CHAPTER-I

INTRODUCTION

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1.4 Ionisation and Dust Grains
1 INTRODUCTION

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1.1 Basics of Star Formation Process

The process of star formation occupies a critical position in astrophysics, because understanding of it is required for the progress to be made on other fundamental problems, including stellar evolution, the properties of interstellar medium, galactic evolution and formation of planetary system. Large clouds of interstellar gas and dust at some point of time become gravitationally unstable, undergo contraction to form at first the pre-stellar bodies. The contraction continues, first at a rapid pace, but later the contraction slows down as the pressure building is rather quickly achieved for two factors: firstly, as the contraction proceeds the density of matter increases: secondly, contraction releases gravitational energy about one-half of which is utilized to increases the internal temperature, the remaining being radiated away. This simultaneous increase of density and temperature causes a rather rapid increase in the gas pressure which checks to
a great extent the initial rapid contraction. As the density goes up, the stellar matter becomes opaque to radiation. Hydrogen and helium being the most abundant elements, a large fraction of the radiation is consumed in their ionisation. Since an overwhelmingly large number of atoms are hydrogen, the internal temperature is restricted to below 10 K until hydrogen becomes mostly ionised. After hydrogen and helium ionisation has become complete, the interior temperature further rises and the star proceeds towards achieving the hydrostatic equilibrium. The currently accepted theory of the pre-main-sequence contraction of star was propounded by Japanese astrophysicist, C. Hayashi (1985). He showed that the surface temperature of the star must be sufficiently high before it can achieve the state of hydrostatic equilibrium with its radius still very large. Very large radius and sufficiently high surface temperature of a star together requires, the star to have very high luminosity. At this stage the opacity of the stellar material is still very high which prevents the smooth transfer of radiation from the interior to the surface. As a result, a large scale convection through the entire body of the star is called into play which carries the required amount of energy to the surface of the star. The star is therefore, said to be in a state of convective equilibrium. It has been shown by Hayashi (1985)
that during the stage of convective equilibrium, the contraction of the star proceeds keeping its surface temperature almost constant. A fully convective interior prevails from a few thousands to a few million years, depending upon the initial mass of the star in the way that the higher mass star has lower time scale. Throughout the contraction period the central core temperature of the star continues to rise, and at a stage the complete convective equilibrium gives way to a radiative core which begins to grow. The subsequent stage of the pre-main-sequence evolution of the star is characterized by the growth of the radiative core to larger and larger size until the convective region is pushed to the other region either to restrict it in the envelope of the star or to remove it altogether out of the stellar body. The former situation is relevant to stars having masses like that of the Sun and lower, while the latter case is relevant to more massive stars. The growth of the radiative core is accompanied by the corresponding increase in core temperature which continues until it becomes high enough to ignite the nuclear fuel at the core. When the nuclear energy generation becomes sufficient to balance the stellar radiation, the gravitational contraction of the star halts for the first time and the star is said to settle on the main sequence.
Star formation appears to occur only in the dense regions of molecular clouds, and in regions of somewhat lower density, even in the same cloud, it does not occur at all. The fraction of the mass of a molecular cloud which is actually transformed into star during the lifetime of the cloud is called ‘efficiency of star formation’. This quantity is very important and crucial for models of galactic evolution. It is generally quoted to be less than 5 percentage (Shu et al. 1987; Lada et al. 1992).

