A Star is Born!

The Formation Process of Stars

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Despite major, important progress in our knowledge of the star formation process in the Galaxy, an endless number of questions, related to the central question “How do stars form?” remain to be answered. Our current understanding of how stars and clusters of stars are formed out of the interstellar matter is discussed here.

Introduction

Until the present century, it was commonly believed that the spaces between the stars were devoid of any observable material. In the 1930s, however, observations revealed that material did exist between the stars and that this material had a pronounced effect on the starlight moving through space. It is this medium (the so called interstellar medium) which provides the raw material for the formation of new stars. A complete understanding of star formation, therefore, must include a complete understanding of the material out of which the stars form. The interstellar medium is divided into two major categories: interstellar dust and interstellar gas.

Interstellar Dust

Although the interstellar dust is far less abundant than the interstellar gas, the effect it has on starlight is far more pronounced because the size of the interstellar dust grains (of the order of 1/1000th of mm) is similar to the wavelength of visible light (about 0.0005 mm for yellow light). The exact nature of the interstellar grains is difficult to ascertain. The best estimates come from an analysis of the way in which the grains scatter light. The indications are that the particles of interstellar dust are elongated particles of frozen water, carbon or silicates. Other constituents are probably also present.
Box 1. Interstellar Molecules

During the last 10 years, radio astronomers have discovered several dozen gaseous compounds among the hydrogen clouds of interstellar space. These complex molecules are observed by virtue of the characteristic wavelengths of electromagnetic radiation they emit or absorb. Many molecular lines, however, have recently been discovered in large cloud complexes and almost all those lines fall in millimeter and centimetre wavelengths. Several of these molecules are of organic variety and are considered to be the materials out of which the building blocks of life are formed. Some of these interstellar molecules are hydroxyl (OH) radicals, ammonia, water, methyl alcohol, methyl cyanide, hydrogen cyanide, formaldehyde and carbon monoxide. These molecules are far less abundant than hydrogen.

Interstellar Gas

The interstellar gas is predominantly composed of hydrogen and of that which remains, most is helium. In the general regions of interstellar space, the density of the interstellar gas is about 1 atom per cubic centimeter (1 atom/cm³). At many places within the galaxy, however, atoms of gas congregate into great clouds or nebulae. In these gas clouds, the density may be as high as 10⁵ atoms/cm³. This density is still, however, far less than the density of the air at the surface of the earth (10⁹ atoms/cm³).

Star Formation

All theories based on current observations indicate that stars are formed as a result of large scale gravitational instability developed in the central region of the massive molecular clouds. Instability leads to collapse and breaking into pieces of the original cloud. Each sub-unit subsequently suffers further collapse and fragmentation leading to the birth of a group of protostars within the cloud, surrounded by a diffuse envelope.

The initial stages of star formation are difficult to observe directly because at that time the cloud (protostar)³ is very cool and therefore does not give off visible radiation. Success has been achieved recently, by making observations with infrared telescopes. Because the cloud is cool, dusty and optically thick, most of the observable radiation falls in the mid infrared 30-100 μm range.

³. A protostar is a star that has already been formed but which is not yet in hydrostatic equilibrium.
The gravitational collapse is isothermal, the compressional heat generated during collapse being radiated away in infrared and other low frequency radiation via heated grains and excited low lying levels of molecules.

**Initial Condition for Star Formation (Jeans Condition)**

In theory the initial condition for star formation can be defined by the requirement that the absolute value of the gravitational energy must exceed the sum of the thermal, rotational, turbulent and magnetic energies. This requirement defines a mass of gas that is gravitationally bound. For this mass to be as small as a solar mass, the requirement can be satisfied only in the coolest, densest part of the interstellar medium.

The mathematical treatment of the problem of gravitational instability and collapse was first considered by Sir James Jeans in 1902.

If the initial density of a cloud of mass is $\rho_0$ and the temperature is $T$ and if it has a dimension greater than some critical length $\lambda_j$ then the cloud will be gravitationally unstable and will contract continuously under gravitational pull. The critical length $\lambda_j$ is called 'Jeans length' and is given by (equating gravitational potential energy with the total kinetic energy)

$$\lambda_j \equiv 6 \times 10^7 (T/\rho_0)^{1/2} \text{ cm}.$$

The corresponding critical mass, called Jeans mass ($M_j$), of a sphere of diameter $\lambda_j$ is

$$M_j \equiv 10^{23} (T/\mu)^{3/2}/\rho_0^{1/2} \text{ gm}.$$

Any cloud of mass $M > M_j$ will be gravitationally unstable and will suffer a continuous collapse so long as the isothermal state is maintained by the collapsing cloud. Jeans criterion of gravitational collapse was however too simplified, with the gravitational instability of a cloud of mass being unaffected by the presence of uniform rotation, turbulence or a uniform magnetic field.
**Box 2. What is the Rate and Efficiency of Star Formation as a Function of Time and Position in our Galaxy and in External Galaxies?**

‘Efficiency’ refers to the fraction of the mass of a molecular cloud that is actually transformed into stars during the lifetime of the clouds. This quantity is crucial for models of galactic evolution. It is generally quoted to be less than 5%. The star formation rate, for the purpose of galactic evolution models, is often assumed to be a simple function of gas density. However, such relations can be true only in a very rough, overall sense. Local star formation appears to occur only in the very densest regions of molecular clouds and in regions of lower density, even in the same molecular cloud, it does not occur at all. Then a ‘rate’, measured in a global sense describes the rate of evolution of molecular cloud material into the high density state.

**Star Formation Phases**

The process of formation of a star can be divided into three phases. The first, known as ‘star formation’, involves massive interstellar clouds or cloud fragments, which have cooled to the point where they are detectable in molecular lines (such as CO) but which are unable to collapse because of an excess of thermal, turbulent, rotational and magnetic energy over gravitational. The second phase, which lasts typically 10^6 years, involves dissipation of much of this energy. The third phase, the protostellar collapse phase, starts when fragments of \( \sim 1M_\odot \) \( (M_\odot \rightarrow \) solar mass) become gravitationally unstable. A fragment then evolves through an increase of 16 orders of magnitude in density and 5 orders of magnitude in temperature. The observable radiation produced during this phase is primarily in the infra-red.

At the end of the collapse, when the object has reached the point where gas pressure can support it in equilibrium against gravity, it has star like properties and it begins contraction in near hydrostatic equilibrium.