Starlight in Darkness

The Birth of Stars

Priya Hasan

This article will briefly review the theory of star formation (SF) and its development using observations. This is very relevant in the present context since planet formation appears to be a by-product of SF, and the whole question of life in the universe and its origin can be viewed with a new perspective.

If the stars should appear one night in a thousand years, how would men believe and adore, and preserve for many generations the remembrance of the city of God?

Nightfall, Isaac Asimov

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Introduction

Humans have been bestowed with a gift from the heavens – the gift of starlight. Imagine that we were on a planet, like Venus, with an opaque atmosphere, or like the people of Lagash in *Nightfall*, a 1941 science-fiction novelette by Isaac Asimov. Their planet is lit by six suns, and they wait for the year 2049, when eclipsing of all the suns would lead to the night of darkness which would reveal stars that madden the people!

We live in a unique world spaced by day and night, reminders of light and darkness; each with its own beauty. The most enchanting component of our skies are the stars. To our ancestors, the most obvious explanation was that they were lanterns, or fireplaces in the skies. Then they noticed patterns, that they moved in concentric circles, about a fixed point in approximately 24 hours. Hence followed the notion of a shell of stars rotating around the Earth, with North and South Poles as the fixed points.

Figure 1. Structure of the Milky Way. (Image credit: ESA).
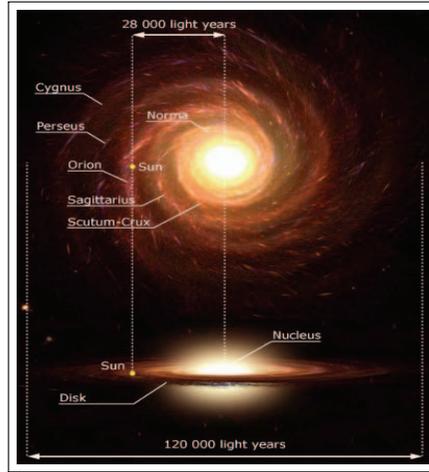
The stars of a galaxy distribute themselves into broadly three components, *viz.* – disc, halo, and bulge (*Figure* 1). The halo is made up of an older population of stars that constitute globular clusters. Globular clusters are made up of low metallicity, dense aggregates of 50,000–100,000 stars, gravitationally bound with orbits that are randomly distributed, which leads to their spherical shape. The stars are redder, older ≈ 10 Gyr[1] and we do not see any signs of SF taking place there. The disc component is made up of spiral arms where young stars are forming even now, as it is gas rich. This is where we find open star clusters which are looser aggregates of stars with typical lifetimes of a few 100 Myr[1]. The nuclear bulge contains the highest density of stars in the galaxy.

[1]Common Units: 1 Myr = 10^6 yr, 1 Gyr = 10^8 yr, 1 parsec (pc) = 3×10^{13} km, 1 light year (ly)= 10^{13} km, 1 $M_\odot$ = Mass of the Sun = 2 $\times 10^{30}$ kg.

The Milky Way is made up of three components – disc, halo, and bulge. Active star formation is taking place in the disc. Star clusters are found in a continuous range of densities of 0.01–100 stars pc^{-3}, with the older globular clusters in the halo and the younger associations, and open star clusters in the gas rich discs.

The primary population of stars in the nucleus is similar to the old stars found in the halo, with a few hot young stars. The core of the Galaxy is highly obscured by dust and gas at visible wavelengths, but can be observed at other wavelengths. Our Galaxy contains a very massive black hole at its center with a mass of $\approx 4.5 \times 10^6$ $M_\odot^1$, which drives many of these processes near the core.

