Star formation

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1 Introduction

Stars are formed from gas and dust that exist between stars known as interstellar medium (ISM). When the interstellar medium have sufficient mass, they collapse under gravity to form stars (Leblanc, 2010). Interstellar medium is estimated to be composed of approximately 70% hydrogen gas, about 28% helium gas and a small percentage of metals such as carbon and silicon (Carroll & Ostlie, 2006).

A number of objects such as HII regions, reflection nebulae, emission nebulae, diffuse interstellar gas and giant molecular cloud which occupy space between stars constitute interstellar medium. The different objects that make up an ISM arise due to variation in particle density, gas turbulence, pressure, temperature, radiation intensity and magnetic field within the medium (Karttunen et al., 2007).

Star formation occurs within the giant molecular cloud part of an ISM. Once a giant molecular clouds is of adequate mass, it collapses transforming its gravitational energy to thermal energy. During collapse, about a half of the gravitational energy is converted to thermal energy while the rest is emitted as radiation into interstellar space (Leblanc, 2010) i.e:

$$\text{Gravitational energy, G} \ = \ \text{Thermal energy} \ (\sim \frac{\text{G}}{2}) \ + \ \text{Radiation to interstellar space} \tag{1}$$

For a giant molecular cloud to collapse, its mass must be greater than Jean's mass, M_J which is mathematically given as:

$$M_J = (\frac{5kT}{\mu M_H G})^{\frac{3}{2}}(\frac{3}{4\pi\rho})^{\frac{1}{2}} \tag{2}$$

Where μ is mean molecular weight, M_H is hydrogen atomic mass, G is universal gravitational constant and ρ is the gas density. The minimum mass needed for a collapsing cloud to trigger and sustain hydrogen fusion during star formation is $\sim 0.08\text{M}_\odot$. The object formed at this stage of star formation is known as a protostar. Protostars can be defined as large self gravitating mass formed due to contraction of giant molecular clouds (Leblanc 2010, Palen 2002).

1.1 Low mass, intermediate mass and Massive stars

Stars can be grouped into three categories based on their masses i.e low mass stars ($\sim 0.075\,M_\odot \leq M \leq 0.2 \pm 0.2\,M_\odot$), intermediate mass stars ($\sim 2.5M_\odot \leq M \leq 8M_\odot$) and massive stars ($M > 8\,M_\odot$). The mechanisms and models used to explain formation of the different categories of stars are largely the same with a few variations. Formation begins with gravitational instability within a GMC resulting in regions of higher density normally caused by shock waves from nearby supernovae. Once a region within the cloud has sufficient mass density to satisfy Jean's condition, the cloud collapses under influence of its own gravity. Such high density regions are called cores.

As the core density increases, its gravitational energy is converted into thermal energy leading to a rise in its temperature. When the core has reached a hydrostatic equilibrium, a protostar is formed within the core (Smith, 2004). Gravitational contraction of a giant molecular cloud takes approximately 10 to 15 million years. Most protostars formed normally have disks surrounding them as shown in Figure 1.

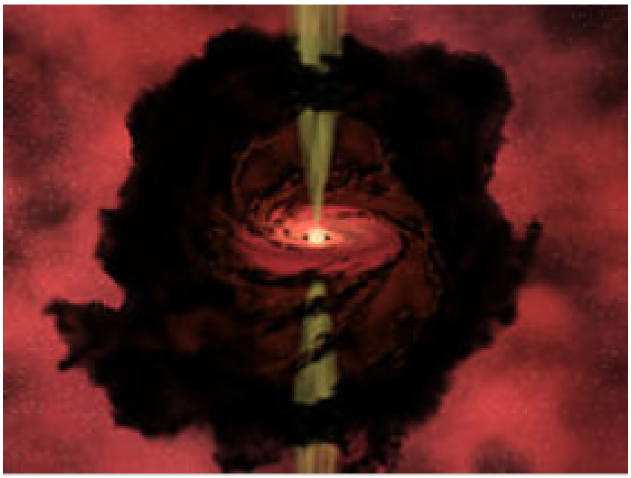

Figure 1: An artist's impression of a protostar being formed in a GMC. The figure illustrates an accretion disc around the protostar and its bipolar jets (https://en.wikipedia.org/wiki/Star).

