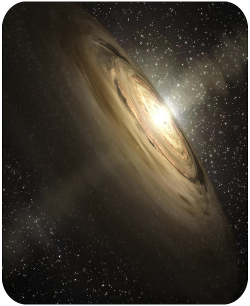
Constructing the Solar System: A Smashing Success

Making Planetesimals: The building blocks of planets



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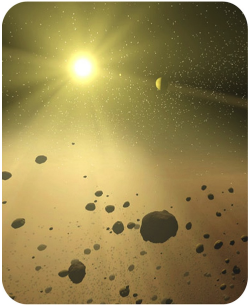
Compton Lecture Series
Autumn 2012



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

   11/24/12 No lecture: Thanksgiving weekend

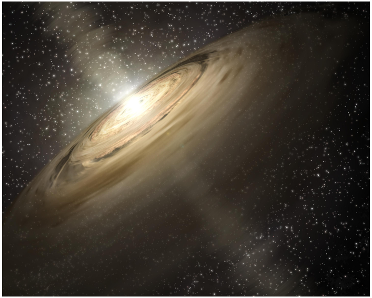
8. 12/01/12 Constructing the Moon

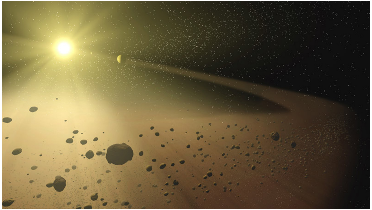
   12/08/12 No lecture: Physics with a Bang!

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 $\sim$ 1 km in the Solar Nebula

Asteroid 4 Vesta —
A surviving planetesimal?

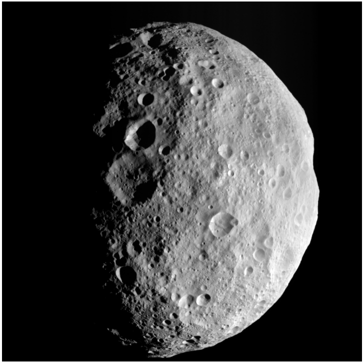


Image courtesy of
NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

Do we still have planetesimals in the Solar System today?

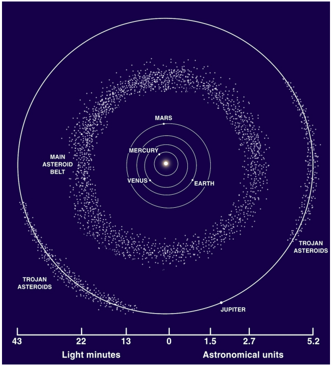


Image courtesy of NASA

- 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

Recap from last week

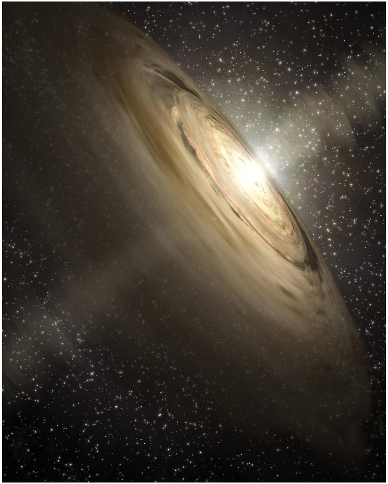


Image courtesy of NASA/JPL-Caltech

- The Sun formed from a nebula
- After formation, we were left with a rotating disk of gas and dust surrounding the young Sun

What happens to the dust and gas?

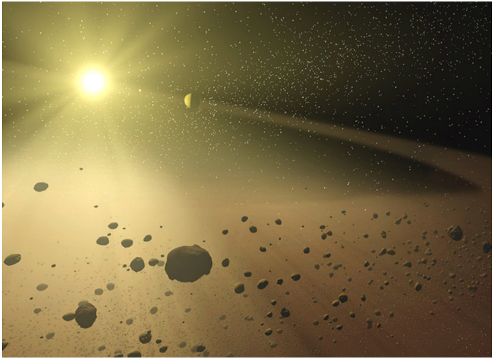


Image courtesy of NASA/JPL-Caltech

- 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

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

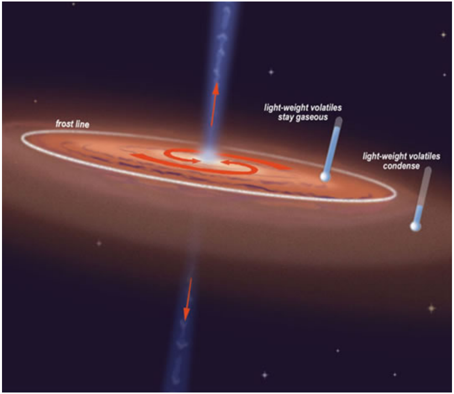
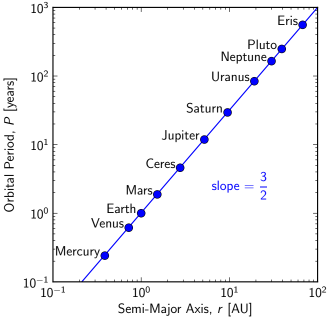