A star that has already formed but which is not yet at hydrostatic equilibrium is called a protostar. It obtains its radiated energy (photons) from the conversion of in-falling kinetic energy in an accretion shock at the edge of a stellar core. Because the in-falling material outside the core is cool, dusty, and optically thick, most of the observable radiation falls in the mid infrared at 30—100$\mu$m. As the protostar accretes, the gravitational energy increases and the radius decreases. To keep the angular momentum constant the centrifugal force increases faster and a stellar wind is generated which first breaks through the infalling material at the rotational poles where the density is lowest. Thus, the bipolar outflow starts in a protostar. Protostar goes through an outflow phase lasting about $10^5$ years with mass loss rates up to $10^{-5}M_\odot$.
years$^{-1}$ (Shu et al., 1988). Most of the mass is in molecular form, observed in CO at velocities of 10-20 km sec$^{-1}$. This out-flowing material has significant interactions with surrounding molecular cloud material. Magnetic-rotational interaction may be the cause for this outflow of molecular components from the star (Shu et al., 1988). During normal phases of stellar evolution, spherical symmetry is an adequate assumption because rotation and magnetic field do not have significant physical effects. But during star formation these effects can be of dominant importance. An overall definitive theoretical calculation of the phases of star formation and protostellar collapse is not yet available. The magnetic flux deduced from observations of interstellar cloud is also not in consistency with that in stars, if the net flux is conserved. Flux freezing breaks down during the phases of star formation when the degree of ionisation is small. This results in diffusion of gas relative to the field, which again causes the flux loss and alleviates the problem to some extent.

1.2 Initial Conditions for Star Formation

The initial conditions 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 the magnetic energies. This requirement defines a mass of the gas that is gravitationally bound. Let us consider gravitational and thermal effects alone. The requirement that the gas be gravitationally bound leads to the determination of a critical radius of the cloud, called Jeans length (Jeans, J. H.; 1920):

\[ R_J = \frac{0.4GM\mu}{R_gT} \]  

(1)

where \( G \) is the universal gravitational constant, \( R_g \) is the gas constant, \( \mu \) is the mean molecular weight, \( M \) is the mass, and \( T \) is the temperature of the star forming cloud. Alternatively, an expression for the Jeans mass, which is the minimum mass that the cloud of given density and temperature \((\rho, T)\) must have to be gravitationally unstable, can be obtained as:

\[ M_J = \left( \frac{5R_gT}{2\mu G} \right)^{\frac{3}{2}} \left( \frac{4}{3\pi\rho} \right)^{-\frac{1}{2}} \]  

(2)

Considering rotational effects in addition to thermal and gravitational effects, the revised expression for the Jeans mass becomes

\[ M_J = \left( \frac{R_gT}{\mu} + 0.2\Omega^2R^2 \right)^{\frac{3}{2}} \left( \frac{4}{3\pi\rho} \right)^{-\frac{1}{2}} \]  

(3)

where \( \Omega \) is the rotational velocity of the cloud. Rotation has a stabilizing influence. Even if gravitational energy initially dominates over rotation, as cloud starts to collapse, the rotational energy increases faster than gravitational energy, and the collapse could be
stopped at relatively low density.

Considering an uniform magnetic field $\mathbf{B}$ in the cloud and considering that the thermal and rotational effects are unimportant, the magnetic Jeans mass for gravitational instability becomes

$$M_J = 10^3 M_\odot \left( \frac{B}{30 \mu G} \right) \left( \frac{R}{2 \text{pc}} \right)^2$$

(4)

If the magnetic field is well-coupled to the gas, then the magnetic flux $\mathbf{B}R^2$ remains constant as the cloud collapse and above equation (4) shows that $M_J$ is constant, that is, the cloud would not be unstable to fragmentation into small masses.

Under typical interstellar conditions, with $T = 100$ K, $n = 10$ \textit{particle cm}^{-3} and $B = 3 \mu G$, the thermal Jeans mass is $10^4 M_\odot$. However, the magnetic Jeans mass is even more restrictive, having a value about $2 \times 10^4 M_\odot$. The clouds are, in general, subdivided into clumps with characteristic mass $10^3 - 10^4 M_\odot$, radii 2-5 pc, temperature 10 K, mean number density $10^2 - 10^3$ \textit{particle cm}^{-3} and magnetic field $3 \times 10^{-5}$ Gauss. Embedded in the clumps are the higher density cloud cores, observed in $NH_3$, $CS$ and other molecules.
1.3 Different Physical Processes in Star Formation

To explain how ammonia cores evolve into stars, one has to solve the problem of hydrodynamics of a self-gravitating fluid with pressure, rotation, and a magnetic field. The equation of state is that of an ideal gas, including dissociation and ionization. The physics of dust particles, including formation, growth, destruction and absorption of radiation, is important for determination of the opacity of the particles, for the cooling of the cloud and for the formation of planets.

