*** N.B. The material presented in this lecture is from the principal textbooks and the internet. I also used a book called “The Solar System Revealed” by Impey & Hartmann and some of my own material from the time I was a teaching assistant for the course “Planets” at the University of California Berkeley taught by Profs. de Pater and Boering. Please note that this PowerPoint presentation is not a complete lecture; it is accompanied by an in-class presentation of the main mathematical concepts (on the transparencies or whiteboard).***
Planetary formation

Planetary formation movie from “Voyage Through the Solar System” accompanying the book “The Universe Revealed” by C. Impey and W. K. Hartmann
Units and scales

- Electron
- Proton
- DNA
- Flu virus
- Living cell
- Giant amoeba
- Fly
- Human
- Airplane
- Pyramid
- Asteroid
- Earth
- Sun
- Typical galaxy
- Universe
- Radius of proton
- Diameter of atom
- Diameter of virus
- Diameter of human hair
- Bacteria
- Radius of walnut
- Human
- Whale
- Diameter of the Earth
- Diameter of the Sun
- Earth's orbit
- Radius of Solar System
- Distance to nearest star
- Diameter of typical galaxy
- Distant edge of visible Universe
- Time for light to cross nucleus
- Period of nuclear vibration
- Period of visible light
- Lifetime of strange particles
- Period of microwaves
- Period of AM radio
- Period of musical middle C
- Period of human heartbeat
- College lecture
- 1 day
- 1 year
- Life of a human
- Lifetime of Roman empire
- Lifetime of a mountain range
- Age of Earth
- Age of Universe
Some questions that we would like to answer in today’s lecture

What causes the seasons on Earth?

How was the Earth’s radius determined?

How was the mass of the Earth determined?

How do we measure masses of distant objects?

How were the temperatures and chemical compositions of the Earth and other planets determined?

Why are the more distant planets from the Sun (giants) large?

Why is there a runaway greenhouse effect on Venus, and given the comparable amounts of Carbon, not on Earth?

How do we know that there is no plate tectonics on Mars?

How well are the models of the planetary interiors constrained?
The cause of the seasons

The angle of illumination, not the distance from the Sun, controls the seasons!
Earth’s radius

Determined by Eratosthenes ~ 3 B.C.

\[
\frac{\alpha}{l} = \frac{360^\circ}{2\pi R}
\]

\[
R = \frac{l \cdot 360^\circ}{\alpha \cdot 2\pi}
\]

Eratosthenes:
\[
\alpha = 7^\circ
\]
\[
l \approx 800\text{km}
\]
\[
R \approx 40000\text{km}
\]
Earth

The flight over Earth movie

Earth seen from Voyager movie
The wavelength \( W \) at which the maximum amount of radiation is emitted is inversely proportional to the temperature: \( W = \frac{0.0029}{T} \)

For bodies emitting thermal radiation, the total energy radiated per unit area is proportional to \( T^4 \)
Moonquakes - what is their cause?
Tides - how do we explain the 12 hour period?
How did the Moon form?
The force of gravity caused by the Sun on Earth is:

\[ F_{SE} = G \cdot \frac{M_{E} \cdot M_{S}}{R_{SE}^2} \]

The force of gravity caused by the Moon on Earth is:

\[ F_{ME} = G \cdot \frac{M_{E} \cdot M_{M}}{R_{ME}^2} \]

The ratio of forces is:

\[ \frac{F_{SE}}{F_{ME}} = \frac{M_{E}}{M_{M}} \left( \frac{R_{ME}}{R_{SE}} \right)^2 \approx 173 \]

Q: So, how can the Moon cause the tides when the Sun attracts the Earth 173 times stronger than the Moon?

A: The tidal force is the stretching force - tides are caused by the difference between the gravity force of one side of the object and that on the other side.

