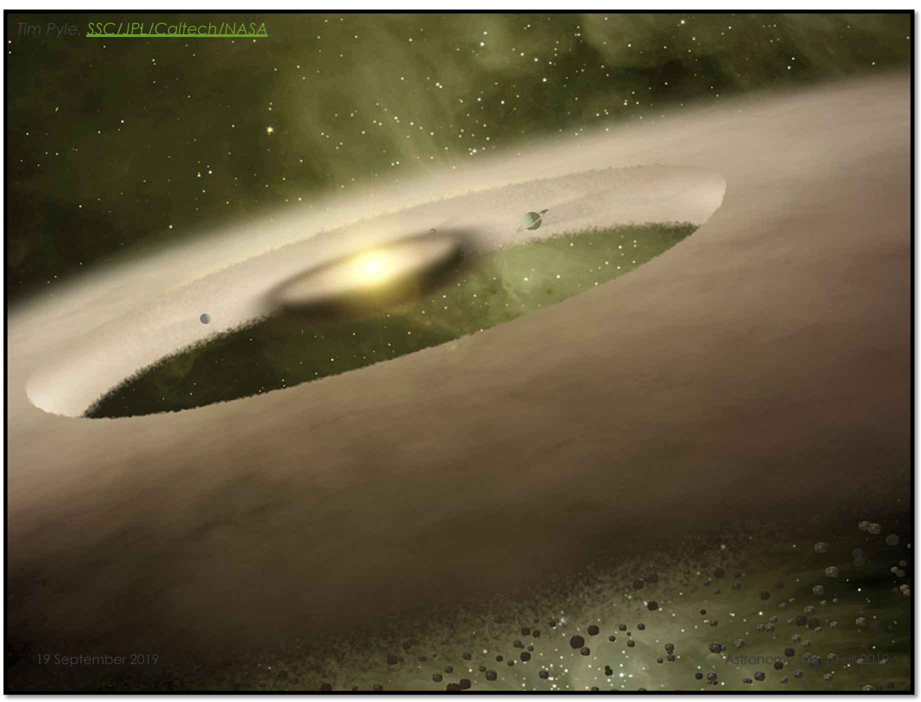
19 September
2019

PROTOPLANETARY DISKS & PLANET FORMATION



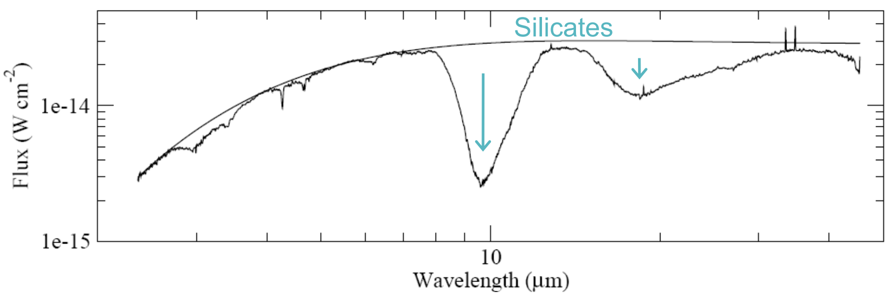
Protoplanetary disks & planet formation

- Formation of molecules on dust-grain surfaces and in the gas phase
- Interstellar molecular clouds
- Gravitational collapse of molecular clouds and the formation of stars and protoplanetary disks
- Star formation rate in the Milky Way: the Drake equation's R_*
- Finding protoplanetary disks: infrared excess and the temperature of dust in disks
- Protoplanetary disk evolution and planet formation

Dust grains in interstellar space

Some dust grains are made of **amorphous** (randomly oriented, non-crystalline) **carbon** – these are the larger end of the particles (the smaller end are the PAHs).

Most are made of the ingredients of silicate minerals – e.g. Si, O, Mg, and Fe – in the proportions found in common **silicate** minerals (e.g. $MgFeSiO_4$) and are also amorphous.



The origin of molecules

Interstellar molecules can get quite complex, and many abundant species are based upon carbon.

- Molecular complexity is extraterrestrial.
- Carbon-based chemistry is not unique to Earth. (Recall also that Earth is rather poorly supplied with C.)

How do molecules form from atoms in the ISM? Three ways:

- Dust grain catalysts
- Ion-molecule reactions
- Neutral-neutral reactions in shocked material

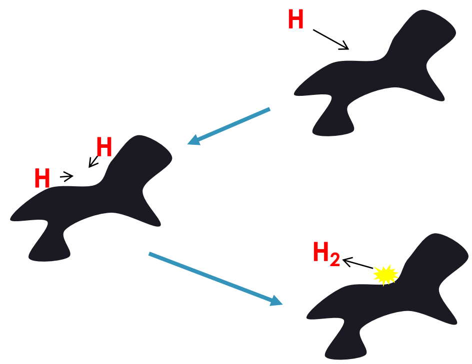
Why is not all the ISM in molecular form?

- Ultraviolet starlight destroys molecules when they are unprotected by lots of gas and dust.

Dust grain catalysis

Perhaps surprisingly, the most abundant molecule, H_2, cannot form by combining two H atoms in gas. Instead, its formation is **catalyzed** by dust grains.

- Colliding with a dust grain, an H atom is likely to lightly stick to the surface.
- Stuck lightly, it moves on the surface in response to surface charges and fields.
- If it finds another H atom, it can combine to form H_2.
  - The energy released in binding can kick the new molecule off the surface.
  - The grain goes away with the recoil momentum.

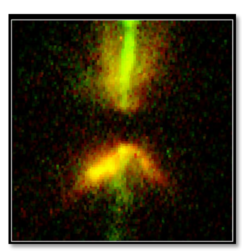


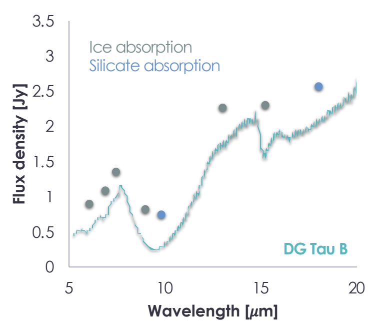
More chemistry on grain surfaces

In very cold regions, molecules can freeze onto the surfaces of dust grains and form "ice mantles."

Eventually, if enough energy (e.g. UV light) is added, the dense concentration of molecules can react to produce even more complex molecules that froze out in the first place.

Interstellar ethanol, for example, is thought to be made this way.





DG Tau B image by Hubble (STScI/NASA), spectrum by Spitzer (Watson et al. 2004)

Ion-molecule reactions

Neutral-neutral reactions can have a high threshold, but ion-molecule reactions have zero threshold.

There are always ions around, as ultraviolet light and high-energy cosmic rays (CRs; mostly high-energy photons) ionize atoms and molecules.

