Star Formation - Summary

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This summary is based on the book Chapter 12 from Carroll, Bradley W., and Dale A. Ostlie. An Introduction to Modern Astrophysics

1 The formation of protostars

Protostars: pre-nuclear-burning objects

Globules and cores in molecular clouds are the sites of star formation. These are typically located in Giant Molecular Clouds (GMCs) or molecular cloud complexes. E.g. The Orian Molecular Cloud Complex.

Important physical conditions for star formation:

- hydrostatic equilibrium → virial theorem: $2K + U = 0$ where K is the kinetic energy and U is the gravitational potential energy
- if the internal kinetic energy is too low, the cloud will collapse
- for simplification we neglect rotation, turbulence, and magnetic fields.
- Jeans criterion: $M_J > M_C$
- Jeans mass $M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho_0}\right)^{1/2}$
- Jeans length $R_J = \left(\frac{15kT}{4\pi G\mu m_H \rho_0}\right)$

There are many examples for external pressure triggering star formation. If external pressureis included in the criteria for gravitational collapse we get the Bonnor-Ebert mass:

$$M_{BE} = \frac{c_{BE}\nu_T^4}{P_0^{1/2}G^{3/2}}$$

Examples for external pressure:

- Supernovae
- winds from star formation regions
- ram pressure from the intergalactic medium

Diffuse hydrogen clouds are stable against gravitational collapse. Dense cores of GMCs are unstable to gravitational collapse (estimate for Jeans mass: Jeans mass is $M_J \sim 8M_\odot$, $M_{BE} \sim 2M_\odot$).

2 Cloud Collapse

The cloud is essentially in free-fall during the first part of its evolution, temperature of the gas remains nearly constant → we can calculate the free-fall timescale $t_{ff} = \left(\frac{3\pi}{32}\frac{1}{G\rho_0}\right)^{1/2}$. This is independent of the initial radius.

- If density of the spherical molecular cloud was uniform → the density will increase at the same rate everywhere → **homologous collapse**
- If the cloud is somewhat centrally condensed → free-fall time will be shorter for material near the centre → density will increase more rapidly near the centre → **inside-out collapse**
- Collapse is quite slow initially and accelerates quickly as t_{ff} is approached + density increases very rapidly during the final stages of collapse.

Fragmentation

- stars preferentially form in groups
- fragmentation: After collapse has begun, any initial inhomogeneities in density will cause individual sections of the cloud to satisfy the Jeans mass limit independently and begin to collapse locally, producing smaller features within the original cloud.
- only about 1% of the cloud actually forms stars.
- While the cloud is collapsing, in the first stage the energy that is released during a gravitational collapse is radiated away (isothermal).

- If the cloud is too dense, the energy can not escape (adiobatic) → the cloud will start to heat up → temperature change affects the value of the Jeans mass → Jeans mass increases with increasing density → a minimum value for the mass of the fragments produced

Additional important factors:
- rotation → Angular momentum present in the original cloud → result in a disk-like structure.
- the deviation from spherical symmetry
- turbulent motions in the gas
- presence of magnetic fields → magnetic pressure and resistance to the compression. (magnetically subcritical or magnetically supercritical)

Ambipolar diffusion: if there is a net defined direction for the motion of neutrals due to gravitational forces, they will still tend to migrate slowly in that direction. This slow migration process is known as ambipolar diffusion. Ambipolar diffusion process can control the evolution of a dense core for a long time before free-fall collapse begins.

3 Evolutionary tracks

Protostar formation model:
- Consider a spherical cloud of approximately 1 $M_\odot$ and solar composition that is supercritical.
- Initially the early stages of the free-fall collapse are nearly isothermal because light near the center of the collapse can travel significant distances before being absorbed by dust.
- Due to an initial slight increase in density toward the center of the cloud, the free-fall timescale is shorter near the center and the density increases more rapidly there (inside-out collapse).
- When the density of the material near the center of the collapse region reaches approximately 10-10 kg m^{-3}, the region becomes optically thick and the collapse becomes more adiabatic. The opacity of the cloud at this point is primarily due to the presence of dust.
- The increased pressure substantially slows the rate of collapse near the core.
- At this point the central region is nearly in hydrostatic equilibrium with a radius of approximately 5 AU. It is this central object that is referred to as a protostar.

