Today in Astronomy 111: planet formation

- Grain growth and sedimentation in protoplanetary disks
- Evolution of protoplanetary disks and the growth of planetesimals
- Sculpting of disks by infant planets: the time scale of planet formation

Tim Pyle, SSC/JPL/Caltech/NASA
Dust-grain growth in the brand-new disk

When brand-new, a protoplanetary disk is a well-mixed combination of gas and small dust grains.

- Interstellar-like dust: amorphous silicates and graphite, typically 0.01 μm in radius, density $\rho_p = 1 \text{ gm cm}^{-3}$, mass $m_p = 4 \times 10^{-18} \text{ gm (4 attograms)}$.
- That is: each grain contains something like $10^5$ atoms.

When dust grains collide roughly head-on they have a high probability of sticking together. Thus they will begin growing, right away. We may take the thermal speed as typical of the relative speed of grains (smaller than the gas thermal speed):

$$v = \sqrt{\frac{2kT}{m_p}}$$
Dust-grain growth in the brand-new disk (continued)

Since the grains are in the constant-growth-rate phase until they get quite large (as you will show in Recitation this week),

\[ \frac{dR}{dt} = \frac{\rho v}{4\rho_p} = \frac{\xi\rho_t v}{4\rho_p} \]

At this rate they will reach a radius \( R_1 \) in a time given by

\[ \tau_1 = \frac{R_1}{dR/dt} = \frac{4R_1\rho_p}{\xi\rho_t v} \]

\[ = 0.1 - 330 - 1.6 \times 10^4 \text{ years} \]

\( (R_1 = 100 \ \mu m, r = 1 - 10 - 30 \text{ AU}) \)
Sedimentation of the disk

Gas in protoplanetary disks is turbulent but not violently so.

- The turbulence stirs the disk sufficiently to keep some tiny grains suspended, but large grains will sink quickly to the equatorial plane (the disk’s midplane).

- The turbulence is insufficient to suspend grains larger than about 0.1 mm (100 µm) for any substantial time.

- Thus the dust settles to midplane, a process called sedimentation after the similar process of silt settling to the bottom of a lake.

  - This should happen right away in the inner disk (< 1 year at 1 AU), and merely quickly in the outer disk (~10^4 years at 30 AU), as we just saw.
The sedimented disk

- The distribution, pressure and temperature of the gas is essentially unaffected by the settling of the dust.
- The dust temperature is about the same as before, but its distribution is radically different, though: scale height a factor of at least 500 less than the gas. For the dust:

\[ \rho(r) = \rho_0 \left( \frac{r_0}{r} \right)^{23/7}, \quad \rho_0 = 5.67 \times 10^{-2} \text{ gm cm}^{-3} \]

\[ H_d(r) = H_0 \left( \frac{r}{r_0} \right)^{9/7}, \quad H_0 = 5.95 \times 10^6 \text{ cm} \]

- With this density increase, sedimentation makes the solid particles grow much faster, as particle growth makes sedimentation happen faster.
Observing sedimentation and grain growth

The youngest stars are too far away, and the angular resolution of current telescopes insufficient, to measure the thickness of disks directly from images.

- Telescope resolution in the nearest star-formation regions (140 pc away) currently corresponds to about 5AU. The dust layer in a sedimented disk would only be about 0.02 AU thick at $r = 30$ AU.

But the scale heights of gas and dust can be worked out from infrared spectra of the entire disk and central star, because different wavelengths come predominantly from different parts of the disk.

- **Gas**: measurement of the disk-star accretion rate, and use of hydrostatic equilibrium, determines $H(r)$.
Observation of sedimentation

- **Dust**: The dust population in young disks is opaque.
  - Each unit area in the disk receives more starlight if the scale height is larger.
  - Thus the disk is warmer at every radius if $H$ is larger.
  - And so every wavelength comes from further out in the disk, and from a much larger area: disks should look **redder** if $H$ is larger.
  - And so they do.

