Planet Formation

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Contents

I. What a model of planetary-system formation has to explain

II. Observational constraints

III. The formation of planets and planetary systems
A small chronology of the world

13.7 Gyr  Big bang; formation of the elements H and He
13.4 Gyr  First stars and galaxies; first supernova explosions produce the heavy elements (C,N,O,Si,Fe,…)
12 Gyr    Formation of the milky way
4.567 Gyr Formation of the solar system; at this point in time the interstellar medium has been enriched with 1% heavy elements
4.5 Gyr   Formation of the earth and the moon
4.45 Gyr  Layer structure of the earth
4.4 Gyr   Solid earth crust
4.2 Gyr   Early ocean
4 Gyr     Plate tectonics
>3.5 Gyr  Earth’s magnetic field
>3.5 Gyr  Origin of life
2.3 Gyr   Formation of oxygen-rich atmosphere; formation of ozone
1 Gyr     “Freeze-out” of inner earth core
0 Gyr     Today
I.
What a model of planetary-system formation has to explain
I. What a model of planetary-system formation has to explain

a. The architecture of our Solar System
   o Terrestrial planets in the inner system, gas giants in the outer system
   o The occurrence of an asteroid belt between the terrestrial and gaseous planet region
   o Kuiper belt
   o Oort cloud
The planets of the solar system
Terrestrial vs. gaseous planets

- Mercury
- Venus
- Earth
- Mars
- Jupiter
- Saturn
- Uranus
- Neptune

- Iron/nickel core
- Rock (silicates)
- Metallic hydrogen
- Water
- Rock

Molecular hydrogen gas changing to liquid at base
3. Swarms of asteroids and comets populate the solar system. Asteroids are concentrated in the asteroid belt, and comets populate the regions known as the Kuiper belt and the Oort cloud.
Oort cloud:
- Extends out to about 50,000 AU
- Contains about a trillion comets
- Comet orbits have random tilts and eccentricities

Kuiper belt:
- Extends from about 30–50 AU
- About 100,000 comets more than 100 km across
- Comets orbit in the same plane and direction as planets

orbit of Oort cloud cometary entering inner solar system
Neptune's orbit
typical Kuiper belt
cometary orbit
I. What a model of planetary-system formation has to explain

b. The existence and formation scenario of the Moon

Kokubo et al. 2000

Canup 2004
I. What a model of planetary-system formation has to explain

c. The architecture of other solar systems

Wyatt 2008

Solar System planets
- Planets inferred from debris disk structures
- Planets known from radial velocity and transit studies
- Planets from imaging studies
I. What a model of planetary-system formation has to explain
d. The gaseous-disk lifetime constraint

Maximum lifetime of protoplanetary disks $10^7$ years

Wyatt 2008
I. What a model of planetary-system formation has to explain

   e. Meteoritic constraints
I. What a model of planetary-system formation has to explain

f. Debris disks

http://upload.wikimedia.org/wikipedia/commons/3/3a/Kuiper_belt_remote.jpg
I. What a model of planetary-system formation has to explain

- The late heavy bombardment

Koeberl 2006
I. What a model of planetary-system formation has to explain

h. The stability over Gyrs

**Fig. 1a and b.** Numerical integration of the averaged equations of motion of the solar system 10 Gyr backward and 15 Gyr forward. For each planet, the maximum value obtained over intervals of 10 Myr for the eccentricity (a) and inclination (in degrees) from the fixed ecliptic J2000 (b) are plotted versus time. For clarity of the figures, Mercury, Venus and the Earth are plotted separately from Mars, Jupiter, Saturn, Uranus and Neptune. The large planets behavior is so regular that all the curves of maximum eccentricity and inclination appear as straight lines. On the contrary the corresponding curves of the inner planets show very large and irregular variations, which attest to their diffusion in the chaotic zone.
II.
Observational constraints
II. Observational constraints

a. Solar System has disk shape

<table>
<thead>
<tr>
<th>Name</th>
<th>Inclination to ecliptic</th>
<th>Inclination to Sun’s equator</th>
<th>Inclination to invariable plane</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Terrestrials</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mercury</td>
<td>7.01°</td>
<td>3.38°</td>
<td>6.34°</td>
</tr>
<tr>
<td>Venus</td>
<td>3.39°</td>
<td>3.86°</td>
<td>2.19°</td>
</tr>
<tr>
<td>Earth</td>
<td>0°</td>
<td>7.155°</td>
<td>1.57°</td>
</tr>
<tr>
<td>Mars</td>
<td>1.85°</td>
<td>5.65°</td>
<td>1.67°</td>
</tr>
<tr>
<td><strong>Gas giants</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jupiter</td>
<td>1.31°</td>
<td>6.09°</td>
<td>0.32°</td>
</tr>
<tr>
<td>Saturn</td>
<td>2.49°</td>
<td>5.51°</td>
<td>0.93°</td>
</tr>
<tr>
<td>Uranus</td>
<td>0.77°</td>
<td>6.48°</td>
<td>1.02°</td>
</tr>
<tr>
<td>Neptune</td>
<td>1.77°</td>
<td>6.43°</td>
<td>0.72°</td>
</tr>
</tbody>
</table>

II. Observational constraints

b. Co-formation of Sun and planets

The sun and the planets of our solar system formed at the same time and from the same material reservoir:

- Elementary abundances
- Age of the meteorites = age of the sun
- Parallel angular momentum of sun and planets

Cowley 1995
The sun and the planets of our solar system formed at the same time and from the same material reservoir:

- Elementary abundances
- Age of the meteorites = age of the sun
- Parallel angular momentum of sun and planets

Radiometric dating:

<table>
<thead>
<tr>
<th>Material</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth (Zircon, Australia)</td>
<td>4.40 Gyr</td>
</tr>
<tr>
<td>Moon (highland rocks)</td>
<td>4.1-4.4 Gyr</td>
</tr>
<tr>
<td>Meteorite (oldest from Mars)</td>
<td>4.5 Gyr</td>
</tr>
<tr>
<td>Meteorite (chondrules)</td>
<td>4.564 Gyr</td>
</tr>
<tr>
<td>Meteorite (CAI)</td>
<td>4.567 Gyr</td>
</tr>
</tbody>
</table>

Age determination of the sun (evolutionary models and helioseismology data):

<table>
<thead>
<tr>
<th>Authors</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guenther &amp; Demarque 1997</td>
<td>4.5±0.1 Gyr</td>
</tr>
<tr>
<td>Bonnano, Schlattl &amp; Paterno 2002</td>
<td>4.57±0.11 Gyr</td>
</tr>
<tr>
<td>Houdek &amp; Gough 2007</td>
<td>4.68±0.02 Gyr</td>
</tr>
</tbody>
</table>
II. Observational constraints

c. Existence and lifetimes of PPDs

Gardner et al. 2006

Dauphas & Chaussidon 2011
Molecular clouds I
Molecular clouds II
Molecular clouds IV: dust and gas

