Star Formation

Chapter 19

Gravity and Heat

- The force of gravity is grabbing onto gas particles as they move through empty space
- At any given time a million particles can come together but do not have enough gravity to overcome the heat pushing them apart
- It will take 10^57 atoms to be enough gravity to begin rotation
- There are only 10^51 subatomic particles in the entire earth

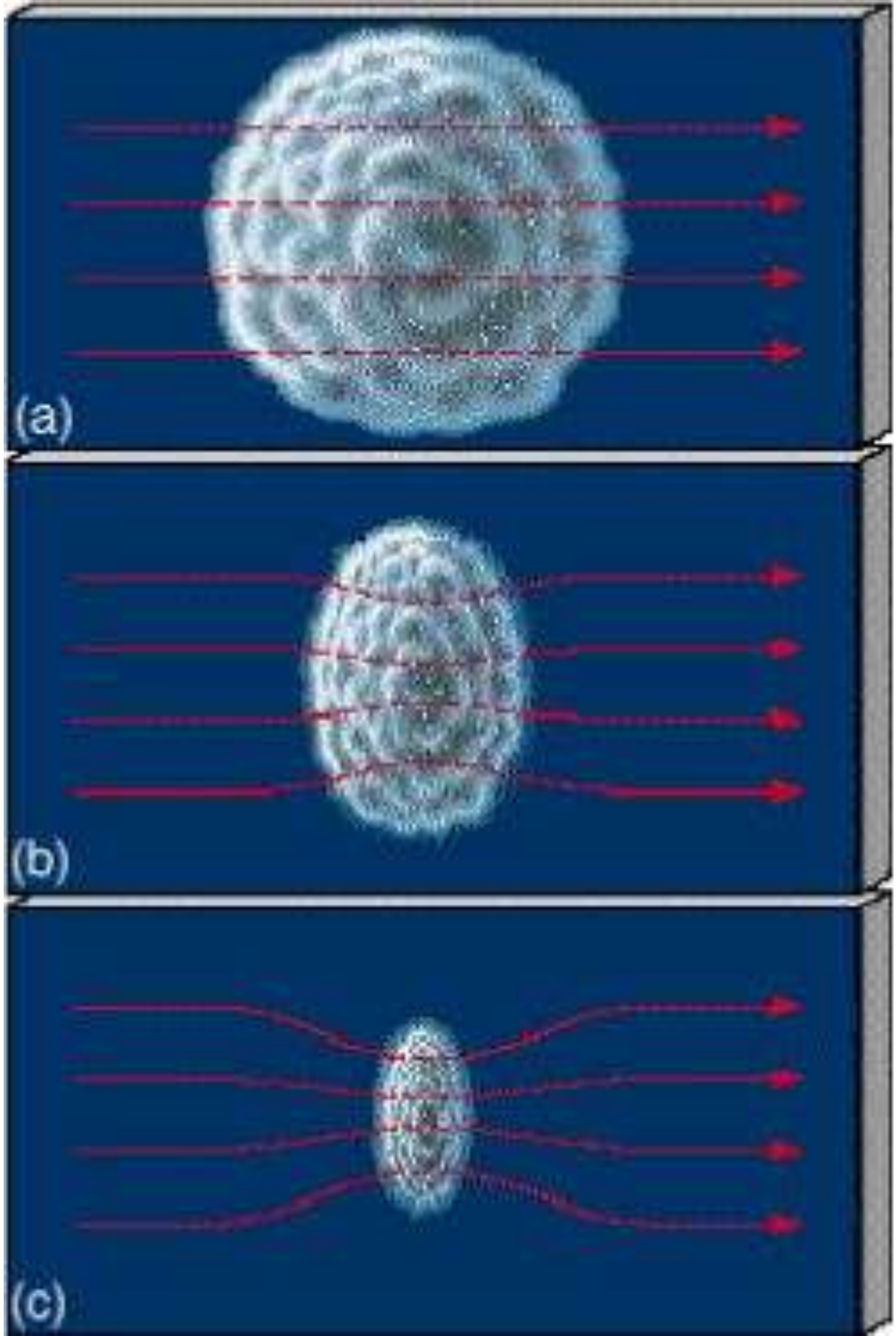
Rotation

- Heat is not the only factor that tends to oppose gravitational contraction.
- *Rotation*—that is, spin—can also compete with gravity's inward pull.
- Creates a bulge around its midsection.
- As the cloud contracts, it must spin faster and the bulge grows—material on the edge tends to fly off into space.
- Eventually, the cloud forms a flattened, rotating disk.

