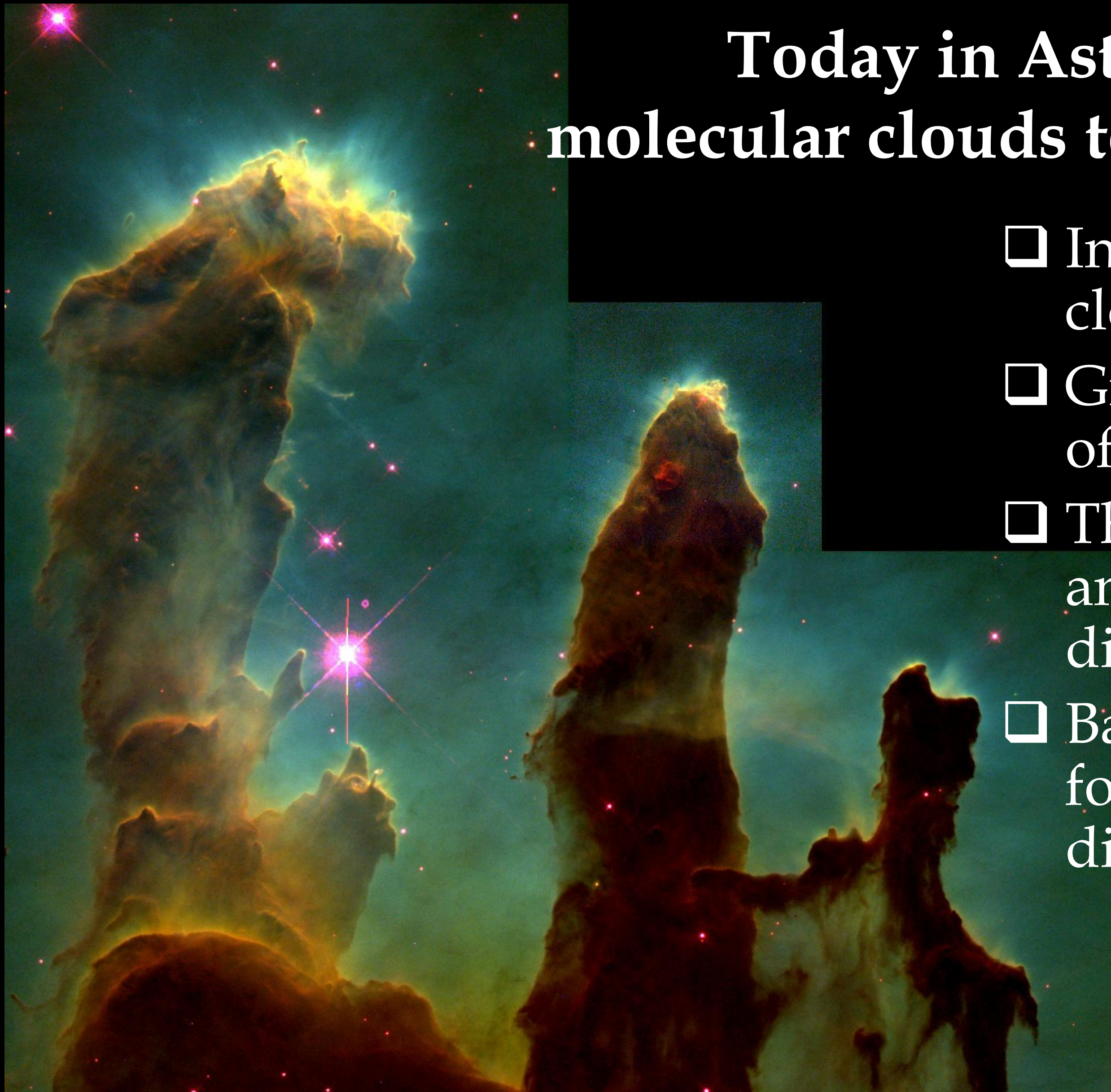
Today in Astronomy 106: molecular clouds to stars and planets



- Interstellar molecular clouds
- Gravitational collapse of molecular clouds
- The formation of stars and protoplanetary disks
- Basic methods for forming planets out of disks

J. Hester, P. Scowen (ASU), HST, NASA

The interstellar medium

The interstellar medium of the Milky Way has a mass of about $2 \times 10^{10}\ M_\odot$

- ❑ Half of it is matter in the form of atomic clouds, filling 40-80% of the Galaxy’s volume.
- ❑ The rest is in **molecular clouds**, shielded from starlight by surrounding atomic clouds, and filling a tiny fraction of the Galaxy’s volume.