UV photon + C $\rightarrow$ $C^+ + e^-$

C^+ + H $\rightarrow$ CH^+ + photon

$CH^+ + O \rightarrow \boxed{CO} + H^+$

CR + $H_2 \rightarrow H_2^+ + e^-$ + CR

$H_2^+ + H_2 \rightarrow H_3^+ + H$

$H_3^+ + CO \rightarrow \boxed{HCO^+} + H_2$

$\Downarrow$

Increasingly complex molecules

Neutral-neutral reactions

When molecular matter is heated, as when a shock wave (supersonic disturbance, like a sonic boom) passes through, neutral-neutral reactions that have high thresholds or are even endothermic (cost energy) can produce species abundantly that are difficult to produce in large quantities otherwise:

$$O + H_2 \rightarrow OH + H$$

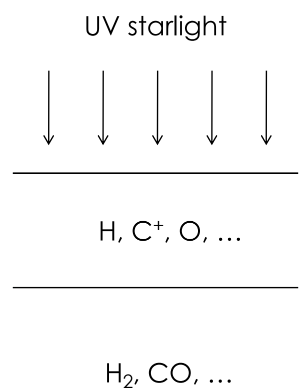
$$OH + H_2 \rightarrow H_2O + H$$

Dissociation of molecules

Molecules can be dissociated by UV starlight. But dust grains can absorb UV and simply warm up a little.

A dusty layer of gas with about 10^{21} H/cm^2 attenuates the general interstellar UV radiation field sufficiently for molecules to form behind it.

This layer, in which matter is mostly atomic, is called the **photodissociation** region.

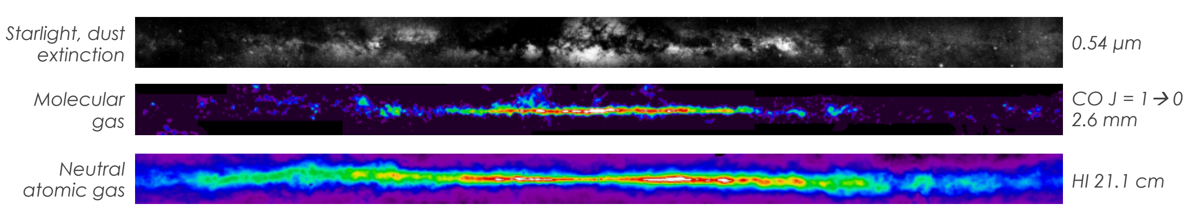


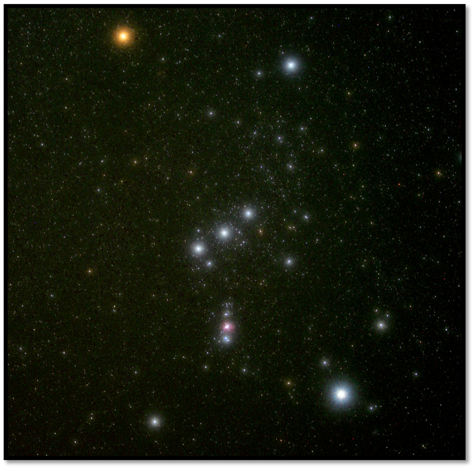
The interstellar medium (ISM)

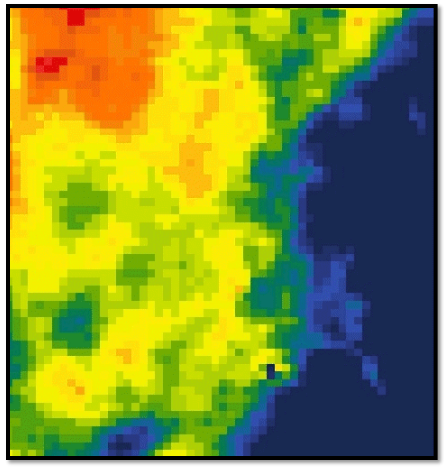
The ISM of the Milky Way has a mass of about $2\times10^{10} M_\odot$ ($M_\odot = 2\times10^{33}$ g = Sun's mass).

90% of it is matter in the form of **diffuse clouds**, mostly atomic in composition, and filling 40-80% of the Galaxy's volume.

10% is in **molecular cloud complexes**, shielded from starlight by surrounding diffuse clouds and filling a tiny fraction of the Galaxy's volume.



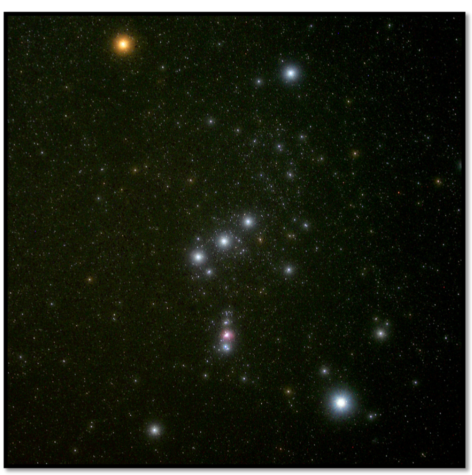


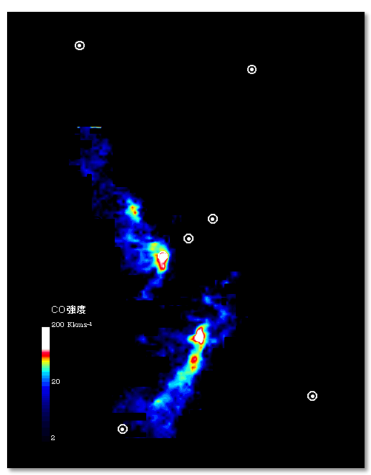


Orion and its diffuse clouds

Left: Visible John Gauvreau

Right: HI content Ron Maddalena, NRAO





Orion and its dense molecular clouds

Left: John Gauvreau

Right: Sakamoto et al. (1994)

Molecular clouds can gravitationally collapse

The molecules in molecular clouds have importance in addition to their potential biological role.

Molecular clouds are gravitationally bound and supported against their weight by pressure and turbulence.

If the clouds cool inefficiently (through emission of light), their pressure can hold them up for a long time.

Molecules radiate efficiently even at very low temperatures because of **collisional excitation** of their rotational transitions.

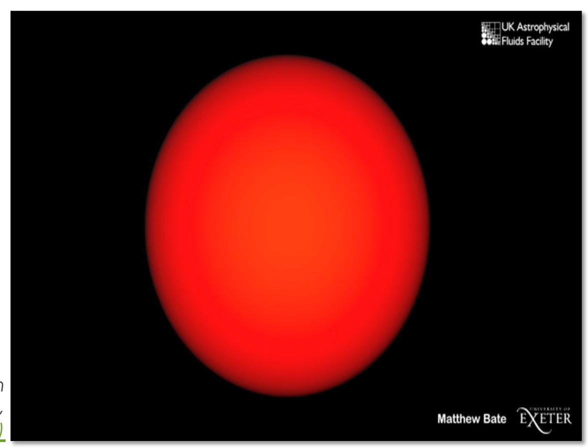
- Two molecules collide; some of the energy of their motion goes into exciting one of them to a higher-energy rotational state.
- The excited molecule returns to its ground state by radiating photons.
- The photons escape the cloud, carrying their energy with them.

Collapsing molecular clouds

While atomic clouds are typically $T = 70 - 100$ K, molecular clouds are typically 10-20 K.

Molecular cooling can rob a molecule clump of its internal heat and pressure and cause it to collapse to a (much) smaller size.