Magnetism

- *Magnetism* can also hinder a cloud's contraction.
- magnetic fields permeate most interstellar clouds.
- As a cloud contracts, it heats up, and atomic encounters become violent enough to (partly) ionize the gas.
- magnetic fields can exert electromagnetic control over charged particles.
- In effect, the particles tend to become "tied" to the magnetic field—free to move *along* the field lines but inhibited from moving *perpendicular* to them.

- The magnetic fields alters the shape of the cloud and elongates it

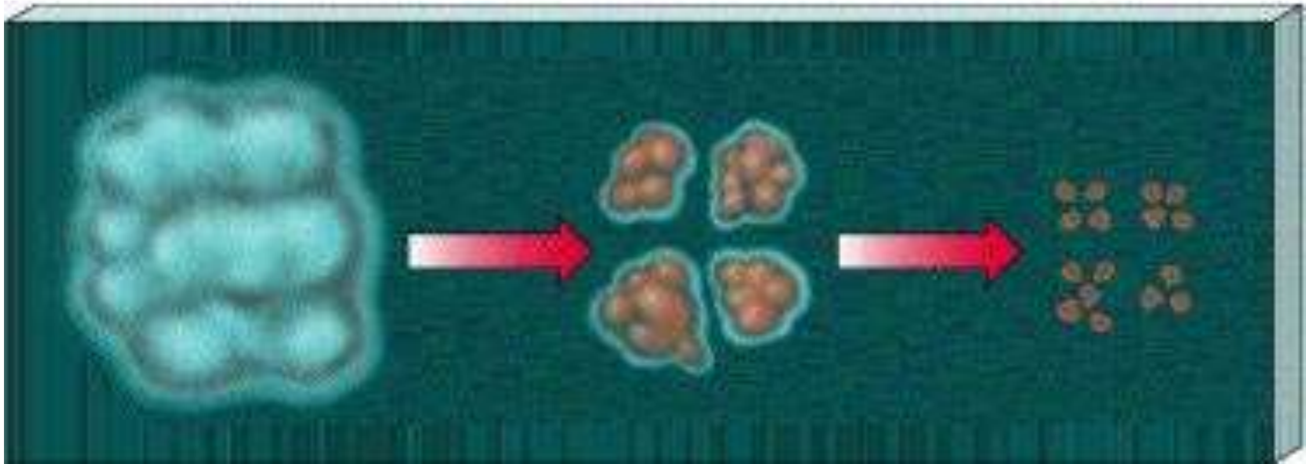


7 Evolutionary Stages to go from gas cloud to main sequence star

STAGE 1: AN INTERSTELLAR CLOUD

- The first stage in the star-formation process is a dense interstellar cloud
- These clouds are vast, sometimes spanning tens of parsecs across.
- Typical temperatures are about 10 K with a density of perhaps 10^9 particles/m^3.
- Stage 1 clouds contain thousands of times the mass of the Sun, mainly in the form of cold atomic and molecular gas.

Fragmentation – forming from a dozen to hundreds of stars



STAGE 2: A COLLAPSING CLOUD FRAGMENT

- contains between one and two solar masses of material
- This fuzzy, gaseous blob is still about 100 times the size of our solar system. Its central density is now some 10^{12} particles/m^3.
- Even though it has shrunk substantially in size, the fragment's average temperature is not much different from that of the original cloud. virtually all the energy released in the collapse is radiated away and does not cause any significant increase in temperature.
- The gas at the center may be as warm as 100 K by this stage. For the most part, however, the fragment stays cold as it shrinks.
- The process of continued fragmentation is eventually stopped by the increasing density within the shrinking cloud. As stage 2 fragments continue to contract, they eventually become so dense that radiation cannot get out easily.
- The trapped radiation causes the temperature to rise, the pressure to increase, and the fragmentation to cease.