Thus, let's consider what are the fractions between the size of Earth and distances between the Earth and the Moon and the Earth and the Sun.

\[ \frac{2R_{E}}{R_{SE}} \approx \frac{2 \cdot 6371 \text{ km}}{1.5 \cdot 10^8 \text{ km}} \approx 8.5 \cdot 10^{-5} \]
\[ \frac{2R_{E}}{R_{ME}} \approx \frac{2 \cdot 6371 \text{ km}}{3.84 \cdot 10^8 \text{ km}} \approx 3.3 \cdot 10^{-2} \]

The ratio between these two numbers is 390.

Thus, the ratio of the stretching forces has to be divided by 390:

\[ \frac{F_{SE}}{F_{ME}} = \frac{173}{390} \approx \frac{1}{2} \]

The Earth is stretched \( \approx 2 \) times stronger by the Moon.
In the tutorial today:

- Tides and Roche's limit
- The strength of rocks/ice - Miranda example
- The basics of vector calculus
The formation of the Moon

First hypotheses for the Moon formation are:

- Fission hypothesis
- Co-accretion hypothesis
- Capture hypothesis
What is the Moon’s interior made of?
The similarity between Moon’s chemical composition and the Earth’s mantle
The formation of the Moon

The alternative hypotheses to the giant impact formation are:
- Fission hypothesis
- Co-accretion hypothesis
- Capture hypothesis
The impact theory and the K-T extinction

• The K-T boundary
• Catastrophism versus uniformitarianism
• The iridium anomaly recorded in rocks supports a meteorite impact
• The evidence found - Chicxulub crater in Mexico

With Prof. W. Alvarez at UC Berkeley

The meteor crater, Arizona
Some events in Earth’s history and their energies

Interplanetary threat or opportunity?
Venus

Venus - general info movie  
Venus topography movie
Mars

Mars - general info movie

Mars topography movie
Mars - some things we (think we) know

- No plate tectonics - indirect evidence from massive volcanoes (no chains like Earth’s hot spots due to plate movements - consider the development of Hawaiian islands versus stable and massive Olympus Mons).
- Thin atmosphere - CO2 dominated, some H2O in polar caps.
- 9 times as massive as the Moon -> more mass has resulted in slower cooling and prolonged volcanic activity.
- Some evidence that water once existed on Mars from widespread riverbeds, dendritic features and carbonates and other deposits.
- Abundance of iron at the surface, which oxidized to produce red colour (nickname: red planet).
- No strong evidence that life existed on Mars.

Venus - some things we (think we) know

- Plate tectonics - different regime than on Earth, sometimes referred to as “Plume” or “Blob” tectonics.
- Thick atmosphere. Some evidence that water was once present from isotopes.
- Strong greenhouse effect exists on Venus.
- Similar volatile elements as Earth upon accretion, however because of the high temperature, there are no oceans. This means that CO2 cannot dissolve in oceans as it does on Earth.
- On Earth: CO2 dissolves in the oceans and forms CaCO3 at the ocean bottoms (sedimentary rocks), recycled in volcanic eruptions -> Carbon cycle. Carbonates form more efficiently at higher temperatures and less efficiently at lower temperatures. This is the Earth’s thermostat.
- Strong evidence for volcanism on Venus.
Some planetary characteristics - contd.

How are gravity and mass determined?
How are the orbital velocities and rotation periods determined?
How are the temperatures and densities determined?
Spectral analysis and the chemical composition

An imaginary planet
Jupiter and Saturn

LECTURE 1 - Introduction

Spectral analysis and the chemical composition
LECTURE 1 - Introduction

- How do we determine the chemical composition of planets? How about their temperatures?
- Volatile versus refractory elements.
- Cosmic velocities and temperatures control current chemical composition of planetary atmospheres.
- Some material probably trapped inside the cores from the differentiation period (e.g. oxygen, sulphur, potassium, etc.).
- Extrapolation from the meteorites.

Why are the giant planets giants?
Giant (Jovian) planets and their interiors

How well are these models constrained?
What are possible sources of biases?
Non-uniqueness?

Jupiter’s atmosphere movie
Neptune movie  Neptune’s moon Triton