It turns out that this is how stars form.

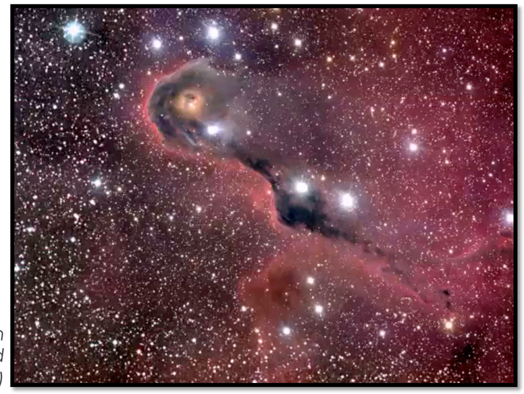


Simulation of star-cluster formation in an initially $500 M_\odot$ spherical cloud, by Matt Bate (2009)

Quick summary of star formation

The Milky Way is not unusual: most spiral galaxies have a large fraction of their gas (0.1-0.5) taken up by molecular clouds.

Much of this fraction is in the form of giant complexes of molecular clouds: massive ($10^4 - 10^6 M_\odot$), very dense (by interstellar standards), as well as fairly cold.



IC 1396: zoom to smaller scales and in wavelength from visible to mid-infrared (R. Hurt, SSC/JPL/Caltech/NASA)

Star formation

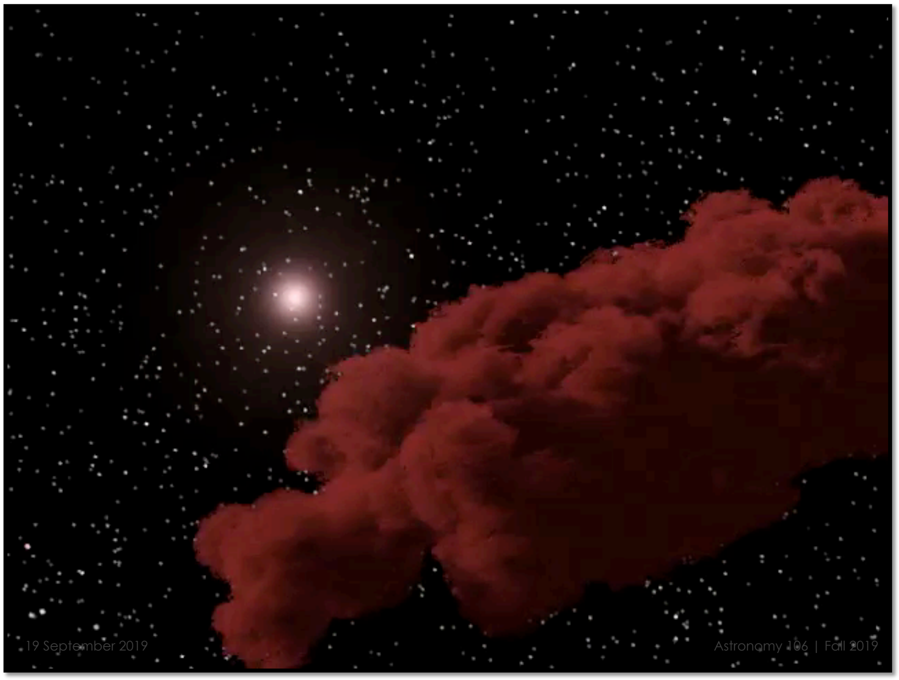
The molecular material can be seen directly with very long wavelength light ($\lambda = 30\ \mu$m – 3 mm) emitted by molecules and dust.

- Molecules are seen by being "heated" into higher rotational energy states by collisions with other molecules. The longer the wavelength, the smaller the energy difference between rotational states.
- Dust grains are seen by their thermal (blackbody) radiation; they are also heated by collisions with molecules and, on cloud edges, by UV light.

As fragments of molecular clouds emit the light we see, they cool down even more.

If a molecular cloud fragment cools enough so that its internal pressure is insufficient to support its weight and any external pressure, it will collapse and its density will rise.

Physical conditions in molecular clouds are often such that the density increase leads to an even greater light-emission (i.e. cooling) rate than before, which causes the fragment to collapse further, thus cooling even faster, thus collapsing even further, etc. This sort of runaway is called **gravitational instability**.



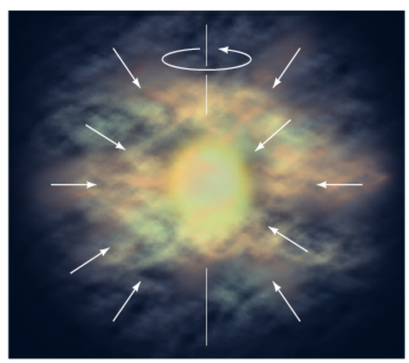
Supernova-induced star formation

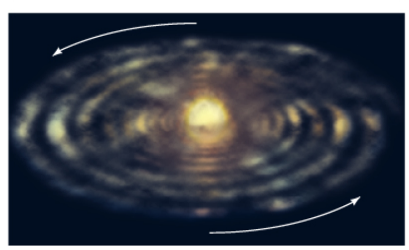
R. Hurt, SSC/JPL/Caltech/NASA

Star formation

In general, the fragment was slowly tumbling before the collapse started. But it has to obey conservation of angular momentum (spin), and now that it is somewhat disconnected from its surroundings, it spins up as it collapses.

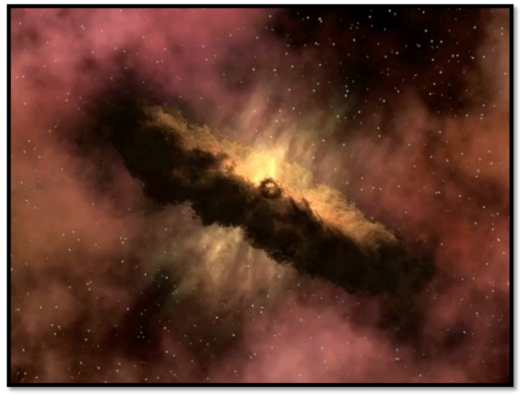
Along the rotation axis, the collapse can proceed freely. In the perpendicular directions, the collapse is stopped by centrifugal support: a **protostar** and a surrounding **disk** have formed.





Star formation

The disk continues to "collapse" in its radial direction, but much more slowly: collisions among molecules and dust grains at slightly different radii (and orbital speeds) slowly convert the angular momentum to heat and allow material to slowly progress toward the center. The central protostar builds up from this **accretion disk**.

