

STAR FORMATION (Ch. 19)

The basics: **GRAVITY** vs. **PRESSURE** (heat; but also rotation and magnetic fields can be important)

Stages (you don't have to memorize numbers of stages in textbook or here, just be able to describe the sequence of events)

1. **Interstellar cloud**—cold ($T \sim 10\text{K}$), large ($\sim 1\text{-}10\text{pc}$), massive ($\sim 10^3 - 10^5 M_{\text{sun}}$), so gravity wins easily over gas pressure (atomic motions—see Fig. 19.2): cloud must break up, or “*fragment*.”

Other inhibitors: [rotation](#), [magnetic fields](#) (More Precisely 19-1, p. 503).

2. Collapsing cloud **fragment**—still cold, size $\sim 0.1\text{-}0.01\text{pc}$. This may fragment further, so have multiple stages of fragmentation (see Fig. 19.3).

3. Fragmentation ceases—center of fragment dense enough to become **opaque** to its own radiation, so it heats up, slowing the collapse. (Previously it was transparent and so could stay cool because radiation escaped easily.) This property makes qualifies the object as a:

4. **Protostar**—now object has a “surface” because it is opaque; this surface is the **photosphere** (the layer where the photons can finally escape into space). So a protostar is defined by when the object becomes dense enough to have a photosphere. It appears in the H-R diagram in upper right (large! See Fig. 19.4)

Protostar heats up by gravitational contraction and accretion of remaining material (from a disk). But the temperature in center is too low for nuclear reactions at this stage.

5. Continued slow contraction (getting fainter), heating. Protostar moves roughly on a vertical track in the H-R diagram (see Fig. 19.6).

6. Central temperature reaches about 10 million K, get ignition of nuclear fusion of H into He.

7. Adjustment to the “zero-age” main sequence. This is when stars can just balance gravity with pressure at all layers, and will spend about 90% of their lives in this stage. (See Fig.19.6)

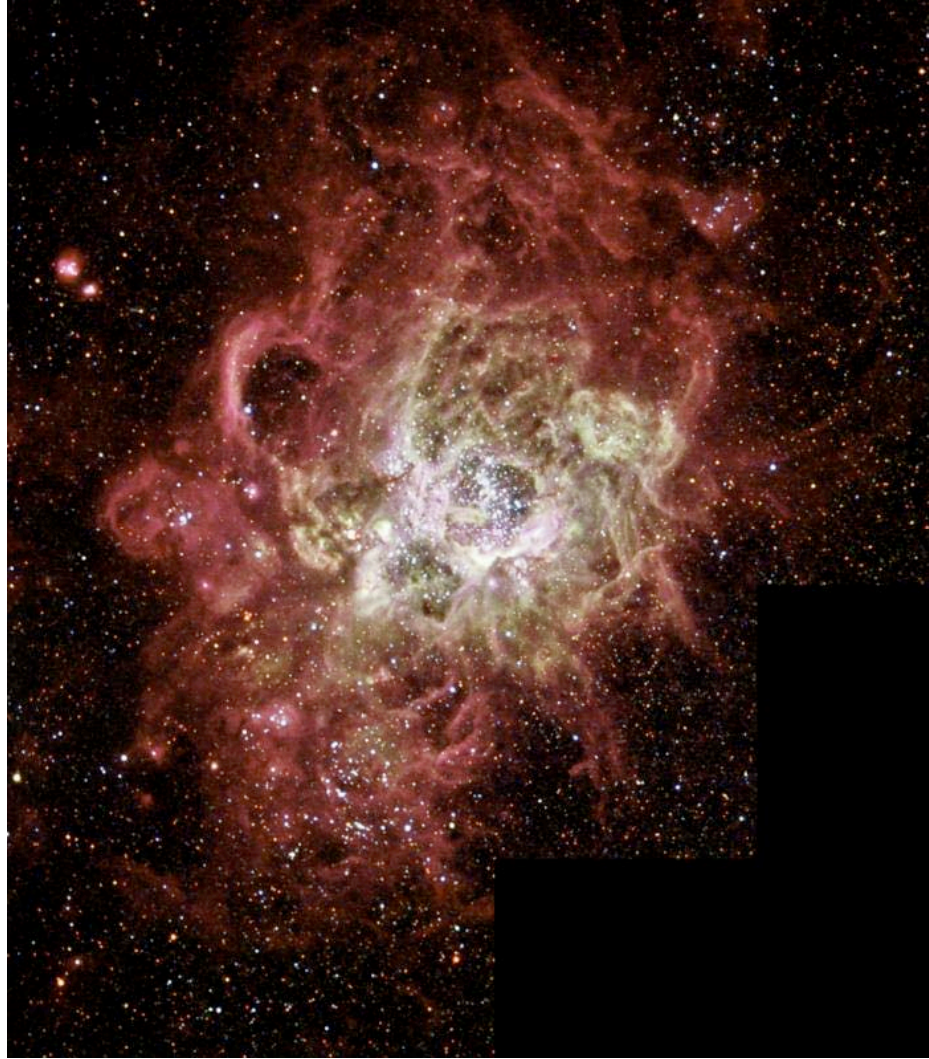
Different stellar masses arrive at the main sequence at different temperatures and luminosities. See Fig. 19.7. So where a star is on the main sequence is ONLY a function of the mass it happened to be born with (with a slight dependence on other things, like its total metal abundance).

