Overview of the Solar System

\[ N = N_0 \cdot f_s \cdot f_p \cdot n_h \cdot f_i \cdot f_c \cdot \frac{L}{T} \]
What is a Star?

A star supports stable Hydrogen fusion

• Upper mass limit: about $120 \, M_\oplus$
  above that radiation pressure blows the star apart

• Lower mass limit: $0.076 \, M_\oplus$
  lower core temperatures are too low for fusion
Brown Dwarfs

Below $0.076 \, M_\odot$, H cannot undergo stable nuclear fusion

But, Deuterium ($^2\text{H}$) fuses at lower temperatures

**Brown dwarfs** are objects that

- fuse all the D in their cores
- have masses between 0.013 and 0.076 $M_\odot$
- burn their D quickly, then slowly cool.
- form like stars.
Brown Dwarf Gliese 229B

Palomar Observatory
Discovery Image
October 27, 1994

Hubble Space Telescope
Wide Field Planetary Camera 2
November 17, 1995

PRC95-48 · ST ScI OPO · November 29, 1995
T. Nakajima and S. Kulkarni (CalTech), S. Durrance and D. Golimowski (JHU), NASA
Planets

• Do not support Deuterium fusion
• Less massive than Brown Dwarfs
• $M < 0.013 \, M_\odot \, (~13 \, M_{\text{Jupiter}})$
• Form in disks surrounding stars

Open Questions:
• Can planets form in isolation (like stars?)
• What is the minimum planetary mass
Making a Model

A hypothesis for solar system formation must explain:

• Patterns of motion of the orbits
• The 2 classes of planets
• Asteroids and comets
• Exceptions

It should be predictive

Does it apply to other solar systems?
Two models

1. Close Encounter – tidal stream (Buffon 1745)
Physics

• Hot gas will expand due to high pressure, rather than collapsing

• Gas pressure $\sim nT$
  – $n$ is gas density
  – $T$ is the gas temperature

• If the pressure exceeds that of the interplanetary medium, it will expand
Two models

2. Nebular Hypothesis (Kant 1755; LaPlace 1790)
Physics

- Large, cold cloud of gas ($D \sim$ few ly)
- Collapse begins
- Gravity pulls cloud together
- Cloud heats (why?)
- Cloud rotates (why?)
- Disk forms (why?)
- Sun forms at hot center
Planet Formation in a Disk

Temperature decreases outwards
Density decreases outwards

At high enough temperatures, everything is gaseous

As temperatures fall, gases condense into solids
# Condensation Sequence

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Condensate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>$\text{Fe}_2\text{O}_3$, $\text{FeO}$, $\text{Al}_2\text{O}_3$</td>
</tr>
<tr>
<td>1300</td>
<td>$\text{Fe}$, $\text{Ni}$</td>
</tr>
<tr>
<td>1200</td>
<td>Silicates</td>
</tr>
<tr>
<td>1000</td>
<td>$\text{MgSiO}_3$</td>
</tr>
<tr>
<td>680</td>
<td>$\text{FeS}$</td>
</tr>
<tr>
<td>175</td>
<td>$\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>150</td>
<td>$\text{NH}_3$</td>
</tr>
<tr>
<td>120</td>
<td>$\text{CH}_4$</td>
</tr>
<tr>
<td>65</td>
<td>Noble gases</td>
</tr>
</tbody>
</table>
### Elemental Abundances

<table>
<thead>
<tr>
<th>Sun</th>
<th>Mass Fraction</th>
<th>Earth</th>
<th>Mass Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.74</td>
<td>Fe</td>
<td>0.32</td>
</tr>
<tr>
<td>He</td>
<td>0.24</td>
<td>O</td>
<td>0.30</td>
</tr>
<tr>
<td>O</td>
<td>0.010</td>
<td>Si</td>
<td>0.15</td>
</tr>
<tr>
<td>C</td>
<td>0.0046</td>
<td>Mg</td>
<td>0.14</td>
</tr>
<tr>
<td>Ne</td>
<td>0.0013</td>
<td>S</td>
<td>0.029</td>
</tr>
<tr>
<td>Fe</td>
<td>0.0011</td>
<td>Ni</td>
<td>0.018</td>
</tr>
<tr>
<td>N</td>
<td>0.00096</td>
<td>Ca</td>
<td>0.015</td>
</tr>
<tr>
<td>Si</td>
<td>0.00065</td>
<td>Al</td>
<td>0.014</td>
</tr>
<tr>
<td>Mg</td>
<td>0.00058</td>
<td>Cr</td>
<td>0.005</td>
</tr>
</tbody>
</table>
Solar Composition at Low Temperature

Table 4.1  Expected abundances in the outer solar nebula

<table>
<thead>
<tr>
<th>Material</th>
<th>Percent (by mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen (gas)</td>
<td>77.0</td>
</tr>
<tr>
<td>Helium (gas)</td>
<td>22.0</td>
</tr>
<tr>
<td>Water (ice grains)</td>
<td>0.6</td>
</tr>
<tr>
<td>Methane (ice grains)</td>
<td>0.4</td>
</tr>
<tr>
<td>Ammonia (ice grains)</td>
<td>0.1</td>
</tr>
<tr>
<td>Rock and metal (solid grains)</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Planet Formation in a Disk: Condensation Sequence

- Solar nebula had uniform composition
- Temperature decreases outwards
- Different materials condense at different temperatures
- H and He never condense
Solar System Layout

Small rocky planets close to Sun

Large gaseous planets further from Sun

Debris fields: asteroids, KBOs, Oort cloud

• **Asteroids**: mostly between Mars and Jupiter
• **KBOs**: mostly past Neptune
• **Oort cloud**: thousands of au
Rocky Planets