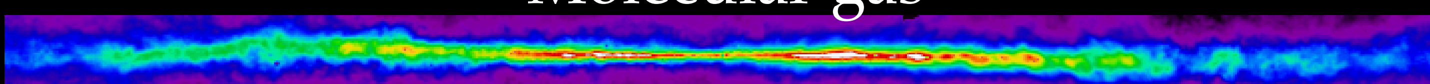
$\lambda = 0.54\ \mu\text{m}$

Starlight, dust extinction

CO $J = 1 \rightarrow 0$

$\lambda = 2.6$ mm

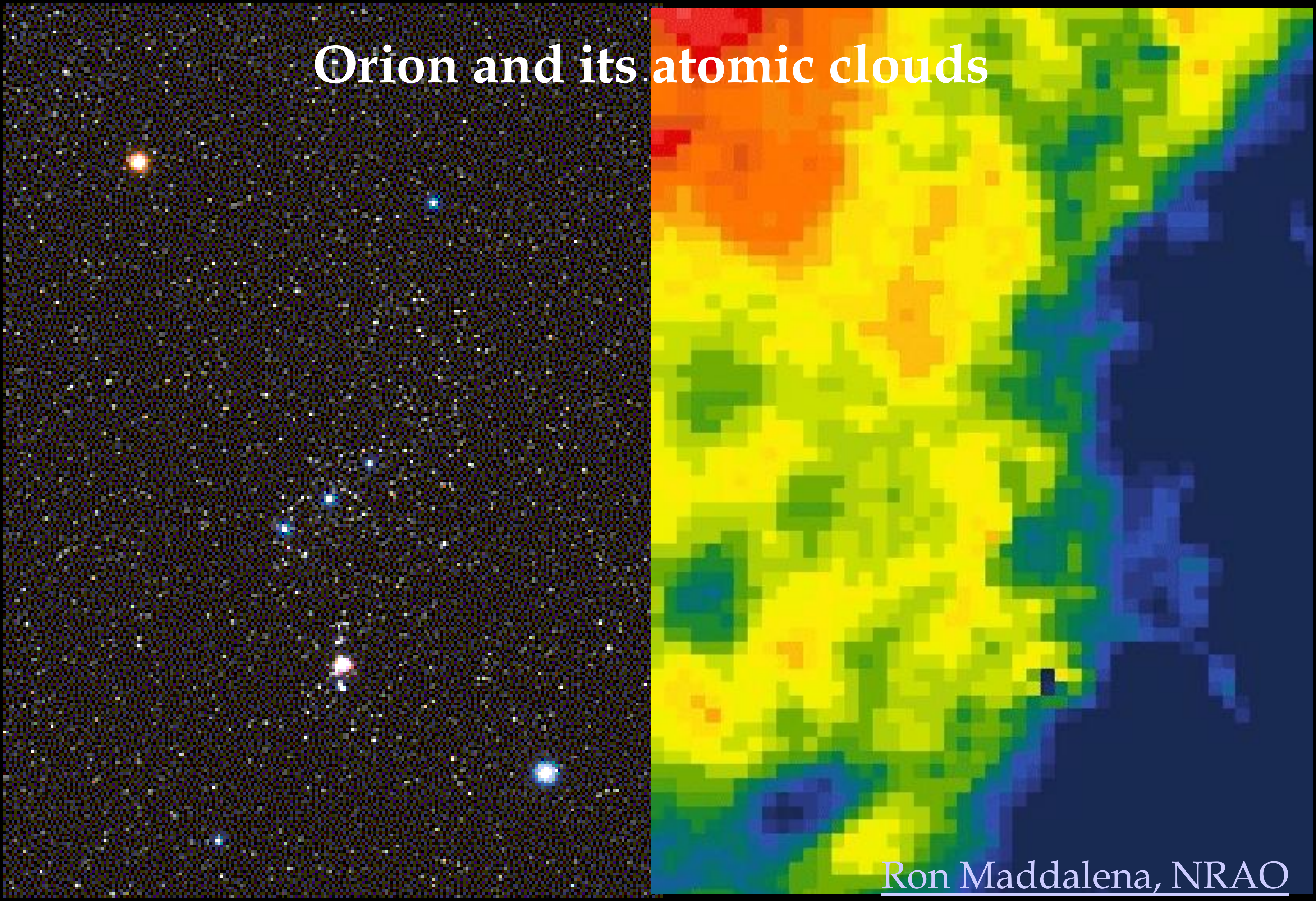
Molecular gas



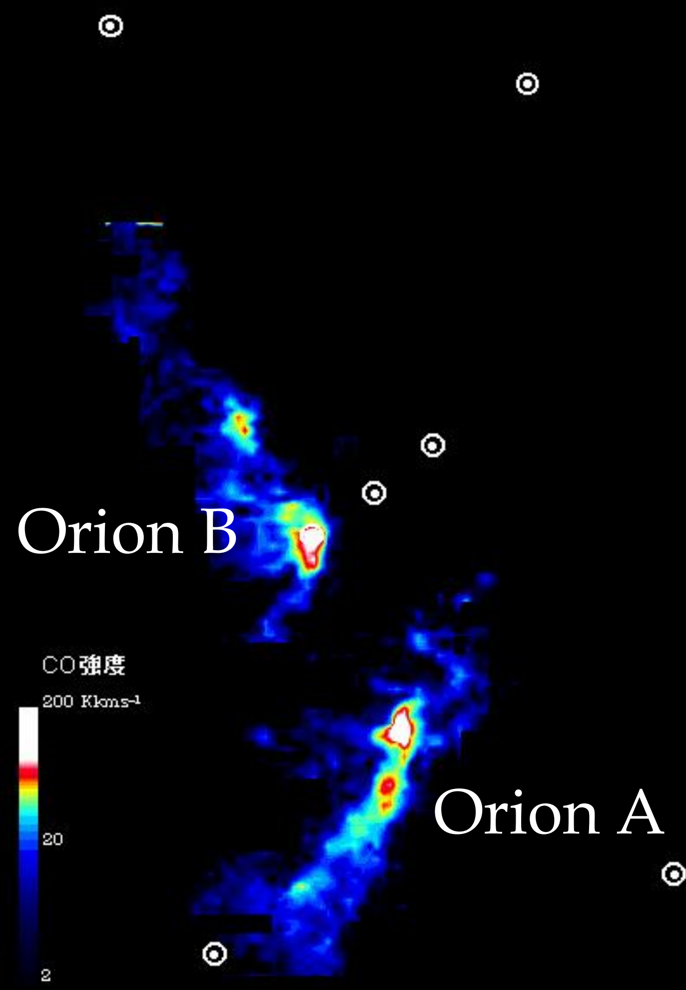
H I $\lambda = 21.1$ cm

Neutral atomic gas

Orion and its atomic clouds



Orion and its molecular clouds



Sakamoto et al. (1994)