Figure 1 Visible and near-infrared images of Barnard 68. Top, deep B,V,I band (0.44 μm, 0.55 μm, 0.90 μm) image (~7’ × 7’) of the dark molecular cloud Barnard 68 taken with ESO’s Very Large Telescope (VLT) located in the Chilean Andes. The cloud is seen in projection against the Galactic bulge. At these optical wavelengths the cloud is completely opaque owing to extinction of background starlight caused by small interstellar dust particles that permeate the cloud. The complete absence of foreground stars projected onto the cloud is a result of the proximity of the cloud to the Solar System (125 pc). The outer radius of the cloud is comparable to the inner size of the Oort cloud of comets that surround the Sun (~10^4 AU). The mass of the cloud is about twice that of the Sun. Bottom, deep B,I,K band image of the cloud constructed by combining an infrared K band (2.2 μm wavelength) image with the B and I images. The K band image was obtained with ESO’s New Technology Telescope (NTT) in the Chilean Andes. At near-infrared wavelengths the cloud becomes transparent and the stars located behind the cloud clearly appear in the image. Because these stars are observed only in the longest of the three wavelength bands, they appear very red in this three-colour image. These are the stars that provide measurements of dust extinction directly through the cloud.
Fig. 1. SCUBA map at 850 μm (left) and SIMBA map at 1.2 mm (right) of Barnard 68, with superimposed $A_V$ contours. The $A_V$ and SCUBA maps have been smoothed to match the SIMBA resolution ($FWHM = 24''$; the beamsize is shown on the right image). All images have been resampled to a pixel size of 12''. The field of view is $5' \times 5'$. $A_V$ contours start at 4 mag and are spaced by 4 mag. For both images, the grayscale is in units of $S/N$. 

Molecular clouds V: the interior
Molecular clouds VI: gravitational collapse

Fig. 2.— The gravitational fragmentation of molecular cloud is shown from a simulation containing initial structure (Klessen et al., 1998). The gravitational collapse enhances this structure producing filaments which fragment to form individual stars. The time $t$ is given in units of the free-fall time.

Fig. 8.— The fragmentation of a $1000 \, M_\odot$ turbulent molecular cloud and the formation of a stellar cluster (Bonnell et al., 2003). Note the merging of the smaller subclusters to a single big cluster.
Stars form in clusters:
the open clusters h und $\chi$ Persei
Planet formation must be a (relatively) fast process!

Maximum lifetime of protoplanetary disks $10^7$ years
II. Observational constraints

d. Dust growth within PPDs

Fig. 3.—Circles, VLA measurements at 7 mm and 3.5 cm; arrow, an upper limit at 6 cm. The long-wavelength spectrum of TW Hya is better fitted by a model in which nearly all of the mass in solids is in centimeter-size grains (solid line) than by the model of Calvet et al. (2002) based on a single-power law grain size distribution (dashed line).
II. Observational constraints
e. Existence and lifetimes of debris disks
II. Observational constraints

e. Existence and lifetimes of debris disks
II. Observational constraints

e. Existence and lifetimes of debris disks
II. Observational constraints

e. Existence and lifetimes of debris disks

Figure 3
Evolution of disk mass derived from submillimeter observations. This plot extends the compilation of ages and masses of Wyatt, Dent & Greaves (2003) to include all debris disks currently detected at submillimeter wavelengths (Greaves et al. 2004b; Liu et al. 2004; Sheret, Dent & Wyatt 2004; Najita & Williams 2005; Wyatt et al. 2005; Lestrade et al. 2006; Williams & Andrews 2006; Matthews, Kalas & Wyatt 2007). The same (representative) sample of protoplanetary disks is included from Wyatt, Dent & Greaves (2003), and an opacity of $45 \, \text{AU}^2 \, M_\oplus^{-1}$ is assumed for both protoplanetary and debris disks. The upper limit on the Kuiper belt dust mass from submillimeter observations (see Greaves et al. 2004b) is also plotted.
II. Observational constraints

f. Extrasolar planetary systems

- Planets around solar-type stars
- Total of 556 extrasolar-planet candidates (8 June 2011)
  - Spectroscopically detected: 507
  - Transits: 135
- Kepler candidates: 1235 (confirmed: 16)
- System with 2 or more planets: 127
- Fraction of stars with planets: 0-25% (depending on metallicity of the star)
II. Observational constraints

f. Extrasolar planetary systems

Figure 7. Number of observed candidates versus semi-major axis for four candidate size ranges. As defined in Table 6, Earth-size refers to $R_p < 1.25 \ R_\oplus$, super-Earth-size to $1.25 \ R_\oplus < R_p < 2 \ R_\oplus$, Neptune-size to $2 \ R_\oplus < R_p < 6 \ R_\oplus$, and Jupiter-size refers to $6 \ R_\oplus < R_p < 15 \ R_\oplus$. Bin size for the semi-major axis is 0.04 AU.
II. Observational constraints

f. Extrasolar planetary systems

Mass distribution of extrasolar planets

Udry et al. 2007

Arbitrary scale

Mmin [M☉]
Orbits of extrasolar planets

Figure 11: Distribution of planet masses and semimajor axes. Parameters for extrasolar planets found from radial velocity and transit and imaging studies were taken from http://exoplanet.eu on 31 January 2008. The shaded yellow region shows the current limits of radial velocity surveys for sun-like stars. Parameters for putative planets inferred from debris disk structures (which have yet to be confirmed) are from HR 4796, Wyatt et al. 1999; Eridani, Ozernoy et al. 2000; Vega, Wyatt 2003; HD 141569, Wyatt 2005b; η Corvi, Wyatt et al. 2005; Fomalhaut, Quillen 2006; and β Pictoris, Freistetter, Krivov & Löhne 2007. Note that these parameters, particularly planet mass, are often poorly constrained.

Wyatt 2008

- **E**: Solar System planets
- **F**: Planets inferred from debris disk structures
- **+**: Planets known from radial velocity and transit studies
- **Δ**: Planets from imaging studies
About the metallicity of stars and the connection to planets

- The search for planets around stars in globular clusters has so far been unsuccessful; stars in globular clusters possess metallicities \(<1\%\).

- The sun possesses a metallicity of \(~1\%\).

- The mean metallicity of stars with extrasolar planets is \(>1\%\).
II. Observational constraints

f. Extrasolar planetary systems

Figure 3: Radius versus mass for giant planets after 4.5 Ga of evolution compared to measured values for four giant planets and four known extrasolar planets. As in fig. 2, the lines correspond to H+He: a pure, $Y = 0.25$, hydrogen-helium composition ($Y = 0.30$); (a): a model with $Y = 0.30$ and a 1.5$M_J$ core; (b): the same model but with $Y = 0.36$. An approximate mass-radius relation for zero-temperature water and olivine planets is shown as dashed and dash-dotted lines, respectively (Courtesy of W.B. Hubbard).
II. Observational constraints

f. Extrasolar planetary systems

Lissauer et al. 2011
II. Observational constraints

g. The existence of chondrules
Chondrule formation

Revised melting events

Precursor dust and partly melted and sintered aggregates

+ CAI fragment

Collisions between partly melted chondrules

Dust

Chondrule fragment

Reduction & metal loss

Melt-gas exchange

Compound chondrule

Igneous rimmed chondrule

Chondrule with foreign grain

Al-rich chondrule with relict CAI

Scott 2007
Chondrule size distribution

Miura & Nakamoto 2006

- LL3
- L3
- EH3
- CO3

Cumulative number [%]

