Today’s lecture

Images courtesy of NASA

1. An overview of the Compton Lecture Series

2. A tour of the Solar System

3. Physical properties of the Solar System
   - What can they tell us about the Solar System’s formation?

4. How was our star born?
   - The *nebula hypothesis* of star formation
Part 1:
Introduction to the lecture series

Image courtesy of NASA
How did the Sun, the planets and the asteroids form?

What were their histories like?

One process dominates throughout Solar System history: Collisions
  - Growth of asteroids and planets
  - Formation of the Moon
  - Extinction of the dinosaurs

After such a violent history, we now have a habitable planet

Which you could call:

... A Smashing Success!

Images Courtesy of NASA
My day job: Making an impact

Computer simulations of collisions between planetesimals

Simulations by T. Davison
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Part 2:
A Tour of the Solar System

Image courtesy of NASA
Relative sizes of the planets in the Solar System
(Orbital distances not to scale)

Image courtesy of IAU/Wikimedia Commons
Structure of the Solar System

- **The Sun**
- **Terrestrial planets**
  - Mercury
  - Venus
  - Earth
  - Mars
- **Asteroid belt**
  - Ceres
  - Vesta
  - Pallas
- **Gas Giants**
  - Jupiter
  - Saturn
- **Ice Giants**
  - Uranus
  - Neptune
- **Kuiper belt**
  - Eris
  - Pluto

Image courtesy of NASA
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Image courtesy of NASA/JPL-Caltech/JAXA/ESA
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Image courtesy of NASA

T. M. Davison
Constructing the Solar System
Compton Lectures – Autumn 2012
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Image courtesy of Wikimedia Commons
Today we will look at the birth of the Sun

First, let's think about the Sun and the planets

What observations do we have to help us understand the formation processes?
The planets orbit the Sun

What do we know about their orbits?

Image courtesy of NASA
Kepler’s laws of planetary motion

- Danish astronomer Tycho Brahe made observations of planetary orbits in the 16th century
- Most accurate record of Mars’ orbit at that time
- After his death in 1601, his assistant Johannes Kepler took over his role as imperial mathematician
- Using Tycho’s observations, Kepler developed some laws describing planetary motion, still in use today
Kepler’s laws of planetary motion

- During his career, Kepler developed 3 laws to describe the motion of the planets
- Although they have been improved upon since, they are still a good approximation
The orbit of every planet is an ellipse with the Sun at one of the two foci. Kepler realized that his calculations could not match Tycho’s observations exactly if he used circular orbits. Eventually he realized that using an ellipse matched the observations much better.
2\textsuperscript{nd} Law
A planet sweeps out equal areas during equal intervals of time

- Planets move faster when nearer to the Sun
- Kepler solved this problem with geometry
- He showed that a planet will sweep out an equal area during a given amount of time
  - Angular momentum is conserved

\[ \text{Area A} = \text{Area B} = \text{Area C} \]
3rd Law
The square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit

Kepler then went on to investigate the relationship between the distance of a planet from the Sun and its orbital period

He found a simple relationship: the square of a planetary period is proportional to the cube of its semi-major axis

\[ P^2 \propto r^3 \]
Put simply:

- The planets all orbit the Sun in the same orbital plane
- They all orbit in the same direction
- Their orbits are near-circular
The Sun is by far the biggest and heaviest object in our Solar System.

We want to know how big it is compared to the planets.

How would we go about finding that out?

How do you weigh the Sun?
How far is the Sun from Earth?

- Kepler’s laws gave us a **scale model** of the relative distances of the planets from the Sun.
- To determine the mass of the Sun, we needed to know the **absolute distance**.
- The first step is to calculate the distance from Earth to another planet.
- Then, using geometry and Kepler’s laws, we can calculate the distance of the Sun from Earth.
How far away is Venus?

- Many attempts made to measure distance to Venus
- The first relatively accurate measurement was made using the **transits** of Venus in 1761 and 1769
  - Using technique suggested by Edmond Halley
  - Go to different locations on Earth; measure the distance between them
  - Record the angle between the transits of Venus on the Sun
  - Use trigonometry to calculate the distance to Venus

Image courtesy of Wikimedia Commons

June 5, 2012, Chicago
How far is the Sun?

