi_e$
- ... the radial displacement Love number $h_2 = g u_r / \Phi_e$

Tidal dissipation (tidal heating rate) is proportional to the imaginary part of the potential Love number $\text{Im}(k)$, and depends on the orbital elements.

$\text{Im}(k)$ is a measure for the tidal phase lag depending on
- structure,
- Rheology (=> temperature),
- orbital state (forcing period)
Tidal heating of Io ...

... is about two orders of magnitude larger than radiogenic heating.

... drives silicate volcanism.
Europa's Ocean

- tidal dissipation in the ice shell and/or the silicate mantle
- an ocean decouples the ice shell from the deep interior
- ocean enhances tidal deformation and dissipation in the ice shell
- heat budget ~70% tidal heating, ~30% radiogenic heating
- conditions may be conducive to biological evolution

140 x 100 km
Oceans in Icy Satellites
Oceans in Jupiter’s Moons

Europa: Ocean between ice-I layer and silicate mantle
Ganymede: Ocean between ice-I and high-pressure ice
Callisto: Partially differentiated, ocean between ice-I and ice-rock mixture
Induced Magnetic Fields

The axis of Jupiter's magnetic field is tilted by 9.6 degrees with respect to the rotational axis.

=> the satellites feel a time varying field

=> the field induces an electrical current (Faraday's law)

=> the current produces a secondary magnetic field (Ampere's law), the induced field
Induced Magnetic Fields

... were detected at Callisto and Europa (Kivelson et al. 1998; Zimmer et al., 2000)

=> very good electrical conductor close to the surface

Interpretation:
ocean + salts (electrolyte)

Interpretation of data at Ganymede is difficult because of the intrinsic field (Kivelson et al., 2003)
Detecting Oceans

Internal structure can be determined by measuring the tidal deformation.

Indirect evidence for oceans can be inferred from $k_2$ (tidal potential) or $h_2$ (tidal amplitudes).

The tidal amplitudes and phase lag strongly depend on the presence of an ocean.
Amplitude at Europa: with ocean $\sim 30$ m, without ocean $< 1$ m

Example: Titan

Graph showing the relationship between Love number $k_2$ and ice thickness, with different colors representing different viscosities ($10^{14}$, $10^{15}$, $10^{17}$ Pa s).
## Detecting Oceans

<table>
<thead>
<tr>
<th></th>
<th>maximum amplitude</th>
<th>h2</th>
<th>k2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europa</td>
<td>~20 – 30 m (~60 cm)</td>
<td>~1.16 – 1.26 (~0.03)</td>
<td>~0.1 – 0.3 (~0.01)</td>
</tr>
<tr>
<td>Ganymede</td>
<td>~3 – 4 m (~20 cm)</td>
<td>~1.0 – 1.5 (~0.2)</td>
<td>~0.5 (~0.08)</td>
</tr>
<tr>
<td>Callisto</td>
<td>~2 – 3 m (~10 cm)</td>
<td>~0.9 – 1.5 (~0.2)</td>
<td>~0.3 (~0.08)</td>
</tr>
</tbody>
</table>

in red: without ocean


*Figure: Diagram showing the structure of Europa, Ganymede, and Callisto with a thin ice layer and a completely frozen layer. Cold brittle ice is also depicted.*
Tidal Deformation of Ganymede

Variation of tidal potential due to eccentric orbit.

Tidal deformation at sub-Jovian point during one Ganymede orbit.

Figure: S. Musiol
Long-term orbital evolution

- rotational period of the planet is shorter than orbital period of the satellite
- satellite raises a tidal bulge on the central planet
- due to dissipation in the planet there is a time-lag in the planet's response to the satellite force
- tidal bulge on the planet is ahead of satellite
- satellite gets accelerated and gains orbital energy and angular momentum
- semi-major axis and orbital eccentricity are increasing
- orbital energy is partly dissipated in satellite's interior
- dissipation in the satellites works in the other direction (semi-major axis and eccentricity are decreasing)
Tides and Orbital Evolution

Internal Structure

Orbital State

Dissipation rate

\[ \dot{E} = \frac{21}{2} \frac{R^5 n^5 e^2}{G} \text{Im}(k) \]

R: radius
G: Gravitational constant
n: mean motion
e: eccentricity
\text{Im}(k): Imaginary part of Love number \( k_2 \)

Thermal State

Rheology

Ice surface

Ice

Ocean
Resonances

Resonances can occur when characteristic periods are close to a ratio of small integers.

