Constructing the Solar System: A Smashing Success

Building the Planets

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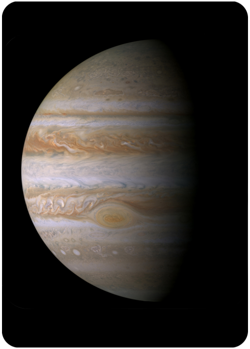
THE UNIVERSITY OF CHICAGO

Compton Lecture Series
Autumn 2012



Compton Lecture Series Schedule

1. 10/06/12 A Star is Born
2. 10/13/12 Making Planetesimals: The building blocks of planets
3. 10/20/12 *Guest Lecturer: Mac Cathles*
4. 10/27/12 Asteroids and Meteorites:
   Our eyes in the early Solar System
5. 11/03/12 Building the Planets
6. 11/10/12 When Asteroids Collide
7. 11/17/12 Making Things Hot: The thermal effects of collisions

   11/24/12 No lecture: Thanksgiving weekend
8. 12/01/12 Constructing the Moon

   12/08/12 No lecture: Physics with a Bang!
9. 12/15/12 Impact Earth: Chicxulub and other terrestrial impacts

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Today's lecture

1. Formation of the terrestrial planets
2. Why are the outer planets so different from the terrestrial planets?
3. Recent advances such as the **Nice Model** and the **Grand Tack** theory

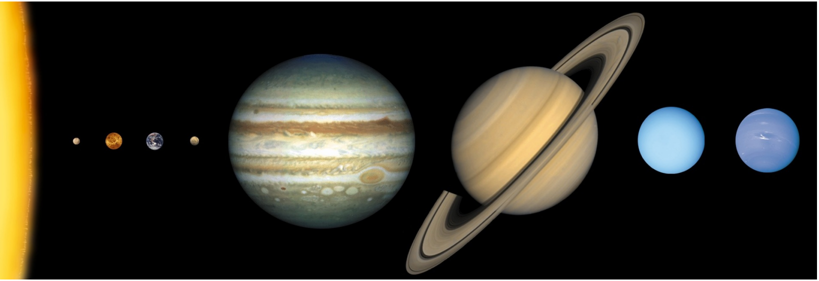


Image courtesy of NASA

From the first two lectures

Several conditions our model of Solar System formation needs to meet

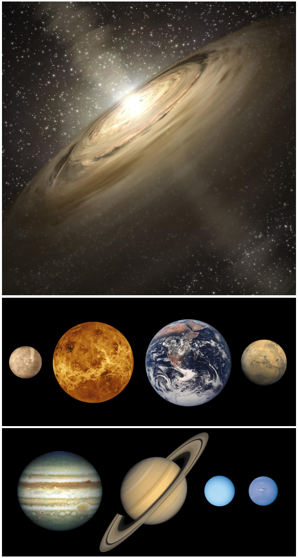
1. The **near-circular orbits** of the planets
2. The planets orbiting in the **same plane** as the Sun's equator
3. The planets all orbiting in the **same direction** as the Sun rotates

   → Nebular disk model

4. The inner planets are **rocky and dense**; the outer planets are **gaseous and large**

   → Today's lecture

Images courtesy of NASA



Part 1:
Building the terrestrial planets

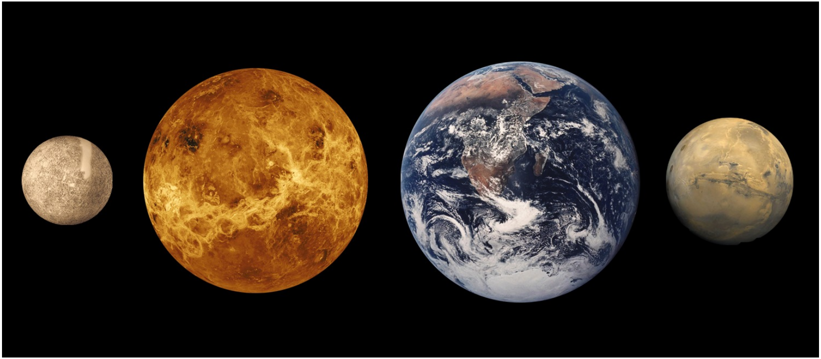


Image courtesy of NASA

Mercury

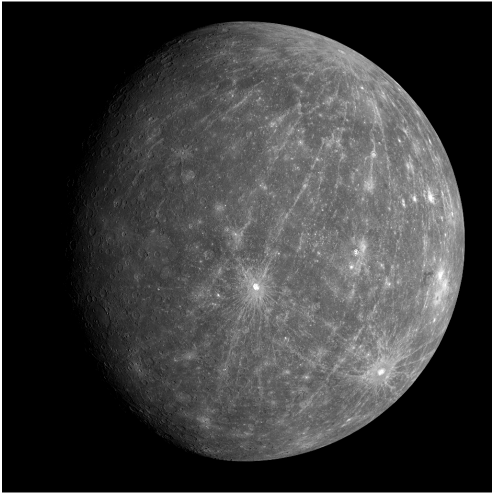
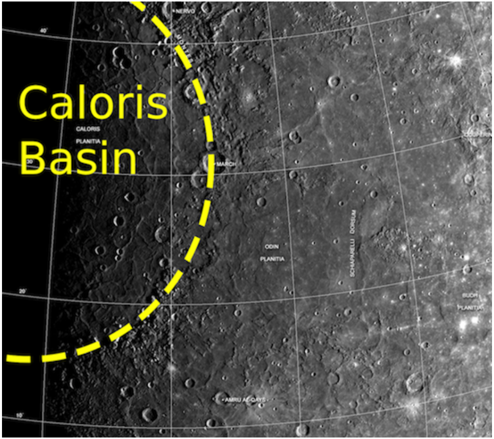


