The Formation and (orbital) Evolution of Exoplanets

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• The Solar System
  - Characteristics
  - Formation
• Extrasolar Planets
  - Orbital parameter
  - Planet disk interaction
  - Dynamical evolution
• Summary
8 planets: **coplanar, circular, uniform orbits** (cf. Kepler candidates)
Historic View:
(Leukippos, 480-420 BC)
“The worlds form in such a way, that the bodies sink into the empty space and connect to each other.”

Modern View:
Collaps of an interstellar Molecular Cloud
Slight rotation ⇒ Flattening
Protosun in center / disk formation
(based on Kant & Laplace, 1750s)

Planets form in protoplanetary disks
≡ Accretion Disks (99% Gas, 1% Dust)
⇒ Flat system, uniform rotation, circular orbits
Accretion disk Structure

3D Magneto-hydrodynamical Turbulence with Radiation Transport in Accretion disks: Stratified Local Shearing Box, (Movie: 6 Orbits) Modeling-Tool: 3D-MHD - Finite Volume Method (Grid: $64 \times 128 \times 512$)

Outcome:
- Saturation level
- Transport efficiency
- Vertical disk structure
- Surface temperature
- Dust particle motion

(Markus Flaig, Tübingen)
Planet Formation

Two main scenarios

Gravitational-Instability (top-down)

(L. Mayer)

Self-gravitating disk
Density-Fluctuations grow
Spiral arms $\Rightarrow$ planets
Fast formation ($10^3$ years)
No cores
(Good for distant planets)

Sequential Accretion (bottom-up)

(NASA, U2)

From small to large particles
Slow formation ($10^6$ Years)
Need: High sticking probability
(Comets, asteroids, solid planets, cores of planets)
(Preferred for Solar System)
Particles have relative velocity with respect to the gas ⇒ frictional forces

Problem I: Fast radial drift towards star  (for 1m Size: 1 AU / 100 Years)
Problem II: Destructive Collisions
Note: Disk is hotter near central star, best condensation beyond iceline
Planetesimals

Collisions

Check growth of planetesimals by collisions/accretion

Modeling Tool: SPH (Smoothed-Particle-Hydrodynamics)

Here: Elastic-plastic strength model, formation and evolution of cracks

2 Basalt Spheres:

Porous Objects:

(cp. small objects in Solar System)

(Christoph Schäfer, Ralf Geretshauzer; Univ. of Tübingen 2005,2010)

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Planet Growth

How to form massive planets

Growth from ‘dust’ to planets

‘Planetesimal-formation’
(Critical first growth phase)

Aggregation (=coagulation)

Gravity-assisted growth

Gas capture

1μm  1mm  1m  1km  1000km

(Dust ⇒ Planetesimals (µm ⇒ 1-10km, through Collisions)
Mass rich planets: Gravitation & Gas Accretion

(C. Dullemond)

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Planet Growth

Gap Opening Process

$M_p = 1 \, M_{\text{Jup}}, \quad a_p = 5.2 \, \text{AU}, \quad$ into disk around $1 \, M_{\text{sol}}$ star

Viscous hydrodynamical evolution ($\alpha$-disk)

Tool: 2D Finite Volume Method

Gap formation limits growth to about $1 \, M_{\text{Jup}}$

Details (gap width & depth) depend on: Viscosity, pressure, planet mass
Moon (S/2005 S1) in Keeler Gap, Cassini (May 1, 2005)
(Gap-Width $\approx 40$ km, Planet-Diameter $\approx 7$ km)

Here: Zero pressure, low viscosity $\implies$ Very clean gap
Grid:
128 x 128

- Central Star
- Roche Lobe

Jupiter-type planet
Nested-Grid System: Centered on Planet (D’Angelo et al. 2002/03)
Summary Formation

- Planets form in protoplanetary disk (in one plane, circular orbits)
- Sequence of sticking collisions
- Inner planets: solid
- Outer planets: gaseous with cores
- Maximum Mass \( \approx M_{\text{Jup}} \) (gap formation)

What about the extrasolar planets?
Epikur (ca. 341-270 BC)
“There is an infinite number of worlds, some similar to ours some very different.”
Exoplanets

Mass and Distance

Small distances (hot Jupiters) & large masses
(Data: exoplanet.eu)

![Graph showing the relationship between mass and distance of exoplanets.]

- Radial Velocity
- Transit
- Solar

 Mass [$M_{Jup}$]

 Distance [AU]

Radial Velocity Transits, and Solar systems are represented in the graph. The distances are measured in astronomical units (AU), while the masses are measured in Jupiter masses [$M_{Jup}$].

$M_{Earth} = \frac{1}{300} M_{Jup}$

$a_{Mercury} = 0.4$AU

⇒ Need migration and mass growth!

W. Kley

Young planets are embedded in gaseous disk

Creation of *spiral arms*:
- stationary in planet frame

**Tools:** Linear analysis,
- 2D hydro-simulations

**Inner Spiral**
- pulls planet forward:
- *positive torque*

**Outer Spiral**
- pulls planet backward:
- *negative torque*

→ **Net Torque**
⇒ **Migration**

Most important: Strength & Direction?

