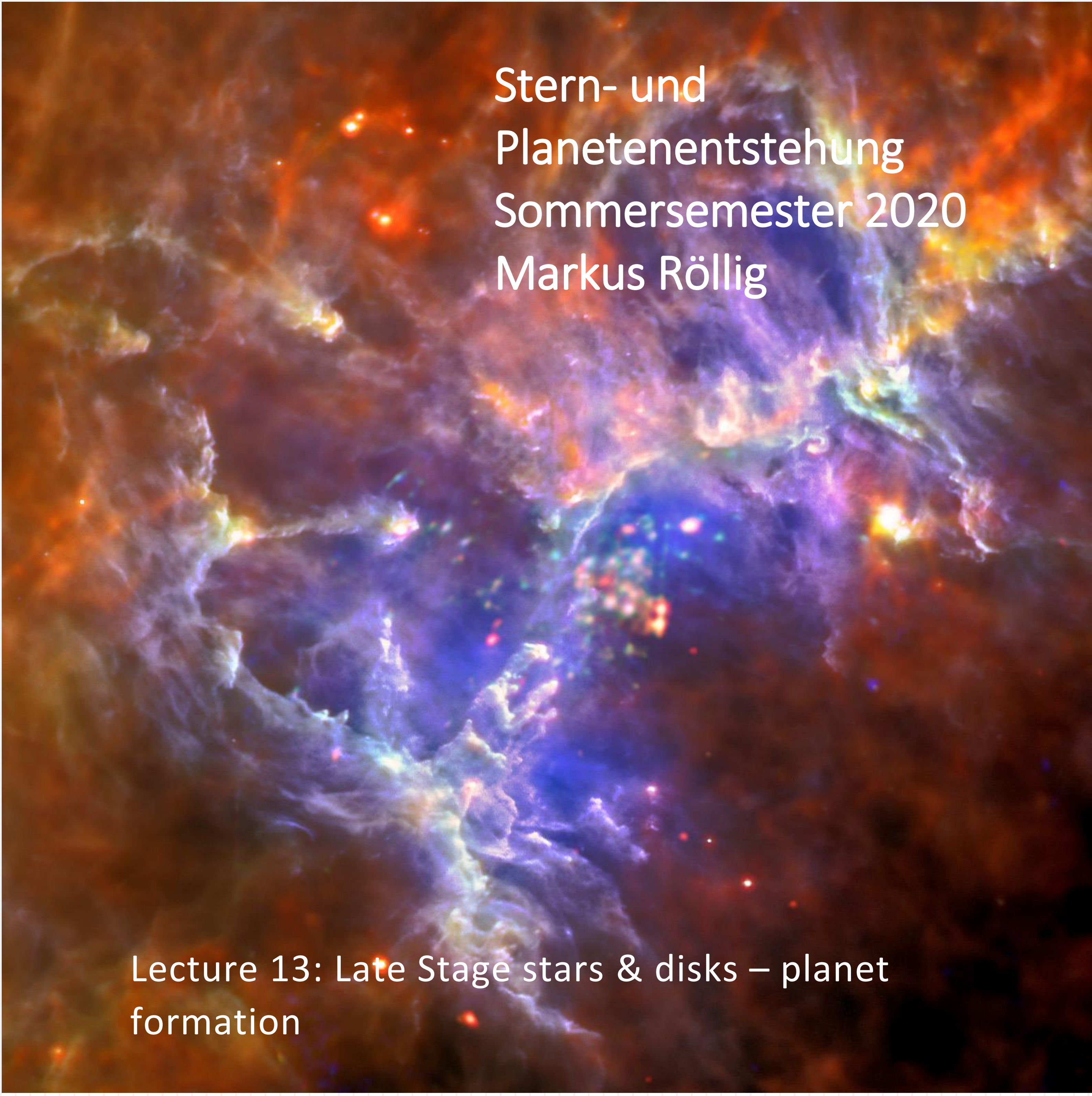


Stern- und Planetenentstehung Sommersemester 2020

Markus Röllig

Lecture 13: Late Stage stars & disks – planet formation

http://exp-astro.physik.uni-frankfurt.de/star_formation/index.php

<u>VORLESUNG/LECTURE</u>
Raum: Physik - 02.201a
dienstags, 12:00 - 14:00 Uhr

<u>SPRECHSTUNDE:</u>
Raum: GSC, 1/34, Tel.: 47433, (roellig@ph1.uni-koeln.de)
dienstags: 14:00-16:00 Uhr

Nr.	Thema	Termin
1	Observing the cold ISM	21.04.2020
2	Observing Young Stars	28.04.2020
3	Gas Flows and Turbulence Magnetic Fields and Magnetized Turbulence	05.05.2020
4	Gravitational Instability and Collapse	12.05.2020
5	Stellar Feedback	19.05.2020
6	Giant Molecular Clouds	26.05.2020
7	Star Formation Rate at Galactic Scales	02.06.2020
8	Stellar Clustering	09.06.2020
9	Initial Mass Function – Observations and Theory	16.06.2020
10	Massive Star Formation	23.06.2020
11	Protostellar disks and outflows – observations and theory	30.06.2020
12	Protostar Formation and Evolution	07.07.2020
13	Late Stage stars and disks – planet formation	14.07.2020

13 LATE STAGE STARS AND DISKS – PLANET FORMATION

In this final chapter, are concerned with the fate of the left-over material from the star formation process, which is mostly collected into accretion disks around them. This chapter discusses how this material is dispersed, and the final one introduces the process by which it can begin to form planets.

13.1 LATE-STAGE STARS AND DISKS

13.1.1 Stars Near the End of Star Formation

Objects of interest here: the class II and class III protostars:

- No remaining envelope
- Stellar photosphere visible
- Young enough:
  - Presence of disks

13.1.1.1 Optical Properties

Main observational signature that has been used historically to define the T Tauri and Herbig Ae/Be classes:

T Tauri: $M \leq 2M_{\odot}$, spectra type G0

Herbig Ae/Be: $M > 2M_{\odot}$, earlier spectral type

- presence of excess optical spectral line emission beyond that expected for a main sequence star of the same spectral class
  - Hα line: $n = 3 \rightarrow 2$
    - in almost all main sequence objects Hα is seen in absorption rather than emission
    - strength of the Hα ranges from
      - booming lines with equivalent widths (EW) of ~100Å
    - to stars that show essentially no feature at Hα (as opposed to absorption for main sequence stars).
  - For T Tauri stars:
    - classical, those with Hα EW $\gtrsim$ 10 Å, and
    - weak-lined, those with Hα EW $\leq$10 Å

- continuum veiling (in addition to excess line emission, these stars show excess continuum emission beyond what would be expected for a bare stellar photosphere)