Diameter [μm]

Lognormal size dist.
II. Observational constraints

h. Meteoritic evidence of formation timescales

NWA 5932, carbonaceous chondrite, CV3

Source: http://tw.strahlen.org/fotoatlas1/meteorite_chondrite1.html
## Radiometric dating of meteorites - long half lives

<table>
<thead>
<tr>
<th>Radioactive Isotope (Parent)</th>
<th>Product (Daughter)</th>
<th>Half-Life (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samarium-147</td>
<td>Neodymium-143</td>
<td>106 billion</td>
</tr>
<tr>
<td>Rubidium-87</td>
<td>Strontium-87</td>
<td>48.8 billion</td>
</tr>
<tr>
<td>Rhenium-187</td>
<td>Osmium-187</td>
<td>42 billion</td>
</tr>
<tr>
<td>Lutetium-176</td>
<td>Hafnium-176</td>
<td>38 billion</td>
</tr>
<tr>
<td>Thorium-232</td>
<td>Lead-208</td>
<td>14 billion</td>
</tr>
<tr>
<td>Uranium-238</td>
<td>Lead-206</td>
<td>4.5 billion</td>
</tr>
<tr>
<td>Potassium-40</td>
<td>Argon-40</td>
<td>1.26 billion</td>
</tr>
<tr>
<td>Uranium-235</td>
<td>Lead-207</td>
<td>0.7 billion</td>
</tr>
</tbody>
</table>

http://www.asa3.org/ASA/resources/wiens.html
Absolute ages – the Pb-Pb method

\[
\left( \frac{^{207}Pb}{^{204}Pb} \right)_P = \left( \frac{^{207}Pb}{^{204}Pb} \right)_I + \left( \frac{^{235}U}{^{204}Pb} \right) \left( e^{\lambda_{235}t} - 1 \right)
\]

\[
\left( \frac{^{206}Pb}{^{204}Pb} \right)_P = \left( \frac{^{206}Pb}{^{204}Pb} \right)_I + \left( \frac{^{238}U}{^{204}Pb} \right) \left( e^{\lambda_{238}t} - 1 \right)
\]

\[
\left[ \frac{\left( \frac{^{207}Pb}{^{204}Pb} \right)_P - \left( \frac{^{207}Pb}{^{204}Pb} \right)_I}{\left( \frac{^{206}Pb}{^{204}Pb} \right)_P - \left( \frac{^{206}Pb}{^{204}Pb} \right)_I} \right] = \left( \frac{1}{137.88} \right) \left( \frac{e^{\lambda_{235}t} - 1}{e^{\lambda_{238}t} - 1} \right)
\]

Age = 4.55 Gyr

Pb-Pb isochrone of meteorites of different types. Canyon Diablo is an iron meteorite containing Pb but almost no U. The point for Earth is obtained from a mixture of river sediments.
Fig. 1. Pb-Pb isochrons for the six most radiogenic Pb isotopic analyses of acid-washed chondrules from the CR chondrite Acfer 059 (solid line), and for acid-washed fractions from the Efremovka CAIs (dashed lines). $^{207}\text{Pb}/^{206}\text{Pb}$ ratios are not corrected for initial common Pb. Error ellipses are $2\sigma$. Isochron age errors are 95% confidence intervals.
## Radiometric dating of meteorites
- **short half lives**

### Table 1. Extinct radioactivities in meteorites

<table>
<thead>
<tr>
<th>Parent nuclide</th>
<th>Half-life (My)</th>
<th>Decay constant (My(^{-1}))</th>
<th>Daughter nuclide</th>
<th>Estimated initial abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samarium-146</td>
<td>103</td>
<td>0.00673</td>
<td>Neodymium-142</td>
<td>(^{146})Sm/(^{146})Sm=(8.4±0.5)x10(^{-3})</td>
</tr>
<tr>
<td>Plutonium-244</td>
<td>80</td>
<td>0.0087</td>
<td>Fission products</td>
<td>(^{244})Pu/(^{238})U=(6.8±1.0)x10(^{3})</td>
</tr>
<tr>
<td>Iodine-129</td>
<td>15.7</td>
<td>0.0441</td>
<td>Xenon-129</td>
<td>(^{129})I/((^{129})I=(1.19±0.20)x10(^{-4})</td>
</tr>
<tr>
<td>Hafnium-182</td>
<td>8.9</td>
<td>0.078</td>
<td>Tungsten-182</td>
<td>(^{182})Hf/(^{190})Hf=(9.72±0.44)x10(^{-5})</td>
</tr>
<tr>
<td>Manganese-53</td>
<td>3.74</td>
<td>0.185</td>
<td>Chromium-53</td>
<td>(^{53})Mn/(^{55})Mn=(6.28±0.66)x10(^{-6})</td>
</tr>
<tr>
<td>Beryllium-10</td>
<td>1.385</td>
<td>0.500</td>
<td>Boron-10</td>
<td>(^{10})Be/(^{9})Be=(7.0±0.8)x10(^{-4})</td>
</tr>
<tr>
<td>Aluminum-26</td>
<td>0.717</td>
<td>0.967</td>
<td>Magnesium-26</td>
<td>(^{29})Al/(^{27})Al=(5.23±0.13)x10(^{-5})</td>
</tr>
<tr>
<td>Niobium-92</td>
<td>34.7</td>
<td>0.200</td>
<td>Zirconium-92</td>
<td>(^{92})Nb/(^{93})Nb=(1.6±0.3)x10(^{-5})</td>
</tr>
<tr>
<td>Palladium-107</td>
<td>6.5</td>
<td>0.11</td>
<td>Silver-107</td>
<td>(^{107})Pd/(^{106})Pd=(5.9±2.2)x10(^{-5})</td>
</tr>
<tr>
<td>Iron-60</td>
<td>2.62</td>
<td>0.265</td>
<td>Nickel-60</td>
<td>(7.9±2.8)x10(^{-8})&lt;(^{60})Fe/(^{55})Fe&lt;(6.3±2.0)x10(^{-7})</td>
</tr>
<tr>
<td>Chlorine-36</td>
<td>0.301</td>
<td>2.30</td>
<td>Sulfur-36 (1.9 %), argon-36 (98.1 %)</td>
<td>(^{35})Cl/(^{35})Cl=(17.2±2.5)x10(^{6})</td>
</tr>
<tr>
<td>Curium-247</td>
<td>15.6</td>
<td>0.0444</td>
<td>Uranium-235</td>
<td>(^{247})Cm/(^{238})U=(5.5±2.0)x10(^{-5})</td>
</tr>
<tr>
<td>Lead-205</td>
<td>15.1</td>
<td>0.0459</td>
<td>Thallium-205</td>
<td>(^{205})Pb/(^{204})Pb=(1.0±0.4)x10(^{-3})</td>
</tr>
<tr>
<td>Cesium-135</td>
<td>2.3</td>
<td>0.30</td>
<td>Barium-135</td>
<td>(^{138})Cs/(^{133})Cs=(4.8±0.8)x10(^{-4})</td>
</tr>
<tr>
<td>Calcium-41</td>
<td>0.102</td>
<td>6.80</td>
<td>Potassium-41</td>
<td>(^{41})Ca/(^{40})Ca=(1.41±0.14)x10(^{-5})</td>
</tr>
<tr>
<td>Beryllium-7</td>
<td>1.46x10(^{-7})</td>
<td>6.86x10(^{8})</td>
<td>Lithium-7</td>
<td>(^{7})Be/(^{7})Be=0.0061±0.0013</td>
</tr>
<tr>
<td>Technetium-97</td>
<td>4.21</td>
<td>0.16464</td>
<td>Molybdenum-97</td>
<td>(^{97})Tc/(^{92})Mo&lt;3x10(^{6})</td>
</tr>
<tr>
<td>Technetium-98</td>
<td>4.2</td>
<td>0.17</td>
<td>Ruthenium-98</td>
<td>(^{98})Tc/(^{96})Ru&lt;2x10(^{3})</td>
</tr>
<tr>
<td>Tin-126</td>
<td>0.23</td>
<td>3.0</td>
<td>Tellurium-126</td>
<td>(^{126})Sn/(^{28})Sn&lt;7.7x10(^{5})</td>
</tr>
</tbody>
</table>