Presence of magnetic field makes physical processes more complex. The magnetic field is important: firstly, for the support of the magnetic cloud clumps against collapse. The typical observed field at the mean clump density is $30 \mu G$. Clump which has mass less than the magnetic Jeans mass, is unlikely to collapse, particularly when turbulent effects are included. For a molecular cloud clump of radius 1 pc, the flux $BR^2 \sim 3 \times 10^{32} \text{ gauss cm}^2$, while for a typical star with a 100 gauss average field the corresponding figure is only $10^4 \text{ gauss cm}^2$. Secondly, the field provides the most likely mechanism to transport angular momentum out of the dense cloud core. The evolution of the cloud core to the point of collapse requires that the field diffuses with respect to the matter
(Nakano and Umebayashi, 1980).

The evidence for existence of magnetic field is given by measurements of the polarization of star light (Vrba et al., 1976; Goodman et al., 1990; Sen et al., 2000) which show that the direction of the field in a cloud is well-ordered, rather than random, indicating that the field may be dynamically important in determining the cloud structure. The component of the field strength in the line of sight can be found by observing the Zeeman effect in neutral H (Heiles, 1988, and 1989) and OH (Goodman et al., 1989). In dark cloud regions with densities up to $10^4$ particles $cm^{-3}$, the measurements give $B_{||} \sim 15 - 130 \, \mu G$.

Table-1: Rotational velocity $\Omega$ of some interstellar objects (Bodenheimer, 1992)

<table>
<thead>
<tr>
<th>Object</th>
<th>Size(pc)</th>
<th>$\Omega(s^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B5$</td>
<td>5.0</td>
<td>$2 \times 10^{-14}$</td>
</tr>
<tr>
<td>TMC1</td>
<td>1</td>
<td>$3 \times 10^{-14}$</td>
</tr>
<tr>
<td>B35A</td>
<td>0.30</td>
<td>$3.4 \times 10^{-14}$</td>
</tr>
<tr>
<td>TMC - 2A</td>
<td>0.04</td>
<td>$7.0 \times 10^{-14}$</td>
</tr>
<tr>
<td>L1524</td>
<td>0.04</td>
<td>$4.6 \times 10^{-14}$</td>
</tr>
</tbody>
</table>
Rotation is detected in molecular clouds and cloud cores through observations of a gradient in the radial velocity as measured at various points across the cloud, by Doppler shift of emission lines in $NH_3$ (Goldsmith and Arquilla, 1985; Heyer, 1988; Goodman et al. 1990). About half of the clouds observed, show measurable rotational velocities; the remainder are presumably rotating below the observational limit. The angular velocity is similar on all scale of size; it is only higher in cloud cores than in molecular cloud clumps as a whole.

The entire star formation process can be divided into three phases: ‘star formation’, ‘protostar collapse’, ‘pre-main-sequence’. The first phase involves physical processes in massive clouds or cloud fragments, which have cooled to a point where they are detected in molecular lines (such as CO) but which are unable to undergo collapse because of excess of thermal, turbulent, rotational, and magnetic energy over gravitational energy. This phase lasts typically for $10^7$ years and involves in dissipation of much of this excessive energy. The protostar collapse phase starts when the massive clouds or cloud fragments become gravitationally unstable. Such unstable cloud then evolves through an increase of almost 16 orders of magnitude in density and 5 orders of magni-
tude in temperature. The observable radiation produced during this phase is primarily in the infrared region. At the end of this protostar collapse phase, the object reaches to a point where gas pressure can support it in equilibrium against gravity. Now it has star like properties and it begins a slow contraction in near hydrostatic equilibrium. For a typical pre-main-sequence contraction phase of a star of mass $1M_\odot$ has the contraction time of about $4 \times 10^7$ years after which nuclear reactions are set off.