E.g., the orbital periods of Io and Europa: $T_{\text{Io}}/T_{\text{Eu}} = \frac{1}{2}$, $n_{\text{Io}}/n_{\text{Eu}} = \frac{2}{1}$

or the synchronous rotation of the Moon: $T_{\text{rot}}/T_{\text{rev}} = 1/1$.

For satellites locked in resonance the mutual perturbations become significantly stronger as compared to the non-resonant case.

For satellites in resonance, conjunctions do not occur stochastically along the orbit, but occur periodically at the same locations. As a consequence, orbital eccentricities are forced.

Resonances are important to maintain tidal heating on long time-scales.
Resonance Coupling in the Solar System

<table>
<thead>
<tr>
<th>Couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1 (synchronous rotation) all large and inner satellites</td>
</tr>
<tr>
<td>3:2 spin-orbit coupling of Mercury</td>
</tr>
<tr>
<td>1:2 Mimas and Tethys (Saturn)</td>
</tr>
<tr>
<td>1:2 Enceladus and Dione (Saturn)</td>
</tr>
<tr>
<td>3:4 Titan and Hyperion (Saturn)</td>
</tr>
<tr>
<td>1:2:4 Io, Europa and Ganymed (Jupiter)</td>
</tr>
<tr>
<td>2:3 Neptun and Pluto</td>
</tr>
<tr>
<td>1:1 Pluto and Charon</td>
</tr>
<tr>
<td>Couplings of small bodies, moons and rings</td>
</tr>
</tbody>
</table>
Examples of Structure formed by Resonance
The Laplace Resonance

The orbital periods of Io, Europa and Ganymede are in a ratio of 1:2:4.
=> conjunctions are repeated periodically
=> strong perturbations
=> orbital eccentricities are forced, i.e. maintained as long as the resonance is stable (~ Gyears)

Conjunctions of Io, Europa and Ganymede
The Laplace Resonance

Io, Europa und Ganymed

2:1 Io - Europa
\[ n_1 - 2n_2 = \nu_1 \]

2:1 Europa - Ganymede
\[ n_2 - 2n_3 = \nu_2 \]

Laplace Resonanz
\[ n_1 - 3n_2 + 2n_3 = \nu_1 - \nu_2 = 0 \]

The orbital evolution of Io, Europa and Ganymede is not independent from each other.

Eccentricities are forced by resonance.

=> Tidal heating can be maintained on geologic time-scales.
- tidal torques of the planet push the satellite outwards (e.g. Earth-Moon system).
- dissipation in the satellite counter-acts this effect
- dissipation in the satellite is an important heat source
- resonance forces eccentricities (maintaining tidal heating of the satellites)
- Angular momentum and orbital energy is transferred from Io to Europa and Ganymede
Tides and Orbital Evolution

**Internal Structure**

- Ocean
- Ice

**Orbital State**

- Dissipation rate

\[
\dot{E} = \frac{21}{2} \frac{R^5 n^5 e^2}{G} \text{Im}(k)
\]

**Thermal State**

- Ice surface
- Rheology

R: radius
G: Gravitational constant
n: mean motion
e: eccentricity
\text{Im}(k): Imaginary part of Love number \ k_2
Io und Europa

Coupled thermal-orbital evolution of Io and Europa
Can Hyperion be captured in resonance by tidal evolution?
Titan-Hyperion 4:3 Resonance

Evolution due to tidal interaction of Titan and Saturn

\[ \sigma_2 : \text{resonance argument: } 4\lambda_{\text{Hyp}} - 3\lambda_{\text{Titan}} - \omega = \pi \text{ (libration)} \]

\[ \lambda : \text{mean longitude, } \omega : \text{longitude of pericenter} \]
Stability Analysis of Terrestrial Planets in the Habitable Zone of HD 72659
The Star HD 72659

Distance: 51.4 pc
Spectral type: GOV
Apparent magnitude: $V = 7.48$
Metallicity: $[\text{Fe/H}]= -0.14$
Mass ($M_{\text{sun}}$): $M = 0.95$
Chromospherically quiet