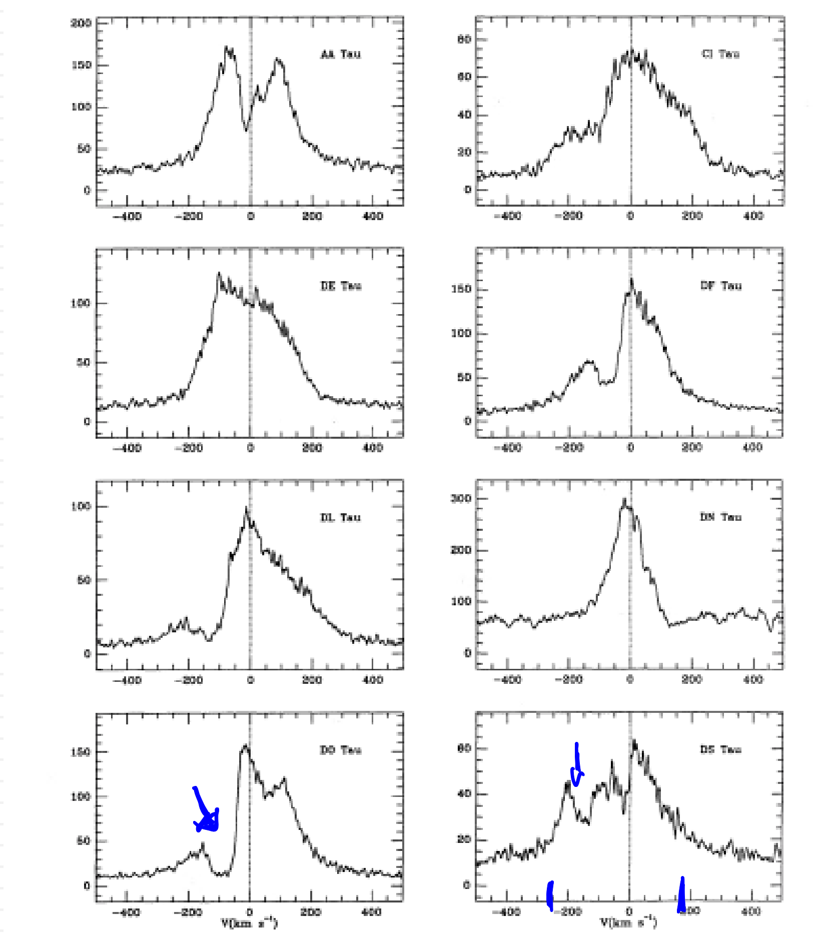
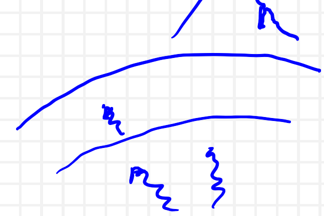


Figure 1 Ha line profiles of T Tauri stars, obtained with the FLWO 1.5 m echelle spectrograph and intensified Reticon detector on JD 2446040 and 2446041. The data have been smoothed over the resolution of approximately 12 km s^{-1} (Calvet et al. 1992)



13.1.1.2 Infall Signatures

For main sequence stars: Hα line profile is a result of:

- absorption at the stellar photosphere
- emission from the chromosphere (which is tricky for ordinary stellar chromospheres, densities too low)
  - Hα implies presence of material at high densities and $T = 5000 - 10000K$
  - Width of Hα requires that this material be moving at velocities of hundreds of km s^{-1} relative to the stellar surface (~ v_{ff})
    - Cannot be thermal broadening (would require 10^6 K)
    - Must be bulk motion!
    - indicates the presence of gas infalling onto the stellar surface

- Infalling gas provides high densities to produce Hα emission
- Temperature produced by internal shocks when the gas collides with the stellar surface
- The hot material would also produce continuum emission (cont. veiling)

Numerical computations show accretion rates of $10^{-11} - 10^{-6} M_{\odot} yr^{-1}$ with a rough correlation $\dot{M}_* \propto M_*^2$.

These accretion rates are generally low enough so that accretion luminosity does not dominate over stellar surface emission.

This seems to indicate that there must be some dense infalling material even around these stars that lack obvious envelopes.

Requires a reservoir of circumstellar material not in the form of an envelope, which is most naturally provided by a disk.

13.1.1.3 FU Orionis Outbursts

In 1936 the star FU Orionis, an object in Orion, brightened by ~5 magnitudes in B band over a few months.

After peaking, the luminosity began a very slow decline (it is still much brighter today than in its pre-outburst state).

Since then many other young stars observed with similar behavior: When available, the spectra of these stars in the pre-outburst state generally look like ordinary T Tauri stars.

- Within 1kpc, the rate of FU Orionis outbursts is ~ 1 per 5 yr.
- SF rate is ~1 per 50 years.
- Implies mean number of FU Ori outbursts per young star is ~ 10

Most popular explanation:

- sudden rise in accretion rate (comparable to embedded phase)
- large accretion luminosity
- decay in emission due to cooling time of gas

Mystery: What can set off the disk?

13.1.2 Disk Dispersal: Observation

Now: Disk around T Tauri stars (and similar stars)

13.1.2.1 Disk Lifetimes

Interesting property: disk lifetime: sets limit on planet formation timescale.

Different observational techniques probe different parts/types of disks.

- Optical line emission ($H\alpha$,…)
  - Disappears after 1 … 10 Myr
  - Inner parts of disk ($\lesssim$ 1AU), which feeds the star, disappears
- NIR ground-based observations
  - More distant parts of disk
  - Out to few AU
  - Similar timescale as inner disk
- Mid-IR (e.g. Spitzer @ 24μm)
  - Out to 10-100 AU
  - a small but non-zero fraction of systems retain some disks out to times of ~10^8 yr.
  - -> **debris disk**

Roughly half the systems lose their disks within ~ 3 Myr.

13.1.2.2 Transition Disks

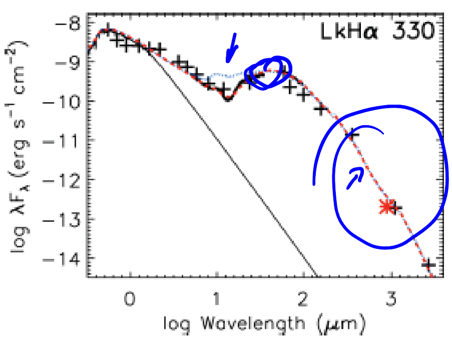


Figure 19.6: The spectral energy distribution of the star LkHα 330 (Brown et al., 2008). Plus signs indicate measurements. The black line is a model for a stellar photosphere. The blue line is a model for a star with a disk going all the way to the central star, while the red line is a model in for a disk with a 40 AU hole in its center.