The first two of these three phases are discussed below. Depending upon the spectral energy distribution, young objects can be classified into three main classes (Lada, 1987). Objects of class-I have the typical spectrum peaks at 60-100 $\mu$m and has little or no radiation in near infrared. This type of objects are also known as an ‘embedded’ IR sources or as a candidate protostar. It is probably surrounded by dust. An object of class-II shows spectrum in IR and also in UV region and they are observable in the visible range of electromagnetic radiation. Class-II objects are often T Tauri stars; they have less circumstellar dust than class-I objects. Such objects are interpreted to be pre-main-sequence stars. A class-III object has a spectrum close to a black body of a single temperature. These are young main-sequence
stars (Walter, 1987).

By counting the number of objects in class-I relative to those in class-II and class-III in a given star formation region, one can make an estimate of the relative amount of time spent in various phases. Kenyon et al. (1990) found that the embedded phase lasts for $1 - 2 \times 10^5$ years by studying the Taurus region, while in the $\rho$ Ophiuchi cloud the corresponding time scale is $1 - 4 \times 10^5$ years.

Table-2 : Major phases of early stellar evolution
(Bodenheimer, 1992)

<table>
<thead>
<tr>
<th>Phases</th>
<th>Size(cm)</th>
<th>$\rho$(gcm$^{-3}$)</th>
<th>$T$(K)</th>
<th>Time(years)</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$10^{20} - 10^{17}$</td>
<td>$10^{-22} - 10^{-19}$</td>
<td>10</td>
<td>$10^7$</td>
<td>Radio</td>
</tr>
<tr>
<td>II</td>
<td>$10^{17} - 10^{12}$</td>
<td>$10^{-19} - 10^{-3}$</td>
<td>$10 - 10^6$</td>
<td>$10^5 - 10^6$</td>
<td>Infrared</td>
</tr>
<tr>
<td>III</td>
<td>$10^{12} - 10^{11}$</td>
<td>$10^{-3} - 1$</td>
<td>$10^6 - 10^7$</td>
<td>$4 \times 10^7$</td>
<td>optical, IR</td>
</tr>
</tbody>
</table>

where, $I=$ star formation phase, $II=$ protostellar collapse, and $III=$ pre-main-sequence

Thus, the sequence of events which lead to a single star formation with a planetary system can be stated briefly as follows.
Starting at densities characteristic of molecular cloud, the frozen-in magnetic field transfer much of the angular momentum out of the cloud on a time scale of $5 \times 10^6$ years. Matter in the cloud becomes less and less tightly coupled to the field, the degree of ionisation drops, and neutral particles are able to drift inward with respect to magnetic field. Through hydrostatic equilibrium, a molecular cloud core forms on a diffusion time scale of about $10^7$ years (Lizano and Shu, 1989; Tomisaka et al., 1990). The density in the central region increases and the cloud core can be observed in ammonia lines (Benson and Myer, 1989). The magnetic field becomes dynamically unimportant in the core and the mass in this region exceeds the thermal Jeans mass. The protostar collapses nearly in free-fall, with conservation of momentum, on a time scale of $10^5 - 10^6$ years. Sasselov and Rucinski (1990) observed such a source in $\rho$ Oph which is estimated to have a density of $10^7 - 10^8$ particles cm$^{-3}$, which would put it well into the isothermal collapse phase. Thus the core forms with an accretion shock at its outer boundary. As material with high angular momentum approaches equilibrium, a disk forms. The core disk structure is still surrounded by an optically thick in-falling envelope. Such a protostar is an infrared source and is identified as a class-I object. As the protostar accretes, the bipolar out-
flow phase starts. A stellar wind is generated which first breaks through the in-falling material at the rotational poles, where the density gradient is steepest and the in-fall ram pressure is the lowest. L1551 IRS5 is a particularly interesting example which shows a bipolar outflow in CO at 10 km sec$^{-1}$, a disk observed in CS (Stocke et al., 1988). At a point of time in-fall stops because it is reversed by the bipolar flow and associated stellar winds or because all the available material have been accreted. Continuation of this process leads to evolution of the disk, driven by the action of turbulent viscosity, gravitational instability or magnetic fields. The mass is transferred inwards while the angular momentum outwards (Ruden and Lin, 1986). The disk is the place of birth of planets.