HD 72659 is similar to the Sun with respect to its luminosity and mass. The habitable zone should be located around 1 AU.
HD 72659 is similar to the Sun with respect to its luminosity and mass. The habitable zone should be located around 1 AU.
The Planet HD 72659b

Found from the Keck Precision Doppler Survey (Butler et al. 2003, Astr. J. 582)
Detection Method: Radial Velocity

Mass: $M > 2.55 \, M_J$

Orbital characteristics:

- Semi-major axis: 3.24 AU
- Orbital period: 2185 d = 5.98 y
- Eccentricity: 0.18

Mass = 2.96 $M_{\text{Jup}} / \sin i$

$P = 9.69 \, \text{yr}$

$K = 42.3 \, \text{m s}^{-1}$

$e = 0.26$

RMS = 7.78 m s$^{-1}$
The Planet HD 72659b

The Solar System
The Planet HD 72659b

The Solar System
Asteroids in the Solar System

The diagram shows the number of catalogued asteroids as a function of their mean distance from the Sun. The x-axis represents the mean distance from the Sun in astronomical units, ranging from 1 to 5 AU, with key points labeled for Earth, Mars, and Jupiter. The y-axis indicates the number of catalogued asteroids. Major asteroids and their resonances are marked, such as Flora, Phocaea, Eos, Themis, Koronis, and others. The resonances are indicated by specific ratios, such as 4:1, 7:2, 3:1, and others, which are critical for understanding the dynamics of asteroid belts and their interactions with the planets.
Resonances in the HD 72659 System

- 5:1 1.108 AU 4th order
- 4:1 1.286 AU 3rd order
- 3:1 1.558 AU 2nd order
- 5:2 1.759 AU 3rd order
- 7:3 1.842 AU 4th order
- 2:1 2.041 AU 1st order
- 5:3 2.305 AU 2nd order
- 3:2 2.473 AU 1st order

Kepler III:

\[
\frac{a_{\text{zen}}^3}{T_{\text{zen}}^2} = \frac{a_p^3}{T_p^2} \Rightarrow a_{\text{zen}} = a_p \left(\frac{T_{\text{zen}}}{T_p}\right)^{2/3}
\]
Resonances in the HD 72659 System

- 5:1  1.108 AU  4th order
- 4:1  1.286 AU  3rd order
- 3:1  1.558 AU  2nd order
- 5:2  1.759 AU  3rd order
- 7:3  1.842 AU  4th order
- 2:1  2.041 AU  1st order
- 5:3  2.305 AU  2nd order
- 3:2  2.473 AU  1st order

Kepler III:

\[
\frac{a_{z}\alpha}{T_{z}\alpha^2} = \frac{a_p}{T_p^2} \quad \Rightarrow \quad a_{z\alpha} = a_p \left(\frac{T_{z\alpha}}{T_p}\right)^{2/3}
\]
The model

Initial conditions
(eccentricity of the giant planet,
semi-major axis of test particle,
12800 model runs)

Numerical integration
of each orbit over 1Ma
(Lie-series method)

Stability analysis
max. eccentricity
criterion

Stability analysis
recurrence plots
and Renyi entropy
Stable orbit (4:1 resonance)
Stable orbit (4:1 resonance)
Stable orbit (4:1 resonance)
Unstable orbit  (7:3 resonance)
Unstable orbit (7:3 resonance)
Unstable orbit  (7:3 resonance)
The model

- **Initial conditions**
  - Eccentricity of the giant planet,
  - Semi-major axis of test particle,
  - 12800 model runs

- **Numerical integration**
  - Of each orbit over 1 Ma
  - (Lie-series method)

- **Stability analysis**
  - Max. eccentricity criterion
  - Recurrence plots and Renyi entropy
Habitable Zone (max. eccentricity criterion)

e_G: eccentricity of giant planet

a_T: semi-major axis of terrestrial planet

Habitable Zone (K_2 entropy criterion)

\[ e_G: \text{eccentricity of giant planet} \]

\[ a_T: \text{semi-major axis of terrestrial planet} \]

Are these Habitable Worlds?

Figure adopted from S. Vance