Image courtesy of NASA

- Small radius ($\sim 0.38 \times$ the Earth)
- High density (second highest of all the planets)
- 70% metal, 30% rock: Large, metallic core
- Possible explanation for small size and large core: Giant impact
- Dominant surface feature: Impact craters

Mercury



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Venus

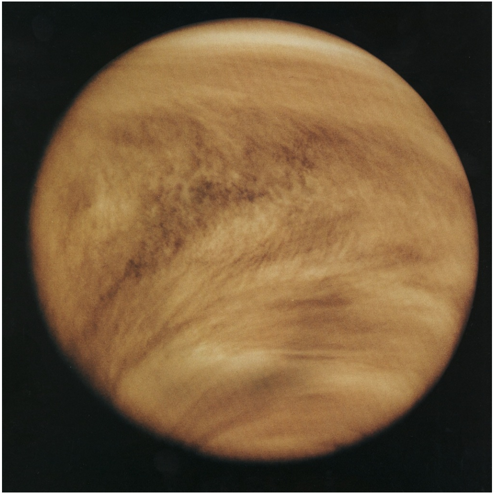

Image courtesy of NASA

- Similar size to Earth (0.95 $\times$ Earth's radius)
- Covered in thick, dense cloud
- Beneath the cloud, there is a geologically active surface
  - Volcanoes, impact craters
- All craters $>$ 3km
  - Clouds prevent smaller impactors reaching surface
  - $\sim$1000 craters

Venus

Image courtesy of NASA

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Image courtesy of NASA

- Most dense of all the planets
- Very active surface
  - Plate tectonics
  - Volcanism
  - Erosion
  - Oceans
- Fewer impact craters than other inner planets / moons
  - Only 182 confirmed craters

Impacts on Earth

Image courtesy of Planetary and Space Science Centre, University of New Brunswick/NASA/Google

Mars

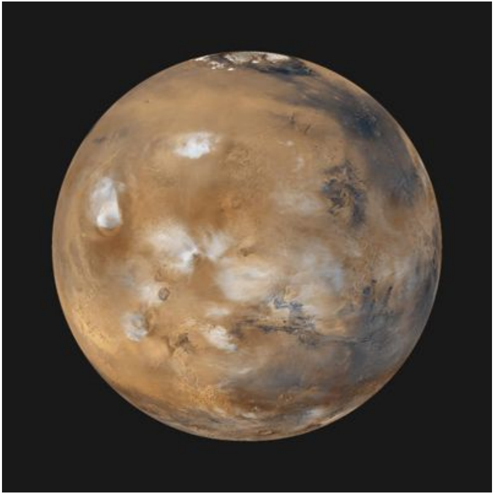

Image courtesy of NASA

- Smaller than Venus and Earth
- Lower density than Earth
- Evidence of volcanism and water on surface
- Surface split in two: Northern Lowlands and Southern Highlands
  - Possibly result of a giant impact

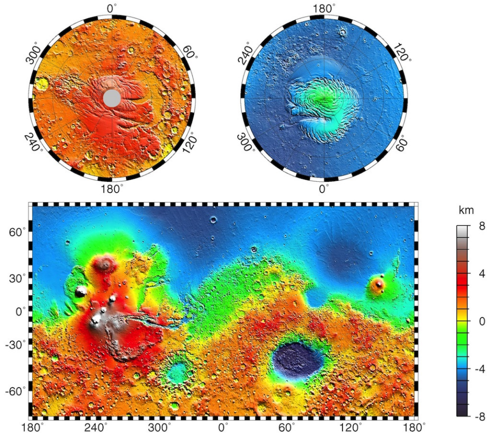

Image courtesy of NASA/JPL-Caltech

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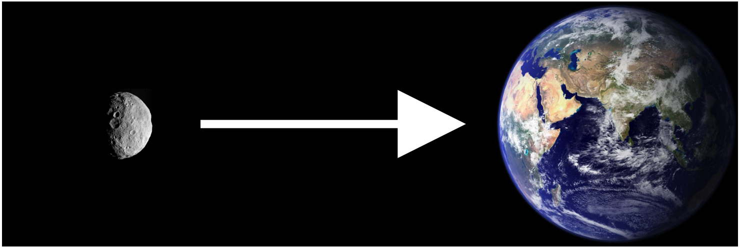
How did the terrestrial planets grow?

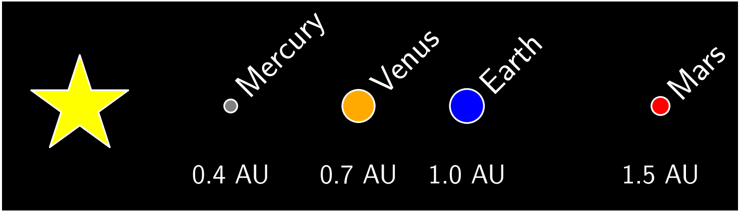


Images courtesy of NASA

- Further collisions between the largest planetesimals (the **oligarchs**) led to growth of larger bodies
  - Gravitational focusing allowed largest bodies to grow efficiently
- Computer simulations of a colliding population of planetesimals allow us to test this hypothesis
- These simulations are called **N-body simulations**

N-body simulations

- We test these models by looking at the results to:
  - See if the outcome results in $\sim$ 4 rocky inner planets
  - See if the planets are at the right distances from the Sun



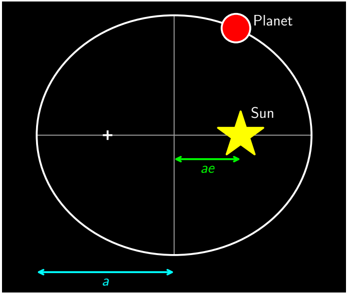
- It is assumed that the Gas Giants had already formed before this stage. We will examine the formation of those planets later in this lecture