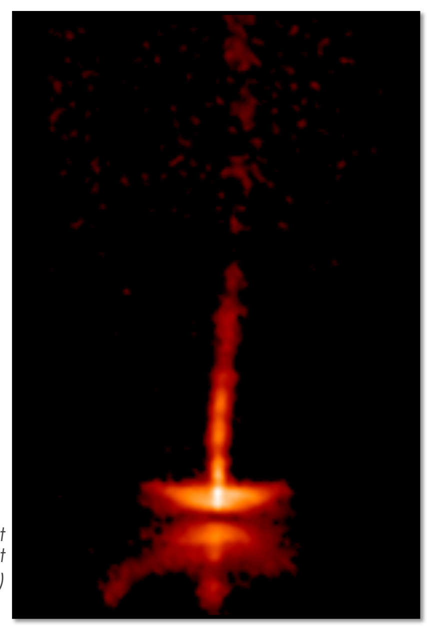


Protostar with accretion disk (R. Hurt, SSC/JPL/Caltech/NASA)

Star formation

For awhile, the central object accretes gas and dust from the disk and drives a bipolar outflow into its surroundings, which is thought to carry off the accreted material's spin.

The star cannot inherit all the spin of the disk without breaking up.



Several HST-WFPC2 images of the jet in the edge-on young stellar object HH30 by Alan Watson et al. (2000)

Star formation

Over time, the disk dissipates due to numerous processes that use up or drive away the surrounding dust and gas. We can see this evolution by looking at the **spectra** of the disk or **images** of the structure of the disk at **infrared** (and longer) wavelengths, because its temperature is ~100 K.

After 3-5 million years, not much (micron-size) dust or gas remains around the star.

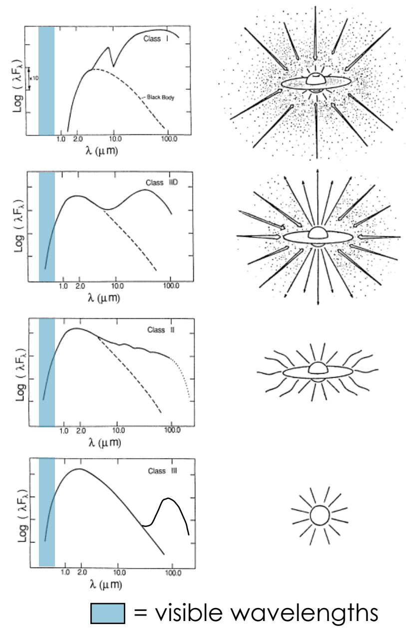


Figure adapted from Wilking (1989)

Stars form in molecular clouds because of

Question!

A. External pressure: a supernova needs to have gone off nearby
B. Gravitational instability: gas blob cools off internally by molecular-line emission and collapses under its own weight
C. Sometimes a little of A but mostly B
D. Sometimes a little of B but mostly A

Disks form around newborn stars because

Question #2

A. External pressure in the form of supernova blasts can only compress things along one dimension
B. Angular momentum makes it difficult for gravitational collapse to proceed in the two dimensions into which material can assume orbital motion.
C. Sometimes a little of A but mostly B
D. Sometimes a little of B but mostly A

The star formation rate in the Milky Way (R_*)

We will estimate our first Drake Equation quantity, the star formation rate R_*, in three different ways using the most up-to-date observations.

One way of estimating this value is by making multiple measurements of the numbers and ages of very massive stars and extrapolating this to the total mass in stars. While rather complicated, this is the way astronomers attempt to measure star formation rates in galaxies outside the Milky Way. The result (Licquia & Newman, 2015) is

$$R_{*,\mathrm{CP}} = (1.65 \pm 0.19) M_\odot/\mathrm{yr}$$

The authors note that values larger by factors of at least 2-3 are usually obtained by counting all the stars, for cases in which that is possible.

The star formation rate in the Milky Way (R_*)

Current rate of star formation: based on counting very young stars still embedded in their placental molecular clouds, and dividing by their typical age

- Result for 20 nearby molecular clouds (Heiderman et al. 2010)
  - Star formation rate: $R = (8.2 \pm 3.8) \times 10^{-4} M_\odot/\mathrm{yr}$
  - Molecular cloud mass: $M = (8.7 \pm 3.5) \times 10^{4}\ M_\odot$
- It is only "easy" to count individual young stars in the nearest clouds. However, it is "easy" to measure the total mass of *dense* molecular clouds in the Galaxy by surveying molecular-line emission over the entire sky (e.g. Kennicut & Evans 2012):

$$M_{\mathrm{total}} = 8 \times 10^{8}\ M_\odot$$

$$R_{*,\mathrm{now}} = R\,\frac{M_{\mathrm{total}}}{M} = (8 \pm 4)\ M_\odot/\mathrm{yr}$$

Star formation rate, R_*

Lifetime average rate of star formation. We know the mass of the stars in the Galaxy from observed extent and rotation speed of the Galaxy and Newton's Laws.

- Same way we know the mass of the Sun from the Earth's orbital extent and speed.
- Complicated, though, by presence of **dark matter** in the Galaxy, so we will skip to the answer (Licquia & Newman 2015):

$$M_* = (6.08 \pm 1.14) \times 10^{10}\ M_\odot$$

- We also know that stars more than 10 billion years old are rare, so the **average** rate of star formation has been something like

$$R_{*,\mathrm{average}} = \frac{M_*}{10 \times 10^{9}\ \mathrm{yrs}} \approx 8\ M_\odot/\mathrm{yr}$$

Star formation rate, R_*

The Milky Way Galaxy's current star formation rate is within the (large!) uncertainties of the lifetime-average rate.

We might expect, as the Galaxy's molecular-cloud supply is gradually used up in the form of very long-lived stars, for the star formation rate to decrease with time over the course of tens of billions of years. Observations may someday show this.

We will adopt $8M_\odot/\mathrm{yr}$, and since the most common stars have mass $M = 0.5M_\odot$, we have

$$R_* = 8\ M_\odot/\ \mathrm{yr} \times \frac{\mathrm{star}}{0.5\ M_\odot} = \boxed{16\ \mathrm{stars/yr}}$$

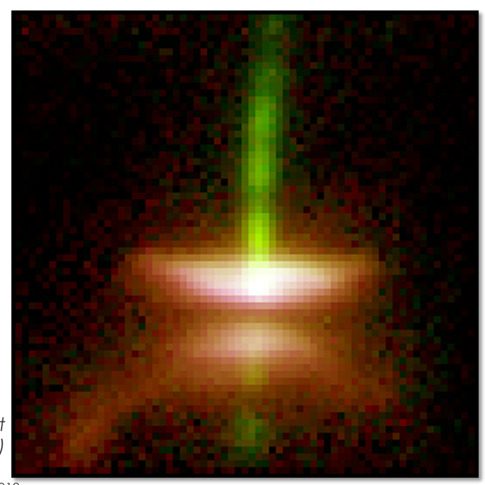
for our **Drake equation input**, noting that it is uncertain by something like a factor of two: the value may actually lie anywhere between 8 and 32 stars per year.

Young stars and protoplanetary disks

The youngest stars are found in close proximity to the molecular clouds from which they formed.

We can measure the age of a **cluster** of young stars by comparing the run of their **luminosities** (total power output in the form of light) and colors with those of older stars which do not belong to clusters.

Young stars are usually surrounded by disks.

