Constructing the Solar System: A Smashing Success

Making Planetesimals: The building blocks of planets

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Compton Lecture Series
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76th Compton Lecture Series outline

1. 10/06/12  A Star is Born
2. 10/13/12  Making Planetesimals: the building blocks of planets
3. 10/20/12  Guest Lecturer: Mac Cathles
4. 10/27/12  Asteroids, Comets and Meteorites: our eyes in the early Solar System
5. 11/03/12  Building the Planets
6. 11/10/12  When Asteroids Collide
7. 11/17/12  Making Things Hot: The thermal effects of collisions
8. 11/24/12  No lecture: Thanksgiving weekend
9. 12/01/12  Constructing the Moon
10. 12/08/12 No lecture: Physics with a Bang!
9. 12/15/12  Impact Earth: Chicxulub and other terrestrial impacts
Today’s lecture

1. Low velocity collisions between dust grains lead to growth of small particles

2. The ‘meter-sized barrier’

3. The growth of planetesimals

4. Runaway/oligarchic growth of planetary embryos

Images courtesy of NASA/JPL-Caltech
What is a planetesimal?

Planetesimal

- A solid object formed during the accumulation of planets
- Internal strength dominated by self-gravity
- Orbital dynamics not significantly affected by gas drag
- Object larger than ~ 1 km in the Solar Nebula

Asteroid 4 Vesta — A surviving planetesimal?

Image courtesy of NASA/JPL-Caltech/UCLA/MPS/DLR/IDA
Do we still have planetesimals in the Solar System today?

As we will see over the coming lectures, planetesimals suffered a variety of fates:

- Some were accreted into planets
- Some were ejected out of the Solar System
- Some spiralled towards the Sun and were evaporated
- And some survived — in what we now call the asteroid belt

Image courtesy of NASA
Recap from last week

- The Sun formed from a nebula

- After formation, we were left with a rotating disk of gas and dust surrounding the young Sun
Some of the dust and gas will be accreted onto the Sun.
Some will go on to form solid bodies.
Today, we will discuss how those solid bodies formed, and what happened to them early in their histories.

Image courtesy of NASA/JPL-Caltech
The structure of the disk

- The disk was heated by the young Sun
- Near to the Sun, temperatures would have been higher than further out
- Silicates and iron compounds would have condensed first close to the Sun
- Further from the Sun, beyond the **snow line** temperatures would have been low enough to allow ices to condense

Image courtesy of the Lunar and Planetary Institute
Recap: Keplerian velocity

- Kepler’s laws predicted what the orbital period would be for a body orbiting at a given distance from the Sun
  \[ P^2 = \frac{4\pi^2}{GM_\odot} r^3 \]

- Since we know the distance and time of the orbit, we know the speed that the object moves around the Sun
  This is called the **Keplerian velocity**

- We can also describe the **angular velocity** using this law
  \[ \frac{360^\circ}{P} = \frac{2\pi}{P} = \sqrt{\frac{GM_\odot}{r^3}} \]
Why did the solid matter settle to the mid-plane?

- For any dust particle at a height $z$ above the midplane of the disk, a gravitational force is exerted downwards towards the mid-plane

$$F_{\text{grav}} = m \frac{GM_\odot}{r^3} z$$

- $m$ is the mass of the particle
- $\frac{GM_\odot}{r^3}$ is the square of the Keplerian angular velocity
- Items that are in the upper regions of the disk settle more rapidly
Particle settling and growth

- μm- to mm- sized particles would settle out of the upper layers of the disk in thousands of years.
- Particles grow at the same time as settling.
- The gas does not settle to the mid-plane in the same way, however, because of a pressure gradient directed upwards.
- Thus, the drag felt by the particle as it moves through the gas balances the gravitational force.
Growth of dust agglomerates

In the lecture I showed a movie of dust grains colliding from Dominik and Tielens (1997). You can see that video online, here:

http://staff.science.uva.nl/~dominik/Research/Coagulation/2DMovies/C_C_ice_R-5_short.mpeg

- How did dust grains grow into larger bodies?
- As the dust was settling towards the mid-plane, low velocity collisions between dust grains occurred
  - Slow speeds (∼ m/s)
- Need to be low velocity to allow them to stick together
- This process results in highly porous dust aggregates
- Stick together because of van der Waals and electrostatic forces
Growth of dust aggregates continues, until...

- Some evidence of these particles is provided by **interplanetary dust particles**
  - Collected in our atmosphere
- Some of these are ‘fluffy’
  - i.e. highly porous material
- But, **how big** could aggregates grow like this?

Image courtesy of Bradley (2004), *Treatise on Geochemistry*
The ‘meter-sized’ barrier

- Aggregates grew to **boulder sized** objects (around a meter in size) by low velocity collisions.
- The time taken to reach this size would vary by the distance from the Sun:
  - At 1 AU (the distance of the Earth from the Sun now), \( \sim 100 – 1000 \) years
  - At 30 AU, \( \sim 60,000 \) years
- When they reached a meter in size, something acted to stop growth.