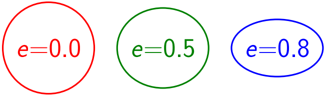
Orbital eccentricity and inclination

Eccentricity

A planet's orbital eccentricity, e is a measure of how elliptical its orbit is

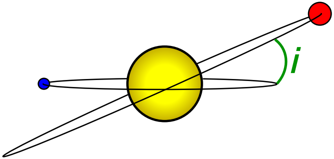
- $e = 0$ means the orbit is circular
- $0 < e < 1$ for an elliptical orbit





Inclination

The orbital inclination, i is the angle between the plane of the orbit of the planet and the ecliptic — which is the plane containing Earth's orbital path



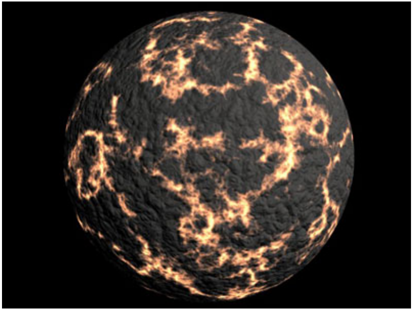
Legend

- **Jupiter**
- **Embryos/Planets**
- **Planetesimals**

In the lecture I showed a movie of an N-Body simulation created by David O'Brien. That simulation can be viewed online here:
http://www.psrd.hawaii.edu/WebImg/OBrien_movie_cjs_simulation.gif

- Within 10's of millions of years, several planets form
- Stable orbits
- Terrestrial planet region 0.5 – 2 AU

Impacts were violent on the early Earth



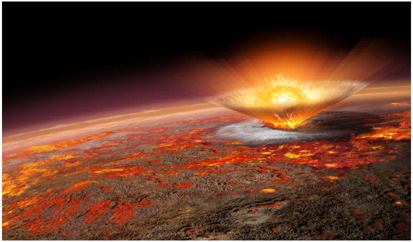
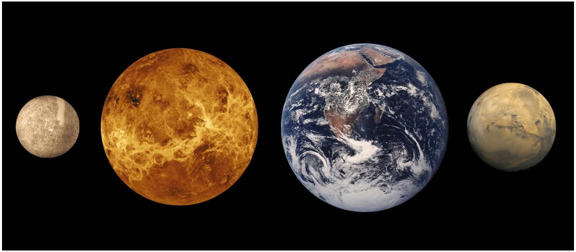


Image courtesy of Don Davis

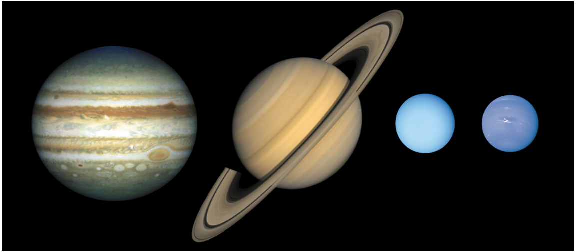
- Soon after its formation, the surface of the Earth would have been molten
  - The **Hadean** period
- Heat from radioactive materials and impacts
- Impacts much more violent, and more common, during the period of planet formation
  - Many more impactors
  - High eccentricity of planetesimals meant higher velocities

Building the planets



Terrestrial planet formation is relatively well understood

Why are the terrestrial planets so different from the gas giants?



Images courtesy of NASA

Part 2:
Building the outer planets

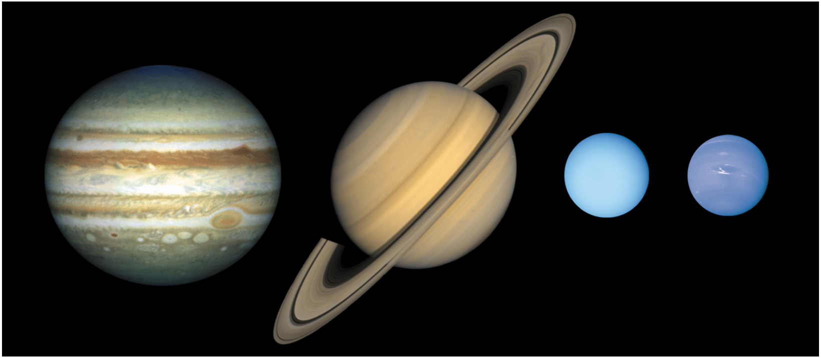


Image courtesy of NASA

Jupiter

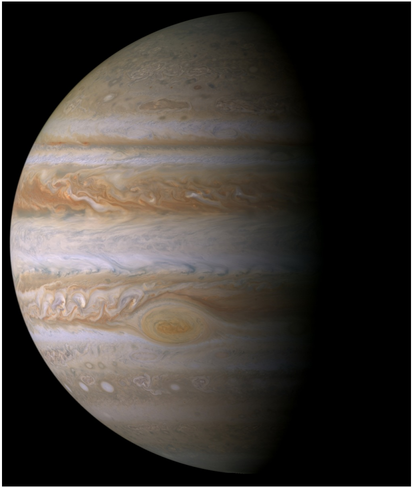


Image courtesy of NASA/JPL/Space Science Institute

- 11 × larger than Earth, 318 × heavier
- Much lower density (4 times lower than Earth)
- Possibly contains a rocky core around the size of Earth
- Atmosphere of hydrogen and helium
- Impacts into the atmosphere of Jupiter are visible as brown spots