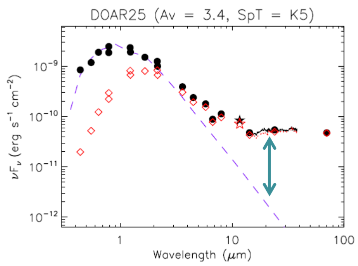


A protoplanetary disk viewed edge-on at visible wavelengths (HH30, STScI/NASA)

Detecting protoplanetary disks

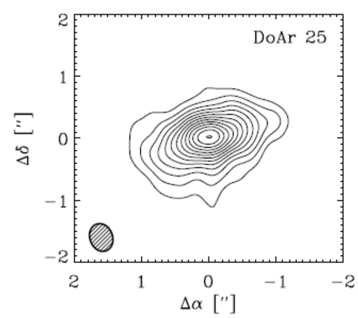
Most disks are too small on the sky, and most telescopes are too small, to easily take good pictures of them. We find them mostly by

- **Infrared excesses**: emission by dust in the disk in excess of the star's total power output. Thousands are known by this method.
- **Millimeter-wavelength interferometry**, in which signals from multiple telescopes are combined to replicate the functions of a very large telescope. Several dozen have been detected this way.



McClure et al. (2010)

Andrews et al. (2009)



Infrared excesses and the temperature of dust grains

The temperature of dust in protoplanetary disks is set by heating from the central star and cooling by the dust's **blackbody radiation**. The infrared excess is this radiation.

All opaque bodies emit radiation. You do not notice it because the light we emit comes out at infrared wavelengths, which our eyes are not sensitive to.

The total **flux** F (power per unit surface area) emitted by an opaque, perfectly light-absorbing body with temperature T turns out to be

$$F = \sigma T^4$$ Stefan's Law

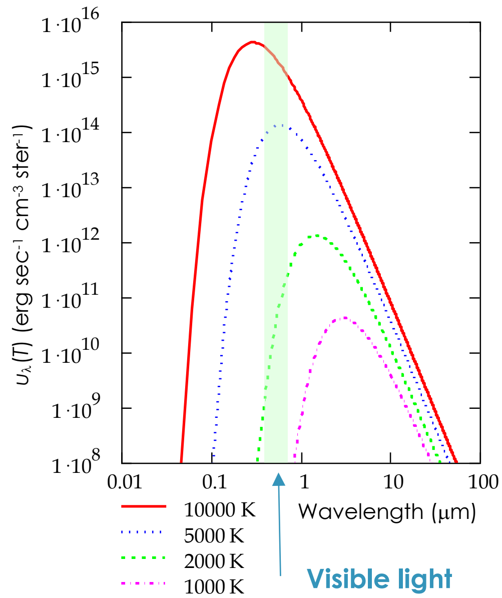
$$\text{where } \sigma = 5.67\times10^{-5}\ \mathrm{erg\ s^{-1}\ cm^{-2}\ K^{-4}}$$ Stefan-Boltzmann constant

So what is the temperature (T) of a dust grain as a function of how far away it is from the star (r)?

Blackbodies

Blackbodies with different temperatures emit different total fluxes and have different spectra.

The wavelength at which a blackbody is brightest is inversely proportional to its temperature. This turns out to be a good way to measure the temperature of distant blackbodies.



Temperature of dust grains

Time for another derivation. You will be responsible for knowing the result and understanding the reasoning, but not for the algebra.

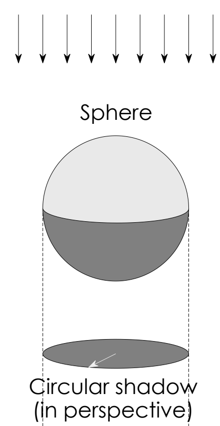
Consider a spherical, perfectly black dust grain with radius a (surface area $4\pi a^2$) which is located a distance r away from a star with luminosity (total light power per unit time) L.

- Starlight flux (power / unit area) at location of grain:

$$F_* = \frac{L}{4\pi r^2}$$

- Spheres cast circular shadows, so the total **power** (energy / unit time) absorbed, P_{abs}, is

$$P_{\text{abs}} = F_* \times (\text{shadow area}) = \frac{L}{4\pi r^2}\pi a^2$$



Temperature derivation

Suppose the dust grain is **uniform** in temperature (same T at all points on its surface). Then the power it emits in blackbody radiation is

$$P_{\mathrm{emit}} = F_{\mathrm{blackbody}} \times \text{surface area} = \sigma T^4 4\pi a^2$$

If its temperature is **constant** in time, then because **energy is conserved**, the grain emits exactly as much power as it absorbs:

$$P_{\mathrm{abs}} = P_{\mathrm{emit}}$$

$$\frac{L}{4\pi r^2}\pi a^2 = \sigma T^4 4\pi a^2$$

$$T = \left(\frac{L}{16\pi\sigma r^2}\right)^{1/4}$$

Dust grain temperature – units

Usually, it will be convenient to use units of solar luminosity, $L_\odot$, and Earth-Sun distance, AU, instead of erg/s and cm:

$$L_\odot = 3.83\times10^{33}\ \mathrm{erg/s}$$

$$\mathrm{AU} = 1.496\times10^{13}\ \mathrm{cm}$$

In which case the equation for dust-grain temperature becomes

$$T = \left(\frac{L_\odot}{16\pi\sigma \mathrm{AU}^2}\right)^{\frac{1}{4}} \left(\frac{L/L_\odot}{\left(r/\mathrm{AU}\right)^2}\right)^{\frac{1}{4}} = 279\ \mathrm{K}\times\left(\frac{L[L_\odot]}{(r[\mathrm{AU}])^2}\right)^{\frac{1}{4}}$$

[x] means "in units of x"

Suppose the Earth were considered to be a large dust grain which acts as a perfect uniform-temperature blackbody. What would its temperature be, according to this procedure?

Question

A. 2790 K
B. 279 K
C. 27.9 K
D. 2.79 K

Albedo

Few grain, or planetary, surfaces are perfectly black. Most reflect some of the light.

We call the fraction of incident light that is reflected the **albedo**, usually give the symbol A.

This reduces the absorbed power by a factor of $1 - A$. That is the same as the star having a factor $1 - A$ lower luminosity, so our formula becomes

$$\boxed{T = \left(\frac{(1-A)L}{16\pi\sigma r^2}\right)^{\frac{1}{4}} = 279\ \mathrm{K} \times \left(\frac{(1-A)L[L_\odot]}{(r[\mathrm{AU}])^2}\right)^{\frac{1}{4}}}$$

You need to understand how to use this equation.

The snow line

If you know the temperature you want, you can also calculate the appropriate distance by solving for r instead of T:

$$\boxed{r[\mathrm{AU}] = \left(\frac{279\ \mathrm{K}}{T}\right)^2 \sqrt{(1-A)L[L_\odot]}}$$

You also need to understand how to use this formula.

Example: the snow line. Ice makes dust grains shiny ($A \sim 0.7$). In the vacuum of space, water ice sublimates at a temperature of 150 to 170 K depending upon what other ices it is mixed with. In a disk, how far away from a $1L_\odot$ star would ice be found?

$$r[\mathrm{AU}] = \left(\frac{279\ \mathrm{K}}{150\ \mathrm{to}\ 170\ \mathrm{K}}\right)^2 \sqrt{(0.3)(1)} = 1.9\ \mathrm{to}\ 1.5\ \mathrm{AU}$$

Suppose the Earth were considered, again, to be a giant dust grain. Its numerous clouds endow it with an albedo of 0.37. What would its temperature be?