Star clusters are nature's samples of stars formed from the same parent cloud and are therefore, of the same age, chemical composition, and at the same distance, differing only in mass. The Russell–Vogt theorem states that mass and chemical composition are the two important parameters that decide a star's fate. Hence,
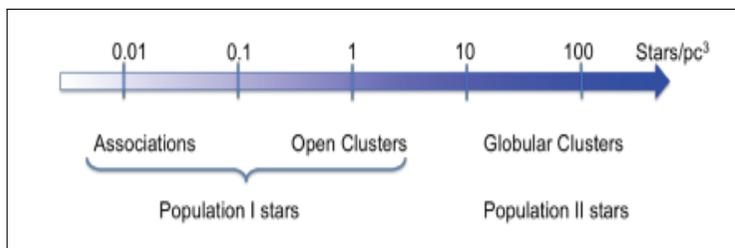
Figure 2. Typical density of associations, open clusters and globular clusters. (Image credit : Moraux, Estelle, Lebreton, Y, Charbonnel C, *Stellar Clusters: Benchmarks of Stellar Physics and Galactic Evolution*, EAS Publications Series, Volume 80–81).

star clusters are widely used as ideal samples to study stellar evolution as all other parameters are fixed, and the mass of stars defines it's evolution. In the present times, they are also very useful in understanding star and planet formation as these are very closely linked processes, planet formation being a by-product of SF . There are also associations, which consist of recently formed stars, not bound gravitationally, at large separations of ≈ 100 pc, and expanding away from some common center, which presumably marks their birthplace. The motion of these stars can be traced back in time to support this conjecture. They are categorized as OB, T and R associations, based on the properties of their stars, which could vary. (*Figure* 2). If the remnants of a stellar association drift through the Milky Way as a coherent set of stars, they are called a 'moving group' or 'kinematic group'.

Open clusters, associations, and moving groups are probably just different realizations of the SF process, differentiated due to the way in which we observe them, their environments and other factors.

1. Voids in the Milky Way: Molecular Clouds

There are regions in the sky that appear as dark patches (*Figure* 3) due to 'extinction' which is the absorption and scattering caused by intervening matter. Extinction is inversely proportional to wavelength and hence observations in longer wavelengths are used.

The star count method was used to estimate the missing number of stars in a region by comparing them to the number of stars in the neighbouring region. These regions are identified as 'giant molecular clouds' (GMCs) and have sizes of 20–100 pc, masses ranging from 10^4–10^6 $M_\odot$, $n \approx 50$–100 cm^{-3}, and $T \approx 10$ K. They are confined to the galactic plane, coinciding with the spiral arms and concentrated in a ring 3.5–7.5 kiloparsec (kpc) in diameter.

Molecular clouds are the cold, dense regions where star formation takes place. They are embedded in gas and dust, and hence have to be observed at longer wavelengths from near infrared to radio. Young stars also emit very strongly in the X-ray region. Hence multi wavelength observations are required to get a complete census of young stars in GMCs.

Figure 3. Colour composite of visible and near infrared images of the dark cloud Barnard 68 with the 8.2-m VLT ANTU telescope and the multimode FORS1 instrument in March 1999. The cloud is completely opaque because of the obscuring effect of dust particles in its interior. It is at a distance of 500 ly[1], and is 0.5 ly in diameter. (Image credit: ESO).

The mass of GMCs is mainly contained in molecular hydrogen and helium atoms. About one percent is made up of dust – typically silicates and/or graphites. Other molecules and their isotopes like CO, NH_3, CN, H_2O, etc., also have been detected, with CO being the most abundant. Molecular hydrogen does not possess a permanent dipole moment. Hence, at the typical temperatures of molecular clouds, it does not emit any radiation. Observations use different tracers such as dust or other abundant molecules, and indirectly estimate the amount of molecular hydrogen. They can be observed in the radio wavelengths by observations of molecular lines, or using dust extinction.

Understanding the formation and evolution of GMCs, is a daunting problem. One immediate issue is the vast range of scales between galaxies and protostellar discs, from 10 kpc -10^{-3} pc. Another difficulty in the study of molecular clouds is the complex physics involved– gravity, magnetic fields, thermodynamics, turbulence, and stellar feedback. The interstellar medium itself is a multiphase medium of atomic, molecular, and ionized hydrogen with a range of temperatures from 10 K–10^8 K, and large differences in density.

James Jeans proposed gravitational collapse as the mechanism for formation of stars. The conditions for this to take place was that the GMC is cold and dense. As the core gains mass, material accretes on to it, forming a disc. When the temperature of the core rises to 10^6 K, nuclear fusion begins and a star is born.

