Chapter 1

Introduction

Mankind has always been fascinated by the celestial sources in the night sky such as stars seen in patterns called constellations, planets and comets. Due to their own light stars are not only one of the most conspicuous objects in the sky but also the building blocks of the Universe. Hence our curiosity to know about their birth and evolution. The study of star formation is one of the most interesting and fundamental topics in astrophysics.

In this chapter, we give an overview of star formation processes with a particular emphasis on massive stars. Towards the end of the chapter, the motivation and objectives of the present study are given along with an outline of the ensuing chapters of the thesis.

1.1 Star Formation: an overview

It is well known that stars form out of dust and gas from dense and cool regions of the molecular clouds throughout the Galaxy (Evans 1999). Star formation is generally believed to be the result of gravitational contraction and subsequent accretion of matter from the parent molecular cloud (Shu et al. 1987; Palla and Stahler 1993). The physical processes involved in star formation are mostly derived from the study of nearby star forming sites including Taurus-Auriga (∼140 pc), Perseus (∼315 pc) and Orion (∼450 pc) molecular clouds. Star formation has been divided into two modes, viz. isolated and clustered modes based on the observational studies of many star forming regions situated at nearby and farther distances from us. Observational studies show that the low-mass stars (M ≲ 3 M⊙) are known to form via both isolated and clustered modes of star formation (Ward-Thompson 2002), while massive stars (M ∽ 8 M⊙) form explicitly only in clustered mode together with low and intermediate mass (3 < M < 8 M⊙) stars.
This section has been divided into four sub-sections dealing with birth sites of star formation, instability conditions for the collapse, low-mass star formation and massive star formation.

1.1.1 Nucleation sites for star formation

Observational studies in various wavelengths (such as optical, infrared, sub-mm/mm) show that the space between the stars in our Galaxy is not empty. The diffuse matter in the form of gas and dust which exists between stars is known as Interstellar Medium (ISM). Studies indicate that the ISM is present in three distinct phases: a cold phase in the form of molecular and atomic hydrogen gas co-existing with dust grains, a warm phase with partially ionised hydrogen gas, and a hot phase with shocked and fully ionised gas. These different phases and their physical properties are summarised in Table 1.1.

Most of the mass of the molecular ISM is in the form of giant molecular clouds (GMCs). Molecular clouds are observed by various molecular emission lines (in mm- and cm-wavelengths), which occur due to transitions in the rotational and vibrational levels. Hydrogen molecules (H\(_2\)) are the most abundant molecules in molecular clouds. However, direct detection of H\(_2\) is very difficult as it is symmetric and homonuclear in nature and does not have a permanent electric-dipole moment, thereby forbidding the vibrational-rotational transitions. Shull and Beckwith (1982) have described in detail the molecular physics of the H\(_2\) molecule in the interstellar medium. H\(_2\) can be identified through its electric quadrupole forbidden transitions in vibrational-rotational modes in the near- and mid-infrared. The carbon-monoxide (CO) molecule is the next most abundant tracer after H\(_2\) and its observations in dense clouds at infrared, sub-mm and millimeter suggest that the abundance ratio CO/H\(_2\) is about 10\(^{-4}\) (about 30% of carbon in CO). CO column density is estimated using low- J (1 \(\rightarrow\) 0, 2 \(\rightarrow\) 1) observations in emission. \(^{12}\)CO molecules are optically thick (optical depth \(\approx\) 100), therefore they trace only outer tenuous regions but not the inner denser regions. Denser regions of molecular clouds are traced by other molecules like NH\(_3\), CS, rare isotopes of CO like C\(^{18}\)O (see Table 1.2 for different tracers for different regions).
Table 1.1: Phases of ISM (adopted from Mathis (1990)).

<table>
<thead>
<tr>
<th>Medium</th>
<th>Phase</th>
<th>$H$</th>
<th>$n$ (cm$^{-3}$)</th>
<th>$T$ (K)</th>
<th>Heating signature</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular clouds, cores</td>
<td>Cold $H_2$</td>
<td>$&gt; 1000$</td>
<td>10 - 50</td>
<td>Cosmic rays</td>
<td>Icy dust</td>
<td></td>
</tr>
<tr>
<td>H I clouds</td>
<td>Cold $H$</td>
<td>30</td>
<td>100</td>
<td>Dust</td>
<td>Diffuse ISM</td>
<td></td>
</tr>
<tr>
<td>Warm H I</td>
<td>Warm $H$</td>
<td>0.1</td>
<td>8000</td>
<td>Dust</td>
<td>Diffuse ISM</td>
<td></td>
</tr>
<tr>
<td>Warm H II</td>
<td>Warm $H^+$</td>
<td>0.03</td>
<td>$10^4$</td>
<td>Photo-ionization</td>
<td>Faint</td>
<td></td>
</tr>
<tr>
<td>H II regions</td>
<td>Warm $H^+$</td>
<td>$&gt; 100$</td>
<td>$10^4$</td>
<td>Photo-ionization</td>
<td>Transient, expanding</td>
<td></td>
</tr>
<tr>
<td>Hot ISM</td>
<td>Hot $H^+$</td>
<td>$10^{-3}$</td>
<td>$10^{6.5}$</td>
<td>SNe shocks</td>
<td>Low mass</td>
<td></td>
</tr>
<tr>
<td>SNRs</td>
<td>Hot $H^+$</td>
<td>Variable</td>
<td>$10^7$</td>
<td>Shocks</td>
<td>Dynamic</td>
<td></td>
</tr>
</tbody>
</table>