Dauphas & Chaussidion 2011
Relative ages – the decay of $^{26}$Al

CHUR = chondritic uniform reservoir

$t_0$: formation of object 0

$t_1$: formation of object 1

Dauphas & Chaussidon 2011
Condensation of 1-10 μm dust from nebular gas

Bulk isochron of CAIs (Jacobsen et al., 2008)

Internal isochron of a fine-grained CAI (MacPherson et al., 2010a)

Agglomeration into mm-cm objects

< 50 ky

Melting and crystallization

Internal isochron of an igneous CAI (MacPherson et al., 2010b)

Dauphas & Chaussidon 2011
Scott 2007
Dauphas & Chaussidon 2011

ΔT after CAIs (My)

- Parent bodies of magmatic iron meteorites
- Parent bodies of eucrites and angrites
- Parent body of ordinary chondrites
- Parent body of CB chondrites

CAIs initial

Oldest chondrule precursors

Chondrules (n=112)

\[ \frac{^{26}\text{Al}}{^{27}\text{Al}} \]

\( 5.2 \times 10^{-5} \) to \( 10^{-5} \)

\( 10^{-6} \) to \( 10^{-7} \)
II. Observational constraints

i. Late heavy bombardment

Fig. 1. Declining crater densities versus time, after Wilhelms (1987). N is the cumulative number of craters >20 km diameter per sq. km. The thin gray bar is the period of the well-defined late heavy bombardment, between the formation of Nectaris and Imbrium, when a dozen lunar basins were formed. Two extensions to the upper left indicate schematically either a lull prior to a cataclysm or a continued high bombardment rate in pre-nectarian times.
II. Observational constraints

j. Formation timescale and mass of Mars

Dauphas & Chaussidon 2011
SNC (Martian) meteorites

SNC =
Shergottites, Nakhlites, Chassignites


Dauphas & Chaussidon 2011

DAG 1037

$\varepsilon^{182}W$ of the martian mantle

Mass of protoMars (present=1)

Time after solar system birth (My)

Time after solar system birth (My)
II. Observational constraints

k. Formation of the Earth and the Moon

Dauphas & Chaussidon 2011
II. Observational constraints

I. Cosmochemical composition of planetary bodies as a function of distance to Sun

<table>
<thead>
<tr>
<th>Object</th>
<th>mean density</th>
<th>uncompressed density</th>
<th>semi-major axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury 🌌</td>
<td>5.4 g cm⁻³</td>
<td>5.3 g cm⁻³</td>
<td>0.39 AU</td>
</tr>
<tr>
<td>Venus ☉</td>
<td>5.2 g cm⁻³</td>
<td>4.4 g cm⁻³</td>
<td>0.72 AU</td>
</tr>
<tr>
<td>Earth ☉</td>
<td>5.5 g cm⁻³</td>
<td>4.4 g cm⁻³</td>
<td>1.0 AU</td>
</tr>
<tr>
<td>Moon ☽</td>
<td>3.3 g cm⁻³</td>
<td>3.3 g cm⁻³</td>
<td>1.0 AU</td>
</tr>
<tr>
<td>Mars ♂</td>
<td>3.9 g cm⁻³</td>
<td>3.8 g cm⁻³</td>
<td>1.5 AU</td>
</tr>
<tr>
<td>Vesta ▼</td>
<td>3.4 g cm⁻³</td>
<td>3.4 g cm⁻³</td>
<td>2.3 AU</td>
</tr>
<tr>
<td>Pallas ♀</td>
<td>2.8 g cm⁻³</td>
<td>2.8 g cm⁻³</td>
<td>2.8 AU</td>
</tr>
<tr>
<td>Ceres ♂</td>
<td>2.1 g cm⁻³</td>
<td>2.1 g cm⁻³</td>
<td>2.8 AU</td>
</tr>
</tbody>
</table>

Planetary densities

Mercury - 5.427 g/cm³
Venus - 5.204 g/cm³
Earth - 5.515 g/cm³
Mars - 3.934 g/cm³
Jupiter - 1.326 g/cm³
Saturn - 0.687 g/cm³
Uranus - 1.27 g/cm³
Neptune - 1.638 g/cm³

Material densities

Iron: 7.9 g/cm³
Silicates: ~2.25-4.25 g/cm³
Carbonaceous material: ~0.8-2.3 g/cm³
Water ice: ~1.0 g/cm³

http://en.wikipedia.org/wiki/Terrestrial_planet
II. Observational constraints

I. Cosmochemical composition of planetary bodies as a function of distance to Sun

Figure 1 Comparison with theoretical models of cosmochemically derived constraints on disk midplane temperatures (CAIs, volatile depletions, FeS, water ice, and comets; see text for references). Solid lines are values of $T_m$ for three Ansatz disk models (Boss 1996a), labeled from top to bottom by the disk masses (inside 10 AU). Dashed line is $T_m$ for a viscous accretion disk model (Morfill 1988) with $\dot{M} = 10^{-5} M_\odot$/year, and a mass of 0.24 $M_\odot$ inside 10 AU.
II. Observational constraints

m. The low (?) abundance of interstellar dust in meteorites and Stardust material

<table>
<thead>
<tr>
<th>Composition</th>
<th>Diameter (μm)</th>
<th>Abundance$^a$</th>
<th>Origins$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(diamond)</td>
<td>0.002</td>
<td>$5 \times 10^{-4}$</td>
<td>SN</td>
</tr>
<tr>
<td>SiC$^c$</td>
<td>0.3–20</td>
<td>$6 \times 10^{-6}$</td>
<td>AGB</td>
</tr>
<tr>
<td>C(graphite)$^d$</td>
<td>1–20</td>
<td>$1 \times 10^{-6}$</td>
<td>AGB, SN II, nova</td>
</tr>
<tr>
<td>SiC type X</td>
<td>1–5</td>
<td>$6 \times 10^{-8}$</td>
<td>SN</td>
</tr>
<tr>
<td>Al$_2$O$_3$ (corundum)</td>
<td>0.5–3</td>
<td>$3 \times 10^{-8}$</td>
<td>RG, AGB</td>
</tr>
<tr>
<td>Si$_3$N$_4$</td>
<td>~1</td>
<td>$2 \times 10^{-9}$</td>
<td>SN II</td>
</tr>
</tbody>
</table>

$^a$Overall abundance in primitive carbonaceous chondrite meteorites.