Note: the “main sequence” is the location in the H-R diagram of all stars of different masses. That is the physical, and correct, way to define the term.

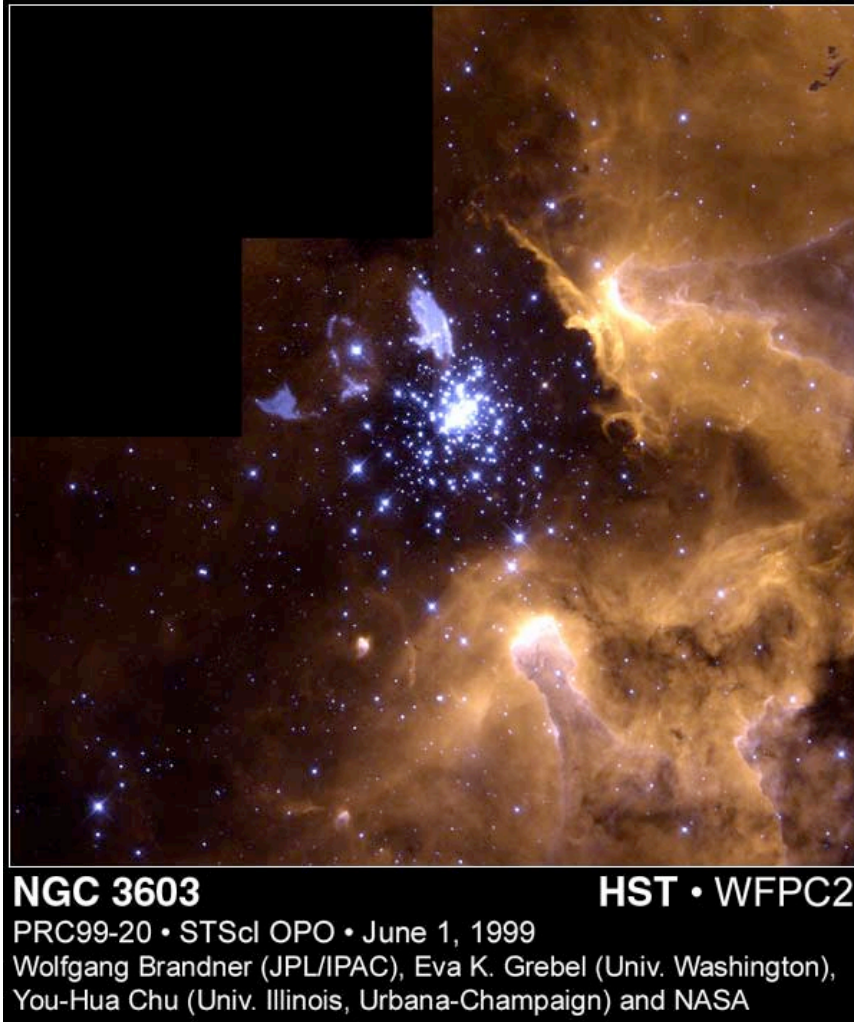
Brown dwarfs: Stars with $M < 0.1M_0$ never get hot enough to ignite H. They just cool off and fade forever. Hard to detect because so faint, but by now 100s have been discovered. (Discovery 19-1, p. 511—you don’t have to read this). It is still unknown whether brown dwarfs, which can be as low-mass as $0.01 M_{\text{sun}}$ or even less, form in the same way stars do, or if some of them form like planets, in disks.

