Nature and Origin of Planetary Systems
$f_p$ and $n_e$
Our Solar System as Example

• We know far more about our solar system than about any other
• It does have (at least) one planet suitable for life
• Start with facts about the solar system
• Then discuss theories of planet formation
• Compare predictions to facts about ours
• Complete our estimate of $f_p$, prepare for $n_e$
General Properties of the Solar System

• Dynamical Regularities
  – Planets orbit in plane, nearly circular
  – Planets orbit sun in same direction (CCW as seen from North Pole)
  – Rotation axes perpendicular to orbit plane
    • Uranus is the exception
  – Planets contain 98% of the angular momentum
  – The Sun contains 99.9% of the mass
April Heliocentric View

Heliocentric Charts by Richard Binzel

Side View

Mercury - Venus - Neptune
Spacing and Composition

• Spacing increases with distance
  – Evenly spaced if plotted logarithmically
  – Missing planet in asteroid belt
• Composition varies with distance
  – Inner 4 are “terrestrial”
    • Small, rocky, thin atmospheres
  – Outer 4 are “gas giants”
    • Gaseous, large, mostly atmosphere

\[
\frac{d_2}{d_1} \approx 1.5 - 2
\]
The Sun would be smaller than a golf ball (4.267 cm). Two-thirds its diameter.

Each of the Gas Giants would be smaller than a BB pellet (4.496 mm).
The Solar System

Distance from Sun

<table>
<thead>
<tr>
<th>.1</th>
<th>1</th>
<th>10</th>
<th>100 AU</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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(M (M⊕) 0.06  1 < .001  95  17

<table>
<thead>
<tr>
<th>.82</th>
<th>.11</th>
<th>318</th>
<th>15</th>
</tr>
</thead>
</table>

Terrestrial | Gas Giants | Icy dwarfs
Asteroids

Composition (%)

<table>
<thead>
<tr>
<th></th>
<th>Rocky</th>
<th>“Icy”</th>
<th>Gaseous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestrial</td>
<td>100</td>
<td>&lt;1</td>
<td>0</td>
</tr>
<tr>
<td>Jupiter</td>
<td>6</td>
<td>~13</td>
<td>~81</td>
</tr>
<tr>
<td>Saturn</td>
<td>21</td>
<td>~45</td>
<td>~34</td>
</tr>
<tr>
<td>Uranus</td>
<td>~28</td>
<td>~62</td>
<td>~10</td>
</tr>
<tr>
<td>Neptune</td>
<td>~28</td>
<td>~62</td>
<td>~10</td>
</tr>
<tr>
<td>Comets</td>
<td>~31</td>
<td>~69</td>
<td>~0</td>
</tr>
</tbody>
</table>

Rocky - iron, silicates, …
“Icy” - at time of formation (H₂O, NH₃, CH₄, …)
Gaseous - H, He
What is a Planet?

• Pluto much smaller than others ($0.002 \ M_{\text{earth}}$)
• Other, similar objects found in Kuiper Belt
  – Including one similar to Pluto (Eris)
    • First named Xena, renamed Eris, goddess of discord, has a moon, Dysnomia, goddess of lawlessness…
• IAU voted in 2006
  – 1. Create a new category of dwarf planet
  – 2. Demote Pluto to a dwarf planet
Back to Nine Planets?

Scientific American, Feb. 2016: Very eccentric orbits of some ice dwarfs suggest that a Neptune-size planet exists 200-1000 AU from Sun.
Theories of Planet Formation

• All start with rotating disk
  – Mass 0.01\(M_\odot\) or more
    • Sum of planet masses 0.001 \(M_\odot\)
    • Consistent with observed disk masses
  – Temperature and Density decrease with distance from forming star
  – Dust plays crucial role
Many disk masses are large enough…

And these masses measure only the small dust. Rocks are invisible to us. But they are based on dust mass times 100. We have less info on gas masses.


Annual Reviews
First Step: Accretion of Dust Grains

Fig. From talk by Jurgen Blum
Second Step: Dust settles to midplane

Williams and Cieza, Annual Reviews
Step 3: Dust in midplane grows to rocks, boulders, …

Artist’s conception: Vega
Step 4: From Boulders to Planets

- Boulders grow to planetesimals
- Planetesimals collide, grow larger
  - Some dust returned in collisions
- Icy dust in outer part of disk
  - Builds bigger, icier planets
  - Internal heat turns ice to gas
- If rock-ice core massive enough
  - Gravitational collapse of gas
  - Gas giants with ring/moon systems
Dust cores and Icy Mantles
($\text{H}_2\text{O}, \text{NH}_3, \text{CH}_4$)

Dust Cores
Iron, Silicon, Oxygen, Carbon

No Dust

“snow” line

Outer Planets

Terrestrial Planets
Transitional disks

- Dust hole: mechanisms
  - Grain growth
  - Photoevaporation
  - Stellar companion
  - Forming planet?

⇒ What about the gas?

Strom & Najita

Van der Marel
A “dust trap” observed last year: Planet forming?

Perez

Just 24 min with ALMA!
Disk with many gaps: Many forming planets?