Molecular clouds can collapse gravitationally

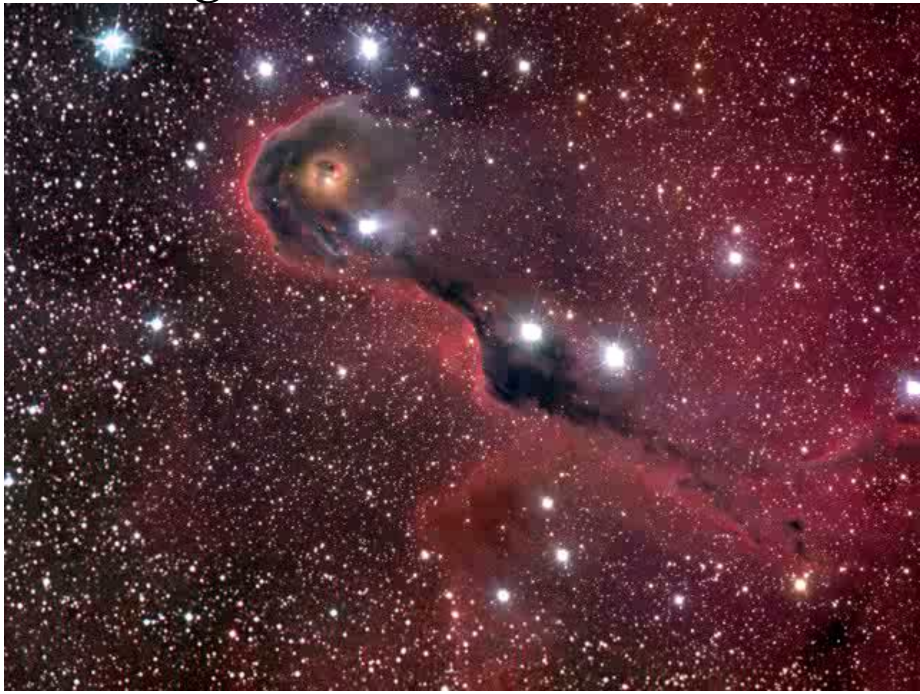
The molecules in molecular clouds have importance in addition to their potential biological role.

- Clouds are 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.
- But molecules radiate efficiently even at very low temperatures, because of their rotational transitions.
- Thus, although atomic clouds are typically T = 70 K, molecular clouds are typically 10-20 K.
- Molecular cooling can rob a cloud of internal heat and pressure, and cause it to collapse to (much) smaller size.

Quick summary of star formation

Spiral galaxies like ours have a large fraction (0.1-0.5) of their mass in the form of interstellar clouds of gas and dust, in about a 100:1 mass ratio in favor of the gas.

- Much of this mass is in the form of **molecular clouds**: massive (10^4 – 10^6 $M_\odot$) very dense (by interstellar standards), cold ($T < 30$ K) and turbulent collections of interstellar matter in which the gas is mostly in molecular form.



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

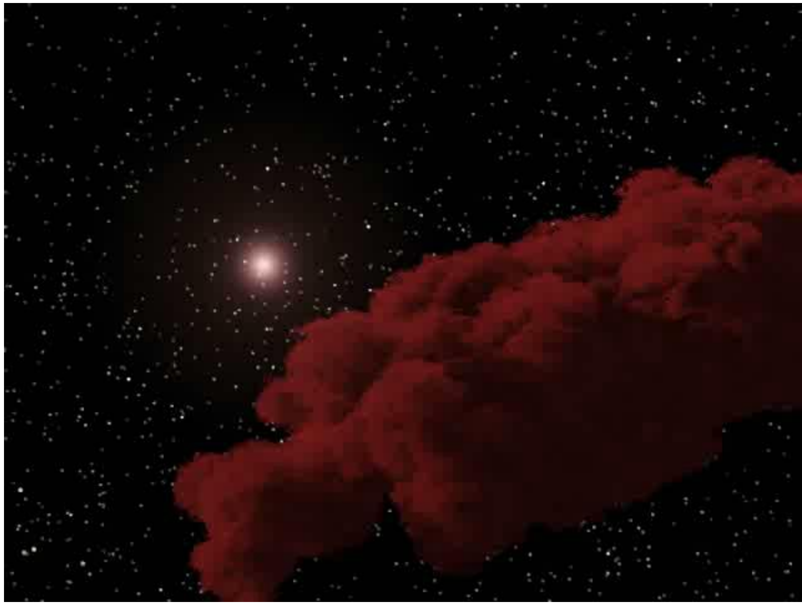
Star formation (continued)

- The molecular material can be seen directly with very long wavelength light ($\lambda = 30\ \mu\text{m} - 3\ \text{mm}$) emitted by molecules and dust.
  - Molecules are seen by being "heated" into higher rotational energy states by collisions with other molecules, and radiating light with wavelength equal to *hc* divided by the energy difference between the 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 further.

Star formation (continued)

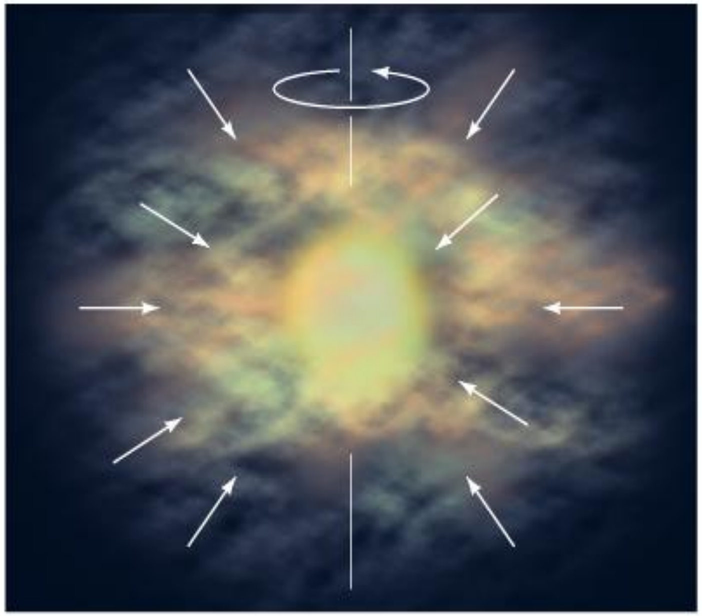
- If a molecular cloud fragment cools enough that its internal pressure is insufficient to support its weight and any external pressure, it will collapse and its density will rise.
- Physical conditions in molecular clouds are often such that the density increase leads to an even greater light-emission (i.e. cooling) rate than before, which causes the fragment to collapse further, thus cool even faster, thus collapse even further, etc. This sort of runaway is called **gravitational instability**.

