The Formation of Planets: Theory

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Outline

1. “Nebula hypothesis”
2. Giant planet interiors
3. Formation of planetesimals
4. Growth of planets
5. Gas accumulation theory
6. Formation of extrasolar planets
7. Summary

”Nebula Hypothesis”

- 4 giant planets: 99.5% of angular momentum, 0.13% of mass
- Kant (1755) explained distributions by “nebula hypothesis“
  - Star and planets formed concurrently
  - Centrifugally-supported flattened disk
  - Pressure-supported center

”Nebula Hypothesis”

- Theoretical models and observations support basic idea
  - Start with collapse of rotating molecular cloud
  - Show angular momentum transfer outward by turbulent viscosity
  - Mass and angular momentum separate via accretion onto protostar
  - Models give reasonable conditions of nebulae from which systems form

Giant Planet Interiors

- Knowledge of giant planet formation from 2 sources
    1. Numerical models
    2. Constraints from planet interiors
- Basic structure
    - Dense core
    - Surrounding envelope (H, He, some metals)
- Flux emitted $\gg$ flux received from Sun (except Uranus)
    - Inner $T =$ few $\times 10^3$K $\Rightarrow$ envelopes are fluid
    - Mostly convective (magnetic field implies this too)
    - Probably true for Uranus also

Giant Planet Interiors

- Uranus and Neptune structure
  - “Rock” core: mixture including ^{56}Fe
  - “Ice” layer: H_20, CH_4, NH_3
  - H and He envelope, enriched with metals
  - Uranus more centrally condensed
- Jupiter and Saturn structure
  - Ice or rock core
  - Inner envelope: metallic H and He
  - Outer envelope: H_2, He
- C/H ratio steadily increases from Jupiter to Neptune

Formation of Planetesimals

- Rotating molecular cloud has too much angular momentum to collapse to a star
  - Material forms a rotationally-supported disk
  - Disk and star have same composition
  - Particles combine inelastically and settle to disk
- Negative pressure gradient → gas rotates at sub-Keplerian velocity
  - Small particles rotate with gas
  - Large particles rotate at Keplerian velocity
  - Medium-sized particles rotate at intermediate rate

Formation of Planetesimals

- Gas creates headwind for relatively large particles
  - Removes angular momentum → inward drift
  - Smaller particles drift less: weak headwind
  - Larger particles drift less: greater mass/surface area ratio
- Orbital decay times can be short
  - ~ 100 years for meter-sized particles at 1 AU from Sun
  - Large radial velocities ⇒ frequent collisions
    - Particles may grow quickly and experience only small radial drift
    - Particles may be lost from disk

Formation of Planetesimals

- Particles of size $\gtrsim 1$ km are relatively “safe” from radial drift
  - Growth to kilometer-sized objects from gravitational instabilities or accretion.
  - Planetesimals reasonably safe from loss until some grow into planetary-sized objects

Growth of Planets

- Planetesimal Keplerian orbits perturbed by gravitational interactions and physical collisions
    - Leads to planetesimal accretion (or fragmentation)
    - Gravitational encounters raise random velocities to escape speed
- If $v_{\rm random} \ll v_{\rm escape}$, planetary embryos grow rapidly
    - Size distribution becomes skewed
    - Accretes most planetesimals in gravitational reach, then ends

Growth of Planets

- Eccentricities of embryos in inner solar system exacerbated by gravitational perturbations
  - Collision of embryos → terrestrial planets
  - timescale in outer solar system > lifetime of disk
- Unless eccentricities are damped, embryos will eject each other from orbit
  - ⇒ runaway growth + migration → outer planets could become massive enough to accrete a lot of gas

Gas Accumulation Theory

- Key problem in planet formation: disks only weakly self-gravitating
  - Supported only by centrifugal force and pressure gradient
  - Any object with density below Roche limit is torn apart
  - nebula densities $\ll$ Roche densities
  - Need to compress mass M within tidal radius R_{T}, where $R_{\mathrm{T}} = a(\frac{M}{3M_{\mathrm{star}}})^{1/3}$, $a =$ orbital distance
- Need local self-gravity enhancement
  - disk instability
  - nucleated instability (large dense core)

Gas Accumulation Theory

- Disk instability may lead to strong density perturbation
  - However, most preplanetary nebulae are stable
    - Disks with low mass
    - Disks with high mass: transfer of disk mass to protostar
  - Moderate mass disk may develop instability
    - Perturbations → clumps
    - Clump could become protoplanet if stable

Gas Accumulation Theory

- Issue of disk instability: formation of core
  - metals present only initially collect in core
  - metals added later collect in envelope
- Models somewhat inconsistent with solar system
  - Saturn would have little or no core
  - Jupiter would have bigger core than Saturn
  - Both would be metal-poor
- Disk instabilities may be possible in other scenarios

Gas Accumulation Theory

- Nucleated instability: accretion onto solid core
- Model from Pollack et al. (1996): concurrent accretion of solids and gas
  - 3 Major components of model calculations
    1. 3 body accretion rate (star, protoplanet, planetesimal)
    2. Stellar evolution code for planet's gaseous envelope
    3. Gas accretion rate
  - Gas and planetesimal accretion rates calculated self-consistently

Gas Accumulation Theory

- Assumptions of Pollack model
  1. Planet is spherically symmetric
  2. Quasihydrostatic
  3. Opacity calculated for solar abundances
  4. Equation of state of envelope is for a solar mixture
  5. No competing protoplanets
  6. Planetesimals well-mixed around protoplanet
- Assumptions not necessarily valid
  - No better assumptions exist
  - Needed for reasonable numerical model

Gas Accumulation Theory

- Calculation parameters in model
  - Fit properties of Jovian planets
  - Fit to observations of disks around young stars
- 3 main phases of accretion of Jupiter and Saturn
  1. Planetesimal accretion rate rapidly increases due to runaway accretion, then decreases due to depletion
  2. Both solid and gas rates are small and constant
  3. Runaway gas accretion when $M_{\text{solid}} \approx M_{\text{gas}}$
- Evolutionary timescale determined by phase 2
  - Accretion of Uranus and Neptune ended in phase 2

Gas Accumulation Theory

- Hydrostatic models assume subsonic gas accretion with little energy dissipation
  - Need to check if hydrostatic equilibrium holds
- First calculation: envelope pulsates after short contraction phase
  - Resulted in mass loss from envelope to nebula (pulsation driven wind)
  - After large fraction of envelope ejected, pulsations end
  - equilibrium state similar to Uranus and Neptune

Formation of Extrasolar Planets

- > 100 extrasolar planets discovered
  - All giant gas planets $\gtrsim M_{\mathrm{Saturn}}$
  - Some orbit very close to star (selection effect)
  - Some have very eccentric orbit (close encounter with other planets)
- Findings challenge prior theoretical models
  - Giant planets form farther from star
  - Low eccentricity

Formation of Extrasolar Planets

- Updated Pollack et al. code can produce planets closer to stars
  - New but physically reasonable parameters
  - Does not apply for planets very close to stars
- Previous models assumed no migration
  - Planets may have formed elsewhere and moved inward
  - Disk-induced inward migration
  - Gravitational encounters

Summary

- Planet structure and composition constrain formation theories
- Molecular cloud collapse begets star and preplanetary disk
- Planets probably grow by one of two mechanisms
    1. Disk instability
    2. nucleated instability
- Extrasolar planet eccentricities and proximities to stars challenge formation theories
- Nucleated instability possible formation planets for both giant planets in our solar system and others