$^b$SN = supernova; AGB = asymptotic giant branch star; RG = red giant.

$^c$SiC grains sometimes contain very small TiC inclusions.

$^d$Graphite grains sometimes contain very small TiC, ZrC, and MoC inclusions.
III.
The formation of planets and planetary systems
III. The formation of planets and planetary systems

a. The general picture
Star formation – an overview

© GEO, after Shu et al. 1987

Molecular cloud

Formation of gas-dust disk

“Clumping” of the dust

Formation of the sun by radial transport of matter

Formation of isolated planets
The five-stage process of planet formation

**Protoplanetary dust**

- **~1 μm**
- Interaction with gas important
- No gravity

**Agglomeration**

- **~1 mm**
- Interaction with gas important
- No gravity

**Planetesimals**

- **~1-100 km**
- Interaction with gas important
- Collective gravity potentially important
- Gas motion important

**Terrestrial planets**

- **~10,000 km**
- No interaction with gas
- Gravity dominates
- Escape velocity > thermal velocity
- (i.e. minimum mass ~10-15 Earth masses)
- Migration potentially important

**Gas accretion (?)**

- **~100,000 km**
- Gravity dominates

**Accretion of planetesimals**

**Gas planets**

**Migration**
### III. The formation of planets and planetary systems

#### b. Dust to planetesimals

##### i. Solar-nebula models

<table>
<thead>
<tr>
<th>Planetary zones: masses and surface densities</th>
<th>Mass ($M_\oplus$)</th>
<th>Fe mass fraction</th>
<th>Solar comp. mass ($M_\oplus$)</th>
<th>Zone limits (AU)</th>
<th>Surface density (g cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.053</td>
<td>0.62</td>
<td>27</td>
<td>0.22</td>
<td>880</td>
</tr>
<tr>
<td>Venus</td>
<td>0.815</td>
<td>0.35</td>
<td>235</td>
<td>0.56</td>
<td>4750</td>
</tr>
<tr>
<td>Earth</td>
<td>1</td>
<td>0.38</td>
<td>320</td>
<td>0.86</td>
<td>3200</td>
</tr>
<tr>
<td>Mars</td>
<td>0.107</td>
<td>0.30</td>
<td>27</td>
<td>1.26</td>
<td>95</td>
</tr>
<tr>
<td>Asteroids present</td>
<td>0.0005</td>
<td>0.25</td>
<td>0.1</td>
<td>2.0</td>
<td>0.13</td>
</tr>
<tr>
<td>Asteroids original</td>
<td>0.15?</td>
<td></td>
<td>30</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Jupiter</td>
<td>318</td>
<td></td>
<td>600–12 000</td>
<td>7.4</td>
<td>120–2400</td>
</tr>
<tr>
<td>Saturn</td>
<td>95</td>
<td></td>
<td>1000–6000</td>
<td>14.4</td>
<td>55–330</td>
</tr>
<tr>
<td>Uranus</td>
<td>14.6</td>
<td></td>
<td>700–2000</td>
<td>24.7</td>
<td>15–40</td>
</tr>
<tr>
<td>Neptune</td>
<td>17.2</td>
<td></td>
<td>800–2000</td>
<td>35.5</td>
<td>10–25</td>
</tr>
</tbody>
</table>

Weidenschilling 1977
Inferred surface densities

A power-law approximation:

\[ \Sigma_s (r) = 1700 \text{ g/cm}^2 \cdot \left( \frac{r}{1 \text{ AU}} \right)^{-3/2} \]

Fig. 1. Surface densities, \( \sigma \), obtained by restoring the planets to solar composition and spreading the resulting masses through contiguous zones surrounding their orbits. The meaning of the ‘error bars’ is discussed in the text.
III. The formation of planets and planetary systems

b. Dust to planetesimals

ii. Metallicity of the solar nebula

<table>
<thead>
<tr>
<th>Model</th>
<th>$T_c$</th>
<th>$\rho_c$</th>
<th>$P_c$</th>
<th>$Y_{\text{init}}$</th>
<th>$Z_{\text{init}}$</th>
<th>$Y_c$</th>
<th>$Z_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>15.696</td>
<td>152.7</td>
<td>2.342</td>
<td>0.2735</td>
<td>0.0188</td>
<td>0.6405</td>
<td>0.0198</td>
</tr>
<tr>
<td>NACRE</td>
<td>15.665</td>
<td>151.9</td>
<td>2.325</td>
<td>0.2739</td>
<td>0.0188</td>
<td>0.6341</td>
<td>0.0197</td>
</tr>
<tr>
<td>AS00</td>
<td>15.619</td>
<td>152.2</td>
<td>2.340</td>
<td>0.2679</td>
<td>0.0187</td>
<td>0.6341</td>
<td>0.0197</td>
</tr>
<tr>
<td>GN93</td>
<td>15.729</td>
<td>152.9</td>
<td>2.342</td>
<td>0.2748</td>
<td>0.02004</td>
<td>0.6425</td>
<td>0.02110</td>
</tr>
<tr>
<td>Pre-M.S.</td>
<td>15.725</td>
<td>152.7</td>
<td>2.339</td>
<td>0.2752</td>
<td>0.02003</td>
<td>0.6420</td>
<td>0.02109</td>
</tr>
<tr>
<td>Rotation</td>
<td>15.652</td>
<td>148.1</td>
<td>2.313</td>
<td>0.2723</td>
<td>0.01934</td>
<td>0.6199</td>
<td>0.02032</td>
</tr>
<tr>
<td>Radius$_{78}$</td>
<td>15.729</td>
<td>152.9</td>
<td>2.342</td>
<td>0.2748</td>
<td>0.02004</td>
<td>0.6425</td>
<td>0.02110</td>
</tr>
<tr>
<td>Radius$_{508}$</td>
<td>15.728</td>
<td>152.9</td>
<td>2.341</td>
<td>0.2748</td>
<td>0.02004</td>
<td>0.6425</td>
<td>0.02110</td>
</tr>
<tr>
<td>No Diffusion</td>
<td>15.448</td>
<td>148.6</td>
<td>2.304</td>
<td>0.2656</td>
<td>0.01757</td>
<td>0.6172</td>
<td>0.01757</td>
</tr>
<tr>
<td>Old Physics</td>
<td>15.787</td>
<td>154.8</td>
<td>2.378</td>
<td>0.2779</td>
<td>0.01996</td>
<td>0.6439</td>
<td>0.02102</td>
</tr>
<tr>
<td>$S_{34} = 0$</td>
<td>15.621</td>
<td>153.5</td>
<td>2.417</td>
<td>0.2722</td>
<td>0.02012</td>
<td>0.6097</td>
<td>0.02116</td>
</tr>
<tr>
<td>Mixed</td>
<td>15.189</td>
<td>90.68</td>
<td>1.728</td>
<td>0.2898</td>
<td>0.02012</td>
<td>0.3687</td>
<td>0.02047</td>
</tr>
</tbody>
</table>

NOTE.—The quantities $T_c$ (in units of $10^7$ K), $\rho_c$ ($10^2$ g cm$^{-3}$), and $P_c$ ($10^{17}$ ergs cm$^{-3}$) are the present-epoch central temperature, density, and pressure; $Y$ and $Z$ are the helium and heavy-element mass fractions, where the subscript "init" denotes the zero-age main-sequence model and the subscript "c" denotes the center of the solar model.
III. The formation of planets and planetary systems

b. Dust to planetesimals

iii. Condensation sequence: temporal or spatial (or both)?