Jupiter

Impact of comet
Shoemaker-Levy 9 in 1994

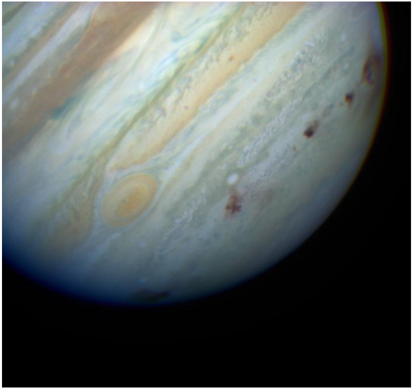


Image courtesy of NASA/Hubble Space Telescope Comet Team

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Saturn

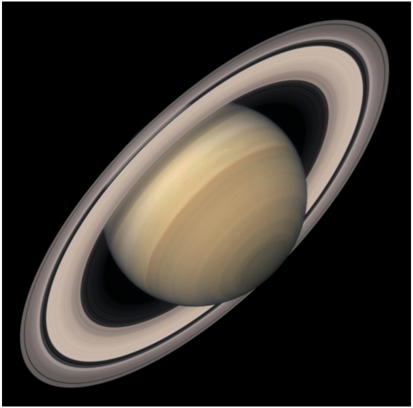


Image courtesy of NASA and The Hubble Heritage Team (STScI/AURA); R.G. French (Wellesley College), J. Cuzzi (NASA/Ames), L. Dones (SwRI), and J. Lissauer (NASA/Ames)

- 9.5 × larger than Earth; 95 × heavier
- Very low density (half that of Jupiter)
- Large atmosphere of hydrogen and helium
- Probably has a small rocky core, similar to Jupiter
- Like all the gas giants, Saturn has rings of dust and ice

Uranus

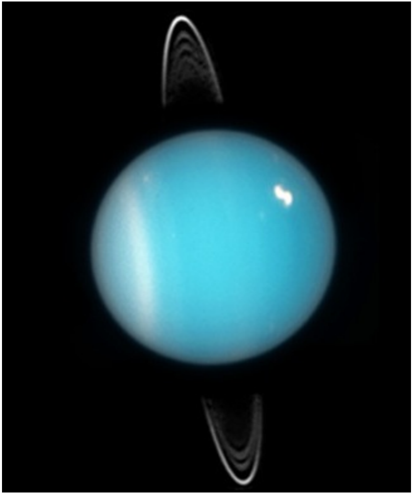


Image courtesy of NASA/JPL/Voyager mission

- Smaller than Jupiter and Saturn;
  4 $\times$ larger radius than Earth
- Similar density to Jupiter
- Along with Neptune, known as an **ice giant**
  - Contains more ices in the atmosphere than Jupiter and Saturn
- Rotates on its side: probably the result of a large impact event

Neptune

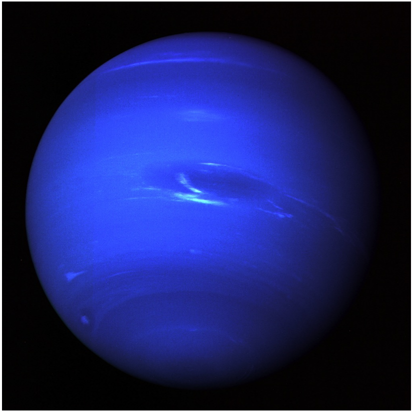


Image courtesy of NASA

- Similar size, density and composition to Uranus
- Contains ices in its atmosphere, like Uranus

Planets comparison

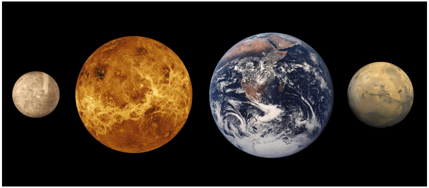


Image courtesy of NASA

- Small, rocky
- Size range 0.4 – 1.0 × Earth
- Thin (or no) atmosphere
- Density range 4 – 5.5 g/cm^3

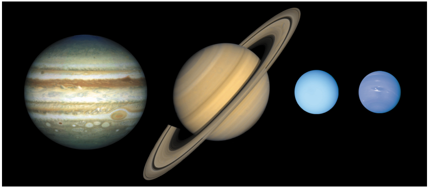
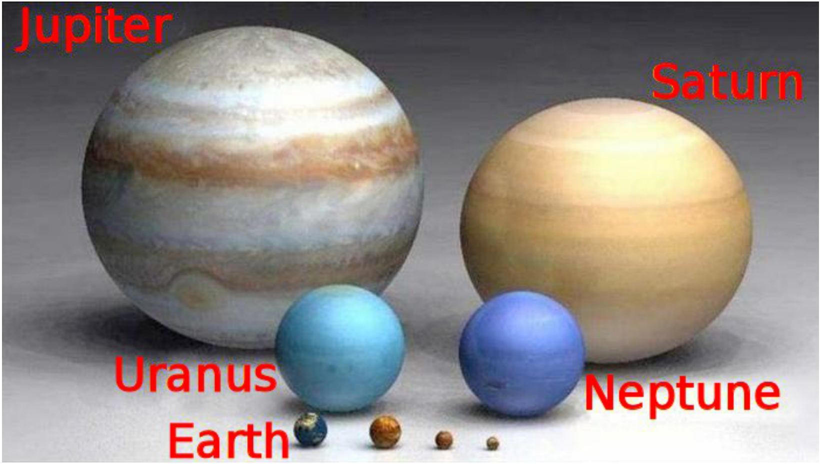


Image courtesy of NASA

- Large, gaseous
- Size range 3.9 – 11.2 × Earth
- Very large atmosphere
- Density range 0.7 – 1.6 g/cm^3

- **Why are the gas giants so different from the inner planets?**
- **How did they form?**

Planets comparison



Building the gas giants: Core accretion theory

- Core of the planet grows rapidly via two-body collisions
  - Same process as for planetesimals and the inner planets
- Gas attracted into envelope surrounding core
- Core continues to grow as more planetesimals collide with it