Infrared spectra of FM Tauri and AA Tauri, two stars/disk which are very similar in all respects except for the degree to which dust is sedimented: 99% for FM Tau, 99.9% for AA Tau.
Observation of grain growth

It’s hopeless to see individual dust grains in distant disks, but:

- The uppermost dust grains are warmer than the opaque dust below, and produce silicate emission features in the spectrum near wavelengths 10 and 20 $\mu$m (lecture, 17 November 2011).

- The spectral shape of the emission features is sensitive to the range of sizes among the uppermost dust grains.

10 $\mu$m silicate feature in two stars/disks with different mass fractions of large (5 $\mu$m radius) and small (<< 1 $\mu$m) dust.
Observing grain growth and sedimentation (continued)

- Use of this to get the large-grain mass fraction, and the color of the continuous emission outside the silicate features to measure sedimentation, reveals a statistically-strong correlation between the two, amidst a large variation.

So grains do grow to large sizes, and settle to mid-plane, in $t < 1$ Myr.

Large-grain mass fraction vs 13-31 µm color index for disks in the 1 Myr-old Taurus young cluster (Sargent et al. 2009). The dashed line is a least-squares best fit.
Headwinds in the disk

Once the solid particles get larger than several cm in radius, forces in the radial direction from gas pressure get very small compared to gravity, and the particles settle into orbits at the normal Keplerian speed.

Gas is still partially supported in the radial direction by pressure, though, so gas and small particles at the same radius as a particle orbit more slowly than the large particles. Large particles thus experience a headwind:

$$v_{HW} = v_K - v = \frac{13}{14} \frac{v_0^2}{v_K}$$

where, as before, $$v_0 = \sqrt{2kT/\mu}$$ and $$v_K = \sqrt{GM_\odot/r}$$. 

Headwinds in the disk (continued)

- The torque the headwind exerts will reduce the particle’s orbital angular momentum: the particle will slowly drift to smaller orbits.
- Small particles now move much faster relative to the large particle, so the large particle grows even faster. To reach a size of 100 km:

\[
\frac{dR}{dt} = \frac{\rho v_{HW}}{4 \rho_p} = \frac{13 \rho v_0^2}{56 \rho_p v_K}
\]

\[
\tau_2 = \frac{R_2}{dR/dt} = 4300 \text{ yr at } r = 1 \text{ AU}
\]
Battle of the planetesimals

So, by a Myr or so,

- a large fraction of the solid mass will be in many hundreds of thousands of ~100-km diameter particles – the sizes of large asteroids and KBOs – which we may henceforth call **planetesimals**.

- When the largest planetesimals reach a few percent of Earth’s size, gravitational focussing finally begins to set in, and the growth rate increases dramatically, leading quickly to runaway accretion.

- So a bunch of lucky planetesimals may have reached runaway growth, and grown to Earth size or larger. These are the major progenitors of terrestrial planets.
Battle of the planetesimals (continued)

- A few really lucky ones, which wound up ten times larger, may undergo runaway accretion of gas, and become giant planets.
- This doesn’t mean that there are not also hot-start giant planets, which would form rather earlier.
- At any size, the planetesimals are numerous, and they can perturb each other’s orbits.
  - This of course leads to lots of orbit crossing, and direct collisions between planetesimals. The largest ones get even larger.
  - The orbital rearrangement, and occasional collisions, will persist for tens to hundreds of Myr.
Chronology of giant-planetary formation in the Solar system

So what do the observations say, about how long it takes to build a planet? In 11 November’s lecture, we described the current best explanation for the unique shape of Saturn’s eighth moon, Iapetus (Castillo-Rogez et al. 2007):

- that Iapetus formed around Saturn,
- And that it formed within 2.5-5 Myr of the appearance of the CAIs.
- Thus Saturn itself must have formed no later than 2.5-5 Myr after the Sun.
- Jupiter would have formed even earlier, if it was always closer to the Sun than Saturn.