Image courtesy of the Lunar and Planetary Institute

Recap: Keplerian velocity



- Kepler's laws predicted what the orbital period would be for a body orbiting at a given distance from the Sun

$$P^2 = \frac{4\pi^2}{GM_\odot} r^3$$

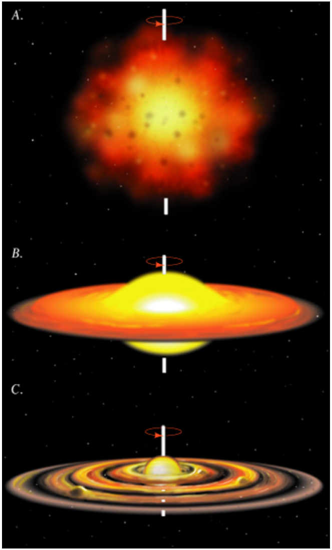
- Since we know the distance and time of the orbit, we know the speed that the object moves around the Sun
  - This is called the **Keplerian velocity**
- We can also describe the **angular velocity** using this law

$$\frac{360^\circ}{P} = \frac{2\pi}{P} = \sqrt{\frac{GM_\odot}{r^3}}$$

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

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

- 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

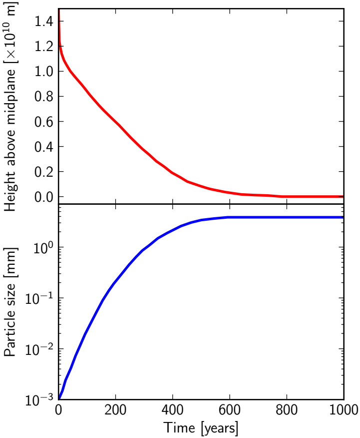


Image adapted from Philip J. Armitage

- 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

Image courtesy of Wikimedia Commons

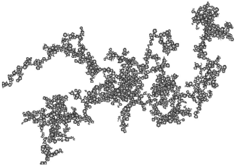


Image courtesy of L.S. Matthews et al (2007)

IEEE Transactions on plasma science

- 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 ($\sim$ 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?

Interplanetary dust particle

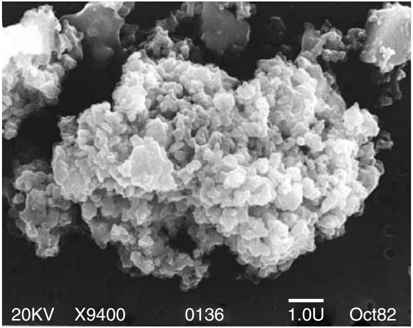


Image courtesy of Bradley (2004), *Treatise on Geochemistry*

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

Growth of dust particle

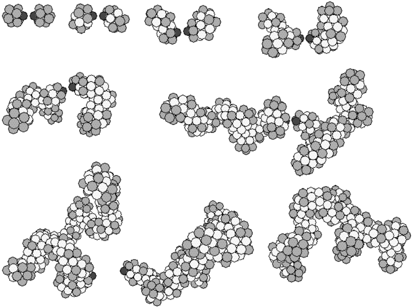
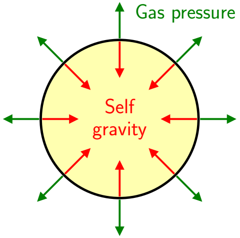
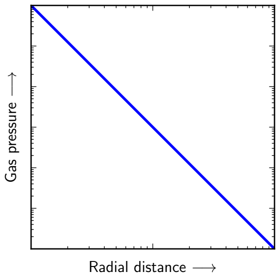


Image courtesy of E. Wright (UCLA)

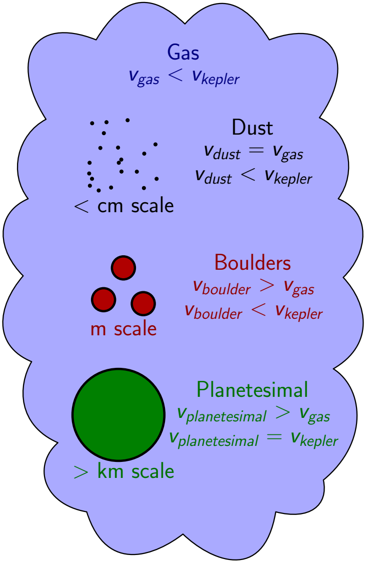
The pressure gradient slowed the gas down