The observation that accreting disks and inner optically thick disks disappear on a few Myr timescales, but that some fraction leave behind very small amounts of mass in the outer disk is a very interesting one. We will now look at the transition from gaseous, accreting T Tauri disks to low-mass debris disks.

Transition disk: significant 24 mm excess, but little or no IR excess (see Figure)

natural physical picture: a disk with a hole in its center (short wavelengths produced close to the star)

Now also confirmed by direct observations:

The holes are remarkably devoid of dust:

- upper limits on the masses of small dust grains within the hole are often at the level of $10^{-6} M_{\odot}$
- sharp edges of the holes indicate that the effect driving them isn't simply the growth of dust grains to larger sizes

13.1.3Disk Dispersal: Theory

We have seen the observations suggest that disks are cleared in a few Myr. We would like to understand what mechanism is responsible for this clearing.

13.1.3.1 Setting the Stage: The Minimum Mass Solar Nebula

Imagine spreading the mass in the Solar System's observed planets into an annulus that extends from its observed orbit to halfway to the next planet in each direction.

Add enough hydrogen and helium so that metal content matches that observed in the Sun.

- Mass distribution of the protoplanetary disk of the Sun must have had (if planets were formed where they are now)
- $M \sim 0.01\ M_{\odot}$ and $\Sigma = \Sigma_0\ \omega^{-3/2}$ $(\Sigma_0 \approx 1700\ g\ cm^{-2}, \omega = r/AU)$
- Main heating solar illumination => $T = 280\omega^{-1/2} K$
- Disk scale height

$$H = \frac{c_g}{\Omega} = \sqrt{\frac{k_B T}{\backslash mu}} \sqrt{\frac{\omega^3}{GM}} = 0.03\omega^{5/4}\ \text{AU} \quad (c_g\text{: gas sound speed})$$

- Disk consists of rocks (~2%) and ice (gas)

$$\Sigma_{rocks} \approx 7\omega^{-\frac{3}{2}}$$

$$\Sigma_{ice} \approx \begin{cases} 0 & T > 170K \\ 23\omega^{-3/2} & T < 170K \end{cases}$$

In other words, rocks are about 0.4% of the mass, and ices, where present, are about 1.3%. Typical densities for icy material are ~1 g cm^{-3}, and for rocky material they are ~3 g cm^{-3}.

13.1.3.2 Viscous Evolution

Obvious mechanism to get rid of disk: accretion onto star.

Viscous evolution without mass re-supply to disk edge.

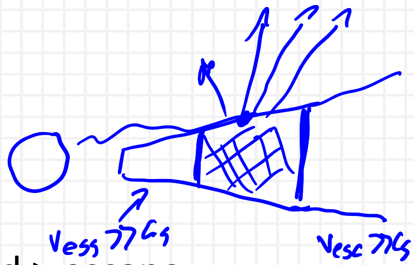
Accretion drains disk and reduces surface density.

T Tauri accretion rates of $10^{-9} - 10^{-8} M_{\odot} yr^{-1}$ and masses of $\sim 0.01 M_{\odot}$ implies: time to drain disk $\sim 1 - 10\ Myr$ (close to observed time).

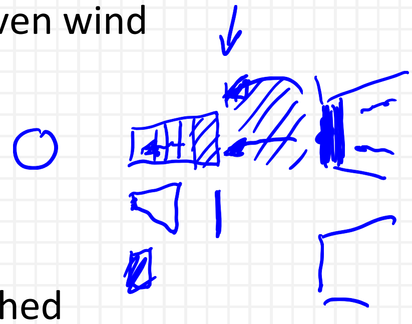
Problem of viscosity origin remains.

13.1.3.3 *Photoevaporation Models*

Alternative mechanism: photoevaporative winds:



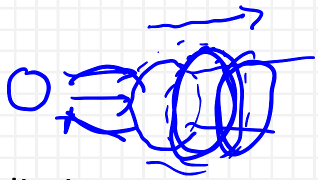
- Disk surface heated by stellar FUV
    - 100-200 K
    - 10^4 K closer to the star
- Far enough from the star the resulting sound speed > escape velocity
- Gas will flow away from the disk in a thermally-driven wind
- Max effect from region where $c_s \approx v_{esc}$
- If radiation intense enough:
    - Gap will form in the disk
    - Accretion cannot bridge the gap
    - Inner disk drains viscously and is not replenished
    - -> hole in the disk



13.1.3.4 *Rim Accretion Models*

In this scenario:

- magneto-rotational instability (MRI) operates only on the inner rim of the disk
- this rim is exposed to direct stellar light
- rim accretes inward while rest of disk is static
- as rim accretes more material is exposed to stellar radiation
- MR-active region grows
- Disk drains inside-out



This model nicely explains why disks will drain inside out. Moreover, it produces the additional result that any grains left in the disk that reach the rim will not accrete, and are instead blown out by stellar radiation pressure -> explains hole.

13.1.3.5 *Grain Growth and Planet Clearing Models*

The final possible mechanism for getting rid of the disk is the formation of planets.

- dust in a disk agglomerates
- forms larger bodies
- opacity per unit mass drops dramatically
- disk appears to disappear
- planetesimals further agglomerate into planets
- significant gravitational effects
- -> clear the gas

Population of solid particle of radius s, density of each is ρ_s , number density n:

$$\rho_d = \frac{4}{3}\pi\, \rho_s\, s^3\, n$$

For a velocity dispersion c_s, the mean time between collisions is:

$$t_{coll} = (n\, \pi\, s^2\, c_s)^{-1} = \frac{4}{3}\frac{\rho_s s}{\rho_d c_s}$$

within one scale height of the disk midplane, we may take

$$\rho_d \approx \frac{\Sigma_d}{H} = \frac{\Sigma_d \Omega}{c_g}$$

Where $\Sigma_d = \Sigma_{rock} + \Sigma_{ice}$. Brownian motion gives:

$$c_s = \sqrt{\frac{3}{2}k_B T} = \sqrt{\frac{3\mu}{2m_s}}c_g \approx 0.1\omega^{-\frac{1}{4}} s_{-4}^{-\frac{3}{2}} \rho_{s,0}^{-\frac{1}{2}} cm\, s^{-1}$$

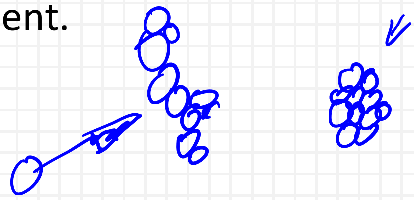
$m_s = \left(\frac{4}{3}\right)\pi s^3 \rho_s$, $\rho_{s,0} = \rho_s/(1\, g\, cm^{-3})$, $s_{-4} = s/(1\mu m)$. We get:

$$t_{coll} \approx \frac{4\sqrt{2}}{3\sqrt{3}}\frac{s\rho_s}{\Sigma_d \Omega}\sqrt{\frac{m_s}{\mu}} = \frac{8\sqrt{2\pi}}{9}\sqrt{\frac{\rho_s^3 s^5}{\Sigma_d^2 \Omega^2 \mu}} = (2.6,0.6)\omega^3 \rho_{s,0}^{\frac{3}{2}} s_{-4}^{\frac{5}{2}}\ \text{yr}$$

Where the two number correspond to the rocky and rock plus ice case.