Iapetus, by Cassini
Core-accretion models can now make Saturn form at its current distance from the Sun in about 3.4 Myr, consistent with the Iapetus constraints.

- Older models took > 10 Myr, due primarily to use of too-small values of the mass of the Sun’s disk, and the mass of ice in the solid particles.
Imaging infant planets in disks isn’t as hard as imaging the thickness of the mid-plane dust layer, though still is currently beyond our grasp.

- But a giant planet would lead to the formation of a radial gap or a central clearing in the dusty disk in which it formed, by its perturbations on orbiting disk material.

- … just as in the case of the moonlets and gaps in Saturn’s rings.
Transitional disks (continued)

Such gaps would start off the size of the planet’s Hill sphere.

- But if the planet is sufficiently massive, it exerts torques on the inner disk that widen the gap...

- … which can leave a central hole between star and inner disk edge.

- The outer disk and planet will exert torques on each other and migrate. The inner disk edge often (always?) winds up coinciding with a planetary mean-motion orbital resonance.

Quillen et al. 2004

Phil Armitage, U. Colorado
The gaps appear in the spectra of (entire) disk and central star as deficits of disk emission over a range of wavelengths, compared to the spectra of ordinary disks.

- Such disks are called **transitional disks**.
- By this means we know of some 200 protoplanetary disks within 1500 ly of the Sun which have few AU – few 10s of AU gaps.
- The vast majority of these gaps must be cleared by objects of substellar mass.
Transitional disks (continued)

And in some 15 these objects, like LkCa 15 below, it is possible at mm wavelengths to resolve the outer disk, revealing the outer boundary of the gap, and the absence of dust within. Same gaps seen in spectra and images.

\[ r_{\text{gap}} = 46 \text{ AU} \]

Espaillat et al. 2007

\[ r_{\text{gap}} = 49 \text{ AU} \]

Andrews et al. 2011
Though disks themselves disappear with a halflife of 3-5 Myr, the fraction of transitional disks among them can be as large among the youngest as among the oldest: **giant planets form abundantly even before 1 Myr** (Kim et al. 2012).
How and when planets form (concluded)

- Terrestrial planet-size objects form by the core-accretion process from dust grains initially in the disk, within the first few Myrs after the formation of the disk.
  - They will still collide with each other fairly frequently for a few hundred Myrs; not all will survive.

- Giant planets form either by gravitational instability growth in the disk, very shortly after the star, or more probably by the core-accretion process, involving runaway accretion of gas onto large terrestrial-planet cores, on time scales of <1-3 Myrs, or both.
  - The disk may perturb their orbits and cause them to migrate; not all will survive.
Evolution of disks after planet formation

After planets form they begin, with the gravitational forces they exert, to perturb the orbits and rotation of smaller Solar-system bodies and each other. This results in

- **orbital migration**: the large-scale changing of planetary orbits.

- **collisions**, which produce small dust grains (“second generation dust”) and occasionally new planetesimals, as in the case of our Moon, formed as a result of a collision between Earth and a Mars-size planetesimal about 60 Myr after the Sun formed.

- **tidal locking**, from tidal torques exerted by the central star on the nearer-by planets.
Evolution of disks after planet formation (continued)

- capture into, or ejection from, resonant orbits. This results in the “sculpting” of belts of planetesimals, as in the case of the main asteroid belt and the Kuiper belt.
- systematic **ejection** of small bodies, sometimes *en masse*.

**Example**: the early history of our Solar system, according to the Nice Model, from the **Planetology Group at the Observatoire de la Côte d'Azur** (Allesandro Morbidelli and coworkers). See next page.

Main events: perturbation of Jupiter and Saturn by each other migrate these planets outward, eventually resonantly perturbing Neptune and Uranus, swapping their orbits and ejecting 99% of the smaller bodies.