- 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

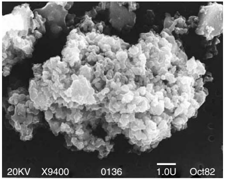


- Gas slower than Keplerian velocity
- Dust particles 'coupled' to gas and swept along at the same velocity
- Boulders ($\sim$ 1 m in size) would have experienced a **headwind** caused by the slower moving gas
  - Headwind slowed the orbits of boulders
  - Orbiting slower than Keplerian velocity caused 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?

Image courtesy of Bradley (2004), *Treatise on Geochemistry*



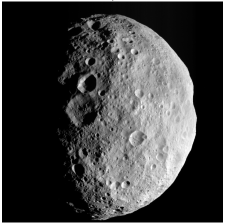
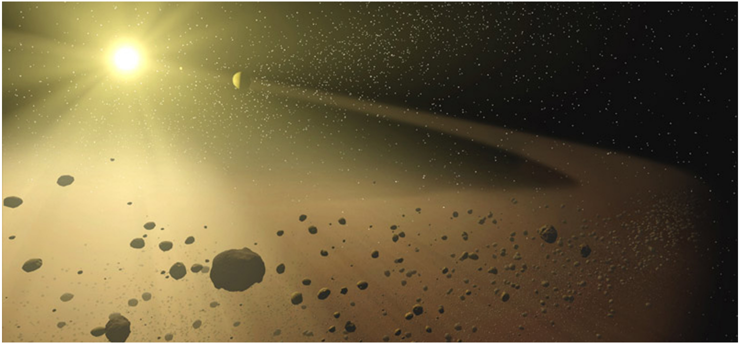


Image courtesy of NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

How did objects break the meter-sized barrier?

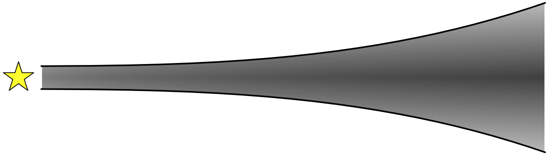


Images courtesy of NASA/JPL-Caltech

- 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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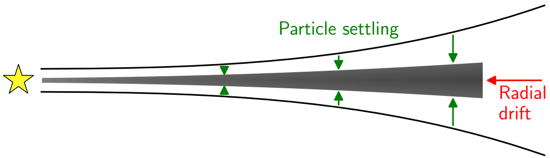
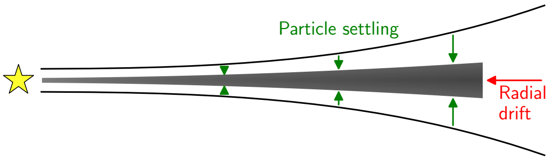


Gravitational instability in a non-turbulent disk

- 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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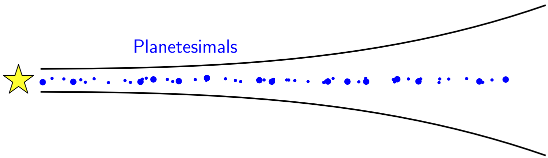
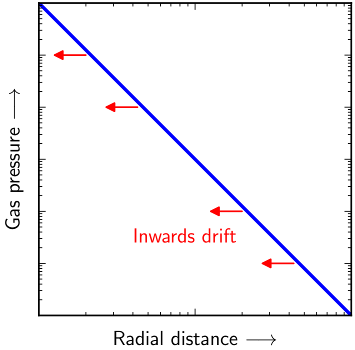


Gravitational instability in a turbulent disk

- 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
Astrophysics of Planet Formation

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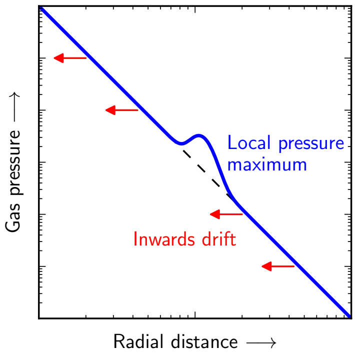

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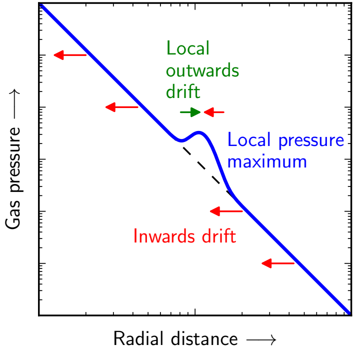