- Formation of an accretion disk.
- The disk is initially hot → few dust grains.
- As the disk cools down, dust particles condense.
- Dust materials: oxides, silicates, organics, ices.
- Particle sizes: sub-µm - µm.

© NASA, after Shu et al. 1987
<table>
<thead>
<tr>
<th>$T$</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1680 K</td>
<td>$\text{Al}_2\text{O}_3$</td>
</tr>
<tr>
<td>1590 K</td>
<td>$\text{CaTiO}_3$</td>
</tr>
<tr>
<td>1400 K</td>
<td>$\text{MgAl}_2\text{O}_4$</td>
</tr>
<tr>
<td>1350 K</td>
<td>$\text{Mg}_2\text{SiO}_4$, iron alloys</td>
</tr>
<tr>
<td>370 K</td>
<td>$\text{Fe}_3\text{O}_4$</td>
</tr>
<tr>
<td>180 K</td>
<td>water ice</td>
</tr>
<tr>
<td>130 K</td>
<td>$\text{NH}_3 \cdot \text{H}_2\text{O}$</td>
</tr>
<tr>
<td>40 K – 80 K</td>
<td>methane, methane ices</td>
</tr>
<tr>
<td>50 K</td>
<td>argon</td>
</tr>
</tbody>
</table>

Scott 2007
III. The formation of planets and planetary systems

b. Dust to planetesimals

   iv. Dust-aggregate velocities in the solar nebula

- Brownian motion (Weidenschilling 1984)

- Vertical sedimentation, radial drift, azimuthal velocity differences (Weidenschilling 1984)

- Gas turbulence (magneto-rotational instability or self-induced) (Balbus & Hawley 1991; Johansen et al. 2006; Weidenschilling 1980; Sekiya 1998)
Motion of protoplanetary dust

- HH 30
- Protoplanetary disk
- Brownian motion
- Drift motions
- Gas turbulence
- Dust subdisk

+ Global transport processes by, e.g., accretion, turbulence, X-wind, photophoresis, …
Weidenschilling 1977
\[ \Sigma_s(r) = 1700 \text{ g/cm}^2 \cdot \left( \frac{r}{1 \text{ AU}} \right)^{-3/2} \]
Critical velocity of 1 m/s reached for 5-cm particles

Andrews & Williams 2007
\[ \Sigma_s(r) = 20 \text{ g/cm}^2 \cdot \left( \frac{r}{1 \text{ AU}} \right)^{-0.8} \]
Critical velocity of 1 m/s reached for 4-mm particles

Desch 2007
\[ \Sigma_s(r) = 50500 \text{ g/cm}^2 \cdot \left( \frac{r}{1 \text{ AU}} \right)^{-2.17} \]
Critical velocity of 1 m/s reached for >1-m particles
III. The formation of planets and planetary systems

b. Dust to planetesimals

v. Collisional dust growth
What happens in a collision between two dust particles/aggregates?

Adhesion force (van der Waals force)

Threshold velocity for sticking

Restructuring

Heim et al. 1999

Poppe et al. 2000

Heim et al. 2005
The importance of the threshold velocity for sticking

- $v_{SG} \approx v_{FR}$
- $v_{SG}$: threshold velocity for single-grain sticking
- $v_{FR}$: threshold velocity for dust-aggregate fragmentation.

The threshold velocity for dust sticking is dependent on the monomer size.

---

Single-grain collisions

Dust-aggregate collisions

- Poppe et al. 2000
- Blum & Wurm 2008
How does dust agglomeration start?
The initial growth phase

Start with monomers at $t_0 = 0$

Observe aggregate mass (distribution) and structure at $t > t_0$

Relative velocities due to Brownian motion, drift, gas turbulence
Consider the simplest cases

<table>
<thead>
<tr>
<th>BPCA</th>
<th>BCCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballistic Particle-Cluster Agglomeration</td>
<td>Ballistic Cluster-Cluster Agglomeration</td>
</tr>
<tr>
<td>( \downarrow )</td>
<td>( \downarrow )</td>
</tr>
<tr>
<td>ballistic hit-and-stick impacts of single dust particles into growing dust agglomerate</td>
<td>ballistic hit-and-stick collisions between equal-mass dust agglomerates</td>
</tr>
</tbody>
</table>

\[ i = 1,024 \]
BPCA
N=2
BPCA
N=4
BPCA
\[ N=8 \]
BPCA
N=16
BPCA
\[ N = 32 \]
BPCA
N=128
BPCA
N=256
BCCA
\[ N=2 \]
BCCA
\[N=4\]
BCCA
\[ N = 8 \]
BCCA
$N=64$
BCCA
N=128
BCCA

N=256
BCCA
$N=1024$
Consider the simplest cases

<table>
<thead>
<tr>
<th>BPCA</th>
<th>BCCA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballistic Particle-Cluster Agglomeration</td>
<td>Ballistic Cluster-Cluster Agglomeration</td>
</tr>
<tr>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>ballistic hit-and-stick impacts of single dust particles into growing dust agglomerate</td>
<td>ballistic hit-and-stick collisions between equal-mass dust agglomerates</td>
</tr>
</tbody>
</table>

$i = 1,024$

![Diagram showing agglomerates]
The initial growth phase

- Gas turbulence
  - Wurm & Blum 1998
  - $\varnothing 1.9 \mu m \text{SiO}_2$

- Differential sedimentation
  - Blum et al. 1998
  - $\varnothing 1.9 \mu m \text{SiO}_2$

- Brownian motion
  - Blum et al. 2000
  - $\varnothing 1.9 \mu m \text{SiO}_2$

Blum et al. 2000

Brownian motion

Blum et al. 1998
The initial growth phase

growth timescale determined by collision timescale

hit-and-stick collisions

monodispersity

fractality
The initial growth phase

- Hit-and-stick collisions
- Mass-size relation \( m \propto s^D \) with \( D \leq 2 \) (fractal aggregates)
- Narrow (quasi-monodisperse) mass spectra
- Temporal mass growth follows a power law

\[
\frac{\bar{m}(t)}{m_0} = \left[ (1 - \gamma) \left( a \frac{t}{\tau} + c \right) \right]^{1/1-\gamma}
\]

Krause & Blum 2004
The initial growth phase

- “Minimum Mass Solar Nebula” model
- Hit-and-stick collisions
- Brownian motion + turbulence
- $t = 0 \ldots 30 \text{ yrs}$
The restructuring/compaction growth regime

Low impact energy: hit-and-stick collisions

- Collisions result in sticking.