1.1.2 GMCs and Gravitational Instability

GMCs are not homogeneous but have a complex structure and are clumpy in nature. GMCs can be fragmented into sub-structures by gravity and turbulent motions. Physical properties of the GMCs, clumps and cores are shown in Table 1.2.

Gravitational collapse of molecular clouds is a result of gravitational instability. Gravitational instability is defined by a condition in which self-gravity of a gaseous object overcomes the resisting forces due to thermal, magnetic, centrifugal and turbulent pressures leading to a collapse. Jeans (1902) derived a relation between the oscillation frequency $\omega$ and the wave number $k$ for a small perturbation; assuming a non-magnetic, isothermal, infinite, homogeneous and self-gravitating medium without turbulent motions. The dispersion
Table 1.2: Physical properties of clouds, clumps and cores (from Smith (2004)).

<table>
<thead>
<tr>
<th>Physical parameters</th>
<th>GMCs</th>
<th>Clumps/ Globules</th>
<th>Cores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (in M⊙)</td>
<td>10⁴ – 10⁶</td>
<td>10²</td>
<td>1 – 10</td>
</tr>
<tr>
<td>Size (in pc)</td>
<td>20 – 100</td>
<td>0.2 – 4</td>
<td>0.1 – 0.4</td>
</tr>
<tr>
<td>Density (in cm⁻³)</td>
<td>100 – 300</td>
<td>10³ – 10⁴</td>
<td>10⁴ – 10⁵</td>
</tr>
<tr>
<td>Temperature (in K)</td>
<td>15 – 40</td>
<td>7 – 15</td>
<td>10</td>
</tr>
<tr>
<td>Magnetic Field (in µG)</td>
<td>1 – 10</td>
<td>3 – 30</td>
<td>10 – 50</td>
</tr>
<tr>
<td>Line width (km s⁻¹)</td>
<td>6 – 15</td>
<td>0.5 – 4</td>
<td>0.2 – 0.4</td>
</tr>
<tr>
<td>Molecular tracers</td>
<td>12CO, ¹³CO</td>
<td>12CO, ¹³CO</td>
<td>NH₃, CS</td>
</tr>
</tbody>
</table>

relation is given below with the assumption of non-vanishing wave number

\[ \omega^2 = k^2 v_s^2 - 4\pi G \varrho_0 \] (1.1)

or

\[ \omega^2 = v_s^2 \left( k^2 - \frac{4\pi G \varrho_0}{v_s^2} \right) \]

or

\[ \omega^2 = v_s^2 \left( k^2 - k_0^2 \right) \]

where \( k_0^2 = 4\pi G \varrho_0/v_s^2 \), \( G \) is the gravitational constant, \( v_s(= \sqrt{kT/\mu m_H}) \) is the isothermal sound speed, \( \varrho_0 \) the initial mass density, \( m_H \) the mass of the hydrogen atom, \( T \) is the temperature and \( \mu \) the mean molecular weight (≈ 2.4 for a fully molecular cloud with 25 \% He mass fraction).

Eq. 1.1 gives the propagation of sound waves with effect of the perturbation by self-gravity. It is clear from Eq. 1.1 that the equilibrium is stable with respect to large \( k (= 2\pi/\lambda) \). In such perturbations (with shorter wavelengths), the right-hand side of Eq. 1.1 is positive, i.e., \( \omega \) is real. If \( k^2 < k_0^2 \) then \( \omega \) is imaginary and perturbations grow exponentially with time, leading to unstable equilibrium. \( k_0 \) is known as the characteristic wave number and the corresponding characteristic wavelength, called Jeans length \( (\lambda_J) \) is defined by

\[ \lambda_J \equiv \frac{2\pi}{k_0} \equiv \sqrt{\frac{\pi}{G \varrho_0}} v_s \] (1.2)

Assuming the perturbation is spherical with diameter \( \lambda_J \), one gets the minimum mass,
called Jeans mass \( (M_J) \) as,

\[
M_J \equiv \frac{4\pi}{3} \rho_0 \left( \frac{\lambda_J}{2} \right)^3 \equiv \frac{\pi}{6} \left( \frac{\pi}{G} \right)^{3/2} \rho_0^{1/2} v_s^3
\]  