HL Tau disk: Young star in Taurus cloud

Image made with ALMA 2014
Formation of Gas Giants (Jupiter, Saturn)

Models for formation of gas giants

- **grav. instability scenario**
  - Cameron, Boss

- **core accretion scenario**
  - Safronov, Hayashi, Mizuno, Bodenheimer

- Protoplanetary disk
- Planetesimals
- Coagulation of planetesimals
- Terrestrial planets
- Cores
- Gas accretion onto cores
- Gas giants

Timeline:
- $10^4$ y
- $10^3$ y
- $10^7$ y
Predictions from Models

- Formation in rotating disk with icy dust can explain many facts about our solar system.
- If we can generalize, expect planetary systems common.
- Expect (?) about 10 planets, terrestrial planets in close, giant planets farther out, spaced roughly logarithmically.
- May still be typical, but not universal…
- Big planets may clear a gap in disk.
A Planet in Formation?

A low mass third object 300 AU from a close binary. Could be a gas giant or a brown dwarf. Contours indicate a disk of dust with a mass of a few Earth masses. Could form a system of moons.

Kraus et al. 2014
Last Steps: Loss of gas, collisions lead to debris disk

Issues for Planet Formation

• The time to build up the giant planets from dust is long in core accretion theories
  – Gas has to last that long to make gas giants
• How long do dust disks last?
  – How long does the gas last?
• Are there faster ways to make planets?
• What about planet building for binary stars?
Time Available to form planets

- The disks around young stars can form planets
- How long do the disks last?
  - Sets limit on time to form planets
  - Half of disks have little dust left by 2 Myr
  - Most gone by 3 to 5 Myr
  - No evidence that gas stays longer
  - Some “debris” around older stars
  - May be evidence of planet building
Disks versus Age of Star
Evidence for Collisions
Formation of Gas Giants (Jupiter, Saturn)

May be only way to make big planets far from star
Other Active Issues

• Some planetary systems are quite different
  – First found were big planets in close
  – But this was due to selection effect
• Locations may differ with mass of star
  – Ices survive closer to lower mass star
  – May get ice giants in close
  – Also planets may migrate inwards
  – May prevent formation of terrestrial planets
Formation of Earth

- Almost entirely rocky material (iron, silicates)
- Radioactive elements heat interior
  - Were produced in supernovae explosions
- Interior becomes molten, iron sinks to core
  - Releases gravitational potential energy
  - Interior even hotter
  - Differentiated planet
- Collision forms Earth-Moon system
- Earth acquires atmosphere
  - Outgassing and delivery by comets
Radioactive Heating

Radioactive nuclei decay (release of nuclear potential energy)

Nuclear potential energy \[\rightarrow\] unstable nucleus \[\rightarrow\] Smaller nuclei (Fission)

e.g. \[^{40}\text{K}\] Potassium, \[^{238}\text{U}\] Uranium

Also emit $\alpha$ particles (He), electrons, gamma-rays

$\rightarrow$ Kinetic energy $\rightarrow$ heat
Inner, solid core
T ~ 7000 K, iron, nickel

Outer, liquid core
Iron, nickel

Lower mantle, iron-rich silicates, solid

Upper mantle, pliable

Asthenosphere

Lithosphere (crust), rigid

Biosphere
Continental Drift Reconstructed

Lithosphere floats on asthenosphere: volcanoes, continental drift
Shows motion of continental plates over last 150 Myr.
Red and green dots show locations of ocean drilling.

http://www.odsn.de/odsn/index.html
Formation of Earth and Moon

\[ \frac{M_{\text{Moon}}}{M_{\text{Earth}}} \text{ Larger than all other planets} \]

Most terrestrial planets have no moons

(Martian moons are captured asteroids)

Moon most likely resulted from giant impact

\[ 0.15 M_{\odot} \]

Moon: \( \sim 0.01 M_{\odot} \)

Earth gets more iron

\[ \rho_{\odot} = 5.5 \text{ g cm}^{-3} \]

Moon mostly silicate

\[ \rho_{\text{Moon}} = 3.3 \text{ g cm}^{-3} \]

Temperature was very high after impact (10,000 - 60,000 K)

Any icy material left?
New model of collision (2012) requires fast-spinning (2 hour days) Earth to match detailed chemistry of Moon, which is very similar to that of Earth. Collision blasts a lot of Earth material into a disk around Earth, where Moon forms.
Origin of Atmosphere

Certain “Noble” gases (e.g. Neon) are more rare in Earth atmosphere than in solar nebula. ⇒ Atmosphere not collected from gas

Reason: Earth is small ⇒ gravity is weak

Temperature in solar nebula is high - atoms moving fast, harder to hold

“Icy” material vaporized by high temperatures, outgased through vents, volcanoes
Alternative: Icy materials brought by comets, asteroids after Moon formation

\[
\begin{align*}
H_2O, NH_3, CH_4 & \rightarrow H_2O, N_2, CO_2 \\
\text{Chemical Reactions} & \\
\text{Ultraviolet Light} & \\
\text{Rain} & \\
\text{Dissolved} & \\
\text{Oceans} & \\
\text{Main constituent of atmosphere} & \\
\text{CaCO}_3 \text{ sediments} &
\end{align*}
\]

No \( O_2 \) on early Earth; No ozone (\( O_3 \)), so no protection from ultraviolet light
Summary

• Planet formation theory suggests planetary systems should be common
• We see evidence of planet building in disks around young stars
• Binary stars with separations around 10 AU may prevent planet formation
• Consider these facts in estimating $f_p$
• Inner, terrestrial planets of sufficient size will differentiate, may get atmosphere, oceans
• Earth may be unusual (big Moon by collision)