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A swarm of planetesimals

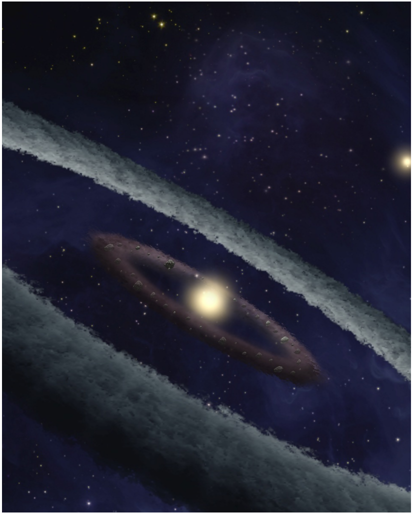
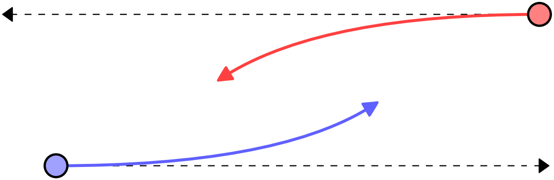


Image courtesy of NASA/JPL-Caltech

- Whichever mechanism led to the growth of planetesimals, a swarm of $\sim$ 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**

Runaway growth

- 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**

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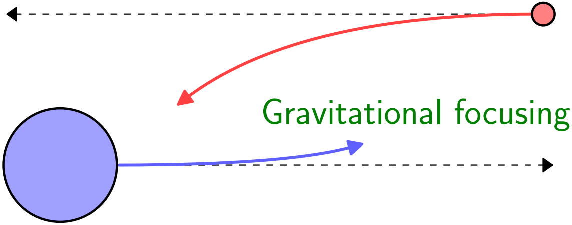

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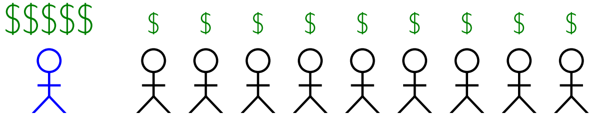

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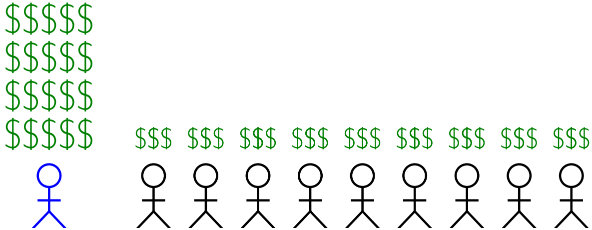

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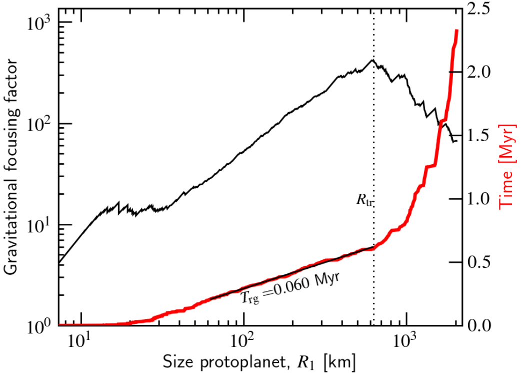
Runaway growth slows down

- 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**



Ormel, C.W. et al. (2010) *The Astrophysical Journal Letters*

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**

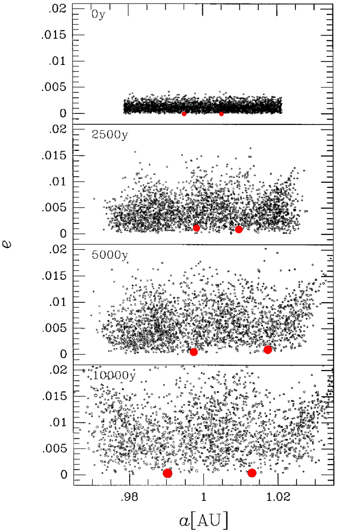


Image courtesy of Kokubo & Ida, 1998 (*Icarus*)

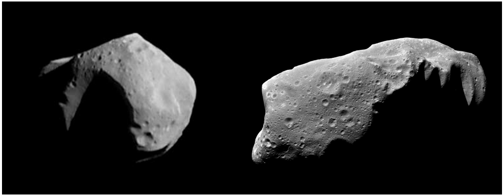
Summary of planetary embryo growth

- 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

Image courtesy of Nature Publishing Group/ TAKE 27/SPL

Next week

- 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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