(1.3)

The conditions for gravitational instability, \( \lambda > \lambda_J \) and \( M > M_J \), are called the Jeans criteria. Using Eq. 1.2 and 1.3 respectively, Jeans length and Jeans mass can be written as below:

Jeans length:

\[
L_J(pc) = \frac{7.82}{\mu} \sqrt{\frac{T(K)}{n_H}}
\]  

(1.4)

Jeans mass:

\[
M_J(M_\odot) = \frac{11.74}{\mu^2} \sqrt{\frac{T^3(K)}{n_H}}
\]  

(1.5)

When the force of gravitational self-attraction well exceeds the internal gas pressure, then free-fall time (i.e., time required for the collapse) of clumps and cores is given by

\[
t_{ff}(yr) = \sqrt{\frac{3\pi}{32G\rho}} = \frac{3.4 \times 10^7}{\sqrt{n_H}}
\]  

(1.6)

where, \( \rho (= m_H n_H \mu) \) is the mass density (gms cm\(^{-3}\)) and \( n_H \), the number density (cm\(^{-3}\)).

Eq. 1.6 shows that the free-fall time is independent of radius and depends only on the density of the GMCs (i.e., homologous collapse). For the typical mean density (\( \sim 10^4 \) cm\(^{-3}\)) of a cloud core the free-fall time is about \( 3.4 \times 10^5 \) years.

Table 1.3 illustrates the value of Jeans mass \( (M_J) \), length \( (L_J) \) and free-fall time scale \( (t_{ff}) \) for clumps and cores. These values are derived using Eqs. 1.4, 1.5 and 1.6 with their typical values of temperature and density from Table 1.2. Free-fall time for core is smaller than clump for gravitational collapse. The Jeans mass is calculated by Elmegreen (1999) and Larson (1998) taking turbulence and magnetic field.
Jeans mass with turbulence is given by,

\[ M_J \propto v_{\text{rms}}^4 P^{-1/2} \quad (1.7) \]

where \( P \) is gas pressure.

Jeans mass including magnetic field is given as,

\[ M_J \propto B^3 \rho^{-1} \quad (1.8) \]

where \( B \) is magnetic field strength.

Another important timescale for understanding the star formation is the Kelvin-Helmholtz contraction timescale \( t_{KH} \). It tells us the time required to start nuclear reactions in the core and reach the zero-age main-sequence (ZAMS) phase. Gravitational potential energy is converted to heat when the cloud core continues to contract due to gravity. The Kelvin-Helmholtz timescale is the ratio of gravitational energy \( \left( \frac{G M_*^2}{R_*} \right) \) to the luminosity and given by

\[ t_{KH} = \frac{G M_*^2}{R_* L_*} = 3 \times 10^7 \left( \frac{M_*}{M_\odot} \right)^2 \left( \frac{R_*}{R_\odot} \right)^{-1} \left( \frac{L_*}{L_\odot} \right)^{-1} \text{yr} \quad (1.9) \]

where \( M_* \) is the stellar mass, \( R_* \) the stellar radius and \( L_* \) the stellar luminosity. The \( t_{KH} \) value for Sun \( (M_* = 1 \, M_\odot) \) is \( 3 \times 10^7 \) yr and for a O type star \( (M_* = 50 \, M_\odot) \) it is of the order of \( 10^4 \) yr.

### Table 1.3: Jeans mass, size and free-fall time for clumps and cores

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>n(cm(^{-3}))</th>
<th>T(K)</th>
<th>(M_J)(M_\odot)</th>
<th>(L_J)(pc)</th>
<th>(t_{ff}) (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clumps</td>
<td>(10^3)</td>
<td>10</td>
<td>2.0</td>
<td>0.3</td>
<td>(1.1 \times 10^6)</td>
</tr>
<tr>
<td>Cores</td>
<td>(10^5)</td>
<td>10</td>
<td>0.2</td>
<td>0.3</td>
<td>(1.1 \times 10^5)</td>
</tr>
</tbody>
</table>

#### 1.1.3 Low-mass star formation

The formation process of low-mass stars is reasonably well understood both observationally as well as theoretically. The star formation process starts with the formation or development of a dense prestellar core due to the gravitational contraction of dense regions of GMCs (André et al. 2000). As further gravitational contraction continues in such a dense
prestellar core, a system thus emerges with a central protostar, surrounded by an infalling envelope and a protostellar disk. In the starting phase, the central source is completely obscured by the dense envelope that provides a source of material for the accretion on the central source. With time, the envelope is destroyed or loses mass as a result of infall onto the central source/disk and an outflow into the surrounding ISM. Finally, the central young star and protostellar disk emerge when the envelope is completely consumed through both outflow and accretion.