Intermediate impact energy: compaction

- Impact energy exceeds energy to overcome rolling friction (Dominik and Tielens 1997; Wada et al. 2007).
- Dust aggregates become non-fractal (?) but are still highly porous.
Overview of possible collisional outcomes

S1 (hit & stick)

S2 (sticking through surface effects)

S3 (sticking by penetration)

S4 (mass transfer)

B1 (bouncing with compaction)

B2 (bouncing with mass transfer)

F1 (fragmentation)

F2 (erosion)

F3 (fragmentation with mass transfer)

Güttler et al., 2010
A simplified collision model for dust aggregates

Güttler et al., 2010
The Full Collision Model

Güttler et al., 2010
The current model has a binary nature.

No smooth transition in porosity and mass ratio.

Critical mass ratio of $r_m = 100$.

Critical porosity of $\phi_c = 0.4$.

Güttler et al., 2010
An experiment to determine the sticking threshold for dust aggregates

- Microgravity experiment (drop tower, suborbital flight)
- Particle diameter: 0.5-1.5 mm
- Initial velocity ~0.1 m/s
- Collisional cooling down to mm/s
Example: bouncing collision

Bouncing collision

$v = 12 \text{ mm/s}$

Dust-aggregate size: 0.5-1.5 mm

Particle diameter: 1 mm
Filling factor: 40%

47 analyzed collisions:
- 6x sticking
- 40x bouncing
- 1x fragmentation

Weidling et al. 2011
Example: sticking collision

Sticking collision

\( v = 9 \text{ mm/s} \)

Dust-aggregate size: 0.5-1.5 mm

- particle diameter: 1 mm
- filling factor: 40%

47 analyzed collisions:
- 6x sticking
- 40x bouncing
- 1x fragmentation

Weidling et al. 2011
Example: multiple sticking collisions

\[ v = 1-10 \text{ cm/s}; \text{ dust-aggregate size: } 180 \, \mu\text{m} \]
The Braunschweig laboratory drop tower

- Laboratory drop tower
- Two aggregates collide in free fall
- Two falling cameras, 1.5 m drop height
- Velocities from 1 cm/s to 3 m/s

Beitz et al. 2011
Low-velocity collisions between large dust aggregates

2 cm diameter, 50% filling factor, velocity: 10 mm/s

2 cm diameter, 50% filling factor, velocity: 1.8 m/s
Dust-aggregate fragmentation in moderate-velocity collisions

- **Bouncing** for $v < 20$ cm/s
- **Fragmentation** with mass transfer for $v > 20$ cm/s

Beitz et al. 2011
Accretion efficiency in moderate-velocity dust-aggregate collisions

Beitz et al. 2011
Accretion efficiency in moderate-velocity dust-aggregate collisions

- **Projectiles:** approx. 1mm, RBD aggregates, partly pre-fragmented
- **Target:** sintered SiO$_2$, filling factor 0.45
- **Velocities:** 2-6 m/s
Accretion efficiency in moderate-velocity dust-aggregate collisions

Kothe et al. 2010
A recent update of the collision model laboratory drop tower

MEDEA experiment (large aggregates)

MEDEA experiment (small aggregates)
A recent update of the collision model
Numerical simulations of aggregate growth in PPDs using the Monte-Carlo method - Mass-porosity evolution

Dust growth in the MMSN model

A. Zsom, C.W. Ormel, C. Guettler, J. Blum, C.P. Dullemond

Zsom et al. 2010
Numerical simulations of aggregate growth in PPDs using the Monte-Carlo method - Results for the mass evolution

Zsom et al. 2010
Numerical simulations of aggregate growth in PPDs using the Monte-Carlo method - Results for the porosity evolution

- 97.5% porosity
- 90% porosity
- 85% porosity (lab experiments)

Zsom et al. 2010
Lessons learned

1. Growth stops due to bouncing → “bouncing barrier”
2. Mass distribution stays narrow
3. Compaction in bouncing collisions is of eminent importance; final porosity “only” ~60-70%
4. Fragmentation regime is only reached for highest turbulence but does not invoke a new growth mode
Where are we in terms of completeness?

- Sizes of protoplanetary dust aggregates:
  - 1 µm
  - 1 mm
  - 1 m
  - 1 km

- Mass ratios of projectile and target:
  - 0
  - 1

- Collision velocities of protoplanetary dust aggregates:
  - $10^{-4}$ m/s
  - $10^{-2}$ m/s
  - 1 m/s
  - 100 m/s

- Porosities of protoplanetary dust aggregates:
  - compact
  - porous
  - very porous

- Protoplanetary dust materials and temperatures:
  - oxides/metals: >1000 K
  - silicates: ~300 K
  - organics: ~200 K
  - ices: ~100 K

- no expt’s
- expt’s
Can there be any collisional growth beyond the “bouncing barrier”?

Windmark et al., pers. comm.
III. The formation of planets and planetary systems

b. Dust to planetesimals

vi. Gravitational instability models

Johansen et al. 2007
Capture of macroscopic particles by long-living gas vortices

- Trapping of solid objects in pressure maxima and/or in anticyclonic vortices.
- Basically all solid bodies with sizes $0.1 - 10 \, \text{m}$ are efficiently captured.
- No escape of dust with sizes $0.1 - 1000 \, \text{m}$ from vortices.
- Low relative velocities within the vortices $\Rightarrow$ collisional growth?
- No shear inside vortices.
- Concentration of the dust particles in the centers of the vortices $\Rightarrow$ gravitational instability?

© H. Klahr (MPIA Heidelberg)

$\Delta$: 1m dust particle
Gravitational instability

- In absence of turbulence, >cm-sized dust aggregates sediment towards the midplane of the protoplanetary disk.
- When the dust density exceeds the gas density, the gas in the midplane is forced to rotate at Keplerian velocity. Due to the shearing between the midplane rotation and the layers above/below the midplane, a Kelvin-Helmholtz instability forms.
- Due to a local variation of the dust-to-gas ratio and, thus, the rotation speed, a streaming instability occurs.
- Gravitationally-bound dust ensembles are formed when the dust size exceeds ~0.1 m.
- Direct formation of planetesimals with sizes up to 100-1,000 km, if fragmentation is negligible.
- However, if collisions results in fragmentation, no net growth occurs (Johansen et al. 2008).
III. The formation of planets and planetary systems

c. Planetesimals to planets

http://www.phys.boun.edu.tr/~semiz/universe/near/18.html#pix
Accretion of planetesimals

- Gas friction is negligible
- Typical collision velocity < escape velocity
  - Gravitational sticking
  - Collision probability increased due to gravitational focussing → large bodies grow faster than small bodies

\[ F_g = \sqrt{1 + \frac{v_e^2}{v_r^2}} \]

Focussing factor
Escape velocity
Relative velocity at infinity
Formation timescales of terrestrial planets