2. Jeans Instability

Sir James Jeans proposed a very simple theory for the formation of stars, based on the Kant–Laplace nebular hypothesis. An inter-
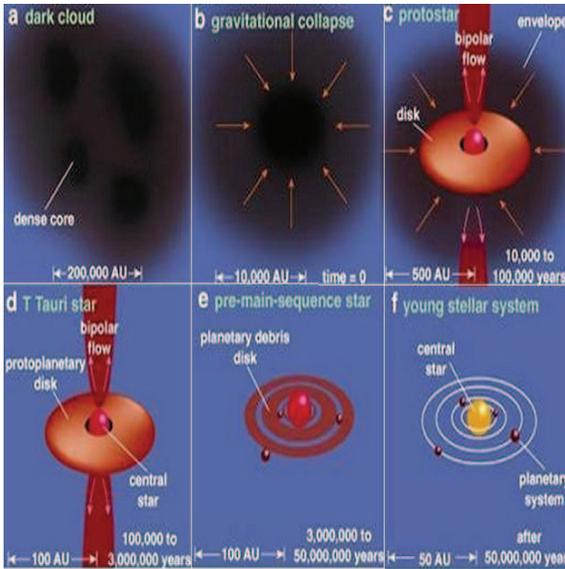
Figure 4. The process of star formation. (Image credit: Spitzer Science Center).

stellar cloud is in hydrostatic equilibrium, i.e., there is a balance between the gravitational force and the gas pressure. He proposed that if a cloud was cold and dense enough, then the gravitational force would dominate, leading to the gravitational collapse of the cloud (*Figure* 4). As the cloud collapses, it breaks into fragments in a hierarchical fashion, until the fragments are close to stellar mass. 'Jeans mass' (M_J) is the characteristic mass of a cloud when this condition gets satisfied and is given by,

$$M_J = 3 \times 10^4 \sqrt{\frac{T^3}{n}} M_\odot,$$

where T is the temperature and n is the density. The centre of the clump collapses to a dense, gravitationally stable core known as a 'protostar', which heats up as it continues to contract. The protostar grows by accreting more material from the surrounding molecular cloud, and thus its core gets denser and hotter. Due to the conservation of angular momentum, this material spirals in towards the star and forms a disc of material that orbits the star, slowly accreting onto the star in bright bursts that illuminate the surrounding cloud. With each burst of accretion, the star becomes hotter, and more massive till it is hot enough for nuclear fusion to take place. At first, the star can only burn deuterium, but as

YSOs are classified based on their spectral energy distribution. Class 0/I are the youngest which evolve to Class II and then the discless Class III sources. The spatial distribution of YSOs can be used to study the progress of SF formation and the influence of its environment. Images from ALMA of HL Tau shows a very clear agreement to this picture of star formation.

it gets hotter it burns hydrogen just like our own Sun. The star is now beginning to shine quite brightly, and the radiation from the star prevents further material accreting onto the star, and may even begin to disperse the remaining material in the disc that still surrounds the star.

Once the star has started nuclear fusion from hydrogen into helium we say that it is born [1]. Hydrogen fusion is the natural source of energy for most stars, and the star continues fusion of lighter to heavier nuclei till it reaches the atomic number of iron. For nuclei heavier than iron, repulsive forces are stronger and fusion becomes an endothermic process requiring energy. Elements heavier than iron are only produced in highly energetic events like supernova explosions.

'Young Stellar Objects' (YSOs) are usually classified using criteria based on the slope of their spectral energy distribution, introduced by Lada [2]. He proposed three classes (I, II, and III), based on the values of intervals of spectral index α given by,

$$\alpha = \frac{d \log(\lambda F_\lambda)}{d \log(\lambda)},$$

where λ, is the wavelength, and F_λ is the flux density.

The spectral index α is calculated in the wavelength interval of 2.2–20 μm. Class 0 stars were objects which showed strong emission at submillimeter wavelengths, but are very faint at $\lambda < 10\mu$m. Later, the class of 'flat spectrum' sources were added.

This classification schema follows an evolutionary sequence, where the most deeply embedded Class 0 sources evolve towards Class I stage, dissipating their circumstellar envelopes. Eventually they become optically visible on the stellar birthline as pre-main-sequence stars.