Small particles that are inherited from the parent molecular cloud will very rapidly collide with one another in the disk: 1µm particle collides ~ 1 million times during disk lifetime.

As particles grow, collisions become much less frequent.



0.25mm particles collide once per Myr

What happens when particles collide?

- Very small particle: attracted by van der Waals forces
  - Low velocity: particle stick
  - High velocity: rebound/shatter

For 1 µm particles, estimated sticking velocities are ~1 - 100 cm s^{-1}, depending on the composition of the body (declines as $\sim s^{-1/2}$).

Smaller than Brownian speed -> 1-10 µm particles will grow very quickly to large sizes

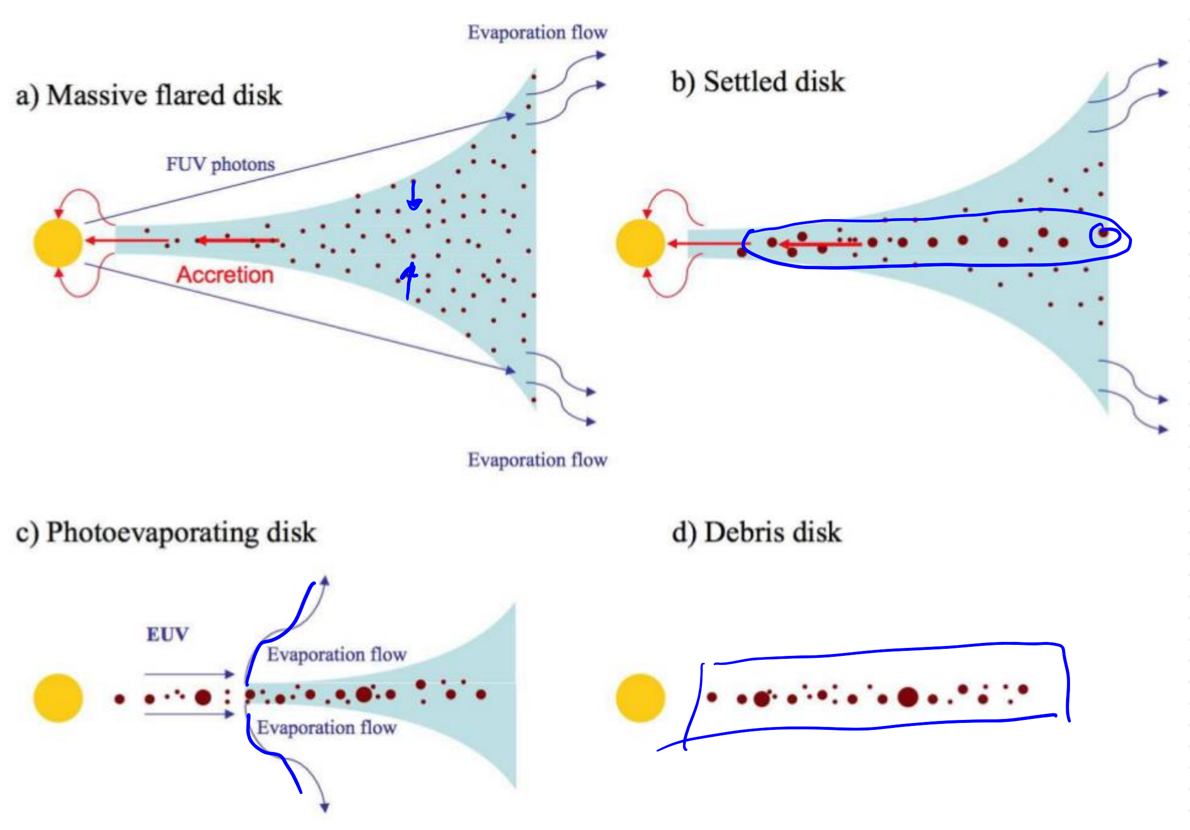


Figure 2 The evolutionary stages of a protoplanetary disk. The typical lifetime of protoplanetary disk is believed to be less than 10 million years (Myr). The flaring of the disk is due to hydrostatic balance. The median mass of Class II YSO disks is 5 times the mass of Jupiter. (Williams and Cieza 2011)