*Image courtesy of E. Wright (UCLA)*
The pressure gradient slowed the gas down

- Near to the Sun, the gas in the disk was under higher pressure than it was in the outer regions
  - There was a **pressure gradient** in the gas, pointing away from the Sun
- This pressure gradient:
  - Introduced a small acceleration on the gas, acting away from the Sun
  - This prevented the gas falling onto the Sun
- The gas would have orbited at a velocity $\sim 0.5\%$ **slower** than the Keplerian velocity
The gas acted to slow the boulders’ orbits

- Gas slower than Keplerian velocity
- Dust particles ‘coupled’ to gas and swept along at the same velocity
- Boulders (~ 1 m in size) would have experienced a **headwind** caused by the slower moving gas
  - Headwind slowed the orbits of boulders
  - Orbiting slower than Keplerian velocity caused the boulders to spiral inwards
  - Rapid inward motion (around 1 AU per hundred years)
- Planetesimals (> 1 km) would have a smaller surface area-to-mass ratio, and would be unaffected by the headwind
Planetesimals formed rapidly

- Planetesimals must have formed **rapidly**
  - If it was not rapid, most solid material would have drifted rapidly inwards when it reached the meter size scale
  - When it reached the hot inner region of the disk near the Sun, that material would have been evaporated
  - This would have halted growth of solid objects

- So, how did objects grow from meter sized to kilometer sized, without falling quickly into the Sun?
How did objects break the meter-sized barrier?

The process by which objects grew from boulders to planetesimals is not well known. Several possibilities exist, depending on turbulence in the disk. In the next few slides, we will examine some of the possible scenarios that could have led to growth of planetesimals.
Collisions in a non-turbulent disk

- Small particles would have settled to the mid-plane
- Gas would have become entrained in this dense mid-plane layer
- Now orbiting at Keplerian velocity again: **No headwind**
- Boulders could now grow by collisional accretion again
- However: May lead to **too rapid growth** to match observations
- Objects smaller than 1 km may be disrupted (broken apart) too easily by collisions in this scenario to lead to growth
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Gravitational instability in a non-turbulent disk

- Particles settle to mid-plane, forming a dense layer.
- Localized regions of the disk formed overdensities, and contracted under gravity.
- Quickly able to form km-sized objects: radial drift no longer a problem.
- However, a shear flow would be induced by the more rapidly rotating dense region: this would induce turbulence, which could make it harder for gravitational contractions to occur.
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Recent work has shown that even in a turbulent disk, gravitational instabilities are possible.

Particles drift in the direction of the pressure gradient (radial drift).

Dense regions are formed by short-lived density maxima created by the turbulence.

Material falling inwards into dense regions (because of radial drift) helps to maintain the high density long enough for km-sized bodies to form.

This would occur fast enough that radial drift of boulders is not a problem.

Adapted from P. Armitage, 2010

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Gravitational instability in a turbulent disk

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A swarm of planetesimals

- Whichever mechanism led to the growth of planetesimals, a swarm of ~100 km sized objects were created in a few thousand years.

- All growth mechanisms are gentle: porosity was maintained as planetesimals grew.

- Planetesimals were too large to be affected by gas drag, and so radial drift no longer obstructed growth.

- The next stage was for planetesimals to grow still further, to form the precursors to the terrestrial planets: **Protoplanets**
Planetesimals are large enough to gravitationally attract each other, leading to **collisions**.

After many collisions, by chance some bodies will grow to be slightly larger than the neighboring bodies. The largest body in a region will gain mass more quickly than the next largest (and so on...), due to **gravitational focusing**.

This stage is termed **runaway growth**.
Runaway growth

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  ![Diagram of planetesimals](image)

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Runaway growth slows down

- Rate of growth becomes limited
- Smaller objects near the protoplanet (the feeding zone) are exhausted
  - Accreted onto the protoplanet
- Velocities of smaller bodies “stirred up” — gravitational focussing is less effective
- Growth continues during a phase called oligarchic growth

Oligarchic growth

- For protoplanets to continue to accrete material and grow, they need to attract objects from outside of their feeding zones.
- The larger protoplanet perturbs the velocity of smaller bodies more, decreasing the number of collisions possible.
- Eventually, the protoplanets could have grown to around the size of the Moon or Mars.
- This could have taken up to a million years.
- At this point, the largest bodies are known as **planetary embryos**.

Image courtesy of Kokubo & Ida, 1998 (Icarus)
This week, we have seen how the disk of gas and dust surrounding the young Sun evolved.

The dust stuck together during low velocity collisions, up to boulder-sized objects.

Then, gravitational instabilities allowed planetesimals to quickly form.

Further collisional evolution led the growth of planetary embryos.
Next week, we will discuss meteorites and asteroids.

What can they tell us about conditions in the disk?

What affected their orbits, and did they evolve?

Images courtesy of NASA/JPL

Images courtesy of H. Raab
Thank you

Questions?
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