2 Low mass star formation

The are a number of theories that explain mechanisms of low mass star formation. One such theory is interaction among protostars or fragments within a massive core. When a number of cores or fragments form within a massive core, they may interact in a manner leading to ejection of one or more of the fragments from the massive core prematurely. This makes the star to form with low mass as it is ejected away from a region of dense cloud where there is enough material to accrete and gain more mass (Bate, 2009).

Accretion of low mass stars can also be stopped by radiation from nearby stars. The nearby radiation pressure can remove much of the envelope and disc material of protostar forcing it to stop accretion (Hester, 1996).

Low mass stars can also form from circumstellar disks of massive stars. The disks can fragment due to gravitational variations within the disk to form low mass stars. The low mass stars formed from the disk normally become low mass companions of the massive stars. Some of the low mass stars can remain bound to the massive stars as a companion while others may be ejected through dynamical interactions with other companions or nearby stars (Shen et al. 2010, Stamatellos et al. 2011).

Lastly, collapsing cores of a GMC are of different masses and therefore result in stars of different masses. Low mass (smaller) cores give rise low mass stars while the massive ones give birth to massive stars (Elmegreen 2011).

3 Massive star formation

3.1 Introduction

Massive stars are stars with masses greater than $8M_{\odot}$ at solar metallicity (Carroll & Ostlie 2006, Crowther et al. 2010, Vink et al. 2013). The stars are quite rare in the Milky way compared to sun-like stars. The ratio of $20M_{\odot}$ to $1M_{\odot}$ stars is $\sim 1 : 100000$ and that of $100M_{\odot}$ to $1M_{\odot}$ stars is $\sim 1 : 1000000$ (Massey, 2003). The rate of formation of massive stars, $\dot{M}$ in units of $M_{\odot}$ per year is low and understanding their formation mechanism is key. Their rate of formation is given as (García et al., 2014):

$$\dot{M} = 6.5 \times 10^{-10} \frac{L_{FIR}}{L_{\odot}} M_{\odot} \mathrm{yr}^{-1} \tag{3}$$

Where $L_{\odot}$, L_{FIR} and $M_{\odot}$ are solar luminosity, far infrared luminosity and solar mass of giant molecular cloud (GMC) respectively.

These stars are astrophysically important despite their small number and low rate of formation in the Milky way. Some of their benefits to the Galaxy include chemical enrichment and high energy supply especially in the UV band. Their UV radiation plays a role in detection of atoms and molecules. This is because the excited molecules and atoms re-radiate in longer wavelengths. The stars are also believed to be a possible explanation to the dark age puzzle where they may have played a role in the re-ionisation of the universe across the great dark age period (Haiman & Loeb 1997).

3.2 Massive star formation mechanisms

Most stars do not exceed the $8M_{\odot}$ limit to be massive stars. Their formation is hindered at birth as the giant molecular cloud (GMC) fragments into smaller denser cores. As the particles in GMCs are accreted by the denser cores within the clouds the gravitational strength of the cores increases. The increasing gravitation of cores result in higher outward shock luminosity due to collision between the cores and the accreted particles. This process stabilises the star at lower masses. The outward shock luminosity stopping the formation can be estimated mathematically as:

$$L_{sh} = G \times M_c \frac{\dot{M}}{R_c} \tag{4}$$

Where M_c is mass of core, R_c is core radius, $\dot{M}$ is inflow rate (Winkler and Newman 1989).

The mass of a star formed depends on the mass of the GMC forming it. An $8M_{\odot}$ star requires a GMC whose mass is $10^3 M_{\odot}$ and a $50M_{\odot}$ one needs at-least a $10^5 M_{\odot}$ cloud to be formed (Zinnecker & Yorke, 2007). It means therefore that massive clouds form more massive cores compared to less massive ones as noted earlier. Initial mass of a star can be approximated from an initial mass function (IMF). The IMF of a massive star is not easy to estimate given their nature of strong stellar winds and binarity (Zinnecker & Yorke, 2007).

A number of theoretical models are in place to explain massive star formation. Simulations done on massive star formation only limit mass of these stars to $\sim 20M_{\odot}$ (Hennebelle & Commerçon, 2014) which is way below the observed masses (Vink et al., 2013). In the 1d models of massive star formation, the radiative pressure of the core is compared to the ram pressure of the gravitationally collapsing mass.

Clear details of processes at the initial stages of massive star formation within the GMCs are not well understood (Krumholz & Bonnell 2007, Beuther et al. 2007). The physical and chemical properties of starless cores have been studied in the effort to understand the initial star forming processes. Some of the physical properties of the cores that astronomers have been keen to study include linewidths, column densities, sizes and masses (Löhr et al., 2007).

