

Chapter 14. Star Formation

Physical States of the Interstellar Medium

The interstellar medium (ISM) consists of gas and dust in the spaces between the stars. The ISM's composition is roughly 90% H and 10% He (by number of atoms).

Stars hotter than 25,000 K (earlier than B2) emit energetic UV photons to ionize hydrogen, called *photoionization*, and the ionized gas is called an “HII region”. “HII” means ionized hydrogen. HII regions emit bright H α line, and appear red.

B stars are bright and blue, but not hot enough to emit UV radiation to ionize the ambient ISM. Dust clouds near B stars can scatter/reflect the starlight and become “reflection nebulae”. Reflection nebulae appear blue, which is the color of B stars.

Without excitation, the ISM would be in a dense, cold state and the gas is in the form of molecules. UV radiation from O and B stars can dissociate the molecules into atoms and further ionize them. These massive stars usually have fast stellar winds and their final supernova explosions can shock-heat the ISM to 10^6 K. The four major states of the ISM are:

ISM	Hydrogen	Temp.	Density
Molecular Cloud	H ₂	10 K	$> 10^3$ H/cm ³
Neutral Atomic Cloud	H	100 K	~ 10 H/cm ³
HII Regions	H ⁺	10^4 K	$\leq 10^3$ H/cm ³
Coronal Gas	H ⁺	10^6 K	10^{-2} H/cm ³

Emission Mechanisms

Both the proton and electron in an atomic H spin. Parallel spins correspond to a higher energy level, and opposite spins a lower energy level. When the electron flips its spin direction from parallel to opposite to the proton's spin, a 21-cm photon will be emitted. This is the famous 21-cm line of HI. (“HI” means neutral atomic hydrogen .)

A hydrogen ion (proton) can recombine with a free electron to become an H atom at a high energy level. Spectral line photons are emitted when the electron cascades down the energy levels. Transitions to the n=2 level produce the Balmer series, e.g., H α , H β , H γ , etc. The H α line at 6563 Å is the strongest line and gives HII regions a red color.

Interstellar gas shock-heated to 10^6 K emits in X-rays.

Interstellar Dust

Dust is mixed with gas in the ISM; denser gas contains more dust. Dust grains provide large surface areas for atoms to gradually build up complex molecules.

Interstellar dust causes “extinction” and “reddening”. Dust scatters light more easily at shorter wavelengths; thus, stars viewed through interstellar dust appear dimmer and redder.

Dark clouds contain so much dust that they block all star lights. Most dark clouds co-exist with large molecular clouds. Some dark clouds are small and isolated, called *Bok globules*.

Protostars, T Tauri Stars, Herbig-Haro Objects

T Tauri are variable stars with spectra similar to F, G, K, M spectral classes. They emit X-rays and show lithium in their atmospheres. T Tauri stars are *protostars*.

Some T Tauri stars show P Cygni lines (emission line with blue-shifted absorption) indicating a mass outflow, while others show inverse P Cygni lines (emission line with red-shifted absorption) indicating a mass inflow. It is now known that T Tauri stars are surrounded by accretion disks and jets. Outflows are observed when a T Tauri star is viewed along the jet, and inflows are observed when viewed along the disk. The outflows, interacting with the ambient interstellar medium, form the *Herbig-Haro (H-H) objects*.

Formation of Solar-Type Stars

Star formation starts with the contraction of a molecular cloud under the force of its own gravity. The gravitational energy is converted to heat in the central core. The conservation of angular momentum causes the infalling gas to spin faster and form a disk. The central protostar continues to accrete material from the disk. After 10^5 to 10^6 yr, the interior of the protostar reaches a temperature of 10^6 K, and deuterium begin to fuse into helium and generate heat. The protostar would brighten up and expand, generating a fast stellar wind. The fast wind blows through the poles of the disk and creates a bipolar outflow, the jets. When deuterium is exhausted, the star contracts. When the interior temperature reaches 7×10^6 K, protons begin to fuse into helium. The star then settles down onto a line on the HR diagram called the *zero-age main sequence (ZAMS)*. The stable stellar life starts.

Formation of Other Types of Stars

T Tauri stars become main-sequence stars with masses of 0.75 – $3 M_{\odot}$. Protostars with masses less than $0.75 M_{\odot}$ are fainter and less known.

Brown dwarfs are stars with mass $< 0.08 M_{\odot}$. They can burn deuterium into helium, but they are not hot enough for thermonuclear burning via p-p chain or CNO cycle.

The formation of massive O stars is not as well-known, since most massive star formation regions are distant and obscured by dust.

Formation and Detection of Planets

The accretion disk around a T Tauri star may be equivalent to the solar nebula and form planets. A disk of 400 AU radius has been detected around the star β Pictoris, and the disk show spectral features of dust and ices similar to those seen in the solar system. It is believed that the disk around β Pictoris is a planetary disk. Recent Hubble Space Telescope images of the Orion Nebula have revealed many planetary disks around stars.

Planets around other stars would be very difficult to detect because they are much dimmer than the star. A star orbits in the star-planet combined gravitational field, and its periodic orbital velocity change allow us to detect Jupiter-sized planets.