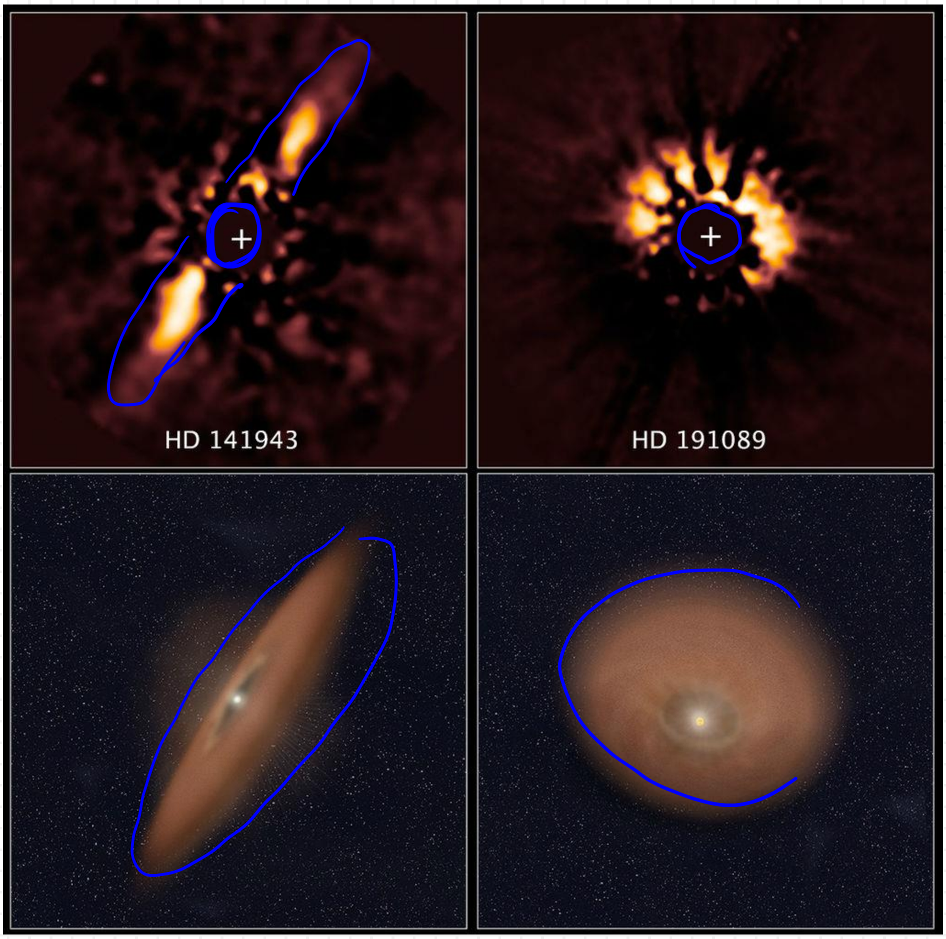


Figure 3 Debris disks detected in HST archival images of young stars, HD 141943 and HD 191089. The two images at top reveal debris disks around young stars uncovered in archival images taken by NASA's Hubble Space Telescope. The illustration beneath each image depicts the orientation of the debris disks. Image Credit: NASA/ESA, R. Soummer, Ann Feild (STScI) Credits: NASA/ESA, R. Soummer, Ann Feild (STScI)

13.2 The Transition to Planet Formation

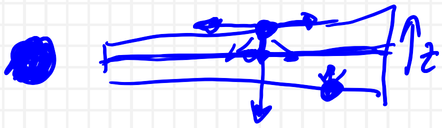
How do these solids evolve?

13.2.1 Dynamics of Solid Particles in a Disk

13.2.1.1 Forces on Solids

not

Disk mass << stellar mass, therefore we can neglect its gravity in radial direction



$$g_r = GM/r^2$$

Vertically, disk and star pull both, but for typical heights, star dominates

$$g_{z,*} = \frac{z}{r}\, g_r = \Omega^2 z$$

z: distance above disk midplane, Ω angular velocity of a Keplerian orbit. Disk is approximately an infinite slab of surface density Σ.

Gravitational force per unit mass by such a slab is

$g_{z,d} = 2\pi G\Sigma$

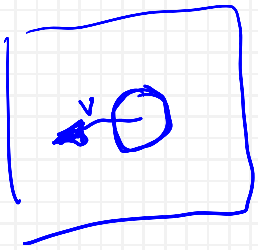
Ratio of stellar to disk force

$$\frac{g_{z,*}}{g_{z,d}} = \frac{\Omega^2 H}{2\pi G\Sigma} = \frac{c_g\Omega}{2\pi G\Sigma} = \frac{Q}{2}$$

Where $Q = \Omega c_g/(\pi G\Sigma)$ is the Toomre parameter for a Keplerian disk.

Thus the vertical gravity of the disk is negligible as long as it is Toomre stable, $Q \gg 1$.

minimum mass solar nebula: $Q = 55\omega^{-1/4}$. Unless we are very far out, stellar gravity completely dominates.

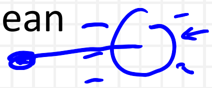


Other force on the solids that we have to consider is drag:

- Aerodynamic drag complicated
- Estimate drag force on small, slowly moving particle
  - Sphere of size s
  - Moving through gas with density ρ and c_s at velocity v relative to mean velocity of gas

$$collision\ rate \approx 4\pi s^2 \frac{\rho}{\mu} c_g$$

If the particle is at rest, collision on the all sides cancel out and mean transferred momentum is zero.



If it is moving: frontside collisions happen with $\sim c_g + v$ and rear face collisions with $\sim c_g - v$ -> net momentum transfer per collision of μv.

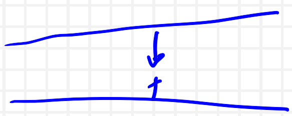
The net rate of momentum transfer, the drag force, is therefore the product of this with the collision rate:

$$F_D = C_D s^2 \rho v c_g$$

where C_D is a constant of order unity.

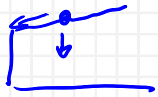
Integration over Boltzmann distribution and assuming elastic collisions give $C_D = 4\pi/3$ -> Epstein drag law.

Larger bodies experience Stokes drag, in which the dependence changes from $s^2\rho v c_g$ to $s^2\rho v^2$.



13.2.1.2 Settling

The vertical equation of motion for a particle is

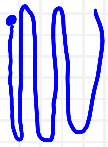


$$\frac{d^2z}{dt^2} = -g_z - \frac{F_D}{\frac{4}{3}\pi s^3 \rho_s} = -\Omega^2 z - \frac{\rho c_g}{\rho_s s}\frac{dz}{dt}$$

- Damped harmonic oscillator

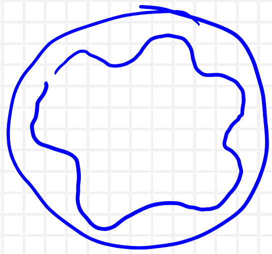
For constant $\rho$the ODE can be solved analytically:

$$z = z_0 e^{-t/\tau}$$

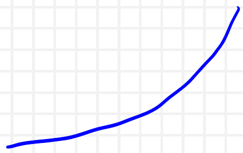


Where

$$\tau = 2\frac{\rho_s s}{\rho c_g}\left[1 - \left(1 - \frac{4s^2\rho_s^2\Omega^2}{\rho^2 c_g^2}\right)^{\frac{1}{2}}\right]^{-1}$$



- For large s:
  - Damping weak
  - Vertical movement is not stopped before they reach midplane
  - Vertical oscillations
- Small s
  - Strong damping
  - Particle slowly drift to midplane exponentially
- Critical s
  - Minimum settling time



$$s_c = \frac{\rho c_g}{2\rho_s\Omega} = 850\omega^{-3/2}\rho_{s,0}^{-1}\ cm$$

Thus all objects smaller than ~10 m boulders will slowly drift down to the midplane without oscillating.

For $s \ll s_c$ we find:

$$\tau \approx 4\frac{\rho_s s}{\rho c_g}\left(\frac{s}{s_c}\right)^{-2} = \frac{\rho c_g}{\rho_s\Omega^2 s} = 270\omega^{\frac{11}{4}}\rho_{s,0}^{-1}s_0^{-1}\ yr$$

Thus 1 cm grains will settle to the midplane almost immediately, while interstellar grains, those ~1 mm in size, will take several Myr to reach the midplane.

In practice coagulation and sedimentation occur simultaneously, and each enhances the other: growth helps particle sediment faster, and sedimentation raises the density, letting them collide more often.

13.2.1.3 Radial Drift

Now consider the radial direction:

- Gas in disk mostly supported by rotation
- Some additional pressure support
- Result: orbits at slightly sub-Keplerian velocities
- Solid bodies do not feel gas pressure!
- Orbit at Keplerian velocities >> gas velocities
- -> drag force on solids

$$\Delta v = \frac{2nc_s^2}{v_K} = \eta v_k^2$$

With $P \propto r^{-n}, \eta = 2nc_s^2/v_k^2$.