1.4 Ionisation and Dust

Near the star forming dark interstellar clouds, there exist new born stars, associated emission nebula or other ionising sources, as a result of which, some parts of the gas in these clouds are always ionised. In the interstellar clouds a typical value of ionisation (the ratio of the number densities of ions to neutral atoms, $n_i/n_n$) has been estimated to be $\sim 10^{-7}$ (Shu et al., 1987). This is inferred from observation of the $HCO^+$, under the assumption
that the cosmic ray ionization rate $\zeta = 10^{-17} \text{sec}^{-1}$. Further, due
to closer proximity to some ionising source some parts of a cloud
may be more ionised. The theoretical work by Elmegreen (1979)
assumes that the cosmic ray ionisation is balanced by 2-body re-
combination of charged particles and recombination in charged
grains. He obtains

$$\rho_i = C\rho_n^{1/2}$$

where $C$ is a weak function of $T$ and is proportional to the
square root of the metal depletion. For a depletion of 0.1 and
$T=10-30 \text{ K}$, one finds $C = 3 \times 10^{-16} \text{cm}^{-3/2} \text{g}^{1/2}$, and the degree
of ionisation is $10^{-7}$ at a density of $10^4 \text{cm}^{-3}$. At very high den-
sity, $> 10^8 \text{cm}^{-3}$, the formula is not applicable because cosmic ray
ionisation effectively shuts off, and $\rho_i$ approaches a constant value.

The presence of dust in molecular clouds is directly appar-
tent from infrared extinction studies which - on the assumption
of a ‘standard’ interstellar extinction curve - often imply very
large visual extinctions. Infrared continuum emission detected
by IRAS (Infra Red Astronomical Satellite) from warm dust in
localised region and from cooler dust in the general interstellar
medium reveals the widespread nature of interstellar dust. The
The following table shows the observed interstellar absorption features attributed to dust.

**Table-3: Observed interstellar absorption features attributed to dust (Whittet, 1988; Tielens, 1989)**

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.9</td>
<td>$NH_3$</td>
</tr>
<tr>
<td>3.0</td>
<td>$H_2O$</td>
</tr>
<tr>
<td>3.4</td>
<td>$C^−H$</td>
</tr>
<tr>
<td>3.5</td>
<td>$CH_3OH$</td>
</tr>
<tr>
<td>3.5</td>
<td>$H_2CO$</td>
</tr>
<tr>
<td>3.9</td>
<td>$H_2S$</td>
</tr>
<tr>
<td>4.6</td>
<td>$OCN^−, SiH$</td>
</tr>
<tr>
<td>4.7</td>
<td>$CO$</td>
</tr>
<tr>
<td>4.9</td>
<td>$OCS$</td>
</tr>
<tr>
<td>6.0</td>
<td>$H_2O$</td>
</tr>
<tr>
<td>6.8</td>
<td>$NH_4^+, CH_3OH$</td>
</tr>
<tr>
<td>9.7</td>
<td>Silicate</td>
</tr>
<tr>
<td>15</td>
<td>$CO_2$</td>
</tr>
<tr>
<td>19</td>
<td>Silicate</td>
</tr>
<tr>
<td>21</td>
<td>Ironoxide</td>
</tr>
<tr>
<td>42</td>
<td>$H_2O$</td>
</tr>
</tbody>
</table>
The silicate features in emission and absorption, near 10 and 20 μm, are also detected in a wide variety of sources and indicate that silicates are the significant component of dust in molecular clouds (Whittet, 1988).

As a result of ionisation of a fraction of gas particles and due to the presence of dusts in the cloud a new environment, called ‘dusty plasma’, is created in the cloud. The free charges in the plasma environment stick on the surface of the dust grains by the process of adsorption (‘adsorption’ is a general phenomena by which free gas molecule stick on the surface of solid grains). Thus, a dusty plasma is formed in the cloud with neutral gas, dusts, charged dusts, ions and electrons. Therefore, the electrostatic force also come into existence.

In the following chapters, the effects of this electrostatic force in star formation process are presented.

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