<table>
<thead>
<tr>
<th>Time$ (yr)</th>
<th>Size</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$10^{-6}$ m</td>
<td>Condensation of dust particles</td>
</tr>
<tr>
<td>$\sim 10^3$-$10^4$</td>
<td>0.1 m</td>
<td>Agglomeration with high sticking probability</td>
</tr>
<tr>
<td>? ($&lt; 10^7$)$^\S$</td>
<td>10 km</td>
<td>Planetesimals with mass $m_0$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time$^# (yr)</th>
<th>Mass</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sim 10^3$</td>
<td>$30 \ m_0$</td>
<td></td>
</tr>
<tr>
<td>$\sim 7\times10^3$</td>
<td>$10^5 \ m_0$</td>
<td></td>
</tr>
<tr>
<td>$\sim 2\times10^4$</td>
<td>$10^6 \ m_0$</td>
<td></td>
</tr>
<tr>
<td>$\sim 6\times10^4$</td>
<td>$10^7 \ m_0$</td>
<td></td>
</tr>
<tr>
<td>$\sim 10^5$</td>
<td>$10^{7.5} \ m_0; 0.01-0.1 \ M_E$</td>
<td>Planetary embryos (isolated)</td>
</tr>
<tr>
<td>$\sim 10^6-7$</td>
<td>$0.1-0.5 \ M_E$</td>
<td>Protoplanets (+ embryos; embryos are slowly consumed)</td>
</tr>
<tr>
<td>$\sim 10^7-8$</td>
<td>$1 \ M_E$</td>
<td>Planets on isolated orbits</td>
</tr>
</tbody>
</table>

$^\S$ Since the formation of the sun
$^\S$ Dispersion of the nebula after $\sim 10^7$ years
$^\#$ Since the formation of planetesimals
Making terrestrial planets

Raymond et al. 2004
Making terrestrial planets

Giant planets as today

Chambers 2001

Giant planets in “compact” configuration

Walsh et al. 2011
Overview of the formation of terrestrial planets

- **$10^4$ km**
- **10 km**
- **1 cm**
- **1 µm**

- **ACCRETION** (Gravitation)
- **GRAVITATIONAL INSTABILITY** (of an ensembles of dust aggregates)
- **AGGLOMERATION** (van der Waals force)
III. The formation of planets and planetary systems

d. Gas accretion

The formation of gas planets

Two hypotheses for the formation of the planets Jupiter, Saturn, Uranus and Neptune:

1. **Gravitational instability** (Boss 2001; 2003; 2007)
   - Pro: fast process.
   - Con: unclear whether the process is feasible (problems with radiation transport); “Brown Dwarf Desert”.

2. **Formation of a 10-15 $M_\oplus$ solid core; gravitational accretion of gas**
   (Pollack et al. 1996; Klahr & Bodenheimer 2006; Klahr & Kley 2006)
   - Pro: gas accretion on solid core well understood and fast (within ~300,000 yrs).
   - Con: formation of a 10-15 $M_\oplus$ terrestrial planet within $< 10^7$ yrs difficult; possible if (1) long-living eddies exist in the gas, which can efficiently trap m-sized bodies (in this case, no need for stages 2-3) or (2) if the mass density is sufficiently high.
Tests of the formation hypotheses of gas planets:

→ Do extrasolar planets possess a core with more than ~2% of the planetary mass? (→ solar metallicity ~2%)

→ Simultaneous measurement of mass and radius of extrasolar planets.

Torres et al. 2008
Reminder: masses and sizes of extrasolar planets
Prediction model 1: core mass / total mass $\sim 0.02$.
Prediction model 2: core mass $\geq 10$-$20$ earth masses.

Charbonneau et al. 2007

Tests of the formation hypotheses of gas planets

Core masses of extrasolar planets

HD 149026 b
Saturn
Jupiter
HD 209458 b

molecular hydrogen and helium
liquid metallic hydrogen
heavy element core
Core masses of extrasolar planets

Model 2

Torres et al. 2008

Model 1

Santos et al. 2005

Planetary metal content ($M_{\text{Earth}}$) vs Stellar metallicity [Fe/H]

Frequency of planets (%) vs Amount of iron relative to the Sun
The formation of gas planets within $10^6$-10$^7$ yrs

Desch 2007: modified model of solar nebula, based on Nice model

Klahr & Bodenheimer 2006: particle shearing within turbulence eddies
The formation of gas planets within $10^6$-$10^7$ yrs
The formation of gas planets within $10^6$-$10^7$ yrs
Has the formation of a gas planet been (indirectly) observed *in statu nascendi*?
III. The formation of planets and planetary systems

e. Dynamical interaction and re-arrangement of planets

http://www.maths.qmul.ac.uk/~masset/moviesmpeg.html
Planet migration und reorganization

Excitation of spiral density waves in the gas by the planet; torque anisotropy between inner and outer disk; in most cases, the influence of the outer spiral wave dominates so that the planet loses angular momentum and spirals radially inward. Stop of migration by (a) clearing of the nebula or (b) tidal friction with the central star.
The *Nice* model for the dynamical evolution of the giant planets of the solar system

Left: before the 2:1 Jupiter-Saturn resonance, center: scattering of Kuiper-belt objects due to radial motion of Neptune, right: after scattering of the Kuiper-belt objects by Jupiter
http://www.obs-nice.fr/morby/LHB/LHBxy.AVI
The *Nice* model for the dynamical evolution of the giant planets of the solar system

Without planetesimal disk

With planetesimal disk

Morbidelli et al. 2007

Gomes et al. 2005
The *Nice* model for the dynamical evolution of the giant planets of the solar system

Desch 2007
(Prediction of the core masses of the giant planets; modified solar-nebula model, based upon Nice model)
III. The formation of planets and planetary systems

f. The late heavy bombardment
III. The formation of planets and planetary systems

g. Exchange of Oort cloud objects in young star clusters

Levison et al. 2010
Conclusions

Dauphas & Chaussidon 2011

- Dust (0.1-10 μm)
  - Gas condensation, inheritance from ISM

- Dust agglomerate (<1 m)
  - Fractal agglomeration, compaction

- Planetesimal (1-1,000 km)
  - Collisional growth, gravitational instability

- Embryo (1,000-5,000 km)
  - Orderly, runaway, and oligarchic growths

- Planet (10,000 km)
  - Chaotic growth
Conclusions

The five-stage process of planet formation

Protoplanetary dust

~1 µm

interaction with gas important
no gravity

Agglomeration

~1 mm

interaction with gas important
cumulative gravity potentially important
gas motion important

Planetesimals

~1-100 km

Terrestrial planets

~10,000 km

gas accretion (?)

gravity dominates
escape velocity > thermal velocity
(i.e. minimum mass ~10-15 Earth masses)
migration potentially important

Accretion of planetesimals

no interaction with gas
gravity dominates

Gas planets

~100,000 km

Migration
Conclusions

The five-stage process of planet formation has the potential to explain/fulfil:

• The architecture of the Solar System ✓
• The architecture of other planetary systems ✓
• The gaseous-disk lifetime constraint ✓
• The existence and formation scenario of the Moon ✓
• Meteoritic constraints ✓
• The late heavy bombardment ✓
• The existence of debris disks ✓
• The stability of the Solar System over 5 Gyrs (?)
THANK YOU FOR YOUR ATTENTION!