Lecture 14: Star Formation

Readings: 20-1, 20-2, 20-3, 20-4, 20-5, 20-7, 20-8

Key Ideas

Raw Materials: Giant Molecular Clouds
Formation Stages:
- Cloud collapse and fragmentation into clumps
- Protostar formation from clumps
- Onset of hydrostatic equilibrium (Kelvin-Helmholtz timescale)
- Ignition of core hydrogen burning & onset of thermal equilibrium

Minimum and Maximum masses of stars

The Sun is Old and in Equilibrium
- Hydrostatic Equilibrium
  - Pressure=Gravity
- Thermal Equilibrium
  - Energy Transport=Energy Generation

How did it get this way?

We cannot observe the whole formation process for a single star. But we can learn a lot from observations of protostars and pre-main sequence stars in different stages of formation. We can learn both what they look like, and, from the number that we see, an idea of how long the various stages last.

Where do Stars come from?

We know that stars are dense balls of hydrogen.
Observations of the *interstellar medium* (the stuff between stars) shows that there is thin hydrogen gas out there

Warm Gas – 10,000 K
Cool Gas – 100 K
Cold Gas – 10 K

Resisting Gravity

The presence of thin H gas in the ISM shows that some gas can resist the pull of gravity

Supported by ideal gas pressure
magnetic force on ions

Gravitational force weak
Not much pressure needed to resist

Gravity is closest to winning in the coolest, densest clouds – the giant molecular clouds.

Giant Molecular Clouds (GMCs)

Clouds of Molecular Hydrogen (H_2)

<u>Properties</u>

Sizes ~10-50 parsec
Masses ~10^5 M_{sun}
Temperatures: 10-30K
Densities: 10^{5-6} atoms/cc

Raw material from which new stars form

Collapse of a GMC

A GMC is supported by its internal pressure
Gas pressure from internal heat
Pressure from embedded magnetic fields

If Gravity becomes larger than Pressure, the entire cloud will start to collapse

Ways to trigger a collapse:
Cloud-cloud collisions
Shocks from nearby supernova explosions
Passage through a spiral arm of the Galaxy

Observational evidence for these ideas are seen

Supernova example

Spiral arm example

Cloud Fragmentation

GMCs are clumpy:
- Clump sizes ~ 0.1 parsecs
- Clump masses ~ few M_{sun}

High-density clumps are more unstable than low-density regions
- Densest clumps collapse first & fastest

Result
- GMC fragments into dense cores
- Cores have masses comparable to stars

Building a Protostar

Cores start low density & transparent
- Photons leak out, keeping the gas cool
- Can't build up pressure & so keep collapsing

Core density rises until it becomes opaque
- Photons get trapped, so gas heats up
- Pressure builds up
- Eventually achieves *Hydrostatic Equilibrium*

Core grows as fresh gas falls onto it.

The protostar phase is Very Short ($10^{4\text{-}5}$ years)

Protostars in this phase are:
- In hydrostatic equilibrium
- Deeply embedded in their parent gas & dust clouds
- Not yet in Thermal Equilibrium

"Short-Lived" + "Hard to See" means very few protostars are observed.

Protostars have Disks: As matter rains onto a protostar
- Matter along the poles free-falls in rapidly
- Matter along the equator falls more slowly due to angular momentum conservation

Result is a flat, rotating disk of gas & dust around the equator of the protostar.

Clearing out the Disk

After the protostar forms, the disk begins to clear away:
    Some of the matter drains onto the star
    Other bits form into planets

Gas clears quickly, in ~ 6 Myr
Dust grains and solids take longer to clear away.
  We see dust and "debris" disks around young low-mass stars

From Protostar to Star

Protostars shine because they are hotter their surroundings
    Need an energy source to stay hot, but
    Central temperature is too cool for nuclear fusion to ignite

Initial energy source: Gravitational Contracton
    Protostar shrinks, releasing gravitational energy
    50 % goes into photons radiated as starlight
    50 % goes into heating the protostar interior

High-Mass Protostars

Gravitational Collapse is very fast:
    30 M_{sun} protostar collapses in < 10,000 years

Core Temperature gets hotter than 10 million K
        Ignites first p-p then CNO fusion in its core

Quickly ionizes and blows away any remaining gas

Low-Mass Protostars

Collapse is slower for low-mass protostars
    1 M_{sun} takes ~ 30 Myr = 30 million years