At 1 AU for our minimal mass solar nebula model $v = 70n\ m\ s^{-1}$.

Drag takes away angular momentum -> solids spiral inwards with stopping time: $t_s = mv/F_D$.

- Very small bodies:
  - $t_s \ll t_p = t_{orbital\ period}$
  - always forced into co-rotation with the gas
  - $v_{drift} \propto s^p$ for $\frac{t_s}{t_p} \ll 1$ (p is positive)
  - inward drift speed rises with particle size at small sizes
- Large bodies
  - $t_s \gg t_p$
  - Drag unable to force solid into co-rotation
  - Always in a near-Keplerian orbit
  - $v_{drift} \propto s^{p-q}$ for $\frac{t_s}{t_p} \gg 1$ (q is positive)
  - inward drift speed decreases with particle size at large sizes
- Intermediate size with max drift speed and min stopping time
  - The drift rate reaches a max for ~1m radius objects with loss time ~100 yr

- For km-sized objects the drift rate is back down to give loss times of 10^5-10^6 yr

13.2.2 From Pebbles to Planetesimals

Problem: once growth reaches ~1 m size, all those bodies should be dragged into the star in a very short amount of time.

13.2.2.1 Gravitational Growth

One solution: mechanism that allows particles to go directly from cm to km sizes, while spending essentially no time at intermediate sizes.

Candidate: gravitational instability

minimum mass Solar Nebula, the gas disk is very Toomre stable Q ~ 50

However, we also saw that solids will tend to settle toward the midplane, and the solids have a much smaller velocity dispersion than the gas. The Toomre Q for the solid material alone is

$$Q_s = \frac{\Omega c_s}{\pi G \Sigma_s}$$

Writing Q_s in terms of Q_g

$$Q_s = Q_g \left(\frac{\Sigma_s}{\Sigma_g}\right)\left(\frac{c_g}{c_s}\right) \approx (240{,}60) Q_g \left(\frac{c_g}{c_s}\right)$$

where the factors of 240 or 60 are for regions with and without solid ices, respectively.

gravitational instability for the solids, $Q_s < 1$ requires that $c_s \leq (30{,}7) cm\ s^{-1}$. If such an instability were to occur, the characteristic mass of the resulting object would be set by the Toomre mass

$$M_T = \frac{4c_s^4}{G^2 \Sigma_s} = (2 \times 10^{19}, 3 \times 10^{17})\ g$$

Adopting $\rho_{i,r} = (1{,}3) g\ cm^{-3}$ material, the corresponding sizes of spheres with this mass are (20, 3) km. This is large enough to avoid the size range where rapid loss occurs.

Detailed computations show that the instability condition turns out to be

$$\rho > 0.62\frac{M_*}{r^3} = 4 \times 10^{-7} M_{*,0}\omega^{-3}\ g\ cm^{-3}$$

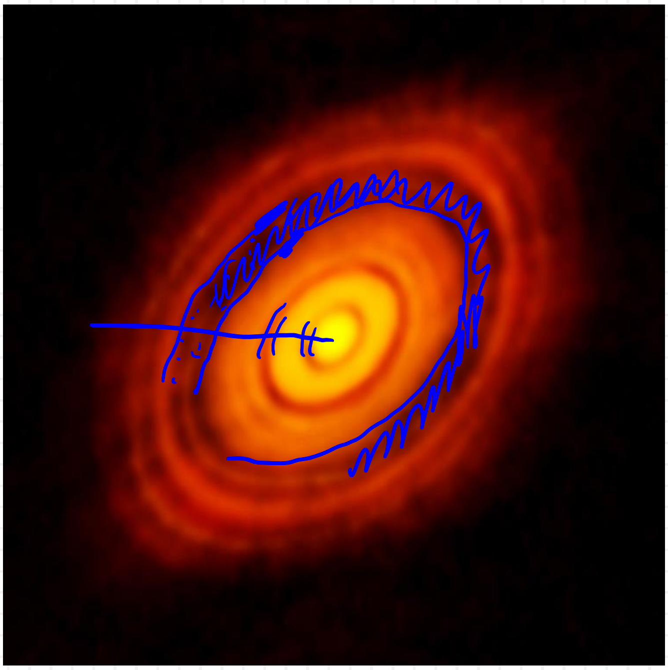
Where $\rho = \rho_s + \rho_g$, $M_{*,0} = \frac{M_*}{M_\odot}$ $and\ \omega = r/AU$

minimum mass solar nebula: $\rho = 3 \times 10^{-9}\ g\ cm^{-3}$

factor 100 too small for instabilities to set in unless density can be increased by factor 100

Kelvin-Helmholtz instabilities form because the gaseous disk rotates faster than the dusty midplane. This dredges up dust particles and can increase the density. Detailed analysis shows that:

gravitational instability cannot be a viable mechanism to jump from cm to km sizes unless a way can be found to enhance the solid to gas ratio in the disk by a factor of ~3 in the icy part of the disk, of ~10 in the rocky part.



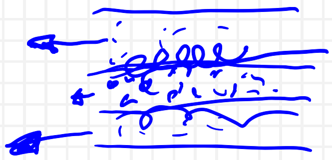


Figure 4 ALMA continuum images of HL Tauri Brogan et al. 2015

13.2.2.2 Hydrodynamic Concentration Mechanisms

Possible ways to increase the solid-to-gas ratio

1. concentration of small particles by eddies in a disk

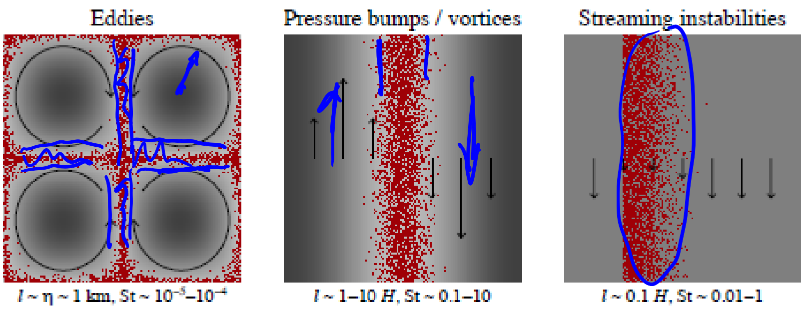


Figure 20.1: Schematic diagram of three mechanisms to concentrate particles in a protoplanetary disk. The left panel shows how small-scale turbulent eddies expel particles to their outskirts. The middle panel shows how zonal flows associated with large-scale pressure bumps concentrate particles. The right panel shows concentration by streaming instabilities. In each panel, black arrows show the velocity field, and the caption indicates the characteristic length scale of the structures shown, where H is the disk scale height.