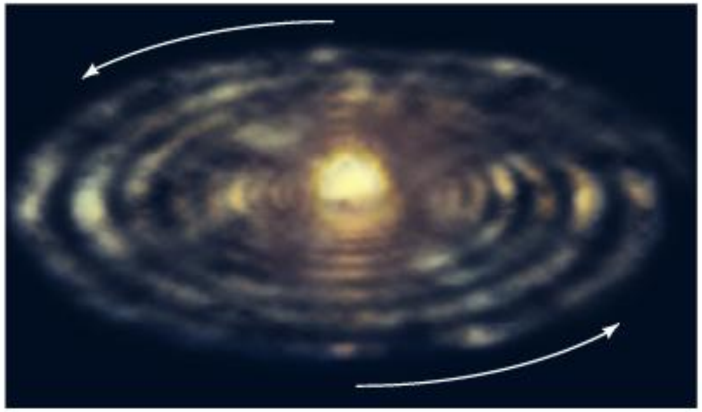


Supernova-induced star formation (R. Hurt,SSC/JPL/Caltech/NASA)

Star formation (continued)

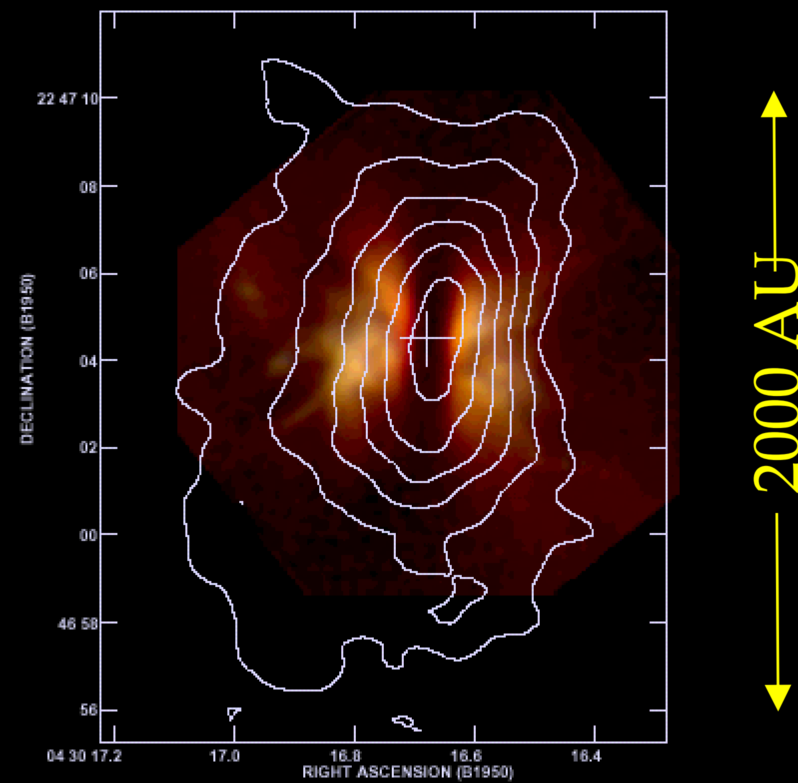
- The fragment was in general slowly tumbling before the collapse started. But it has to obey the conservation of angular momentum (spin), and now that it is somewhat disconnected from its surroundings, it spins up as it collapses.
- Along the rotation axis the collapse can proceed freely, but in the perpendicular directions the collapse is stopped by centrifugal support: a disk has formed.





Star formation (continued)

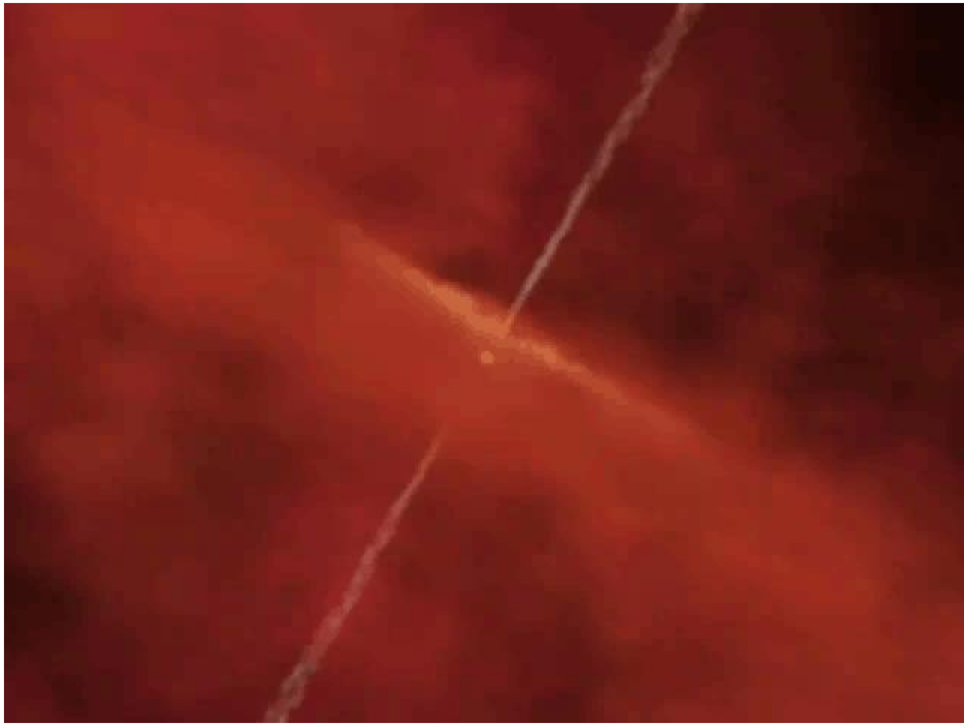
For typical molecular-cloud fragments, with $M = 1\ M_{\odot}$ the size of the disk would be expected be a few thousand AU. Sure enough, we see flattened structures of similar mass and size in molecular clouds.



IRAS 04302+2247, in ^{13}CO emission (OVRO) and scattered near-infrared light (HST). From D. Padgett et al. 1999.

Star formation (continued)

- 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 converts the angular momentum to heat, and allows material slowly to progress toward the center. Soon a central **protostar** builds up from this **accretion disk**.

