The Birthplace of Planets

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Outline of the talk

1. Solar System and exoplanets
2. Astrophysical context of planet formation
3. Protoplanetary disks
4. Building blocks of planets
5. Planet formation
6. Planet migration
7. Lessons from the Solar System
8. Summary
Solar System and Exoplanets
Asteroid belt

Kuiper belt

Rocky planets

Gaseous planets

Oort cloud
It wasn’t always like that...

Earth/Moon
Mercury
Venus
Mars
Jupiter
Saturn

2000 BC
Babylonian

Heliocentric
model

16th
Copernicus

Comets are not
atmospheric
phenomena

Galilean
moons

17th
Galileo

Saturn’s rings
and moons

18th
Halley

Halley’s comet

19th
Piazzi

Uranus

20th
Wolf

Saturn’s moons

16th
Copernicus

Geocentric
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Saturn’s moons
4122 planets and 3063 planetary systems (671 multiple planet systems) detected and confirmed with different methods.

Source: exoplanet.eu, October 2019
51 Pegasi / 51 Pegasi b

- 51 Peg is the first “main-sequence” star discovered hosting an exoplanet.
- 51 Peg b is a giant planet (half the mass of Jupiter).
- Semi-major axis 0.05 AU (Mercury is 0.39 AU).
- Orbital period of 4 days.

**Hot Jupiter**

Different to our Solar System.
Orbital migration of the planetary companion of 51 Pegasi to its present location

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Here we show that, if the companion is indeed a gas-giant planet, it is extremely unlikely to have formed at its present location. We suggest instead that the planet probably formed by gradual accretion of solids and capture of gas at a much larger distance from the star (∼5 AU), and that it subsequently migrated inwards through interactions with the remnants of the circumstellar disk.
Nobel prize in Physics 2019

For the discovery of an exoplanet orbiting a solar-type star

Michel Mayor
Prize share: 1/4

Didier Queloz
Prize share: 1/4
Kepler Orrery

Planetary systems discovered by Kepler observatory
Astrophysical context of planet formation
Nebular hypothesis

- Bodies rotate in the same direction
- Low inclinations / eccentricities

Planets condense from a primitive solar atmosphere
From galaxy clusters to planets

Credits: NASA/Hubble

Credits: Mark McCaughrean (Max-Planck-Institute for Astronomy), C. Robert O’Dell (Rice University), and NASA/ESA

Credits: Illustris collaboration

Credits: NASA/Hubble
Protoplanetary disks
How do planets form?

- Molecular cloud collapses
- Small dust grains merge into larger bodies and form the first planetary cores
- Planet cores accrete gas/dust from the disk
- Rocky planets are believed to form in the final stages
- The system finally relaxes dynamically towards an equilibrium configuration
Disk formation

Source: pressbooks.bccampus.ca/astronomy1105/chapter/21-1-star-formation/
Protoplanetary disks

- Gaseous disks rotating orbiting a central object
- Small fraction of dust
- Typical size of 100-1000 AU
- Live for ~1-10 Myr
- Factories of planets
Where do we find disks?
HL TAU & Tw hydra

450 light years away from us (1 arcsec)
DSHARP

“Disk substructures at high Angular resolution Project”
Dusty disks

Credits: ESO/H. Avenhaus et al./E. Sissa et al./DARTT-S and SHINE collaborations

SPHERE at VLT

Credits: ESO/H. Avenhaus et al./E. Sissa et al./DARTT-S and SHINE collaborations
STAR + GAS + SOLIDS = PLANETS
Building blocks of planets
Solids dynamics

\[ S = 4\pi R^2 \quad \text{vs} \quad V = \frac{4}{3} \pi R^3 \]

Cross section of the body
Friction forces

\[ \frac{S}{V} \propto \frac{1}{R} \]

Mass of the body
Inertia

The smaller the object, the larger the surface to volume ratio
Solids dynamics

Solids behave differently depending on their size and mass

Small solids trace air flow

Larger solids partially trace air flow

Even larger solids decouple almost completely from air flow
Solids dynamics in protoplanetary disks

Circular motion

Velocity

Centripetal force

Centripetal forces (idealized picture)

Gravity of the central star faster than Pressure gradient

Dust particles Gas

Drag force

Headwind felt by the solids (~200 Km/h)
Solids dynamics in protoplanetary disks

- Drag force depends on:
  - Particle size
  - Ambient density
    - Denser medium is able to remove momentum more efficiently
- Small particles are well coupled to the gas
  - Dynamics governed by drag forces
- Large particles are decoupled from the gas
  - Dynamics governed by inertia / external forces
From stardust to planets

Monomers → Aggregates → Pebbles → Planetesimals → Planets

- μm
- mm
- m
- km
- Mm

Images:
- Red Blood cell
- Sesame seed
- Tree
- Mountain
- Planets
Microgravity experiments
Bremen University
Growth barriers

Weidlin et al. (2011)

Beitz et al. (2011)
Dust growth

Before collision

Sticking (S)  Bouncing (B)

Mass Transfer (MT)  Erosion (E)

Fragmentation (F)

Blum & Wurm (2008)

Windmark et al. (2012)
Growth barriers

**Fragmentation**

**Drift**

Big particles get destroyed by collisions or by falling into the star.
How do we concentrate dust?

Johansen et al. (2014)

Eddies

Pressures bumps

Streaming instability

Johansen et al. (2014)
Monodisperse vs polydisperse particles distributions may affect the dynamics and formation of the building blocks.