Observational evidences, like the existence of bipolar outflows (Wu et al. 2004) and accretion disks (Burrows et al. 1996; Simon et al. 2000) associated with low-mass stars (see Fig. 1.1), support the theoretical model about their formation (van Dishoeck et al. 1995; Hogerheijde 1999; McKee and Ostriker 2007; van Kempen et al. 2008; Evans et al. 2009). In case of low-mass stars, the Kelvin-Helmholtz timescale is larger than the free-fall timescale (i.e., \( t_{KH} > t_{ff} \)). This implies that the pre-main-sequence (PMS) evolutionary phases of low mass stars are sufficiently long making it possible to identify and observe these phases during the evolution of low mass stars (Shu et al. 1987).

The advent of modern technology, specially in infrared and sub-mm wavelength regions, brought about a revolution in the study of star formation in the earliest phases with good spatial resolution and high sensitivity. Such facilities provide an opportunity to study the earliest stages of star formation, which are always deeply embedded in their natal material and accessible only in longer wavelengths (i.e., infrared, sub-mm) due to lower extinction in these wavelengths.

Lada and Wilking (1984) and Lada (1987) classified the PMS stages of low mass stars into three evolutionary classes, Class I, II and III, based on the slopes (i.e., spectral index) of their Spectral Energy Distributions (SEDs) in the infrared region. Later André et al. (1993) included in the classification scheme, another very early phase of the evolution called Class 0. SEDs of young stellar objects (YSOs) consist of emission not only from photospheres but also from disks and envelopes around them; the latter contributing mainly at wavelengths longer than 2 \( \mu m \).

The slope of a SED is defined by

\[
\alpha_\lambda = \frac{d \log (\lambda F_\lambda)}{d \log (\lambda)} \tag{1.10}
\]
for wavelengths longer than 2 $\mu$m. Schematic SEDs of different classes of low-mass stars are shown in Figure 1.2. A brief description of each of the four evolutionary stages is given below:

*Class0* sources (young protostars) are deeply embedded, having positive $\alpha_\lambda$ with ratio $L_{\text{submm}}/L_{\text{bol}} > 5 \times 10^{-3}$, where $L_{\text{submm}}$ is the luminosity measured at wavelengths longer than 350 $\mu$m and $L_{\text{bol}}$ is the bolometric luminosity. They have a cold single-temperature blackbody SED peaking at sub-mm wavelength region with bolometric temperature ($T_{\text{bol}}$) $< 100$ K and an age of $\sim 10^4$ yr. One of the main characteristics of such sources is the presence of powerful and collimated molecular CO outflows from the central source.

*ClassI* sources (evolved protostars) have SEDs much broader than those for a single temperature in Class 0. They too have a positive $\alpha_\lambda$, with $T_{\text{bol}} \sim 70 - 650$ K and contain smaller envelope masses than Class 0 sources with an age of $\sim 10^5$ yr. Molecular outflows are also present in Class I sources but are less collimated than in Class 0.

*ClassII* sources have negative $\alpha_\lambda$ with $T_{\text{bol}} \sim 650 - 2880$ K and their SEDs peak around 2 $\mu$m. These sources are also known as Classical T-Tauri Stars (CTTS) with an age of $\sim 10^6 - 10^7$ yr. In this stage, sources have thick accretion disks and CO outflows are mostly absent.

*ClassIII* sources have negative $\alpha_\lambda$ with $T_{\text{bol}} > 2880$ K and having SEDs for a single stellar blackbody (photosphere), peaking at optical or infrared wavelengths. These sources have no or very little evidences of IR-excess and may still have thin or anemic accretion disks. These are also known as Weak-Lined T-Tauri Stars (WTTS) with age of $\sim 10^6 - 10^7$ yr.

It is obvious that there is a significant improvement in the understanding of low-mass star formation and their different evolutionary stages. But, the model described above for the low mass stars does not entirely work for massive stars due to many reasons discussed in the next sub-section.
Fig. 1.1: a: Infrared view of the bipolar jet HH 212 (M.McCaughrean, ESO/VLT). b: Hubble Space Telescope infrared images of a dense circumstellar disk surrounding the young source IRAS 04302+2247 (left side) and the source HH30 (right side) with powerful jets from the central proto-star (from D.Padgett/STScI/NASA).
1.1.4 High-mass star formation

Massive stars (M \( \gtrsim \) 8 M\(_{\odot} \)) have a major impact on the evolution of the Galaxy. They are responsible for heating molecular clouds and enriching the interstellar medium with heavy elements. Massive stars are capable of changing the structure of their parent cloud and influence the star formation process via intense winds, UV radiation, massive outflows, expanding HII regions and supernovae explosions. At sufficiently farther distances, they may trigger fresh star formation.