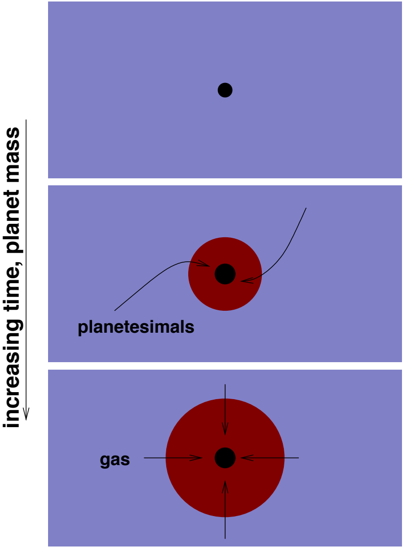
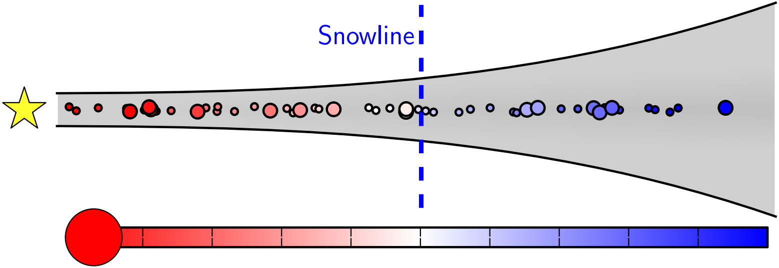


Image courtesy of P. Armitage

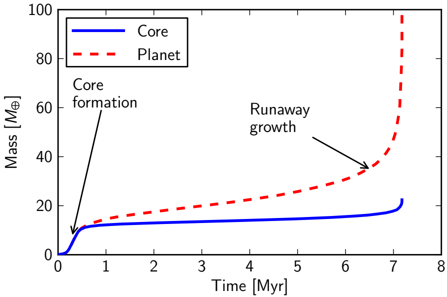
How did the cores form so quickly?

- The core must grow rapidly while gas is still present in the disk
- How did they form more quickly than the inner planets?
- Further from the Sun:
  - More mass in an annular disk
  - Colder temperatures: ices condense
- All that extra mass means more collisions and therefore faster growth



Building the gas giants: Core accretion theory

- Core forms quickly
  - Takes ∼ 0.5 Myr
- Hydrostatic growth
  - Slow accretion of gas from disk
  - Feeding zone grows with planet
  - Takes ∼ 7 Myr
- Runaway growth
  - When the mass of the gas becomes larger than the mass of the core, runaway growth starts



Adapted from Rice & Armitage 2003

Part 3:
Recent advances

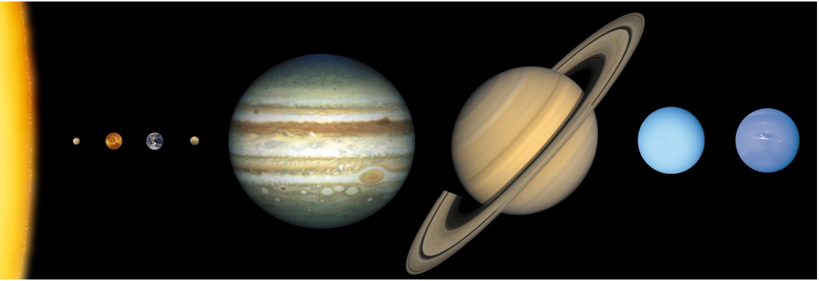
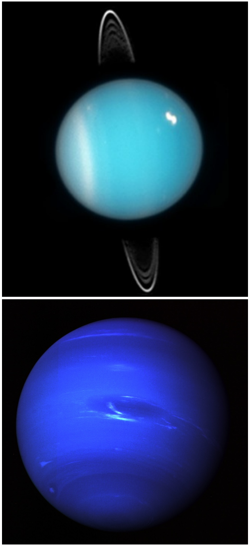


Image courtesy of NASA

Some open questions

1. Uranus and Neptune could not form in the current locations fast enough
   - Gas not dense enough
2. The giant planets all have $e, i > 0$
   - The gas should have dampened the orbits down to circular and coplanar
3. There is not enough mass in the Kuiper belt to form Pluto and the other dwarf planets
   - Mass of Kuiper belt is around the mass of the Moon



Images courtesy of NASA/JPL

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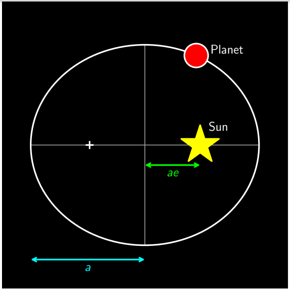

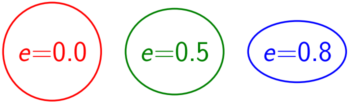

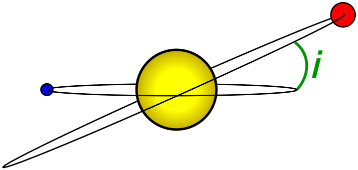

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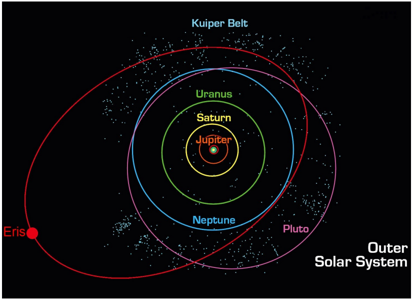
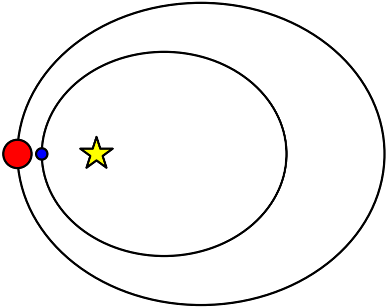