Also known as Terrestrial planets

Metallic core plus rocky mantle

Minimal atmospheres
Gas Giant Planets

Also known as Jovian planets

Large rocky core surrounded by gaseous envelope

Form outside the “ice line”

<table>
<thead>
<tr>
<th>Planet</th>
<th>$M_{\text{core}}$ ($M_\oplus$)</th>
<th>$M_{\text{atm}}$ ($M_\oplus$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jupiter</td>
<td>10-40</td>
<td>300</td>
</tr>
<tr>
<td>Saturn</td>
<td>20-30</td>
<td>75</td>
</tr>
<tr>
<td>Uranus</td>
<td>10-15</td>
<td>2-3</td>
</tr>
<tr>
<td>Neptune</td>
<td>10-15</td>
<td>2-3</td>
</tr>
</tbody>
</table>
Planetary Sizes
Resulting Solar System

Inside Frost Line:
small rocky planets

Outside Frost Line:
large gaseous planets
Recap: The Solar System in Scale

If the Solar System were the size of a football field

- **Sun**: radius = 0.4 inches (1 cm)
- **Earth** is on the 2.5 yard line; radius = 0.1 mm
- **Jupiter** is on the 13 yard line
- **Saturn** is on the 24 yard line
- **Pluto** is 100 yards away
- The **Oort Cloud** is 10-50 miles away
- The nearest star, **α Centauri**, is 412 miles away
The Debris

- **Solar wind** removed gas
  - Small planetesimals remained

- **Asteroids**: remaining rocky planetesimals
  - Planet formation inhibited between Mars and Jupiter
  - Initially lots of planetesimals
  - Most crashed into inner planets or were ejected

- **Comets**: remaining icy planetesimals
  - Initially all throughout outer solar system

- **KBOs**
  - accreted too slowly
Barringer Crater, Arizona

Diameter: 1.2 km. Depth: 170m. Rim: 45m. Age: 50,000 years. Impactor: 50m Fe-Ni meteor
Origin of the Moon (Luna)

Luna is too large to have been captured by Earth
• Composition different than Earth
  – Moon has lower density (less iron/nickel)
  – Could not have formed in same place/time as Earth
• Giant Impact
  – Many large planetesimals leftover during SS formation
  – Collision between proto-Earth and Mars-sized object
• Possible outcomes
  – Change in axial tilt
  – Change in rotation rate
  – Complete destruction
  – outer layers of Earth blown off
A Mars-sized planetesimal crashes into the young Earth, shattering both the planetesimal and our planet.

Hours later, our planet is completely molten and rotating very rapidly. Debris splashed out from Earth’s outer layers is now in Earth orbit. Some debris rains back down on Earth, while some will gradually accrete to become the Moon.

Less than a thousand years later, the Moon’s accretion is rapidly nearing its end, and relatively little debris still remains in Earth orbit.
Debris: Minor Planets

951 Gaspra  19 x 12 x 11 km

241 Ida       58 x 23 km

443 Eros      40 x 14 x 14 km
Osiris-Rex at Bennu

arrived
03 Dec-2018

101955 Bennu:
492 m diameter

19 km standoff

1.25 km orbit
12/31/18

Return 60 g to Earth, Sept 2023
Unlike most asteroids, Vesta and Ceres are closer in size to Pluto and the Earth’s moon.

- Vesta: 326 miles (525 km) diameter
- Ceres: 590 miles (950 km) diameter
Kuiper Belt Objects
Also known as
• Trans-Neptunian Objects (TNOs)
• Dwarf Planets
• Include Pluto/Charon

Sedna
~900 km radius
80 AU from Sun
Eris (2003 UB313)

- Radius: 1200 km
- Mean distance from Sun: 68 au
- $e=0.44$, $i=44^\circ$
Ultima Thule

31 km long

$\text{a: 44 au P: 268 years}$
Comets
Debris: Comets
Comets

Comet Wild-2
Stardust mission flyby
January 2006

Nucleus: 5 km
Comet Churyumov-Gerasimenko from Rosetta at 62 km, 12 September 2014
How Big?
Planet Formation
Planet Formation

Planet formation in flattened disks, dictated by conservation of angular momentum.

Model explains the shape of our Solar System
HL Tau: Environs and ALMA image

Taurus Star Forming Region
Wide Field Image at Optical Wavelengths
Credit: Paul Kalas (UC Berkeley)

HL Tau with ALMA
Planet forming disk
HL Tau’s coiled jet

XZ Tau
Dust around HL Tau
Lick H-alpha 358
Herbig-Haro 30
Planet Formation

Young Stellar Disks in Infrared

CoKu Tau1, DG Tau B, Haro 6-5B, IRAS 04016+2610, IRAS 04248+2612, IRAS 04302+2247

HST • NICMOS

D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA
Fraction of Stars with Disks

β Pictoris
Debris Disks

HD 141569

5.6 billion miles

Diameter of Neptune's Orbit

HR 4796A

5.6 billion miles

Diameter of Neptune's Orbit
Exoplanets

2009-07-31

20 au

Jason Wang / Christian Marois
What is the value of $f_p$?

- Our Sun has planets.
- Planets and stars seem to form together.
- Based on that, we can set the fraction of stars with planets to 1.

We’ll reassess $f_p$ in week 10, when we look for planets around other stars.
N Update

\[ N = N^* f_s f_p n_h f_i f_c L/T \]

- \( N^* = 4 \times 10^{11} \)
- \( f_s \sim 0.2 \)
- \( f_p \sim 1 \)

\[ N = 8 \times 10^{10} n_h f_i f_c L/T \]