High-mass stars: You may have noticed that most of the illustrations of star-forming regions you are shown are colorfully illuminated. That is because you are being shown regions where high-mass stars have formed—only they have enough UV radiation to heat and ionize the surrounding cloud, making an emission nebular, as discussed previously in ch. 18. Here are a few images---however don't get the idea that star formation involves only massive stars. The most common stars *by far* are low-mass stars, but they aren't hot enough to have much UV, and are faint too. They are observed, but not in such a spectacular manner.

Here are a few regions of star formation in which the high-mass stars have done their work—in fact they are probably disrupting the parent cloud, which will once again become part of the ISM.



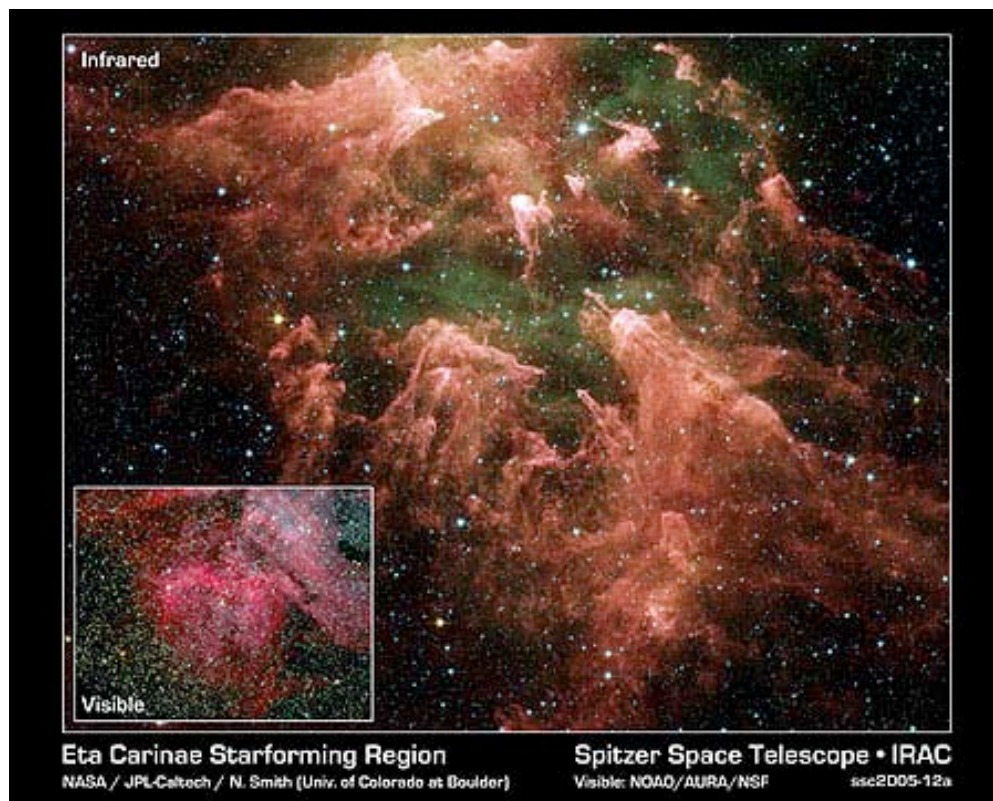
NGC 604, is one of the largest known regions of star birth seen in a nearby galaxy. NGC 604 is similar to familiar star-birth regions in our Milky Way Galaxy, such as the Orion Nebula, but it is vastly larger in extent and contains many more recently formed stars. This monstrous star-birth region contains more than 200 brilliant blue stars within a cloud of glowing gases some 1,300 light-years across, nearly 100 times the size of the Orion Nebula.