Image courtesy of NASA

The answer may lie in orbital resonances



- Remember from last week the role that orbital resonance can have on the asteroids
- In the Nice model, the same applies for the Giant Planets

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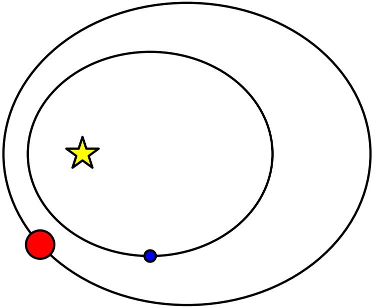

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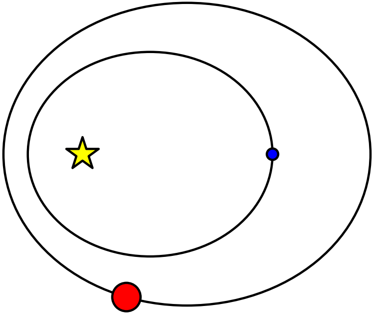

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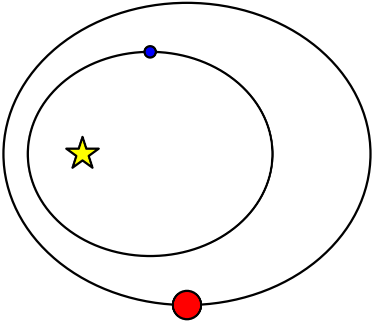

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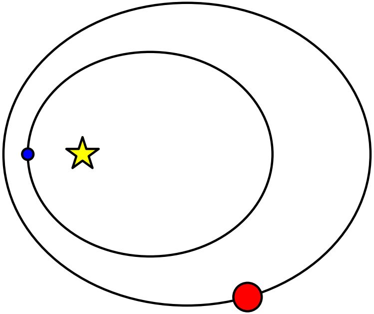

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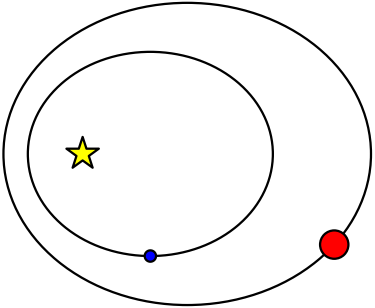

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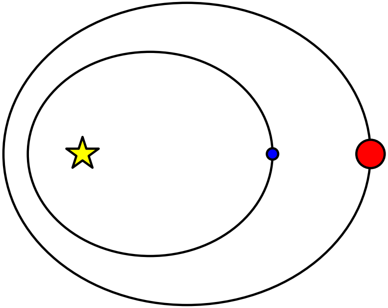

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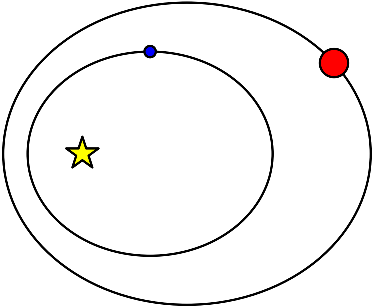

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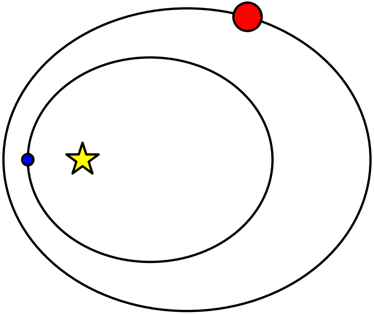

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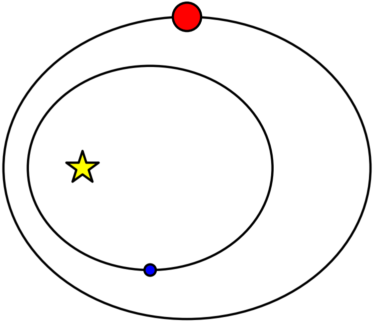

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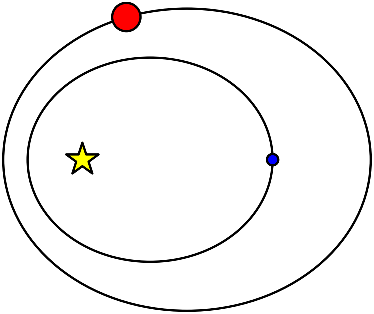

- Remember from last week the role that orbital resonance can have on the asteroids
- In the Nice model, the same applies for the Giant Planets

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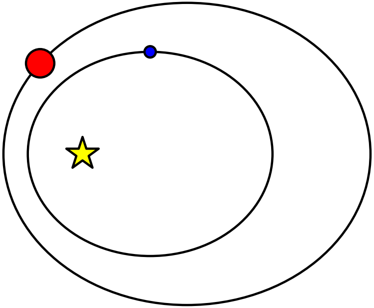

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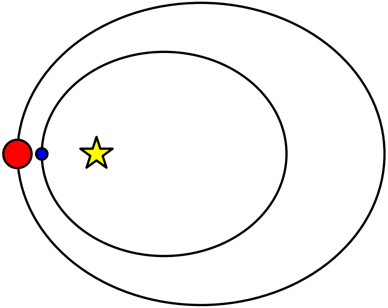


- Remember from last week the role that orbital resonance can have on the asteroids
- In the Nice model, the same applies for the Giant Planets

The Nice Model

Top-down view of the Solar System

Image courtesy of Wikimedia Commons

In the lecture I showed a movie of the Nice Model. A version of that movie can be viewed on YouTube, here: `http://www.youtube.com/watch?v=6LzQfR-T5_A`