Ω

- rotating disk with corotating coordinate system Ω: angul. velocity
- rotating eddy in disk
- gas at distance r from center of eddy is rotating with speed v_e
- two forces acting on gas: pressure gradient and Coriolis force
- static eddy requires that these two forces are equal to centripetal force associated with circular motion of eddy

$$2\Omega v_e - \frac{1}{\rho}\frac{dP}{dr} = -\frac{v_e^2}{r}$$

- in slowly rotating eddy ($\frac{v_e}{r} \ll \Omega$) we can ignore the right hand side, thus

$$\boxed{v_e = \frac{1}{2\rho\Omega}\frac{dP}{dr}}$$

  - if eddy is associated with pressure maximum $\frac{dP}{dt} < 0$ then $v_e < 0$, i.e. clockwise rotation
  - eddies associated with pressure minima $\frac{dP}{dt} > 0$ produce counter-clockwise rotation
- consider the dynamics of a solid particle moving through the eddy
  - if clockwise rotation
    - $v_e < 0$
    - material that is further from the star is orbiting somewhat more slowly
    - material further from the star will have a smaller velocity difference with the sub-Keplerian solids
    - material that is closer to the star is orbiting somewhat more rapidly

$F_D < F_D$

        - material that is closer to the star will have a somewhat larger velocity difference
    - drag force is therefore smaller on the far side of the eddy
    - drag force is therefore larger on the near side
- as solids drift from large radii inward and encounter the eddy
    - rate of drift slows down
    - they tend to pile up at the location of the eddy
- a potential mechanism to raise the local ratio of solids to gas, and thus to set of gravitational instability

Can something provide a pressure jump and thus can produce clockwise eddies? Yes: streaming instability

- Imagine that somewhere the local density of solids relative to gas is slightly enhanced
- We are in the mid-plane (partially sedimented), therefore the inertia of solids is non-negligible
- Drag force from solids to gas is not entirely negligible
- Tries to make the gas rotate faster - closer to Keplerian
- Reduces difference in gas and solid velocities
    - where the solid to gas ratio is enhanced, the
    - solids force the gas to rotate closer to their velocity
    - which in turn reduces the draft force and thus the inward drift speed
    - if solid particles are drifting inward
    - when they encounter a region of enhanced solid density
    - they will slow down and linger in that region
    - Instability because
        - Slowing down drift
        - Enhances solid density even further
        - Potential runaway

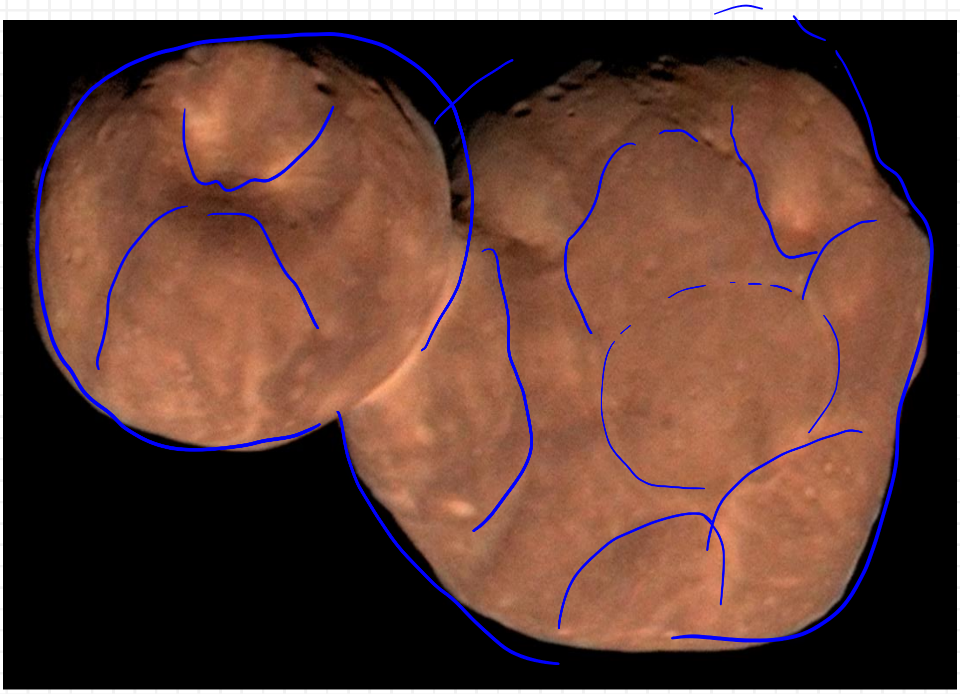


Figure 5 This composite image of the primordial contact binary Kuiper Belt Object 2014 MU69 (nicknamed Ultima Thule) – featured on the cover of the May 17 issue of the journal Science – was compiled from data obtained by NASA's New Horizons spacecraft as it flew by the object on Jan. 1, 2019. The image combines enhanced color data (close to what the human eye would see) with detailed high-resolution panchromatic pictures. (Credits: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute/Roman Tkachenko)

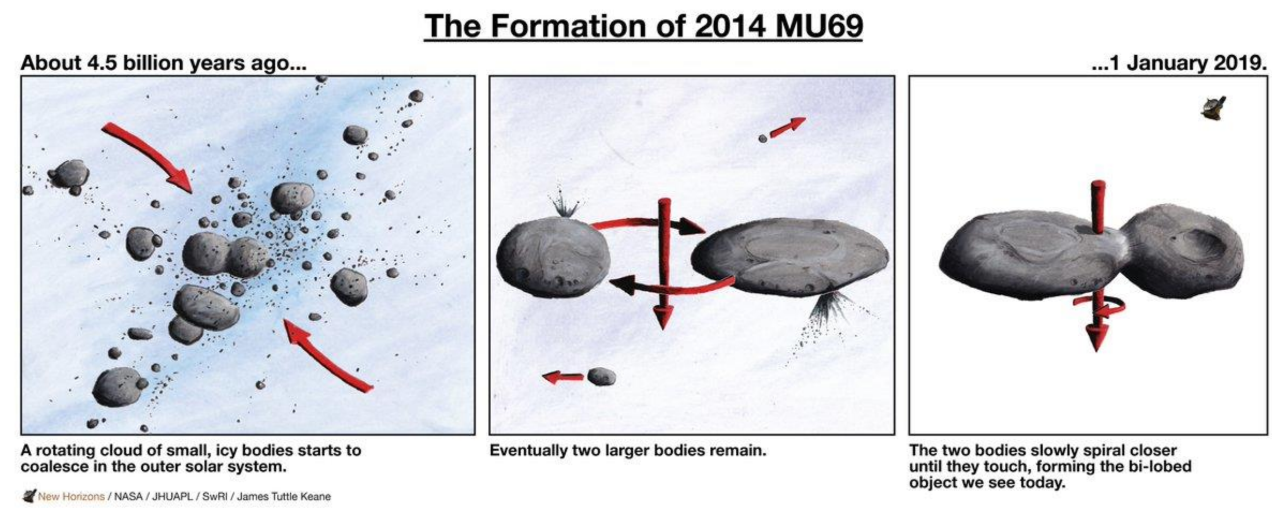


Figure 6 Illustration depicting the formation sequence of Arrokoth. Ultima Thule used to be 2 separate objects. It likely formed over time as a rotating cloud of small, icy bodies started to combine. Eventually, 2 larger bodies remained & slowly spiraled closer until they touched, forming the bi-lobed object we see today. Credits: NASA/JHUAPL/SwRI/James Tuttle Keane