Protostar evolutionary tracks
- The protostars are hot enough to produce some radiation → they show up on the H-R diagram to the right side of the main sequence.
- while in the protostar stage the object moves upwards and towards the left on the H-R diagram towards the main sequence.
- While in this stage, the protostar continues to accrete material and grow.
- temperatures in the deep interior of the protostar hav increased enough that deuterium (^{2}H) begins to burn
- infrared sources embedded within dense cores or Bok globules.
- short-lived objects
- 2 peaked spectra
- at the end of the evolution → Hayashi track: boundary between 'allowed' hydrostatic stellar models and those that are 'forbidden.' → left of the Hayashi track, convection and or radiation (proper star)
- At the end of the protostar stage the star becomes a pre-main sequence star

pre-main sequence star
- The pre-main sequence star moves towards the left to reach the main sequence on the H-R diagram.
- star is completely convective during approximately the first one million years of the collapse → deuterium burning
- central temperature continues to rise → radiative core → temperature near the center has become high enough for nuclear reactions to begin → nuclear reactions eventually stabilise
- at the end the star reaches the zero-age main sequence (ZAMS)
- the time required for stars to collapse onto the ZAMS is inversely related to mass

If the stable hydrogen-burning is not obtained → **brown dwarf**. These are objects in the range between 0.013 $M_\odot$ and 0.072 $M_\odot$.

From observational studies it is apparent that more low-mass than high-mass stars form when an interstellar cloud fragments. → initial mass function (IMF) → massive stars are extremely rare

Massive stars form in a different way compared to low mass stars

4 HII regions

When O or B stars start to radiate → the intense radiation ionises the surrounding material → HII regions.

- radiation is emitted in the ultravio
- equilibrium, the rate of ionization must equal the rate of recombination;
- When recombination occurs, the electron does not necessarily fall directly to the ground state but can cascade downward, producing a number of lower-energy photons, → red line of the Balmer series (H_α)
- Strömgren spheres - Strömgren radius
- 0.1 pc to greater than 100 pc.

The effect of massive stars once they start to radiate can stop further star formation. The strong radiation can quickly destroy the remainder of the molecular cloud.

OB Associations: Groups of stars that are dominated by O and B main-sequence stars are referred to as OB associations.

5 TTauri stars

T Tauri stars are an important class of low-mass pre- main-sequence objects. They have rapid irregular variations in luminosity, with timescales on the order of days. They have strong emission line → shapes of those lines: broad emission peak is an absorption trough at the short-wavelength edge. This is called a **P Cygni profile.** The P Cygni profile is produced by an expanding mass shell. → star is experiencing significant mass loss.

An **inverse P Cygni** profiles (redshifted absorption) on timescales of days, indicating mass accretion rather than mass loss.

6 FU Orionis stars

The luminosities of the stars increase by four magnitudes or more, with the increases lasting for decades. The inner disk can outshine the central star by a factor of 100 to 1000, while strong, high- velocity winds.

7 Herbig Ae/Be stars

Herbig Ae/Be stars: These pre-main-sequence stars are of spectral types A or B and have strong emission lines. Their masses range from 2 to 10 $M_\odot$ and they tend to be enveloped in some remaining dust and gas.

8 Herbig-Haro Objects

Herbig-Haro objects: jets produced by young protostars → jets expand supersonically into the interstellar medium, collisions excite the gas

9 Young stars with circumstellar disks

Often we can observe dust disk around young stars. These are debris disks, leftover material from the star formation. → planest can form from these.
Proplyds: protoplanetary disks associated with young stars