Big changes happen when Juptier and Saturn reach an orbital resonance

- Uranus and Neptune move outwards (and switch position!)
- The Kuiper Belt started with higher mass that was scattered by the planets' changing orbits
- The resonance moves the planets into higher e, i orbits

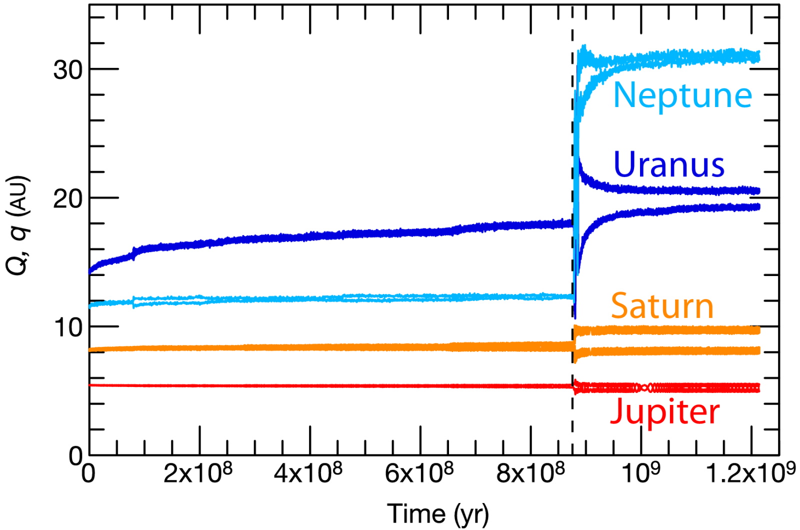


Image adapted from Gomes et al. (2005), *Nature*

Nice Model outcomes

- In summary, the Nice model offers one possible mechanism to match some observations of the Solar System:
  - Uranus and Neptune formed closer to the Sun than they are now
  - This overcomes the problem that at their current locations, there would not have been enough material to form planets of that size
  - Allows them to reach their present large sizes and then migrate outwards

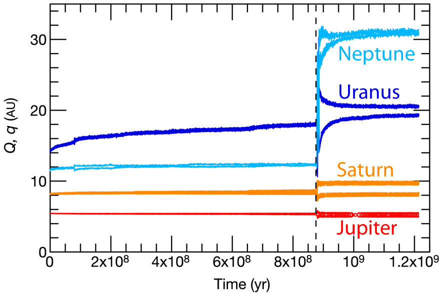


Image adapted from Gomes et al. (2005) *Nature*

Nice Model outcomes

- In summary, the Nice model offers one possible mechanism to match some observations of the Solar System:
  - The resonance of Jupiter and Saturn throws all the giant planets into higher e, i orbits
  - Explains why they are not closer to circular orbits

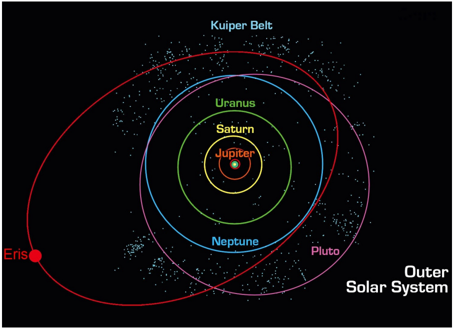


Image courtesy of NASA

Nice Model outcomes

- In summary, the Nice model offers one possible mechanism to match some observations of the Solar System:
  - The dwarf planets formed in the Kuiper Belt when there were still many planetesimals present
  - Most of that mass was lost in the resonance event, explaining the smaller mass today

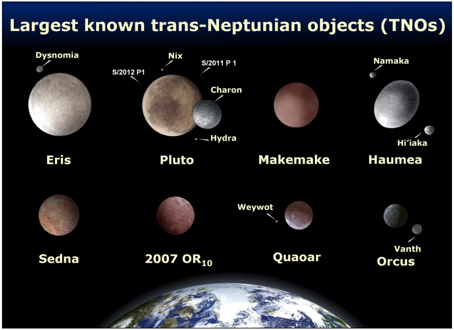


Image courtesy of Wikimedia Commons

What does this mean for the rest of the Solar System?

Mare Imbrium

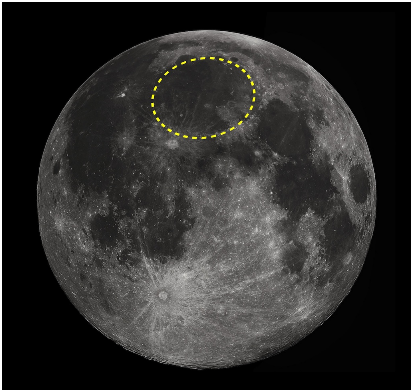


Image courtesy of Wikimedia Commons

- Lots of objects from the Kuiper belt thrown inwards towards the inner Solar System
- Evidence for this on the Moon!
  - e.g. The Lunar basins such as Mare Imbrium
- We'll cover this in the lecture about the Moon

Mars is too small!

- One more open question: **Why is Mars is so small?**
- Greater orbital distance; should be larger than the Earth
- However, it is actually only one tenth of the mass of Earth
  - Why?

