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## Lecture #3: Orbits and Gravity

- Laws of Planetary Motion:
  - Kepler's Laws.
  - Newton's Laws.
- Gravity.
- Planetary Orbits.
- Spacecraft Orbits.



Astronaut floating in space, likely during a mission, illustrating the concept of orbits and gravity.

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## The Main Point


Motions of planets, moons, and asteroids can be very accurately predicted because of the underlying laws of planetary motion and gravity discovered by Kepler and Newton.

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## Laws of Planetary Motion

- Ptolemaic (geocentric) and Copernican (heliocentric) systems made specific predictions about where the planets would be over time.
- What was needed was high quality *data* to test these competing models.
- Tycho Brahe (1546-1601):
  - 20+ years of careful measurements.
  - Best data available, and pre-telescopic!

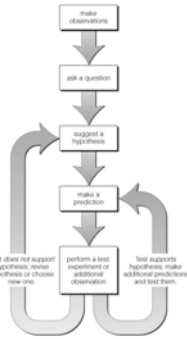


Portrait of Tycho Brahe, the astronomer who provided high-quality pre-telescopic data.

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## The Scientific Method



```

graph TD
    A[make observations] --> B[ask a question]
    B --> C[suggest a hypothesis]
    C --> D[make a prediction]
    D --> E[perform a test, experiment or additional observation]
    E --> F[analyze results]
    F --> G[conclude]
    F --> C
    F --> D
  
```


The Scientific Method flowchart shows a cycle: make observations, ask a question, suggest a hypothesis, make a prediction, perform a test, experiment or additional observation, analyze results, and conclude. The process loops back from analyze results to suggest a hypothesis and make a prediction.

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## Laws of Planetary Motion

- Tycho provided the *data*, but his apprentice provided the key new *model*.
- Johannes Kepler (1571-1630)
  - Mathematician, theorist.
  - Tycho's data weren't fit well by models of Ptolemy or Copernicus.
  - Worst case: Mars. WHY?
- Kepler's 20 years of studies led him to discover three *Laws of Planetary Motion*.

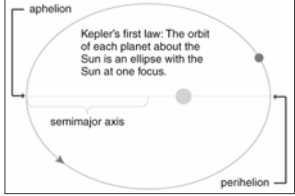


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## Kepler's First Law

- Each planet moves about the Sun in an orbit that is an *ellipse*, with the Sun at one *focus* of the ellipse.



Kepler's first law: The orbit of each planet about the Sun is an ellipse with the Sun at one focus.




Fundamentals of an Ellipse

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## Kepler's Second Law

- The straight line joining a planet and the Sun sweeps out equal areas in space in equal time.



Near perihelion, in 30 days a planet sweeps out an area that is short but wide.

Near aphelion, in 30 days a planet sweeps out an area that is long but narrow.

The areas swept out in 30-day periods are all equal.

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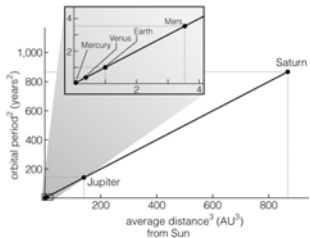
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## Kepler's Third Law

- The squares of the planets' periods of revolution are in direct proportion to the cubes of the semimajor axes of their orbits:

$$p^2 = a^3$$

where:  
 p = orbit period in years  
 a = semi-major axis, in AU  
 (1 AU = 150 million km)  
 ("Astronomical Unit")



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## Planetary Motions


- Kepler's discoveries were spectacular!
- *BUT...* They are *empirical* laws only.
- **WHAT FORCES** control this behavior?
- The answer was provided by Isaac Newton.

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## Newton and Gravity

- Isaac Newton (1643-1727)
  - Mathematician, philosopher.
  - Synthesized observations and results of Tycho, Kepler, and Galileo.
  - Invented calculus!
  - Formulated three *Laws of Motion* for all objects (not just planets).
  - Discovered the *Universal Law of Gravity* to explain the motions of planets (and everything else!)
  - Provided the framework for the later telescopic discovery of Neptune, based on gravitational perturbations of Uranus' orbit.



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## Newton's Laws of Motion


- First Law:
  - An object at rest remains at rest. An object in motion remains moving uniformly in a straight line unless acted on by an external force.
- Second Law:
  - The change of motion of a body (acceleration) is proportional to the force acting on it ( $F = ma$ ).
- Third Law:
  - To every action, there is an equal and opposite reaction.