**Typically:** Outer spiral wins
⇒ **Inward Migration**

**New problem:** Too rapid!!

Need corotation Torques
Radiative Disks

(Masset, 2001)
Migration

Physics matters

\[ \frac{\partial \Sigma c_v T}{\partial t} + \nabla \cdot (\Sigma c_v T \mathbf{u}) = -p \nabla \cdot \mathbf{u} + D - Q - 2H \nabla \cdot \mathbf{F} \]

Specific Torque \( [a^2 \Omega^2] \) vs. Time [Orbits]

- Isothermal
- Adiabatic
- Local cool/heat
- Fully radiative

Outward Migration

Inward Migration

Inclusion of radiation desaturates torques

\( M_p = 20 M_{Earth} \)

(Kley & Crida '08)
Migration Evidence

- Observed: \( \approx 40 \) multi-planet extrasolar planetary systems
  \( \approx 1/4 \) contain planets in a low-order mean-motion resonance (MMR)
  mostly in a 2:1 configuration (eg. GJ 876, HD 128311, HD 82943, ....)
  but also 3:2 (HD 45364) and 3:1 (HD 60532)
  In Solar System 3:2 between Neptune and Pluto (plutinos)

- Resonant capture through convergent migration process
  dissipative forces due to disk-planet interaction

- Existence of resonant systems
  \( \implies \text{Clear evidence for planetary migration} \)

- Hot Jupiters (Neptunes)
  \( \implies \text{Clear evidence for planetary migration} \)
Migration

Flow field & Mass grow

Surface Density

Green Dot: Planet
Green Line: Roche-Lobe

$m_p = 1 \, M_{\text{Jup}}$
$a_p = 5.2 \, \text{AE}$

Flow-Field

→ Mass growth!
up to a few $M_{\text{Jup}}$
→ prograde rotation

(W. Kley)
Eccentricity Distribution

Large eccentricities (similar to binary stars) (Data: exoplanet.eu)
Eccentricity  Low mass Planets on eccentric Orbits

Torque on planet due to disk

\[ \Gamma_{\text{disk}} = \int_{\text{disk}} (\vec{r}_P \times \vec{F}) |_z d\Omega \]

Power: Energy loss of planet

\[ P_{\text{disk}} = \int_{\text{disk}} \dot{r}_P \cdot \vec{F} d\Omega \]

\[ L_p = m_p \sqrt{GM_*a} \sqrt{1 - e^2} \]

\[ \frac{\dot{L}_p}{L_p} = \frac{1}{2a} \left( \frac{e^2}{1 - e^2} \right) \frac{\dot{e}}{e} = \frac{\Gamma_{\text{disk}}}{L_p} \]

\[ E_p = -\frac{1}{2} \frac{GM_*m_p}{a} \]

\[ \frac{\dot{E}_p}{E_p} = \frac{\dot{a}}{a} = \frac{P_{\text{disk}}}{E_p} \]
Eccentricity in 3D radiative disks

Fix planet mass $M_p = 20M_{Earth}$
- Vary initial Eccentricity

Vary Planet Mass $10 - 200M_{Earth}$
- Same $e_0 = 0.40$

(Bitsch&Kley ’10)

- $e$-damping for all planet masses.
  
  Small $e$: exponential damping, large $e$: $\dot{e} \propto e^{-2}$

- Same applies to Inclination

$\Rightarrow$ Need multiple objects! (and Scattering)
Distant planets

Directly imaged planets

Large distances (several hundred AU)

(Data: exoplanet.eu)

Radial Velocity
Transit
Solar
Imaged
Distant planets  Gravitational-Instability

Consider local density perturbation in disk

Analytical

Stability-Criterion (Toomre)

\[ Q \equiv \frac{c_s \kappa_0}{\pi G \Sigma_0} > 1 \]

with

- \( c_s \) = sound velocity
- \( \kappa_0 \) = Epicyclic-Frequency (\( \Omega_K \))
- \( \Sigma_0 \) = surface density

• Pressure & Rotation stabilize
• Density destabilizes

Numerical

Evolution of an isothermal Disk
- Finite-Difference Hydrodynamics
- Viscous Disk

(Tobias Müller, Tübingen)

Disk heats up upon compression, need fast cooling

Require: coolingtime \( \approx \) period \( \Rightarrow \) fast formation

Only in large distances from star (for ca. 30-50 AU, no cores)
**Binary Parameter**  \((\approx \gamma \ Cephei)\)

\[ M_1=1.6 \ M_\odot , \quad M_2=0.38M_\odot , \quad a_b=22 \text{ AU}, \quad e_b=0.36 \]

**Grid:**  \([0.5, 8.0] \text{ AU}\)
2D viscous accretion disk
locally isothermal
\[ r_{\text{min}} = 0.5, r_{\text{max}} = 8.0 \text{ AU} \]
Grid: \( 200 \times 200 \)

Density structure:

Planet Formation: made more difficult
- Disk heating
- Enhanced collision velocities
Planet Formation  Summary

- Planets form in protoplanetary disk
- Sequential accretion vs. grav. instability
- Initial collisional stage not well understood
- Close in Planets through disk migration / Scattering
- Eccentric/Inclined planets through grav. scattering

- Modeling Tools:
  - Solid State Physics/Collisions
  - 3D Magneto-Hydrodynamics
  - 2D/3D Radiation-Hydrodynamics
  - Self-Gravity of Disk
Thank you for your attention!