- The Venus transit technique in the 1700’s gave us a good estimate of the distance to the Sun: $\sim 150$ million km
- Recent high precision measurements have been made by bouncing radio waves off Venus and measuring their travel times
- Current best estimate of the Earth–Sun distance is $\sim 149.6$ million km
- So, now we know how far the Sun is from us, and how long an orbit takes (1 year)
- How do we find how heavy the Sun is?
Forces that act on a planet allow us to weigh the Sun

- A planet is kept in orbit because gravity pulls it towards the Sun.
- We can describe that force using Newton’s law of gravity:
  \[ F = G \frac{Mm}{r^2} = mr \frac{4\pi^2}{P^2} \]
- A centripetal force describes the force that keeps something moving in a circle.
- Since these both describe the same thing, we can equate them:
  \[ P^2 = \left( \frac{4\pi^2}{GM_\odot} \right) r^3 \]  Remember Kepler?  \( P^2 \propto r^3 \)
- Plug in all the known quantities, and we find that \( M_\odot = 1.99 \times 10^{30} \) kg.
- The Sun is >99% of the Solar System mass.

Images courtesy of Wikimedia Commons.
Part 3:
A Star is Born

Image courtesy of NASA/JPL-Caltech
Origin of the Sun

- OK, so we know the Sun is big, and dominates our Solar System
- But, where did it come from? How did it form?
- A theory to explain the formation of the Sun must also explain:
  1. The Sun containing most of the mass
  2. The near-circular orbits of the planets
  3. The planets orbiting in the same plane as the Sun’s equator
  4. The planets all orbiting in the same direction as the Sun rotates
  5. The inner planets are rocky and dense; the outer planets are gaseous and large

Images courtesy of NASA
The Nebula Hypothesis

- Current theory is known as the nebula hypothesis, because it is thought that the Sun, and all of the planets, formed from what is known as a **nebula**

- Theory first developed by Kant (1755) and expanded by Laplace (1799)

**Immanuel Kant**

Image credit: Wikimedia Commons

**Pierre-Simon Laplace**

Image courtesy of Académie des Sciences, Paris
What is a nebula?

- A nebula is an interstellar **molecular cloud** of gas and dust.
- Composed mainly of hydrogen, helium, and molecules such as carbon monoxide.
- ~1% of cloud is sub-micrometer dust particles.
- ~1% is gaseous molecules and atoms of elements heavier than helium.
- Pre-collapse clouds are **cold**: typically ~10 K (~440°F).
- The cloud was supported against self gravity by turbulence, magnetic fields, gas pressure and centrifugal force.

The Eagle Nebula

Image courtesy of NASA/Jeff Hester and Paul Scowen (Arizona State University)
Cloud collapse

- The nebula originally had a **very low density**, and was several light years across.
- Around 4.57 billion years ago, a small **overdensity** in the cloud occurred.
  - We don’t know for certain what caused the overdensity.
  - Most probable scenario: a shock wave from a nearby supernova.
- This more dense region started to attract material from the surrounding region, and the cloud began to **contract**.
- The contracting region grew by a **runaway process**, growing bigger and causing faster contraction.
As the nebula collapsed towards the center, gravitational potential energy was converted to kinetic energy of the gas and dust.

This energy was converted to heat as particles collided.

The protosun became the hottest part of the nebula.
- That’s where most of the mass was concentrated.
- When the central core region was hot enough (10 million K) to initiate nuclear reactions: The Sun was born as a star.

But, what stopped the cloud collapsing further?
Self gravity acts to contract the Sun further.

The increased density and temperature in the Sun caused a net pressure pointing outwards.

The strength of its self gravity force is equal to the strength of the gas pressure.

The young Sun does not collapse further because it reaches a state of hydrostatic equilibrium.
The rotating nebula

The nebula would have been slowly **rotating** as it began to collapse.

The laws of conservation of momentum dictate that as something gets smaller, it must rotate faster to conserve its angular momentum.

\[
\text{Angular momentum} = \text{mass} \times \text{velocity} \times \text{radius}
\]

As the radius decreased during collapse, the velocity must have increased.

Gravitational collapse is more efficient along the spin axis.

Resulted in a spinning disk of material, with most of the mass concentrated at the center.

- The **protoplanetary disk**
The Orion Nebula is another example of where stars are being born. Some stars even appear to have a protoplanetary disks.
Where does that leave us?

At this point in the story, we have a **young star** (the Sun), at the center of a **rotating disk** of gas and dust.

Assuming the planets form from this disk, this matches the observations that the planets:

- Are coplanar
- Orbit in the same direction
Next time

- Formation of **solid materials** in the disk
- **Growth** of km-scale bodies
  - The building blocks of the terrestrial planets and asteroids

Image courtesy of NASA/JPL-Caltech