Planet Formation

Nebula Hypothesis: Kant (1755) - Laplace (1796)

Planets formed from a flat nebula

(Laplace: Matter thrown off the Sun after it had condensed in its current state)

Nebular Hypothesis was revived by von Weizsäcker (1944) and Kuiper (1951): Planets in the Solar System formed from a slowly rotating cloud of dust and gas.

Quantitative Description for terrestrial planets:

Victor Safronov (1969): "Evolution of the Protoplanetary Cloud and Formation of the Earths and the Planets"

Today

Gas-rich protoplanetary disks ($\tau \sim 3$ Myr)

Gas-poor debris disks (late stages of planet formation)

Observational Constraints:

a) Solar System

- Temporal and cosmochemical evolution
- Distribution of mass and angular momentum (concept of minimum mass solar nebula)
- Core masses of Jupiter & Saturn
  15-20 $M_\oplus$ for Saturn; 7-20 $M_\oplus$ for Jupiter
- Co-planar orbits; circular; same direction
- Distribution of minor bodies (asteroid belt, Kuiper belt)
- Small mass of Mars relative to Earth & Venus

b) Extrasolar Planets

Large diversity of planetary systems and exoplanet properties (biases of different detection techniques)

- Hot Jupiters & Neptunes (migration / interaction)
- High frequency of Super-Earths / Mini-Neptunes
- Massive Jupiters around A-type Stars
- Planets on eccentric orbits
- Planet pairs locked into dynamical mean-motion resonances (Early diff. migration via planet-disk interactions)
- Planets on retrograde and inclined orbits (dynamical interaction)
- Planets in binaries
- Strong correlation of stellar metallicity with gas giant formation

Two scenarios

a) Core accretion - gas capture theory

(Safronov 1969, Mizuno 1980, Lissauer, Wetherill, Weidenschilling, Kenyon, ...)

b) Gravitational instability theory

(Kuiper 1951, Cameron 1962, Boss, Durisen, ...)

Gravitational instability theory

Remember Jeans criterion:

Density fluctuations in isothermal medium become unstable if it's λ fullfills $\lambda^2 > \pi c_s^2 / G\rho$

Safronov (1960) and Toomre (1964) retrieved the Jeans condition in a flat disk, including diff. rotation, gravity, and pressure effects.

$$Q = (c_s \kappa / \pi G \sigma) < 1 \quad \text{(instability)}$$

[local instability to axisymmetric perturbations]

General idea for early calculations

Spherically symmetric condensations of approximately Jovian mass and solar composition formed.

→ Calculations involved the solution of the standard equations of stellar structure including radiative and convective energy transport and grain opacities: Contraction timescales depend on grain opacities ($\sim 10^6$ yr)

If $T > 2000K$ is reached → Hydrodynamic collapse on a timescale of 1 yr

- Boss (1998) indicated that a protoplanet of $1 M_J$ could indeed form a core of a few $M_\oplus$ in line with estimates of the core mass of Jupiter
- Only recently full numerical simulations of gravitational instability in disks with necessary spatial resolution → mostly massive disks needed

<u>Other issues</u>

a) Disk must not only be gravit. unstable, but it must be able to cool efficiently ($\tau_{cool} < 3\,\Omega_K^{-1}$ - Gammie 2001)

b) Giant gaseous protoplanets would be formed in short timescales of about 1000 yrs

c) Gas giants with ~10 Jupiter masses at 100 AU could be formed; challenge is rapid mass transport inwards by spiral arms

d) No natural explanation for metallicity - giant planet frequency relation because star determines radiative losses

Core accretion - gas capture theory

Formation of a swarm of planetesimals and accretion on a planetary embryo in a certain feeding zone (Safronov 1969)

Other assumptions

Total material budget in planet-forming zone was conserved and converted into the final planet mass:

Concept of "Minimum mass solar nebula"

(The solid-surface density just sufficient to correspond to the solid mass of final planets)

growth time for Earth: $100 \cdot 10^6$ yrs for Earth (consistent with estimates for growth time for Earth)

Wetherill (1980):

~ 100 lower-mass objects with large spread over the terrestrial planet zone → same timescale with approximately the correct number of objects

(→ Mars problem: too low mass compared to Earth & Venus)

Core accretion scenario (modern concept)

a) Dust particles grow to meter-sized bodies.

I: μm-sized grains grow through mutual collisions to fluffy fractal-type aggregates ($m \sim D^{1.9}$)

Relative velocities: Brownian motion, radial drift, sedimentation, turbulence)

II: cm-sized grains reach collis. velocities of 10 m/s which leads to compaction and fragmentation

b) Meter-sized bodies decouple from gas and would migrate in 100 yrs

- Reduction of migration speed in turbulent flow with pressure bumps
- gravitational instability in dust sublayer forms planetesimals (~10 km - 100 km)

c) Runaway growth

Planetary embryos form by gravitational "clearing" of the planetesimal feeding zone.