Question

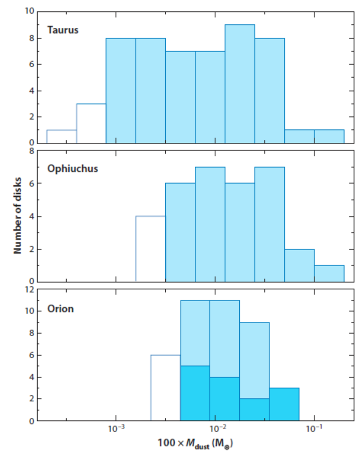
Protoplanetary disk mass

In the youngest stellar clusters, protoplanetary disks are found around essentially every star.

The masses of the disks can be measured by various means – notably via dust emission seen at millimeter wavelengths.

Disks turn out typically to have masses several percent of their central stars – plenty out of which to make planets.

- At least $0.03 M_\odot$ of disk was necessary to make our planets.



Disk-mass census in three nearby young stellar clusters (Williams & Cieza 2011)

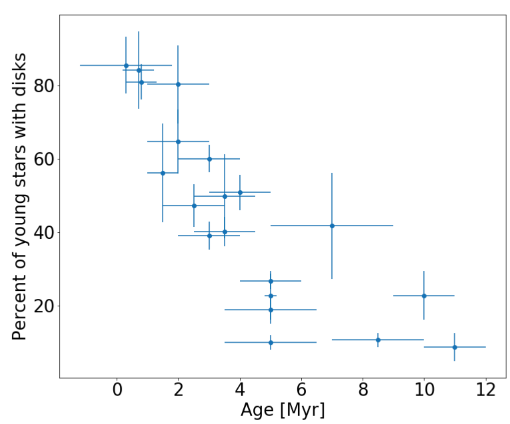
Protoplanetary disk evolution

Protoplanetary disks do not live very long – they vanish with a half-life of about 3 Myr.

Planet formation is only one of several processes that can eliminate the disk. Most others involve dispersal by the central star's light or magnetism.

If planets can form in 3 Myr or less, practically all stars will have planets – in Drake equation terms, $f_p = 1$

Sure enough, they do.



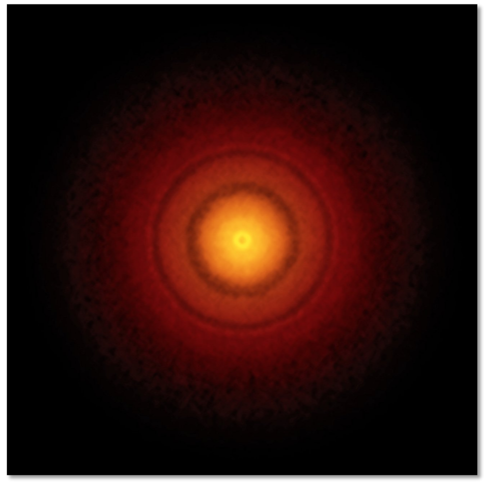
Disk census in young clusters within 1500 light years of the Sun (Kim et al. 2013)

How planets are thought to form

For a long time (Swedenborg 1734, Kant 1755, Laplace 1796), it had been though that the Solar System must have formed from a disk-shaped nebula.

When the youngest stars were found to always be surrounded by dusty disks in the 1970s, such disks were immediately identified as the birthplaces of planetary systems.

Unfortunately, these planets are very difficult to directly observe, since they are outshone by their stars and dust in the disks.

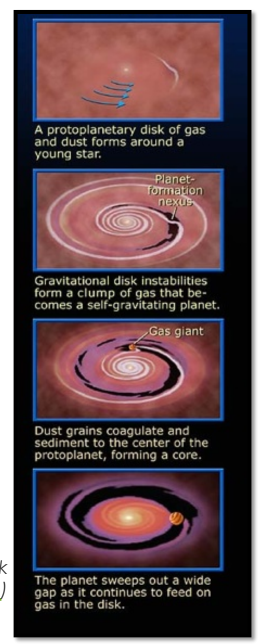


The disk around TW Hydrae (ALMA)

Planet formation by gravitational instability

Two of the three mechanisms people have thought up for planetary formation from disks are similar to the collapse of molecular clumps into protostars:

- Rapid growth of gravitational instabilities in the gas (Kuiper 1951, Cameron 1962, Boss 2001). This would be a good way to make gas-giant planets directly and rapidly.
- Rapid growth of gravitational instabilities in the dust (Goldreich & Ward 1973). This would be a good way to make terrestrial planets or rocky cores for giant planets.



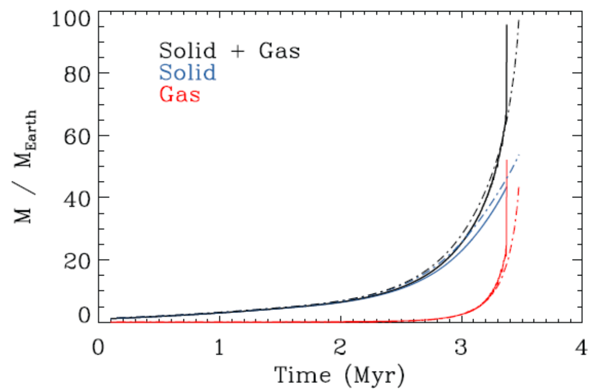
Instability growth in a gas disk (NASA, A. Field (STScI))

Planet formation by core-accretion

The third is **core-accretion**: two-body collisions combine small solid bodies (starting with dust grains) into larger ones, eventually resulting in planet or planet-core size bodies.

This is much slower than the other methods, but it is faster than it sounds because the rate of accretion of the largest bodies increases rapidly with the size of these bodies.

These days, it looks like **most planets form by core-accretion**, though some very massive ones far from their stars may give a good argument for G-I.



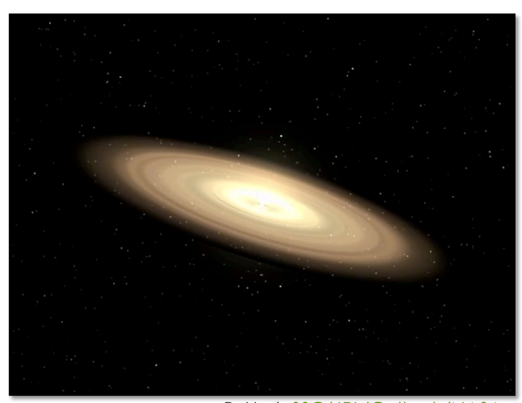
Core-accretion model for the formation of Saturn (Dodson-Robinson et al. 2008)