The formation processes of high-mass stars are much less understood compared to these of low-mass stars. High-mass stars are born deeply enshrouded in the dense optically thick cores of molecular clouds present throughout the Galaxy and form mostly in cluster environment. In sharp contrast with low-mass stars, the high-mass stars have Kelvin-Helmholtz timescale shorter than the free-fall timescale (i.e., \( t_{KH} < t_{ff} \)). This indicates that massive stars begin their hydrogen burning (ZAMS) phase while still in their natal dense cores and accreting matter.
The smaller values of $t_{KH}$ (compared to $t_{ff}$) for massive stars reflect that their PMS evolution is very rapid compared to their low-mass counterparts, making it very difficult to observe the critical earliest phases of their evolution. Going by the Salpeter initial mass function (Salpeter 1955), massive stars are rare (i.e., small in number), usually situated at large distances ($\gtrsim 1$ kpc), suffer high extinction ($A_v \gtrsim 100$) and have relatively short formation/evolution timescales compared to low-mass stars. Also they are able to produce large luminosity ($10^4 - 10^6 L_\odot$) due to their large temperature, intense flux of ionising photons and a tremendous radiation pressure ($P_{rad} \sim L_\star/4\pi r^2 c$, where $L_\star$ is the stellar luminosity and $c$ is the speed of light), which rapidly clears the material around it, hampering the process of accretion. The radiation pressure can also be defined as below:

$$P_{rad} = 10^{-6} \left( \frac{L_\star}{5 \times 10^4 L_\odot} \right) \left( \frac{r}{1500 \, AU} \right)^{-2}$$ (1.11)

The radiation pressure becomes an impediment for the accretion process to continue and sets a limit on the mass of a star beyond which the accretion may not contribute to star formation. This limit on stellar mass, about $10 \, M_\odot$, is set by the balance between radiation force and gravitational force. Thus, the radiation pressure can halt the accretion process and set the upper limit of stellar mass function (Larson and Starrfield 1971; Wolfire and Cassinelli 1987; Jijina and Adams 1996).

All these factors inhibit the study of massive star formation, particularly the earliest phases of their evolution. A massive star emits UV photons with energy $\geq 13.6$ eV, sufficient to ionise hydrogen and generate an ionised region called an HII region. Unlike in the high mass stars, the Lyman continuum fluxes from low-mass stars are not sufficient enough to create an HII region. The radius over which ionizing photons are effective, called the Strömgren radius (Franco et al. 1990), can be calculated from the equilibrium between the ionisation and recombination rates and is given by

$$R_s = \left( \frac{3}{4\pi \alpha} \right)^{1/3} N_{UV}^{-1/3} n_e^{-2/3}$$ (1.12)

$N_{UV}$ being the rate of ionising UV photons, $n_e$ the electron density and recombination coefficient $\alpha [\text{cm}^3 \, \text{s}^{-1}] \simeq 2.6 \times 10^{-10} \, (T[K])^{-3/4}$, which is temperature dependent. For a O type star with $T = 40,000$ K, $n_e = 10 \, \text{cm}^{-3}$, $\alpha = 2.6 \times 10^{-10} \times (40000)^{-3/4}$ and $N_{UV} = 5$
\times 10^{48} \text{ photons/s}; R_s \text{ is found to be nearly 4 pc (from Eq. 1.12).}

However, it must be noted that the Strömgren sphere does not represent the true observed HII regions but provides a model for physical conditions around a hot star with uniform density. Observationally, it is known that the HII regions show different sizes and shapes. Dyson and Williams (1980) proposed a model of expansion of an HII region with time given by,

$$R(t) = R_s \left(1 + \frac{c_s \times t}{4R_s} \right)^{4/7}$$

where, $c_s$ is the sound velocity in the ionised gas ($c_s = 15 \text{ km s}^{-1}$) and $R_s$ is defined in Eq. 1.12.

**Models for massive star formation**

Recent reviews by Beuther et al. (2007); Zinnecker and Yorke (2007); McKee and Ostriker (2007) cover the details of various theoretical studies on formation processes of massive stars. A brief account of different important theoretical models is presented here:

- **Monolithic collapse model**
  Low-mass star formation is explained by accretion process (with a typical accretion rate $\sim 10^{-6} M_\odot \text{ yr}^{-1}$) and which cannot be directly applied to the massive stars due to their strong radiation pressure, which can directly halt the accretion of material onto the central object. McKee and Tan (2003) proposed what is called a turbulent core model to overcome the radiation pressure for the formation of massive stars through accretion process. In this model, massive stars form in the supersonic turbulent cloud cores with high accretion rates $\sim 10^{-3} M_\odot \text{ yr}^{-1}$. These authors justify their model with the observed high pressure and turbulent motions associated with many dense massive cores. The high value of accretion rate is sufficient to overcome the radiation pressure of the central source. Through this process a massive star takes about $10^5$ yr to form.

- **Competitive accretion in a proto-cluster environment**
  In the competitive accretion model, massive protostars in the dense cluster environment gain mass from unbound material through nearby clouds of gas with different
and higher accretion rates in a competing manner with other protostars of low- and intermediate-masses (Bonnell et al. 1997, 2001).