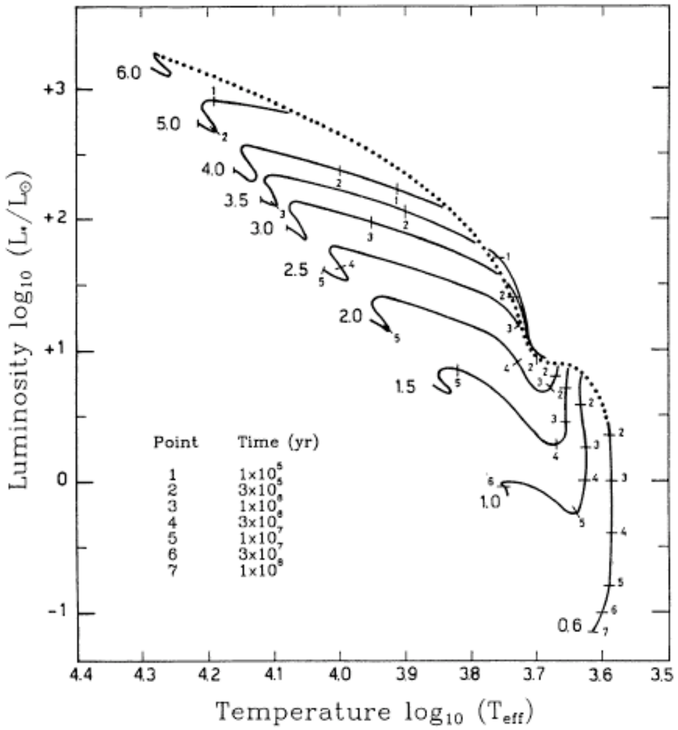
0.2 M_{sun} takes ~1 Gyr = 1 billion years

Core Temperature gets > 10 Million K

Ignite p-p chain fusion in the core

Settles slowly onto the main sequence

FIGURE 20-9 in your book is incorrect. Here are the paths on the H-R diagram.



Palla & Stahler 1993

Stars do not begin the protostar phase with the total mass they will have at the end. They are still accreting mass while collapsing slowly.

Mass steadily increases

Deuterium burning is an important energy source (even though only 1 H atom in 10^5 is a deuterium atom.

$^2H + p \rightarrow {}^3He + \gamma$

Happens when T>1 million K
Star is quite opaque and fully convective.

Stars move from right to left along the dotted line (the stellar birthline). When they stop accreting mass, they then follow the solid line labeled with their mass.

Extension: Why the decrease in Luminosity for low-mass stars once mass accretion is done?

Keep in mind the Luminosity-Radius-Temperature Relation

$$L = 4\pi R^2 \sigma T_{surface}^4$$

In a low-mass protostar, opacity is high. Energy is transported by convection.
T cannot drop quickly in this case, so even for a large star, the temperature is still warm.

Large Radius+Warm Temperature=Large Luminosity

As the star contracts, the radius gets smaller, but the temperature stays about the same.

Therefore the Luminosity drops.

The Main Sequence

As the core heats up, H fusion runs faster
    Core temperature & pressure rises
    Collapse begins to slow down
    Pressure=Gravity & collapse stops
    Energy created by H fusion=Energy lost by shining

Reaches the Zero-Age Main Sequence as a full-fledged star in Hydrostatic & Thermal Equilibrium

Minimum Mass ~ 0.08 M_{Sun}

Below 0.08 M_{Sun}, the core never gets hot enough to ignite H fusion

Becomes a Brown Dwarf
    Resemble “Super Jupiters”
    Energy: K-H mechanism
    Only few hundred are known (very faint)
    Shine mostly in the infrared

These are the T dwarfs

Maximum Mass ~ 100-150 M_{Sun}

Above 100-150 M_{sun} the core gets so hot
    Radiation pressure overcomes Gravity
    Star becomes unstable and disrupts itself

Ultimate mass limit is not precisely known

Such stars are extremely rare (few per galaxy)

What can we see?

We see stars in all phases of their life cycles
    If the phase is long, we see many in that phase
    If the phase is short, we see few in that phase

The Pre-Main Sequence Phase is longer for lower-mass protostars:
    We see a few low-mass protostars
    High-mass protostars are very rare

Main sequence phase is very long
    We see more main-sequence stars than protostars

Observational Evidence

No gas – no recently formed main-sequence stars
Gas – recently formed main-sequence stars

We see dense molecular cores with infalling gas.

Pre-main-sequence stars appear only below the birthline. Otherwise they remain shrouded in dust and gas, accreting masss.

Current Questions about Star Formation

We have a good qualitative explanation for star formation, but we are still working on good quantitative models;

When is accretion onto the protostar stopped? How is the mass of the core related to the mass of the final star?

What explains the ratio of high-mass to low-mass stars formed?

Why are some regions of galaxies more efficient at star formation than others?

Why are stars spinning so slowly?