$\frac{\sigma}{\Omega_0}$

$\propto \sqrt{\epsilon}$

$\propto \epsilon$
END OF THE FIRST PART
Planet formation
Two planet formation scenarios

Core accretion model

Bottom-up

Gravitational instability

Top-down
Core accretion: Planetesimal accretion

- Assisted by gravitational focusing
- Big gravitational bodies
- Depends on the radius of the accreting body (cross section)
- It takes long time
Core accretion: Pebble accretion

- Small negligible gravitational mass particles accrete onto large gravitating bodies in gas-rich environments

- It basically depends on the mass of the gravitating body and the surrounding density, not its size

- It is fast and very efficient

Pebble accretion is also a planetesimal formation mechanism
Core accretion or Gravitational instability?

- **Star GJ 3512**
  - Mass $\sim 0.1 \, M_{\text{sun}}$

- **Planet GJ 3512 b**
  - Mass $> 0.46 \, M_{\text{jup}}$
  - Period: 204 days
  - Eccentricity: 0.44

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Morales et al. (2019)
Planet migration
Orbital migration of the planetary companion of 51 Pegasi to its present location

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The recent discovery¹ and confirmation² of a possible planetary companion orbiting the solar-type star 51 Pegasi represent a breakthrough in the search for extrasolar planetary systems. Analysis of systematic variations in the velocity of the star indicate that the mass of the companion is approximately that of Jupiter, and that it is travelling in a nearly circular orbit at a distance from the star of 0.05 AU (about seven stellar radii). Here we show that, if the companion is indeed a gas-giant planet, it is extremely unlikely to have formed at its present location. We suggest instead that the planet probably formed by gradual accretion of solids and capture of gas at a much larger distance from the star (∼5 AU), and that it subsequently migrated inwards through interactions with the remnants of the circumstellar disk. The planet’s migration may have stopped in its present orbit as a result of tidal interactions with the star, or through truncation of the inner circumstellar disk by the stellar magnetosphere.
Gravitational perturbations

Credit: Joseph Hahn
Planet-disk interaction

- Gravitational interaction between the embryos and the surrounding material
  - Disk feels gravity of the planet (accelerated by the planet), which, by action-reaction law, accelerates also the planet
- Embedded planetary cores evolve dynamically because of this force

Planet migration
Types of interaction

Large-scale perturbations

Localized perturbations
Alternative frame of reference
Types of interaction

Large-scale perturbations

Localized perturbations
The outcome depends on the planet mass
How do we simulate planet migration?

FARGO3D

A versatile MULTIFLUID HD/MHD code that runs on clusters of CPUs or GPUs, with special emphasis on protoplanetary disks.

Website: fargo.in2p3.fr
Documentation

Clone
HTTPS: git clone https://bitbucket.org/fargo3d/public.git
SSH (bitbucket user required): git clone git@bitbucket.org:fargo3d/public.git

Some outcomes of this interaction

- Planets migrate mostly inwards
  - Fast inward migration problem
- Orbits are circularized
  - How do we explain eccentricity of exoplanets?
- The inclinations are also damped
  - How do we explain retrograde planets?
- Several planets can end-up in mean-motion resonances

Circular and coplanar orbits are an outcome of these models, which is in good agreement with the Solar System
Do we have observational evidence of this interaction?

**HD 100453**
Wagner et al. (2015)

**SAO 206462**
Stolker et al. (2016)

**MWC 758**
Benisty et al. (2015)

**HD 14257**
Avenhaus et al. (2014)

**Elias 2-27**
Credit: B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO)

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**PDS70**
Müller et al. (2018)
Planetesimal-driven migration

Star

Scattering

Planet

Eccentric planetesimals

Planet moves outward

Levison et al. (2007)
What can we learn from the Solar System?
Nice model

Morbilé, et al. (2007)

Gomes, et al. (2005)
Grand tack hypothesis

Recipe to form a Solar System

- Bimodal initial distribution of S-type and C-type asteroid
- Inward migration of Jupiter and Saturn scatter away S-type asteroids
- When Jupiter and Saturn are locked in Mean motion resonance, they migrate outwards
- The inner Solar System is formed from the residuals

Morbidelli & Raymond (2016)
Ultima Thule

- Located at the Kuiper belt
- Farthest, and perhaps the oldest, object explored by a spacecraft
- Can it tell us how the building blocks of planets form?

Credits: NASA/Johns Hopkins Applied Physics Laboratory/Southwest Research Institute, National Optical Astronomy Observatory
Streaming instability can explain this?

Nesvorny et al. (2019)
Constraining models

Jupiter blocks drifting particles from the outer Solar System

Weber et al. (2018)

Haugbølle et al. (2019)
All planetary systems are different

Raymond et al. (2018)
Summary
Summary

- Stars are formed in molecular clouds
  - Disks are formed together with the star
    - Disks are dusty disks
- Planetary bodies form from dust
  - Dust needs to growth before forming the planets
    - Barriers
- If we overcome the barriers, a planetary core is formed
  - Planets interact with the disk (and other planets) gravitationally
    - Planets move while they form
- When the disk dissipates, the system relaxes dynamically
  - Instabilities and ejections may occur
- If the planets are at the right distance from the star → liquid water
... “Given our lack of understanding of these issues, even most successful formation models remain on shaky grounds.”