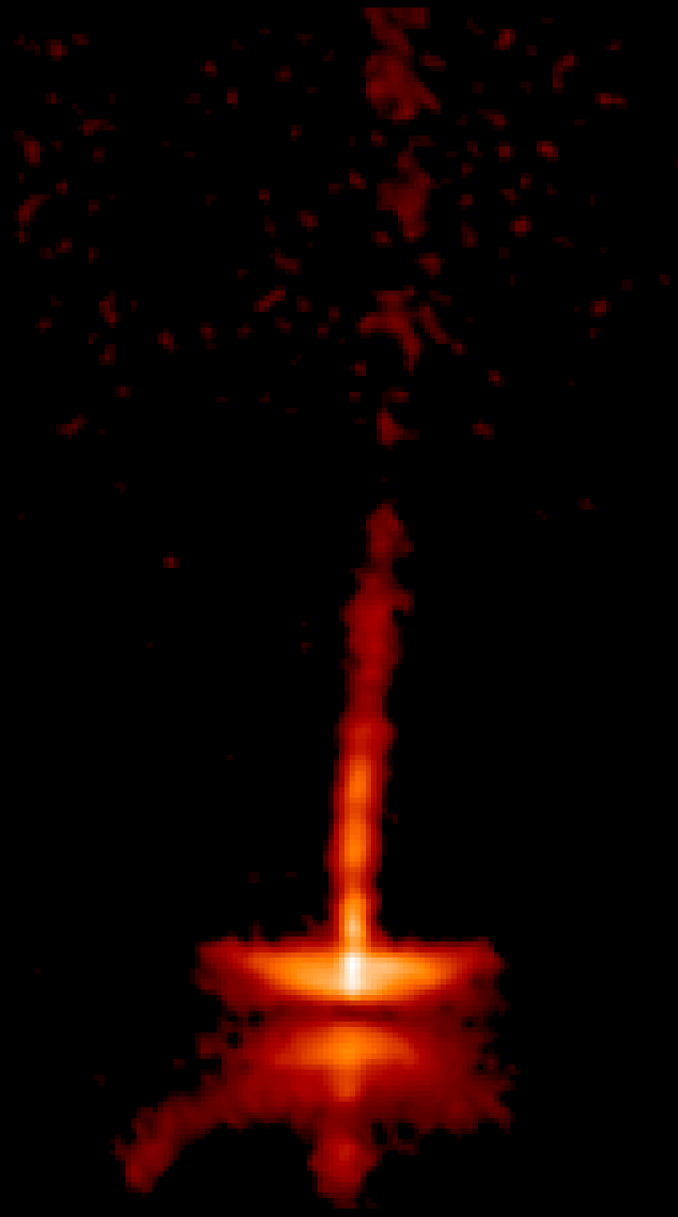


Protostar with accretion disk (R. Hurt, SSC/JPL/Caltech/NASA)

Star formation (continued)

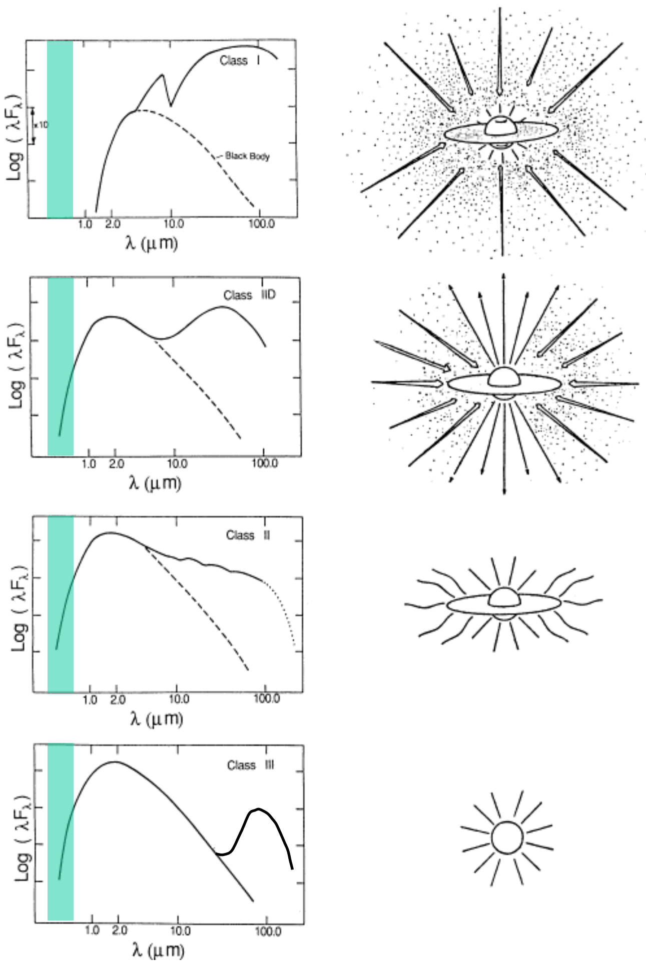
- For a while, the central object accretes gas and dust from the disk, and drives a bipolar outflow into its surroundings, which is thought to carry off the accreted material's spin.

  The star can't inherit all the spin of the disk, without breaking up.



At right: several HST-WFPC2 images of the jet in the edge-on young stellar object HH30, by Alan Watson et al. (2000).

How stars are seen to form (continued)