- **Stellar collisions and mergers in very dense systems**
  This model is very different from the low-mass star formation. Bonnell et al. (1998) proposed a model for formation of massive stars based on the cluster environment of massive stars. In this model, massive stars form through the physical collision and merging of low- and intermediate- mass stars. This process can occur only in regions of very high stellar densities of about $10^8$ stars pc$^{-3}$ for low mass stars and such high densities have not been observed so far. A stellar density of up to $10^6$ stars pc$^{-3}$ is reported in the densest regions of W3 IRS5 (Megeath et al. 2005).

Current observational scenario for high-mass star formation was summarised by Churchwell (2002); van der Tak and Menten (2005); Zinnecker and Yorke (2007); Beuther et al. (2007); McKee and Ostriker (2007). These authors have divided the evolution of individual massive stars into the following evolutionary stages based on observations from infrared through radio wavelengths that are very useful in tracing the cool dust regions, dense molecular gas and ionised emission regions, where these stages are manifested.

1. Infrared Dark Clouds (IRDCs) as birth places for high mass stars
2. High-mass protostellar objects (HMPOs) representing very early stages
3. Hypercompact (HCHII) and ultracompact HII (UCHII) regions
4. Compact classical HII regions

IRDCs were first identified as long dark filamentary features through infrared images from the Infrared Space Observatory (ISO; Perault et al. (1996)) and the Midcourse Space Experiment (MSX; Egan et al. (1998)) space missions. IRDCs are believed to be the precursors of clustered, massive star formation. IRDCs are known as the densest parts of the giant molecular clouds and are characterized by low temperatures ($< 25$ K), high column densities ($\sim 10^{23} - 10^{25}$ cm$^{-2}$) and high volume densities ($> 10^5$ cm$^{-3}$) (Bergin and Tafalla (2007); Rathborne et al. (2010) for more details).

HMPOs represent the second observable evolutionary stage in the high-mass star formation process. The phase in which the molecular cloud core starts to undergo free-fall collapse
and form massive protostar, is known as HMPO. Hot molecular core is observationally identified with its lack of radio continuum emission. These are small (0.1 pc) and dense ($n \sim 10^5 - 10^7 \text{ cm}^{-3}$) cores of the molecular gas with temperatures ($T \sim 100 - 200 \text{ K}$) associated with massive star forming regions (Keto 2002; Kurtz et al. 2000). HMPOs are younger than the hot molecular core (HMC) sub-phase that is traced by methanol maser emission (Hill et al. (2005) and references therein).

It has been suggested that HMPOs represent the early phase in the development of Hyper-compact (HCHII) and Ultra-compact HII (UCHII) stages. HMPOs have very strong dust continuum emission and lack free-free emission, while HCHII (size $< 0.01$ pc ) and UCHII (size $< 0.1$ pc ) regions are traced by strong free-free emission. HCHII regions represent individual photoevaporating disks (Keto 2007) and UCHII regions represent the disk-less stars photoionising their envelopes and cocoons. A HCHII region is known to show broad radio recombination line profiles, with typical velocity dispersions of 40 - 50 km s$^{-1}$ (Gaume et al. 1995; Johnson et al. 1998) and a UCHII region has recombination line widths of about 30 - 40 km s$^{-1}$ (Keto et al. 1995). Classical HII regions expand hydrodynamically and disrupt the parent molecular cloud.

Bipolar molecular outflows are commonly associated with young high-mass stars (Shepherd and Churchwell 1996; Zhang et al. 2001; Beuther et al. 2002a; Anandarao et. al. 2004; Zhang et al. 2005). These molecular outflows are much more massive and energetic with higher outflow entrainment rates than those associated with low-mass stars (Bachiller 1996). High accretion rates were noticed in the study of several massive star forming regions (which harbours HMPOs, Hyper- and Ultra compact HII regions) from molecular line observations (Fuller et al. 2005; Keto and Wood 2006). Recently Takashi and Kazuyuki (2009) numerically solved the detailed structure of the accreting protostar and reported the evolution of massive protostars with high accretion rates ($> 10^{-3}\text{ M}_\odot\text{yr}^{-1}$).

Interferometric observations in the sub-mm and mm bands provided evidence for the presence of accretion disk-like structures (also toroidal/ring like shapes) around young massive stars (Mundy et al. 1996; Shepherd and Kurtz 1999; Trinidad et al. 2003; Beltran et al. 2004; Patel et al. 2005; Curiel et al. 2006; Furuya et al. 2008). Cesaroni et al. (1997) and Zhang et al. (1998) observed a disk ($> 10,000$ AU) in Keplerian rotation around one luminous young source, IRAS 20126+4104, which is also associated with an outflow (Cesaroni et al. 1997, 2005) (see Fig. 1.3).
In recent years, the *Spitzer* Space Telescope\(^1\) (Werner 2004) has produced a wealth of useful data in mid- and far- infrared regions with better sensitivity and improved spatial resolution. *Spitzer*-IRAC images have been used to trace many signatures associated with young massive stars such as toroidal/ring structures (see Fig. 1.4), outflow lobes (see Fig. 3.9 of Chapter 3) and jets (see Fig. A.3 of Appendix A), which are similar to the observed features associated with low mass stars in their early formation phase. These observational evidences show that massive stars are formed in a similar manner to the low mass star but with higher accretion rates in clusters rather than in isolation.