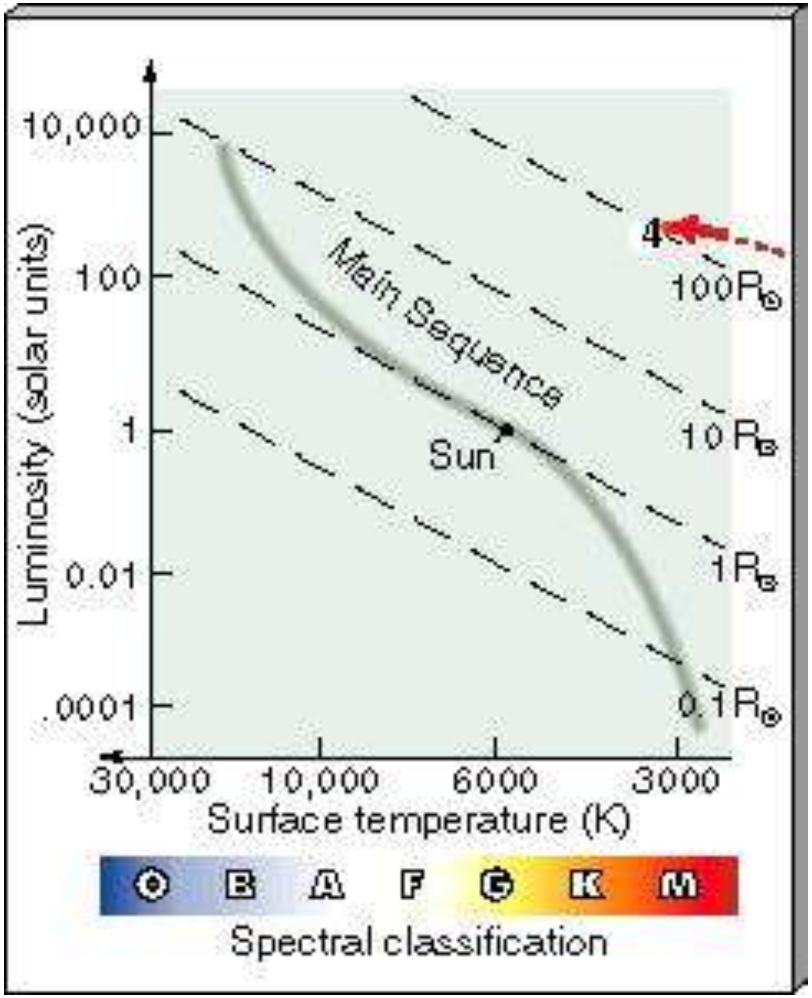
STAGE 3: FRAGMENTATION CEASES

- Several tens of thousands of years after it first began contracting, a typical stage 2 fragment has shrunk by the start of stage 3 to roughly the size of our solar system
- The central temperature has reached about 10,000 K—hotter than the hottest steel furnace on Earth.
- The density increases much faster in the core of the fragment than at its periphery to approximately 10^{18} particles/m^3 (still only 10^{-9} kg/m^3 or so).
- The dense, opaque region at the center is called a protostar—an embryonic object perched at the dawn of star birth.
- Its radius continues to shrink because its pressure is still unable to overcome the relentless pull of gravity.
- After stage 3, we can distinguish a *photosphere*.

STAGE 4: A PROTOSTAR

- As the protostar evolves, it shrinks, its density grows, and its temperature rises, both in the core and at the photosphere.
- Some 100,000 years into development it reaches about 1,000,000 K. Still not hot enough to ignite the proton—proton nuclear reactions that fuse hydrogen into helium.
- About the size of Mercury's orbit. Heated by the material falling on it from above, its surface temperature has risen to a few thousand kelvins.
- Knowing the protostar's radius and surface temperature, we can calculate its luminosity. Surprisingly, it turns out to be several thousand times the luminosity of the Sun.
- Even with surface temperature only about half that of the Sun, it is hundreds of times larger
- Because nuclear reactions have not yet begun, this luminosity is due entirely to the release of gravitational energy as the protostar continues to shrink

- By the time stage 4 is reached, our protostar's physical properties can be plotted on the Hertzsprung—Russell (H—R) diagram