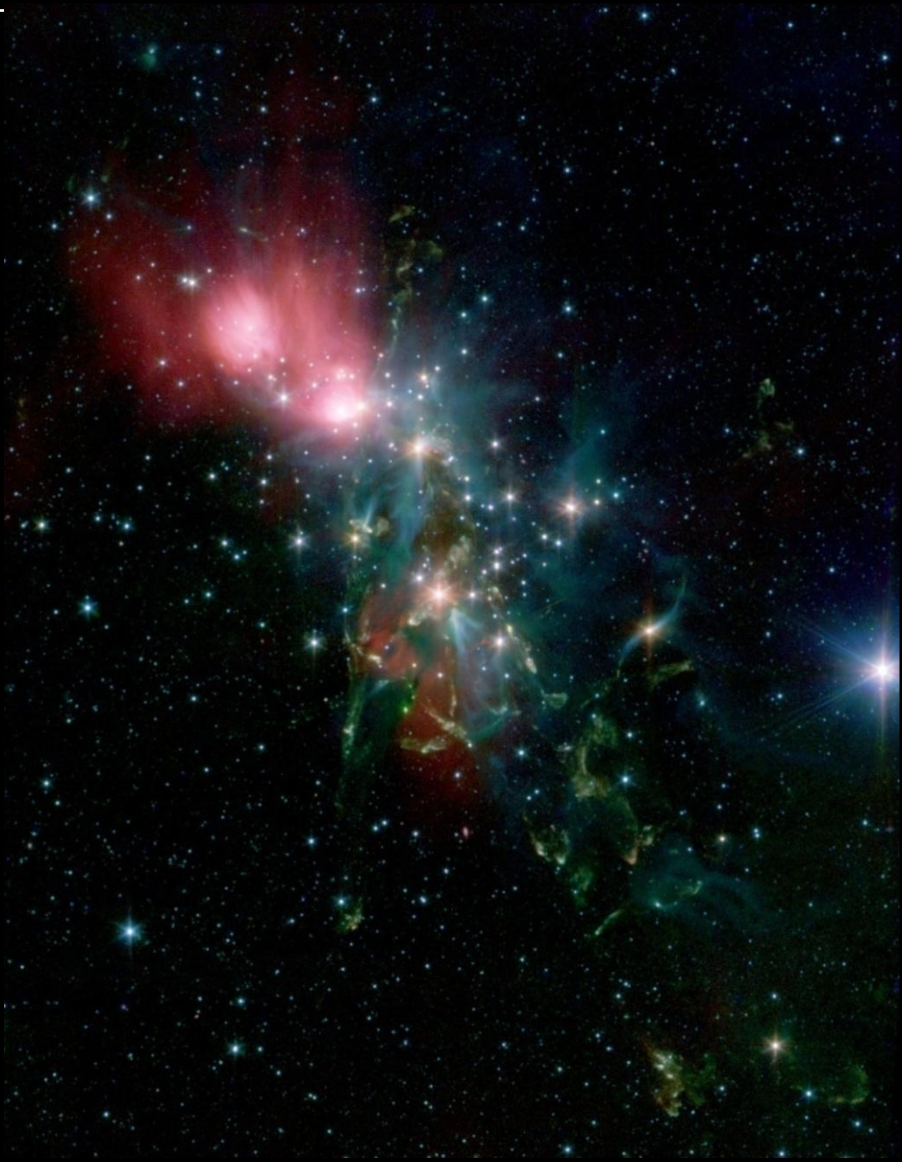
= visible wavelengths

- Over time, the disks dissipate, due to numerous processes that use up or drive away the surrounding dust and gas. We can see this evolution by looking at **spectra** of the disks, or **images** of the structure of the disk, at infrared (and longer) wavelengths, because their temperatures are ~100 K.
- **After 3-6 million years, not much (micron-size) dust or gas remains around the stars**.

Figure adapted from Wilking 1989, PASP **101**, 229

Mid-lecture Break

- ❑ Homework #1 is due Thursday.
- ❑ Homework #2 will be on WeBWorK tomorrow evening. It will be due on Thursday, 26 May.
- ❑ A practice exam will also appear on WeBWork Wednesday.
- ❑ Recitations start today, and will continue each week until the end of the course.



NGC 1333 at mid infrared wavelengths (NASA Spitzer Space Telescope)

Last year, the President cancelled the Return to the Moon, and directed NASA instead to work on more advanced rockets and space-probe technology. Your reaction?

A. What a wimp. We want to go back to the moon ASAP.
B. Good, we need that 0.2% of the budget back for more urgent expenditures.
C. Good. No more spending money and risking lives with outdated rocket technology.

As a fraction of the federal budget, how does current spending on NASA compare to that during the Apollo missions to the Moon?

A. A factor of ten more

B. Slightly more

C. About the same

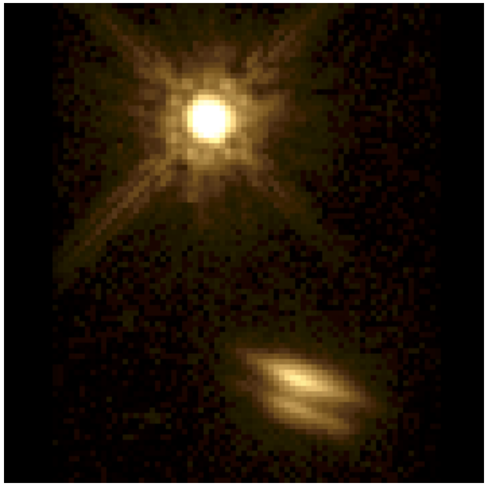
D. Slightly less

E. A factor of ten less

How planets are thought to form

For a long time (since Kant 1755, Laplace 1796), it has been thought that the Solar system must have formed from a disk-shaped nebula.

- Thus, when the youngest stars were found always to be surrounded by dusty disks, in the 1970s, such disks were immediately identified as the birthplaces of planetary systems.
- Unfortunately, the planets can't currently be seen directly, as they are outshone greatly by the stars and the dust in the disks.

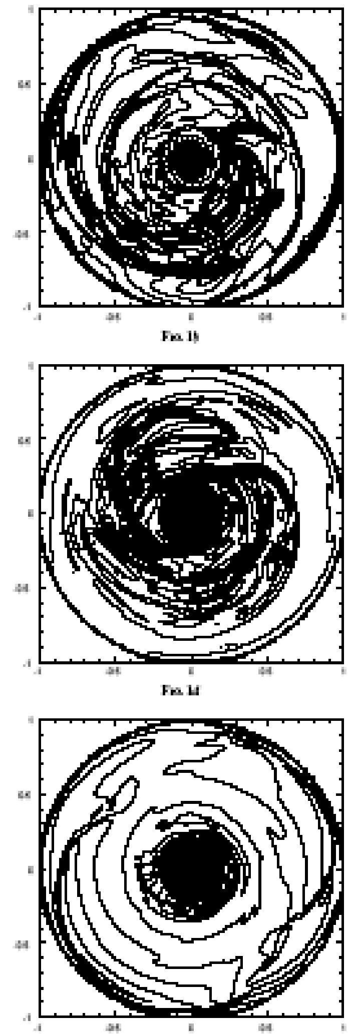


HK Tau/c, by D. Padgett and K. Stapelfeldt, with the HST.