Transitional disks

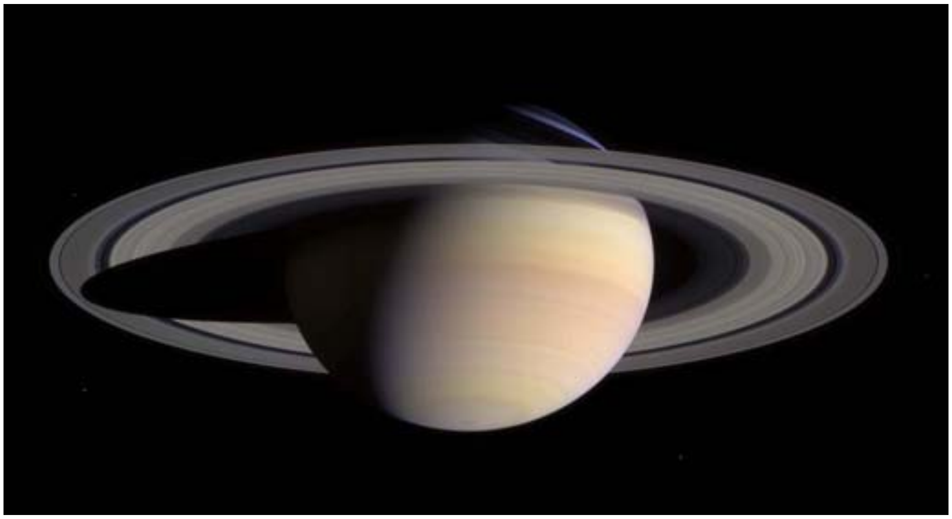
There are easier ways to detect planets recently formed within disks than to see the planet in an image: look for the planet's "wake."

A giant planet like Jupiter would cause the formation of a radial gap or a central clearing in the dusty disk in which it formed by gravitational influence on orbiting disk material.

…just as in the case of the moonlets and gaps in Saturn's rings.

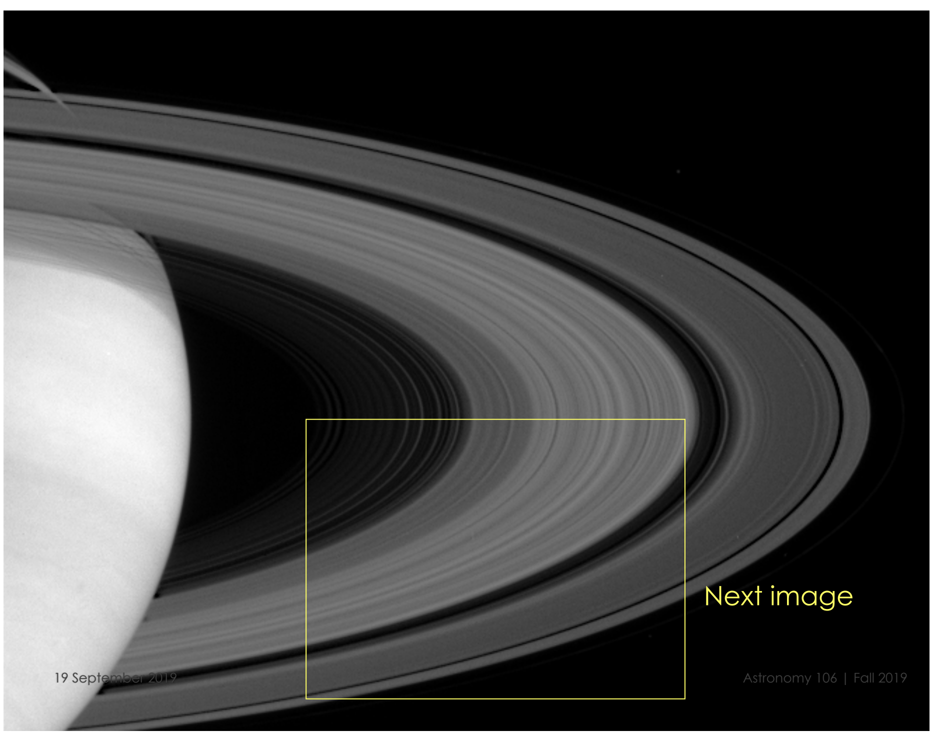


R. Hurt, SSC/JPL/Caltech/NASA



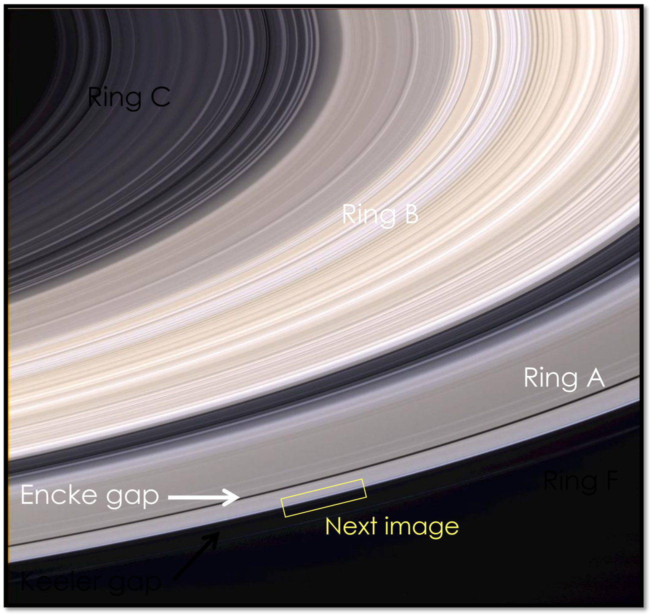
Saturn’s rings: gaps and moonlets

Image from the Cassini satellite (NASA/JPL)



Saturn’s rings: gaps and moonlets

Image from the Cassini satellite (NASA/JPL)



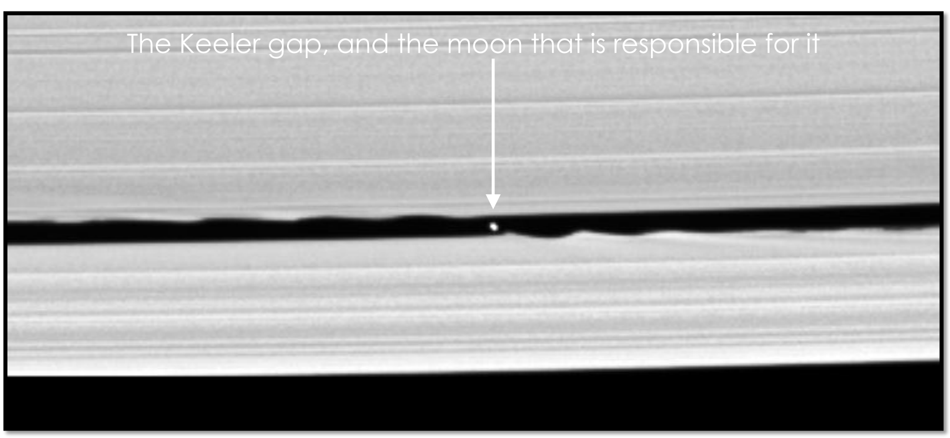
Saturn's rings: gaps and moonlets

Cassini division caused by the moon Mimas, which lies slightly outside the rings.