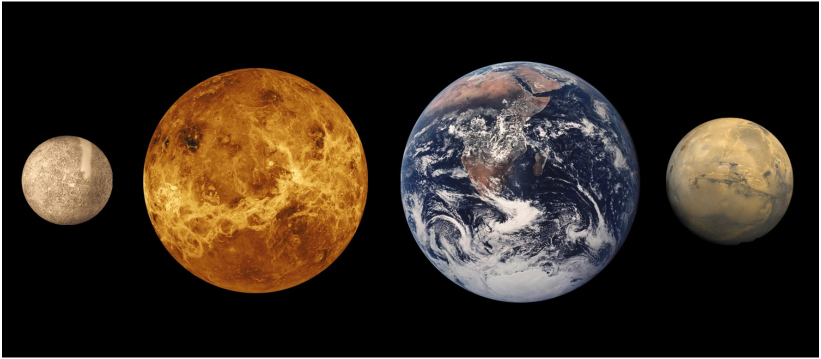


Image courtesy of NASA

Mars stopped growing early

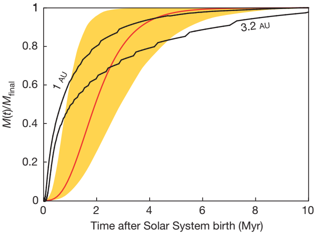


Image courtesy of Dauphas and Pourmand (2011) *Nature*

- Recent cosmochemistry studies by researchers at UChicago
- Measured the isotopic compositions of Martian meteorities
- Able to estimate the time that Mars stopped growing
  - Mars must have stopped growing after only 2–4 million years
  - Well before Earth stopped growing (10's of millions of years)
  - i.e. Mars was a **stranded planetary embryo**

Mars and the Grand Tack

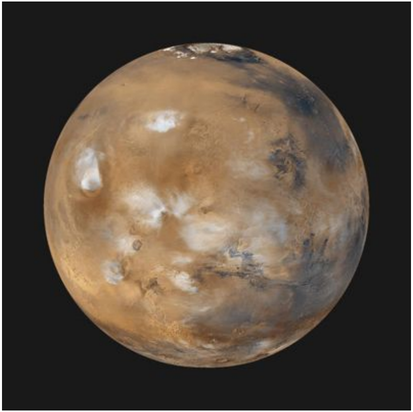


Image courtesy of NASA

- So, we think that Mars was an embryo that just stopped growing
- What could cause it to stop?
- Several recent models provide possible reasons
- We will look at one of them now, called the Grand Tack model

The Grand Tack Scenario

- Jupiter migrates inwards due to currents in the gas
- Moves from 3.5 AU to 1.5 AU

In the lecture, I showed some movies of the Grand Tack model. You can view those movies, and see some more detailed discussion of the model, on Sean Raymond's website, here:
`http://www.obs.u-bordeaux1.fr/e3arths/raymond/movies_grandtack.html`

The Grand Tack Scenario

- Saturn also moves inwards
- 3:2 resonance with Jupiter means both planets move outwards
- Planetesimals (asteroids) are scattered and mixed in the process

In the lecture, I showed some movies of the Grand Tack model. You can view those movies, and see some more detailed discussion of the model, on Sean Raymond's website, here:
`http://www.obs.u-bordeaux1.fr/e3arths/raymond/movies_grandtack.html`

The Grand Tack Scenario

- Asteroid belt ends up as a mix of some bodies that formed outside Jupiter and some that formed inside
- Fits with prediction from last week about the E, S and C class asteroids
- Planetesimal disk ends at around 1 AU — which helps to explain the small size of Mars

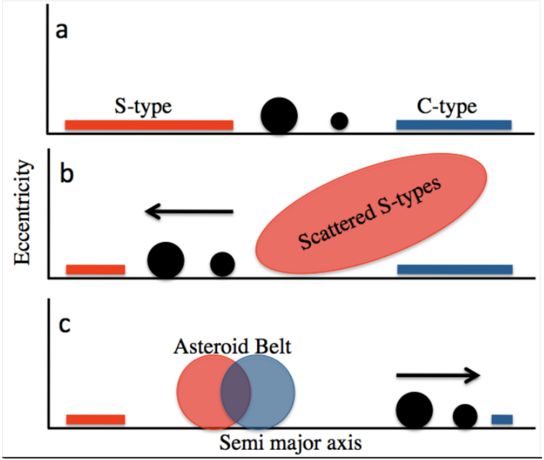


Image courtesy of K. Walsh

Other scenarios could work instead

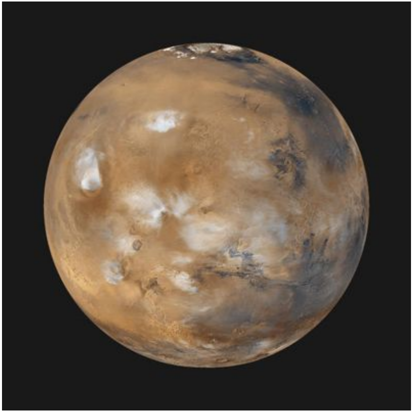
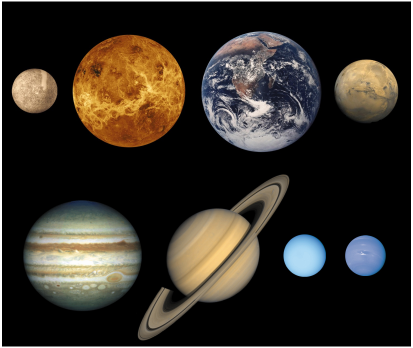


Image courtesy of NASA

- One example is called **planetesimal-driven migration**
- Mars pushed outwards by gravitational interations with lots of planetesimals
- Moves outwards until it leaves the region most populated by planetesimals
- Once there, growth is halted

Summary



Images courtesy of NASA

- Inner planets grow by pairwise collisions
- Gas giants grow quickly due to extra mass in outer disk from condensed ices
- Cores quickly grow, and accumulate large gaseous atmospheres
- Migration of gas giants can lead to severe consequences in the inner Solar System
  - Mars is small
  - Mixed asteroid belt

- Next week: Collisions

Thank you

Questions?