Therefore, it is still not clear whether massive star formation is a scaled up version of low-mass star formation or is a result of a fundamentally different process. Crucial to this question is the study of the early stages of high-mass stars such as HMPOs and UCHII regions, to look for similar signatures (as found in disks and outflows in low-mass stars) associated with these stages.

**Spectral Energy Distribution Modeling**

Modeling of Spectral Energy Distributions (SEDs) of massive young protostars provide important inputs on various physical parameters of the sources, which can not otherwise be possible through direct observation. Therefore, in recent years, several workers have given much needed attention to the SED modeling of young stellar objects (YSOs) (Whitney et al. 2003a,b, 2004). The understanding of the physics of low-mass star formation has significantly progressed and the same physics has been incorporated in radiative transfer calculations to analyse SEDs of individual sources in massive star forming regions.

The SED modeling tool developed by Robitaille et al. (2006) was successfully tested on low-mass YSOs in nearby star forming regions. These models assume an accretion scenario with a central source associated with rotationally flattened infalling envelope, bipolar cavities, and a flared accretion disk, all under radiative equilibrium (Bjorkman and Wood 2001). The model provides a set of physical parameters associated with a particular source instead of analysing the shape of a single SED (see Robitaille et al. (2007)). The model grid consists of 20,000 models of two-dimensional Monte Carlo simulations of radiation transfer with 10 inclination angles, resulting in a total of 200,000 SED models. The model

\(^1\)see [http://ssc.spitzer.caltech.edu/](http://ssc.spitzer.caltech.edu/)
output gives 14 physical parameters of the individual source which can be divided into 3 categories: the central source parameters (stellar mass, radius, luminosity and temperature), the infalling envelope parameters (the envelope mass, accretion rate, outer radius, inner radius, cavity opening angle and cavity density), and the disk parameters (disk mass, accretion rate, outer radius, inner radius, flaring power, scale height and inclination). The current version of the SED fitting tool covers the mass range from $0.1M_\odot$ to $50M_\odot$. The tool fits the best fit model along with a group of models that is interpolated to different apertures at different wavelengths depending upon the beam sizes. This group of models is selected on the basis of the criterion given as below:

$$\chi^2 - \chi^2_{\text{best}} < 3$$  \hfill (1.14)

Recently, Grave and Kumar (2009) applied these SED models for samples of HMPOs and derived their disk and envelope accretion rates to be $10^{-6} - 10^{-3} M_\odot$ yr$^{-1}$. However, there are limitations in these SED models because they do not account for accretion luminosity from envelopes and multiplicity of sources which are very important for the study of the massive young objects (see Robitaille (2008) for justification).

### 1.2 Motivation for the present work

Massive stars heat their natal dust cocoons, where they are born and emit predominantly mid-infrared radiation. Hence, to understand the processes involved in the formation of massive stars and their relation to their surroundings, we need to study them at longer wavelengths which suffer lower extinction. These sites are accessible to mid- and far-infrared observations that can probe very deeply embedded objects. High spatial resolution is very important at these longer wavelengths to observationally identify individual sources from their cluster environment, where they are born. The *Spitzer* Infra-Red Array Camera (IRAC) (Fazio et al. 2004) provides an opportunity, with an unprecedented high spatial resolution in thermal infrared wavelength regime, that is very useful in identifying embedded sources in massive star forming regions. IRAC has four wavelength bands covering the region 3.6 - 8.0 $\mu$m, i.e., Ch1 (3.55/0.75), Ch2 (4.49/1.0, Ch3 (5.73/1.43) and Ch4 (7.87/2.91 $\mu$m). Thus, with the *Spitzer* Space Telescope, it is now possible to identify deeply embedded massive stars in their early phases of formation and model them. This provides the motivation for the present work, viz. to look into regions in which HMPOs
and the driving engines of UCHII regions are associated and to identify their counterparts in the infrared using IRAC images and characterise their physical parameters (like mass, age, temperature, luminosity and accretion rates etc.) by modeling their SEDs.