Additional important factor in cross section

$$\pi b^2 = \pi r^2 \left(1 + v_{esc}^2 / \sigma^2\right)$$

v_{esc} - escape velocity ; σ - relative velocities

$$\frac{dm}{dt} = \rho_{planet} \cdot \sigma \pi b^2 \approx \Sigma_{planet} \cdot \Omega \, \pi r^2 \left(1 + v_{esc}^2 / \sigma^2\right)$$

$$H_p = \sigma / \Omega \qquad \rho_{planet} = \Sigma_{planet} / H_p = \frac{\Sigma_{plan} \cdot \Omega}{\sigma}$$

Θ - v_{escp}^2 / σ^2 - Safronov factor

At the beginning of the process σ small and $\Theta >> 1$

$$\frac{dm}{dt} \simeq \Sigma_{\text{planet}}\, \Omega\, \pi r^2\, \Theta = \Sigma_{\text{planet}} \cdot \pi\, \Omega\, r\, \frac{4GM}{\sigma^2}$$

and $r \sim m^{1/3}$

$$\boxed{\frac{dm}{dt} \sim m^{4/3}}$$

m(t) diverges to infinity with time; formation of planetary embryos in feeding zone which dominate velocity dispersion: "oligarchs"

d) Self-regulated growth

Runaway ends when core (oligarch) dominates velocity dispersion and material in Hill sphere is depleted ($r_H = a\,(m/3M_*)^{1/3}$)

Maximum mass of a single body that has consumed all of the planetesimals in its Hill sphere → Isolation mass

$$M_{iso} \sim \Sigma_{\text{planet.}}^{3/2}\ M_*^{-1/2}\ a^3$$

$a = 1\,\text{AU}$ $\Sigma_p = 10\,\text{g/cm}^2$ → $\sim 0.1\,M_\oplus$

$a = 25\,\text{AU}$ → $9\,M_\oplus$

Isolation mass played role for terrestrial planets

For giant planets may or may not have played a role depending on disk model

e) Grav. scattering and random collisions lead to the formation of terrestrial planets with timescales 10 - 100 Myr

Giant planet formation

- Mizuno (1980) found that for a critical mass of about 10 $M_\oplus$ there is no hydrostatic equilibrium (Full calculation by Bodenheimer & Pollack 1986)

- Final mass determined by gas reservoir and how fast gas can be accreted

Phases

a) Core formation (~1 Myr)

b) Hydrostatic growth (slow accretion of gas) (~10 Myr)

c) Rapid growth when critical core mass is reached and $M_{env} \geq M_{core}$; rate of accretion accelerates dramatically

d) Gas accretion reaches limiting value; equilibrium region of protoplanet contracts inside the effective accretion radius

e) Accretion stops → Planet enters isolation stage and contracts / cools at constant mass to its present stage

Challenges

a) One has to produce relatively massive core

b) There must still be enough gas in the disk

c) Migration into the central star

Modifications

a) Reduced opacities reduces formation timescale and one can form Jupiter with a lower mass core in the disk lifetime

b) Reducing planetesimal accretion allows earlier runaway envelope

Planet Migration

Type I: Acts on small planets which excite
density waves at Linblad resonances
waves interior to planet: positive torques
waves exterior to planet: negative torques

Sum of torques is negative → inward migration

0.2 Myr for 1 MEarth at 5 AU

(Same torques also ~~dope~~ damp eccentricity)

No significant perturbations of density profile

Type II: More massive planets open a gap:

(Linearity breaks down when $M_{pl} / M_* > (H/r)^3$
$\Rightarrow \sim 30\ M_{Earth}$)

Gap structure depends on M_{pl}, α, disk structure

Planet is locked to ~~d~~ disk evolution (viscous evol.)

Type III: Runaway migration associated with co-orbital torques

Lindblad resonances correspond to locations in the disk where the perturbing potential's frequency in the matter frame matches the epicyclic frequency

$$\omega(r) = m|\Omega_p - \Omega(r)| = \pm \kappa(r)$$

Giant Impacts

- Very late in the formation of solar system, collisions between big protoplanets/embryo's can take place leading to giant impacts

a) Earth-Moon system

- Moon/Planet mass ratio bigger than for other satellite/planet configurations
- Low density of Moon → shattered Earth crust
- Impact of Mars-sized body required

b) Rotational axis of Uranus

- knocked over by impact?

c) Chem. composition of Mercury

- High density, hardly any rock mantle
- Giant impact removed the mantle?

Debris disks

- After ~10 Myr most gas-rich protoplanetary disks are gone
  (Removal processes)
- Dust grains could be removed from the system by radiation pressure and drag (Poynting-Robertson)
- Tiny, but measurable mass of solids detected ("Vega-like" stars)
  Example: β Pic → carries also a planet

In this phase: Orbits planar and circular
Accretion and ejection of remaining planetesimals;
Belt structures in debris disks