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 very rapidly.
- ❑ Rapid growth of **gravitational instabilities in the dust** (Goldreich and Ward 1973). This would be a good way to make terrestrial planets, or rocky cores for giant planets.

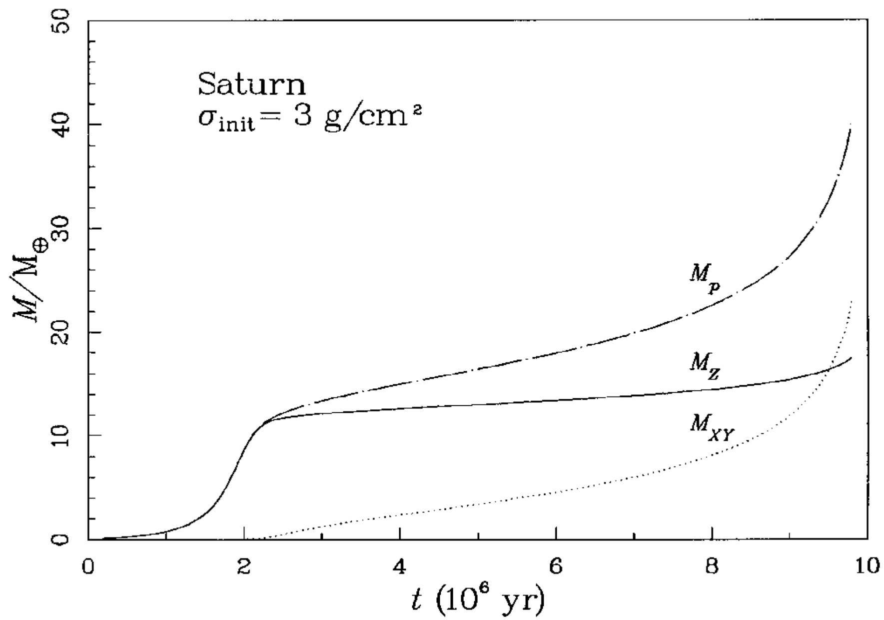


At right: instability growth in a 400-year-old gas disk, shown in calculations separated by 16 years (Boss 2001)

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 turns out to be much slower than the other methods, but it's faster than it sounds, because the rate of accretion of the largest bodies increases rapidly with the size of these bodies.



Core-accretion model for the formation of Saturn (Pollack et al.1996)

Chronology of giant-planetary formation

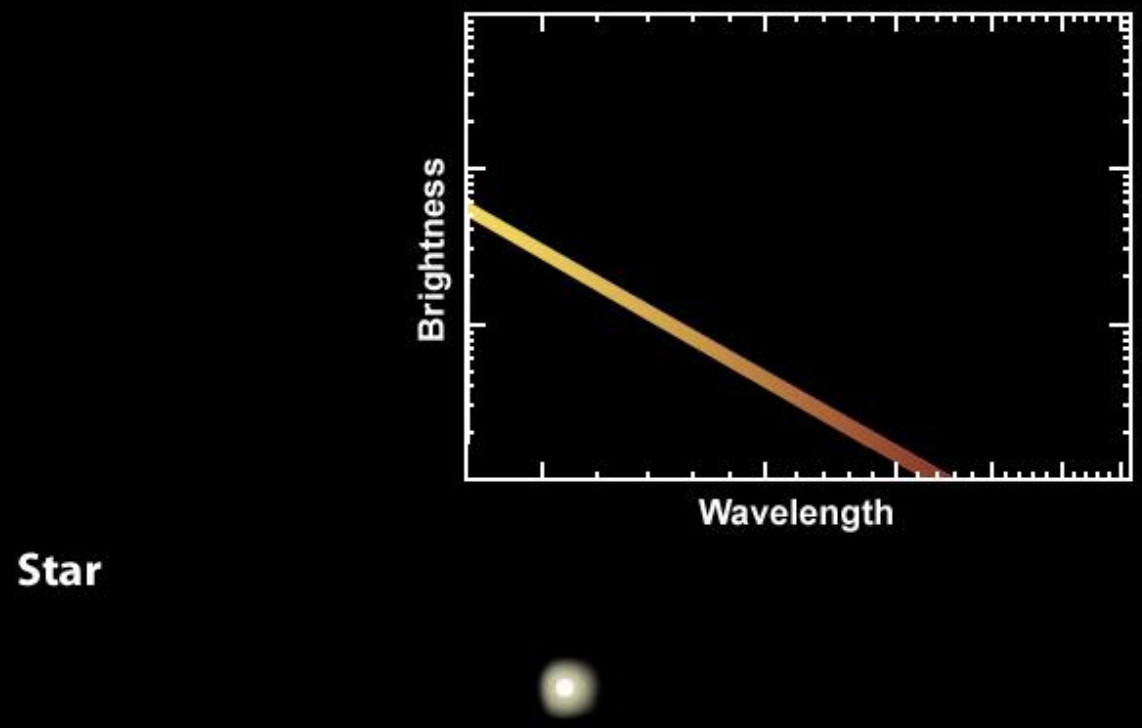
These days we know that giant planets form in disks within 1-3 Myr of the central star's formation.

- The star and disk are too bright to hope for seeing the planets directly with current techniques.
- However, the planets create gaps and central holes in the disks, and these are much more conspicuous than the planets.

R. Hurt, SSC/JPL/Caltech/NASA

- The gaps are created gravitationally, in the same manner as small moons create gaps in Saturn's rings.