Final Images

(source: Wikipedia):

PDS 70 (V1032 Centauri) is a low-mass T Tauri star in the constellation Centaurus. Located approximately 370 light-years from Earth, it has a mass of 0.82 $M_\odot$ and is approximately 10 million years old. The star has a protoplanetary disk containing two nascent exoplanets, named PDS 70b and PDS 70c, which have been directly imaged by the European Southern

Observatory's Very Large Telescope. PDS 70b was the first confirmed protoplanet to be directly imaged.

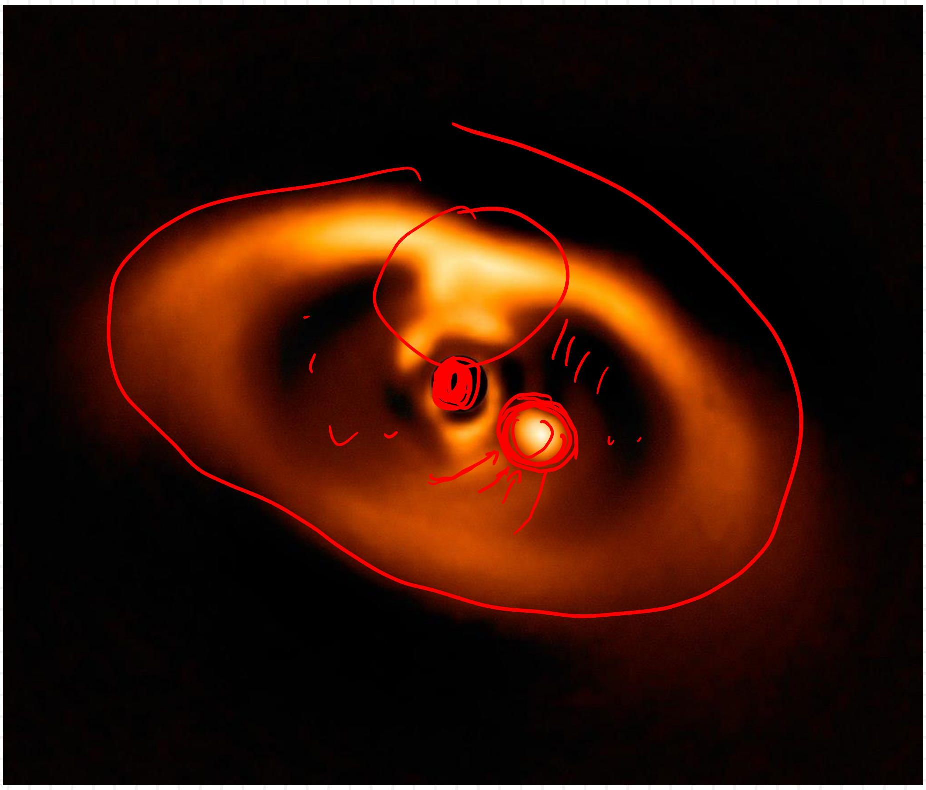
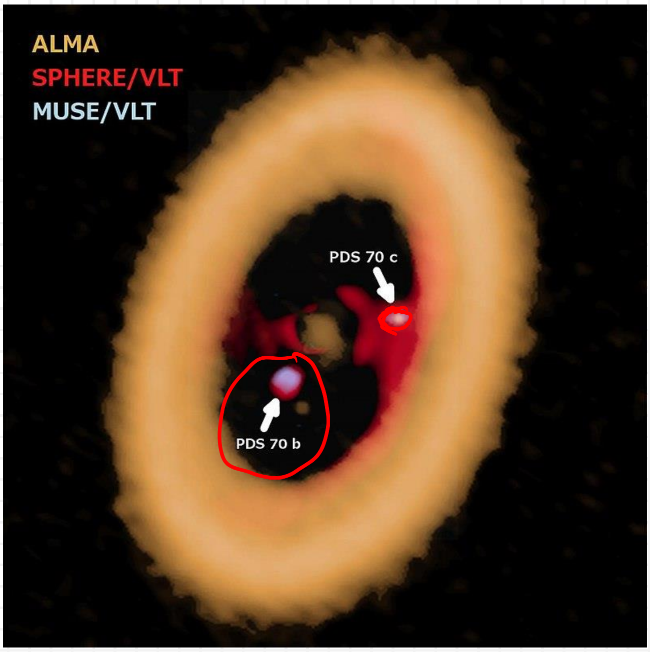


Figure 7 This spectacular image from the SPHERE instrument on ESO's Very Large Telescope is the first clear image of a planet caught in the very act of formation around the dwarf star PDS 70. The planet stands clearly out, visible as a bright point to the right of the centre of the image, which is blacked out by the coronagraph mask used to block the blinding light of the central star. Credits: ESO/A. Müller et al.

Circumplanetary Disk



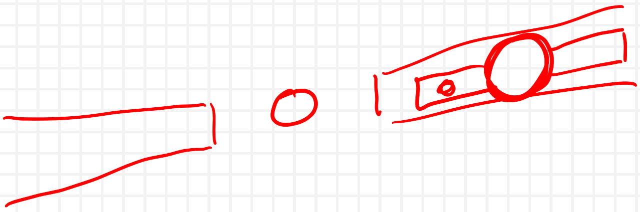


Figure 8 Circumplanetary disk around exoplanet PDS 70c. Composite image of PDS 70. Comparing new ALMA data to earlier VLT observations, astronomers determined that the young planet designated PDS 70 c has a circumplanetary disk, a feature that is strongly theorized to be the birthplace of moons. PDS 70 c is at a distance of 5.3 billion kilometers from its star, or approximately the distance of Uranus. Also visible in this image is another young planet, PDS 70 b, which lies at about the same distance from its star as Neptune; and the remains of a protoplanetary disk, which these planets formed out of. Credits: ALMA (ESO/NAOJ/NRAO) A. Isella; ESO