This single view nicely illustrates the entire stellar life cycle of stars, starting with the Bok globules (dark clouds) and giant gaseous pillars (emission nebulae), followed by circumstellar disks, and progressing to evolved massive stars in the young starburst cluster. To the upper right of center is the evolved blue supergiant called Sher 25. The star has a unique circumstellar ring of glowing gas that is a galactic twin to the famous ring around the supernova 1987A--see the image of SN 1987A in the next chapter. Near the center of the view is a so-called starburst cluster dominated by young, hot Wolf-Rayet stars and early O-type stars. A torrent of ionizing radiation and fast stellar winds from these massive stars has blown a large cavity around the cluster (*like the Local Superbubble you read about in ch. 18*). The most spectacular evidence for the interaction of ionizing radiation with cold molecular-hydrogen cloud material is the giant gaseous pillars to the right and lower left of the cluster. These pillars are sculptured by the same physical processes as the famous pillars Hubble photographed in the M16 Eagle Nebula. Dark clouds at the upper right are so-called Bok globules, which are probably in an earlier stage of star formation. To the lower left of the cluster are two compact, tadpole-shaped emission nebulae. Similar structures were found by Hubble in Orion, and have been interpreted as gas and dust evaporation from possibly protoplanetary disks (proplyds). The "proplyds" (short for "protoplanetary disks) in NGC 3603 are 5 to 10 times larger in size and correspondingly also more massive.



The Carina Nebula is a large bright nebula which surrounds several open clusters of stars. Eta Carinae, one of the most massive and luminous stars in the Galaxy, is one of them. The nebula lies at an estimated distance between 6,500 and 10,000 light years from Earth. It is located in the constellation of Carina. The nebula contains multiple O-type stars.



The brilliant supermassive star, Eta Carinae is too bright to be observed by infrared telescopes. The downward-streaming rays hint at its presence above the edge of this picture from the Spitzer Space Telescope. Ultraviolet radiation and stellar winds from Eta Carinae and its siblings have shredded the cloud to pieces, leaving a mess of tendrils and pillars. This shredding process triggered the birth of the new stars uncovered by Spitzer. The inset visible-light picture of the Carina Nebula shows quite a different view. Dust pillars are fewer and appear dark because the dust is soaking up visible light. Spitzer's infrared detectors cut through this dust, allowing it to see the heat from warm, embedded star embryos, as well as deeper, more buried pillars.

Observations relevant to star formation

Most star formation does not appear nearly as spectacular as the regions shown above. Those massive stars are the signposts of star formation, but when we observe clouds where massive stars have not yet formed, we can see the stages of star formation occurring.

Fragments—Recall that fragmentation of a massive cloud is one of the first stages in the formation of stars. They are observed mostly by molecular spectral lines (but also dust extinction) These are the smaller molecular/dark clouds from chapter 18 (interstellar medium), embedded in larger “giant molecular clouds.”

Cocoon stars—shrouded by dust (and gas) still falling onto the protostar, so glow mainly in the IR. All are seen associated with molecular clouds and their fragments. Can't see the photosphere of the star itself, just the heated dust around them.

Protostars—stars for which the dust has cleared enough for a direct view of their photospheres; they appear above the main sequence, and about to settle down to their main sequence lives. The T Tauri-type stars are the best examples.

Disks—At good resolution, most protostars show evidence of substantial disks of gas and dust (recall how crucial this is for planet formation!). Can see in visual and infrared radiation—in fact the excess infrared radiation in the spectrum of a star is usually taken as indicating a disk is there. See Figs. 19.10, 19.11.

Protostellar winds—Probably clears the star of its remaining debris (except planets); often seen as very energetic bipolar outflows (See Figs. 19.11, 19.12).

Shock waves (sec. 19.5—you can skip the reading, but understand how a compression could trigger collapse of a gas cloud)—from stellar winds and explosions (to be discussed later).