Image from the Cassini satellite (NASA/JPL)

Saturn's rings: gaps and moonlets

Image from the Cassini satellite (NASA/JPL)

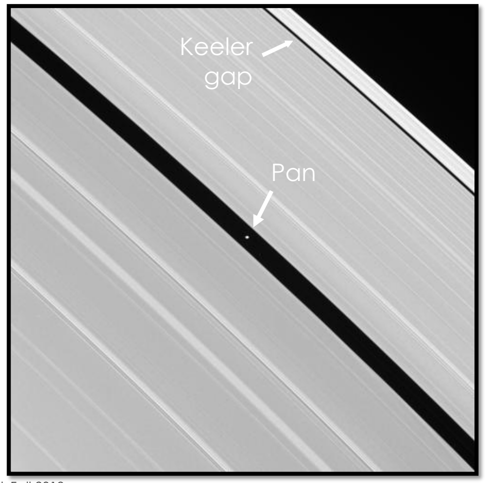


Saturn's rings: gaps and moonlets

Notice how much easier it is to see the gap than the moonlet that made it?

Gaps can be seen in images, but…

…in principle, also seen as "gaps" in the blackbody emission of dust within the disks.



The Encke gap and the moonlet Pan. Image from the Cassini satellite (NASA/JPL)

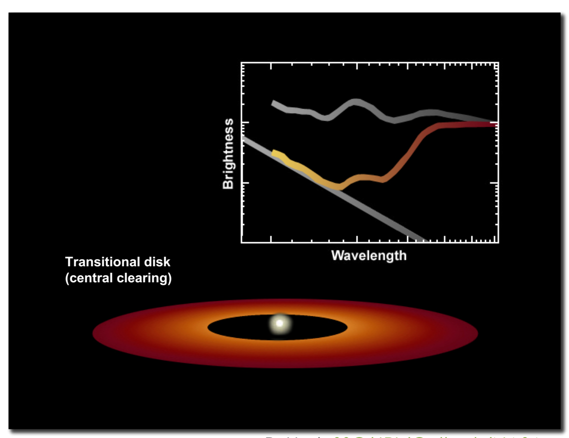
Transitional disks

In some protoplanetary disks, gaps appear as deficits in the infrared excess 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 a few-AU to few-10s-of-AU gaps.

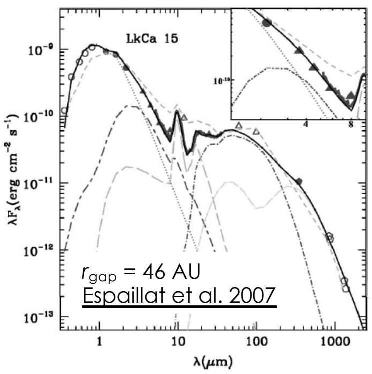
The vast majority of these gaps must be cleared by objects of giant planetary mass.

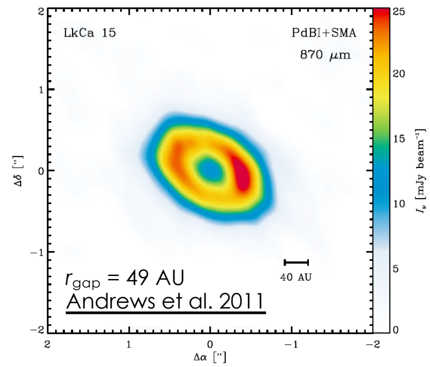


R. Hurt, SSC/JPL/Caltech/NASA

Transitional disks

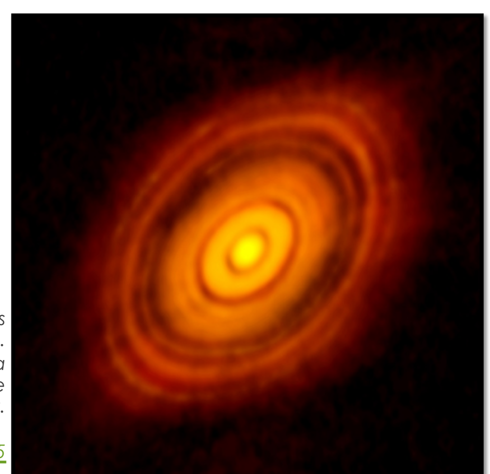
So far, in some 15 of these objects like LkCa 15 below, it is possible to resolve the outer disk at millimeter wavelengths. This reveals an outer boundary of the gap and the scarcity of the dust within. We see the same gaps in spectra and in the images.





Smaller gaps in a younger disk

Recent observations at wavelength 1 mm by the new Atacama Large Millimeter Array (ALMA) of a 0.5 Myr-old young star called HL Tauri revealed a concentric nest of gaps, **each probably harboring a giant planet**.



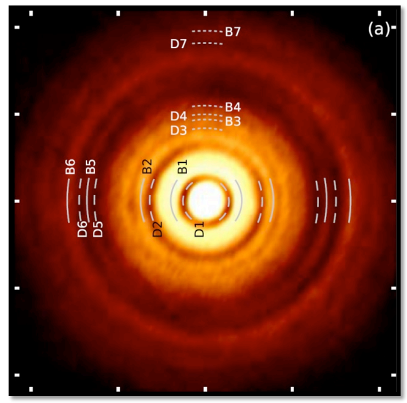
HL Tau, as observed. The system lies 457 light-years from the Solar System. Gaps do not appear circular when a tilt of 46.72° is inferred between the rotation axis and our line of sight.

ALMA partnership 2015

Smaller gaps in a younger disk

Observed emission is predominantly from mm-size dust grains in the disk; star and planets not seen in image.

HL Tau is young enough that it is still embedded in its natural envelope, through which the disk is seen.



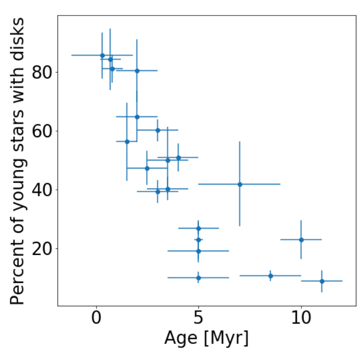
Digitally de-tilted. Tick marks 50 AU apart; gaps D1, D2, D5, and D6 lie 13.2, 32.3, 64.2, and 73.7 AU from the star.

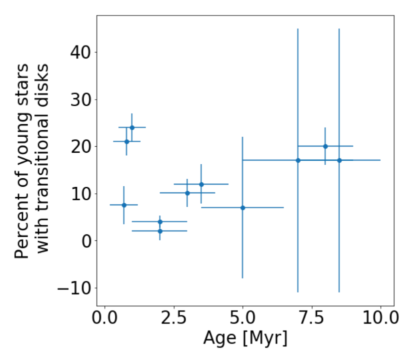
Orbits of Jupiter, Saturn, Uranus, and Neptune shown for comparison.

ALMA partnership 2015

Transitional disks

Though disks themselves disappear with a half-life of 3 Myr, the fraction of transitional disks among them can be as large among the youngest as the oldest (5-20%). Giant planets are quite common among even the young stars we see.





Kim et al. 2013

The innermost gap in HL Tau's disk lies $r = 13.2$ AU from the star, which has a luminosity $L = 6.6L_{\odot}$. What is the temperature of the dust grains there, if they have an albedo $A = 0.7$?

Question