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## Newton's Laws of Motion

- Newton's 1<sup>st</sup> law really says *momentum is conserved*.
  - Momentum = mass times velocity.  
= mass times (speed, direction).
  - For *angular* motion, momentum = mass times velocity times distance from the axis of rotation.

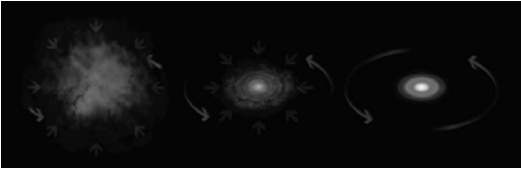


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## Newton's Laws of Motion

- *Conservation of Angular Momentum* is a fundamental concept in planetary science, to which we will return many times...



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## Other Fundamental Properties

- *Mass*:
  - The amount of "stuff" in an object ("stuff" means protons and neutrons and other subatomic particles) [grams].
  - Mass  $\neq$  Weight! *Weight* describes the force acting on mass.
- *Volume*:
  - The physical space occupied by an object [cm<sup>3</sup>].
- *Density*:
  - Mass / Volume = Mass per unit Volume [g/cm<sup>3</sup>]
  - "How tightly packed".

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## Some typical densities

Material	Density (g/cm <sup>3</sup> )
Neutron Star	$\sim 10^{15}$
Gold	19.3
Mercury	13.6
Lead	11.4
Iron	7.9
Earth (bulk)	5.6
Typical Rock	2.5
Water	1.0
Wood	0.8
Styrofoam peanut	0.1
Comet tail	$\sim 10^{-16}$
Universe	$\sim 10^{-29}$

Rocky planets: Earth (bulk), Typical Rock  
Gas giant planets: Mercury, Lead, Iron, Earth (bulk), Typical Rock, Water, Wood

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## Gravity: The Tie that Binds

- Newton showed that *gravity* is the force that bends the planets' straight line paths into ellipses.
- More generally, he showed that gravity is a *fundamental attractive force* among all bodies everywhere in space.
- Gravity obeys an *inverse square law*:
  - Gravitational force =  $GM_1M_2 / R^2$ .
  - $M_1, M_2$  are two masses,  $R$  is their separation.
  - $G$  is a universal constant (Appendix A).

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## Kepler Revisited

- Newton found that Kepler's third law is actually a simplified version of a more exact expression:
  - If  $p$  in years,  $a$  in AU, and  $M$  in solar masses, then
 
$$p^2 \cdot (M_1 + M_2) = a^3$$
 [notice: if  $M_1=1$  and  $M_2 \ll M_1$  then  $p^2 \approx a^3$  ]
- A Powerful Result!
  - If we can simply observe the period of rotation of one object about another (a planet around the Sun, a satellite around Jupiter, ...) and their separation, we can deduce the *mass* of the system!

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## Planetary Orbits

- Generally circular.
- Most in same plane.
- Gap between Mars, Jupiter:
  - Asteroid belt.
  - Why there?
- Many asteroids have high  $e$ .
- Most comets have high  $e, i$ .
- Is this arrangement typical?

Object	$a$ (AU)	$p$ (yr)	$e$ (°)	$i$ (°)
Mercury	0.39	0.24	0.21	7.0
Venus	0.72	0.62	0.01	3.4
Earth	<b>1.00</b>	<b>1.00</b>	0.02	<b>0.0</b>
Mars	1.52	1.88	0.09	1.85
1 Ceres	2.77	4.60	0.08	10.6
Jupiter	5.20	11.9	0.05	1.31
Saturn	9.54	29.5	0.06	2.49
76/P Halley	17.9	76.0	0.97	162
Uranus	19.2	84.1	0.05	0.78
Neptune	30.1	164.8	0.01	1.78
Pluto	39.5	248.6	0.25	17.2
1992 QB1	44.2	359.4	0.08	2.2
C/Hyakutake	1003	32,000	0.99	125

(Appendix E)

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### Overhead view

a

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### Oblique view

b

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Kuiper Belt

Oort Cloud

Many more objects out there!

- 1 million+ asteroids?
- 1 trillion+ comets?
- The solar system does not end at Neptune!
- More details: Lec. 32...

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## Summary

- Kepler
  - Discovered three empirical laws of planetary motion.
- Newton
  - Discovered three generalized laws of motion.
  - Derived the basics of gravitational theory.
- Motions of planets, moons, asteroids, and comets can be very accurately predicted!
- These discoveries laid the foundation for the current Golden Age of spacecraft exploration.

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## Next Lecture...

- Seasons.
- Timekeeping.
- Calendars.
- Readings for next week:
  - Chapters 2.2 and S1.

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