These can compress nearby (or even fairly distant) matter, can induce *more* star formation.

The image below is often cited as a case of shock-driven star formation:



Shock-Driven Star Formation

Hodge 301, seen in the lower right hand corner of this image, lives inside the Tarantula Nebula, which resides in our Galactic neighbor, the Large Magellanic Cloud. Many of the stars in Hodge 301 are so old that they have exploded as supernovae. These exploded stars are blasting material into the surrounding region at speeds of almost 200 miles per second. The high-speed matter is plowing into the surrounding Tarantula

Nebula, shocking and compressing the gas into a multitude of sheets and filaments, seen in the upper left portion of the picture.

So star formation may *propagate* like a chain reaction, and in fact can be modeled like a disease epidemic. (See possible example, Fig. 19.15 in text.)

Here is a high-resolution image of a star-formation region that appears to be a case of propagating star formation.



This image illustrates a perfect case of sequential star formation in a nearby galaxy where new star birth is being triggered by previous-generation massive stars. A collection of blue- and white-colored stars near the left of the image are among the most massive stars known anywhere in the universe. The region around the cluster of hot stars in the image is relatively clear of gas, because the stellar winds and radiation from the stars have pushed the gas away. When this gas collides with and compresses surrounding dense clouds, the clouds can collapse under their own gravity and start to form new stars.

One feature that all the star-formation regions shown above, and in general, have in common is that they are all groups, or “**clusters**” of young stars. No star has yet been seen forming in isolation, that is, not in a cluster. This is a boon for astronomers, because star clusters give us the best chance to test the theory of stellar evolution, as described next.

Star Clusters (sec. 19.6)

Groups of stars all located in the same volume of space, i.e. **all at the same distance**, and so presumably **all formed at the same time**; i.e. all stars in a given cluster have the same age. Best chance to test theories of stellar evolution!

Can easily get H-R diagram using only apparent brightnesses, because effect of distance would be to just shift all the L's by the same factor (vertically in H-R diagram). Make sure this makes sense to you!

2 main types of clusters

A. Open clusters

Most have ~100-10,000 stars, size ~ 1-10 pc.

Some show main sequence (MS) populated all the way to spectral type O (massive) \Rightarrow must be very young (less than ~ few million years)

Some have MS only populated up to yellowish (cooler, less massive) spectral types \Rightarrow most massive stars have died, so older.

Can see that you can get ages of clusters by extent of the MS. Find that open cluster ages vary from very young (~few million yr.) to very old (~10 billion yr.)

This shows that star formation has been an ongoing process in over the whole history of our galaxy. But notice that they are *all* found in the disk of the Milky Way—a gigantic hint about how our Galaxy formed (we'll come back to this).

B. Globular clusters

Very dense clusters, up to 10^6 stars within ~ 50 pc size.

Most are very distant ($\sim 1,000$ to $100,000$ pc), and are *not* distributed in the disk of the Milky Way \Rightarrow they form a spherical “halo” around the Milky Way.

H-R diagrams: MS includes low mass stars, but **NO** stars with mass $>$ about 0.8 solar masses \Rightarrow all are old! Ages ~ 12 -17 billion years.

These were almost certainly the first objects to be formed in our Galaxy. Note: Abundances of all elements heavier than carbon are very small compared to the sun and most other stars (because they formed when the Galaxy was relatively “pollution free”—we’ll return to this later, too).

\rightarrow Make sure you understand the H-R diagrams in Figs. 19.18-19.19. It is important to see that the simplest ideas about the lifetimes of stars predict the “peeling off” of the main sequence with age, but you can only observe this in clusters, because all the stars there were born at the same time.

\rightarrow With ages of clusters, we can determine the age of our Galaxy (about 10 billion years)—this will turn out to be close to the age of the universe, because most galaxies formed when the universe was young. The Galaxy must have been a disk for most of that time, since all the open clusters are concentrated along the Milky Way.

\rightarrow And from the metal abundances in the oldest clusters (globular clusters), we start to realize that the fraction of material that is heavy elements has increased with time, consistent with the idea that *all elements heavier than hydrogen and helium were produced in stars.*