Stars of all masses show outflows during their PMS stages. While in the case of low mass YSOs, it is fairly well-established that the outflows and disks are phenomenologically related, observations have just begun to show that massive PMS stars too have disk/disk-like structure of accretion. As far as the intermediate and high-mass PMS sources are concerned, there have been catalogues prepared from CO line survey observations (Lada (1985) for low to high luminosity objects; Shepherd and Churchwell (1996), Shepherd et al. (2000) and Zhang et al. (2007) for high luminosity objects). These studies indicated that the intermediate-/high-mass sources too follow the basic relationship between outflow parameters and those of the driving source in a way similar to the well-established case of low mass sources. However, the statistics are poor for young massive stars. Recently, there have been systematic studies of outflow phenomenon associated with HMPOs and these studies have provided improved statistics for the range of masses covering early B stars.
Fig. 1.4: The RGB colour-composite image of IRAS 20293+3952 from Kumar et al. (2009) obtained by coding the Spitzer-IRAC hi-res deconvolved IRAC Ch4, Ch3 images, and near-infrared (normal) 2.2 µm image as red, green and blue respectively. White contours (15 σ and 60 σ levels above the mean background) display continuum subtracted H$_2$ narrow band emission at 2.12 µm. Figure exhibits the ring structure around the IRS1 source. Location of UCHII regions is represented by 2 cm Radio contours with black solid lines.
But the possible relation between outflow parameters and physical parameters of the driving engines has not been well established. Therefore, this is one of the main motivations of the present work. IRAC provides very high sensitivity and arc-sec spatial resolution to detect embedded YSOs allowing for first time to estimate the surface density of YSOs in massive star forming regions. The surface density of YSOs provides an important input/clue for the formation of stars in embedded clusters. In addition to, IRAC photometry, ratio maps of IRAC images are very helpful to study the atomic/molecular emission regions created by massive stars due to their interaction with the immediate surroundings. The energy released (i.e., the amount of UV photons) from O and early B type stars (Panagia 1973) is different, therefore their interaction with their surrounding will be different and complex. Hence, it is very interesting to look for such regions, where O and early B type stars are present. Also, it is important to look for sites of fresh star formation triggered by winds, UV radiation and expanding HII regions associated with young massive stars.

1.3 Objectives of the Thesis

To summarise, the objectives of the present work are:

1. Identification of mid-IR counterparts of HMPOs, which represent the pre-UCHII phase. In some of the HMPOs, known to be outflow sources, it is important to identify their driving engines and derive their physical parameters such as, mass, luminosity and accretion rate through SED modeling using observed imaging data. Therefore, one of the important aims of this work is to compare the physical parameters of HMPOs against the observed outflow parameters.

2. The central ionising sources of UCHII regions are known to be O and early B stars because of their ability to ionise the regions surrounding them. Nevertheless, many of them are still deeply embedded not to be optically visible. Therefore, one of the objectives of this study is to identify the mid-IR counterparts of the driving engines of the UCHII regions and to derive their physical parameters through SED modeling using observed imaging data.

3. To carry out mid-infrared photometric study of a few massive star-forming regions, taking into advantage of arcsec spatial resolution of Spitzer-IRAC data, through which it is possible to identify embedded YSOs, especially young massive protostars. Determination of cluster sizes of YSOs and their spatial density which give
important clues to understanding the star formation. Finally to derive the physical properties of selected YSOs through their SED modeling. The thesis also includes the study of the interaction and feedback of massive stars to their immediate environments.

1.4 Outline of the thesis

The afore-mentioned work will be described in the ensuing chapters, the outline of which is as follows:

Chapter 2: In this chapter, we describe the driving engine-outflow relationships for the HMPOs known as the driving sources of the outflows. We will present the results of SED modeling of mid-IR counterparts of HMPOs identified through \textit{Spitzer-GLIMPSE} images and report their relation with physical parameters like mass, age and accretion rates with observed outflow properties like outflow mass, momentum, velocity and entrainment rates. We will also present the work on the identification of the mid-IR counterparts of the driving engines of UCHII regions and characterise their physical properties through SED modeling.

Chapter 3: We report detailed studies on the massive star forming region AFGL 437 using \textit{Spitzer-IRAC} archival images. In this work, we have identified many new YSOs using IRAC colour-colour diagram and have investigated one young high-mass protostellar source with its outflow lobes using IRAC ratio image, which indicates that the source is in its accretion phase. Also, we will highlight the results on its environment, which tells us about the interaction of massive stars with its surroundings.

Chapter 4: We present the detailed study on another massive star forming region M8 (Lagoon Nebula) using \textit{Spitzer-IRAC} archival images. In this work, we have identified many new YSOs using IRAC colour-colour diagram and have investigated the PAH cavity structure nearby a high-mass star. Also, we will highlight the results of the interaction of massive stars with immediate and far distant environment in causing triggered star formation.

Chapter 5: In this chapter, we present ground-based near-infrared JHK photometric ob-
servations of one massive star forming region, namely, IRAS 05375+3540 from the Mt. Abu IR observatory. In addition, space-based Spitzer-IRAC images on this massive star forming region will be presented. We focus on and examine the photometric results obtained on this source and their surroundings using the infrared images.

**Chapter 6:** This chapter summarises the results produced in the thesis and outlines future directions for further study.