To understand massive star formation, it is important to understand the dense cores in massive star forming regions and find out how they differ. Sánchez-Monge et al. (2013) studied and classified dense cores in massive star forming regions as protostellar, quiescent starless or perturbed starless. They used linewidths, opacity, rotational temperature and ammonia column densities of massive star cores. They found out that the features of massive star forming regions and those of low mass star forming regions do not vary much.

The massive star formation processes are generally affected from the early stage by nearby more advanced massive cores in the cloud through their temperatures, their stronger winds, turbulence, relative motions, gravitational interactions. The effect is experienced more in massive star clouds compared to low mass star ones (Ward-Thompson et al., 2007).

3.2.1 Models of massive star formation

Two models that have been proposed to explain the formation of the massive stars are core accretion model and competitive accretion model.

3.2.1.1 i) Core accretion model In the core accretion model, the giant molecular cloud breaks into smaller portions of denser clouds called cores. The core that forms massive stars are more massive than those forming low mass stars (McKee & Tan, 2003). The different core masses arise due to the fact that the cloud cores have differential gravitational force, magnetic strength and turbulence within them. The stars or star systems (e.g. binary stars) formed in this model are due to accretion of materials from the cores forming the stars and not outside the cores (Krumholz & Bonnell, 2007). Since a core is localised, the accretion within the core is not as violent or strong as if materials were accreted from far distances outside the core.

3.2.1.2 ii) Competitive accretion model In this model, the giant molecular cloud fragments and forms a full cluster at once. The gravitational potential of the cluster becomes higher than the surrounding region, which causes it to accrete mass from the surrounding region. Each core in the cluster then competes for the mass being accreted by the cluster until a star is formed. The stars near the centre of mass (CM) of the cluster accrete more material compared to those that are further away making them more massive. This is because the CM is gravitationally stronger than the outer parts of the cluster. The stars near the CM therefore gain more mass until they become massive compared to stars on the periphery of cluster as illustrated in Figure 2 (Krumholz & Bonnell, 2007). The distribution of stars in a cluster in which massive stars concentrate at the centre compared to cluster outskirts agree with Zinnecker & Yorke (2007).

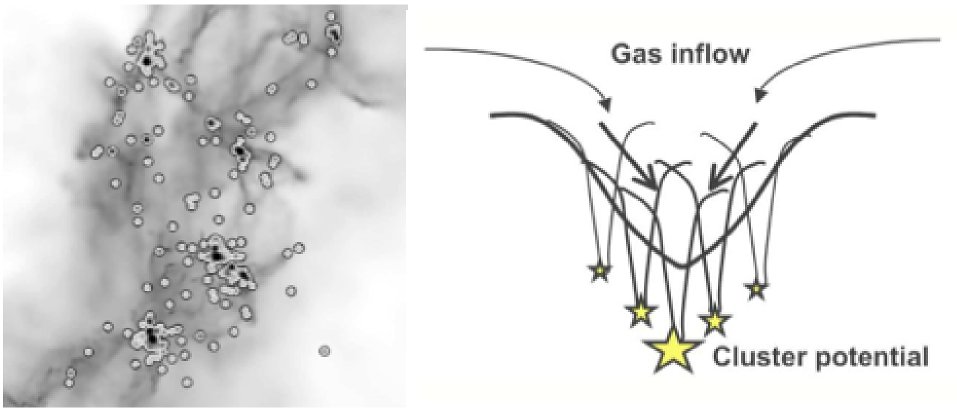

Figure 2: The location of the most massive stars in a simulation of cluster formation (left) shows their preferential location in the centres of clusters due to competitive accretion. The right panel shows a schematic of the competitive accretion process as the cluster funnels gas down to the cluster core. The stars located there are therefore able to accrete more gas and become higher-mass stars. The gas reservoir can be replenished by infall into the large-scale cluster potential (Krumholz & Bonnell, 2007)

4 coclusion

The general process of star formation has been extensively studied and is understood quiet well. The process takes place in the GMCs which fragments into clumps/cores. The clumps collapse under their gravity which result in release of thermal energy. The thermal energy then sets up thermal pressure that stops more collapse of the cores and eventually stabilise into a star when hydrostatic equilibrium of the core is reached. It is also worth noting that stars tend to form in groups and not in isolation. They form as binary stars or multiple star systems. The multiple systems of stars are called clusters and have stars of varied masses from low mass to massive ones.

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