STAGE 5: PROTOSTELLAR EVOLUTION

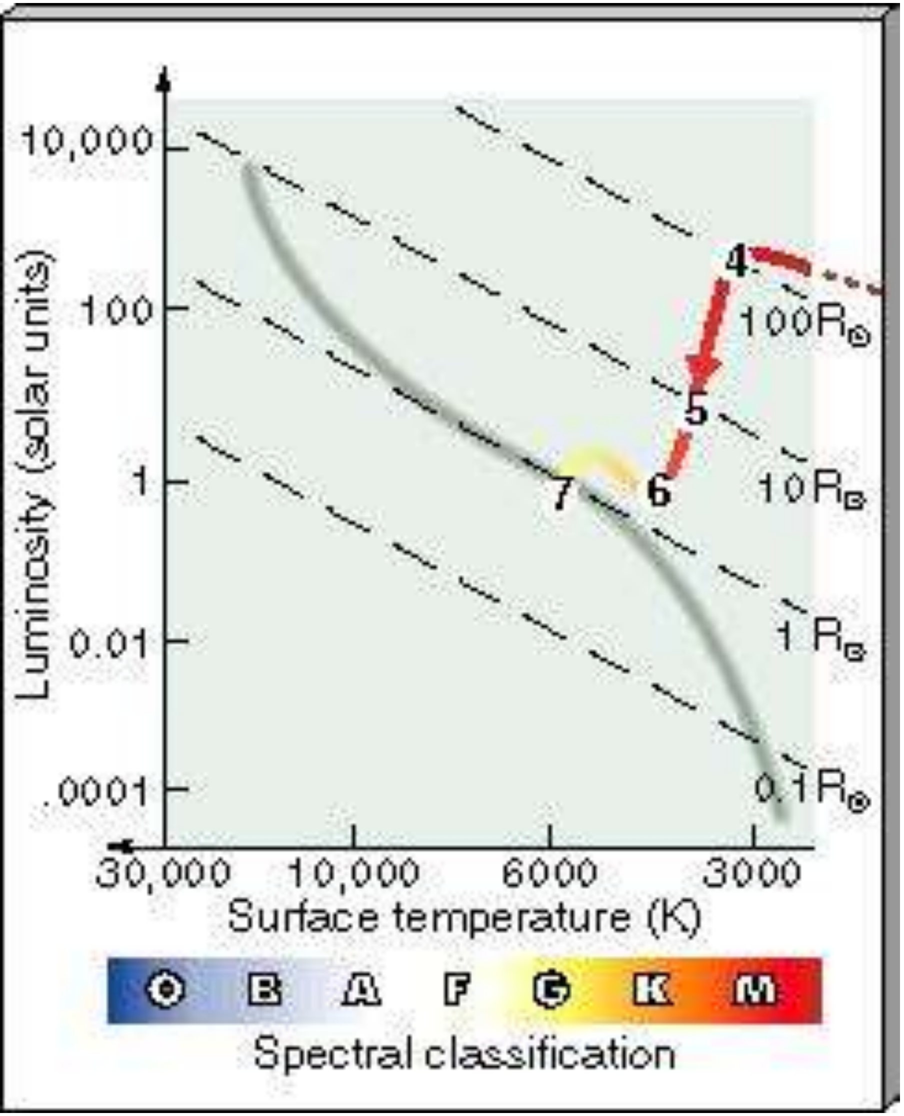
- By stage 5 the protostar has shrunk to about 10 times the size of the Sun, its surface temperature is about 4000 K, and its luminosity has fallen to about 10 times the solar value.
- The central temperature has reached about 5,000,000 K. The gas is completely ionized by now, but the core is still too cool for nuclear burning to begin.
- Events proceed more slowly as the protostar approaches the main sequence. The cause of this slowdown is heat—even gravity must struggle to compress a hot object.
- The contraction is governed largely by the rate at which the protostar's internal energy can be radiated away into space.
- As the luminosity decreases, so too does the contraction rate.

STAGE 6: A NEWBORN STAR

- Some 10 million years after its first appearance, the protostar finally becomes a true star.
- By stage 6, when our roughly 1—solar mass object has shrunk to a radius of about 1,000,000 km, the contraction has raised the central temperature to 10,000,000 K, enough to ignite nuclear burning.
- Protons begin fusing into helium nuclei in the core, and a star is born.
- The star's surface temperature at this point is about 4500 K, still a little cooler than the Sun. Even though the newly formed star is slightly larger in radius than our Sun, its lower temperature means that its luminosity is somewhat less than the solar value.

STAGE 7: THE MAIN SEQUENCE

- Over the next 30 million years or so, the stage 6 star contracts a little more.
- The central density rises to about 1032 particles/m3 (more conveniently expressed as 105 kg/m3), the central temperature increases to 15,000,000 K, and the surface temperature reaches 6000 K.
- By stage 7, the star finally reaches the main sequence just about where our Sun now resides. Pressure and gravity are finally balanced.
- The evolutionary events just described occur over the course of some 40—50 million years. Although this is a long time by human standards, it is still less than 1 percent of the Sun's lifetime on the main sequence.
- Once an object begins fusing hydrogen and establishes a "gravity-in/pressure-out" equilibrium, it burns steadily for a very long time. The star's location on the H—R diagram will remain virtually unchanged for the next 10 billion years.



- The changes in a protostar's observed properties are shown by the path of decreasing luminosity, from stage 4 to stage 6, often called the Hayashi track. At stage 7, the newborn star has arrived on the main sequence.

Failed Stars

- Some cloud fragments are too small to ever become stars, Jupiter is a good example.
- Jupiter did not have enough mass for gravity to crush its matter to the point of nuclear ignition.
- If Jupiter, or any of the other jovian planets, had continued to accumulate gas from the solar nebula, they might eventually have become stars (probably to the detriment of life on Earth)
- This is an example of a brown dwarf - objects which are frozen somewhere along their pre-main-sequence contraction phase, continually cooling into compact dark objects