Chronology of giant-planetary formation: million-year-old “transitional disks”



[R. Hurt, SSC/JPL/Caltech/NASA]

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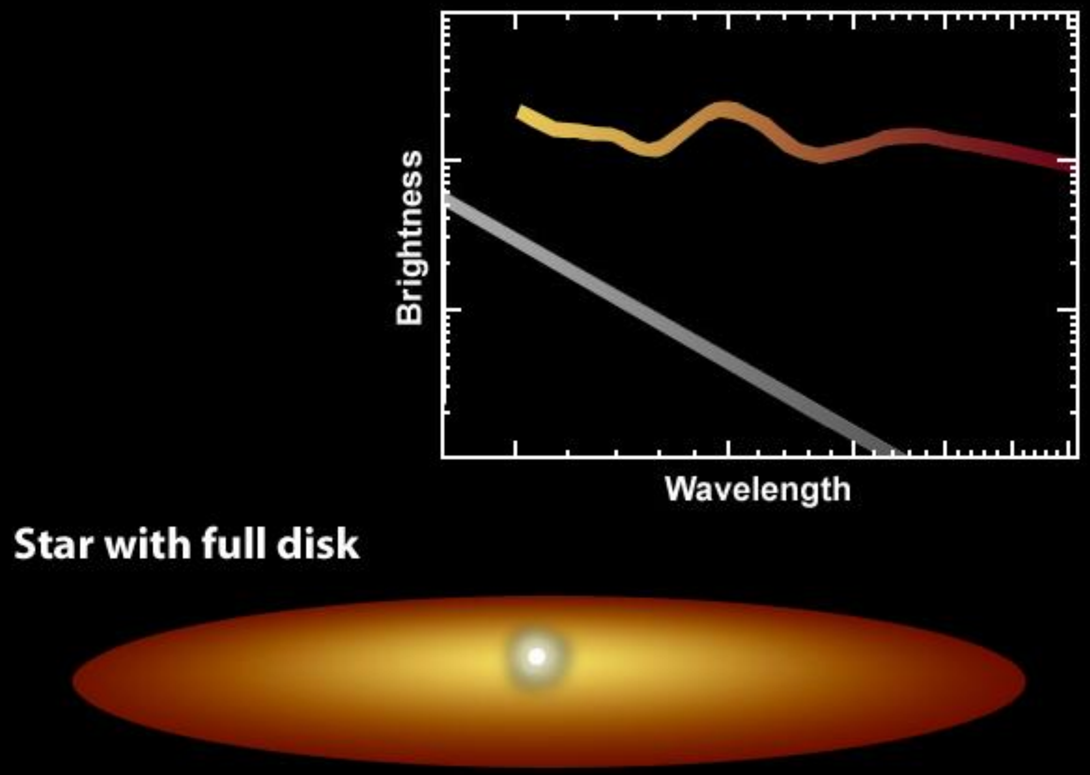

[R. Hurt, SSC/JPL/Caltech/NASA](#)

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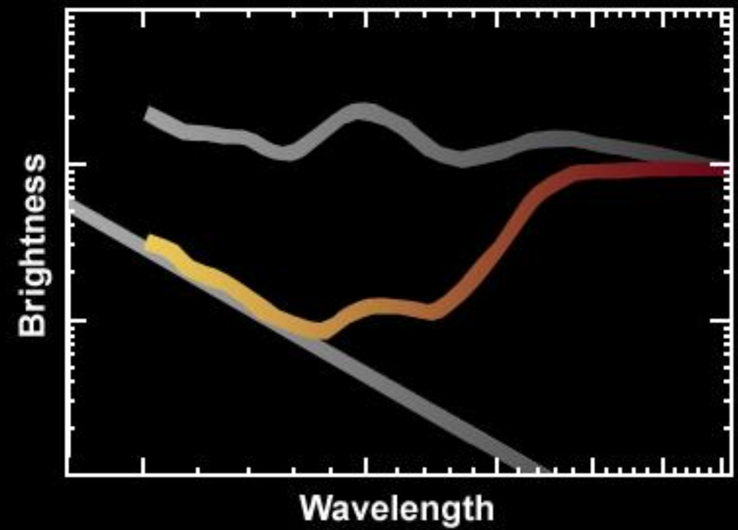

Transitional disk

R. Hurt, SSC/JPL/Caltech/NASA

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

We have two ways to estimate this: the current rate, and the average rate over the MW's lifetime.

- **Current** rate: based on counting nearby young stars, determining how the number/time depend upon the amount of gas measured by its molecular emission. Result (Evans 2009):

$$\rho_* = \left(9.4\times10^{-8}\,\frac{M_\odot}{\text{year ly}^2}\right)\times\left(\frac{\Sigma_{\text{gas}}}{1.88\times10^{-5}\,M_\odot\,\text{ly}^{-2}}\right)^{2.3}$$

The Galaxy has $M_{\text{gas}} = 2\times10^{10}\,M_\odot$ spread over a disk about 33,000 ly in radius (area $= \pi r^2 = 3.3\times10^9$ ly^2) , so this comes to $R_* = \rho_* \pi r^2 = 23 M_\odot\,\text{year}^{-1}$.

The star formation rate, R_* (continued)

- We also know how much mass there is in stars in the Galaxy, from the speed and radius of the solar system's orbit around the Galactic center, and Newton's Laws:
  - balance the acceleration from the gravity of stars closer to the Galactic center, GM_{closer}/r^2,
  - and the acceleration of the SS's circular orbit, V^2/r.

  Measure V (250 km/sec) and r (26,000 ly), know G:
  $M_{\text{closer}} = 1.2\times 10^{11}\ M_\odot$ therefore total $M_* \approx 2.4\times 10^{11}\ M_\odot$
- We also know that the age of the Galaxy is 12 Gyr, so the **average** rate of star formation has been something like

$$R_* = \frac{M_*}{12\times 10^9\ \text{years}} \approx 20 M_\odot\ \ \text{year}^{-1}.$$

The star formation rate, R_* (continued)

- So the current and lifetime-average star formation rates aren't much different – indistinguishable, in fact, given the uncertainties.
- This perhaps means that the rate hasn't changed much at any time through the Galaxy's life.
- Since the most common stars have $M = 0.4\ M_\odot$,

$$R_* \approx 20 M_\odot \ \ \text{year}^{-1} \times \frac{\text{star}}{0.4 M_\odot} = 48 \text{ stars year}^{-1}$$

For our Drake equation input let's take a nearby round number:

$$\boxed{R_* = 50 \text{ stars year}^{-1}.}$$