The most important result of this picture of SF is the co-formation of stars and planets from the protoplanetary discs, and it has been recently validated by observational evidence by the Atacama Large Millimeter/submillimeter Array (ALMA). *Figure* 5 reveals
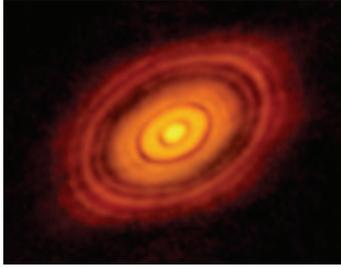
Figure 5. ALMA image of the young star HL Tau and its protoplanetary disc. (Image credit: ALMA–NRAO/ESO/NAOJ; C Brogan, B Saxton – NRAO/AUI/NSF).

Figure 6. A far-infrared image of the Taurus molecular cloud, showing the filamentary structure of the gas. (Image credit: Herschel Space Observatory).

in astonishing details, the planet-forming disc surrounding HL Tau, a Sun-like star located approximately 450 ly from Earth in the constellation Taurus.

3. Filaments

Molecular clouds have considerable structure, which is quite filamentary, formed by variable densities of gas and dust, causing variable extinction, very clearly seen in Herschel images (*Figure* 6).
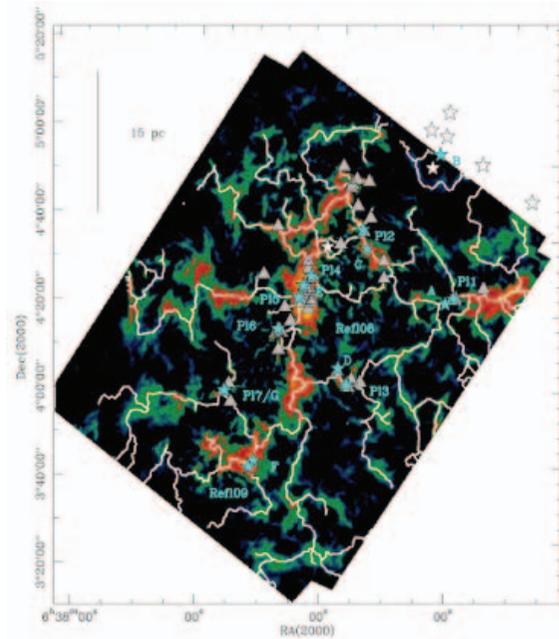
This structure is thought to arise due to a combination of shock compression (due to collisions between material) and self-gravity (filaments can form gravitationally-stable structures on their own). These filaments can be seen on all spatial scales, large and small [3].

Many of these filaments are dense, containing masses of many times the mass of our Sun in molecular gas. This high density implies that they can be gravitationally unstable, which can lead them to collapse and potentially form stars. Simulations of filaments suggest that a single filament can actually lead to the for-

Star clusters are found where filaments overlap. The obvious question is whether the filament collision occurs before, after, or even during the SF process. Observational evidence supports all the above scenarios, and that could be possible because of the wide range of environments present, leading to the realizations of all possible cases.

mation of multiple stars.

This picture where SF occurs in dense gas is seen in all the star forming regions – both the youngest stars appearing on the densest parts of the filaments, and on small scales (like NGC 1333), and on much larger scales of giant molecular clouds such as the Orion A cloud.

Figure 7 shows filaments and star clusters in a star forming region known as the Rosette molecular cloud. The background image shows the distribution of dense gas in the cloud, with the density of the gas ranging from low (black) to high (green and red). Also are marked (in white) the positions of the filaments that make up the molecular cloud, and on top of that (the turquoise stars) are the positions of known star clusters, typically at points where filaments overlap. In somewhat older regions, we start to see clusters of stars where there is no gas and the filamentary structure has dissolved, but the gas morphology could imply it being blown away by the young stars.

Embedded clusters are the earliest signs of star formation. The crucial step is the detection of YSOs because of the high levels of extinction.

4. Embedded Clusters

Embedded clusters are the earliest units of SF, made of young stars embedded in gas and dust, invisible in the optical region. They have sizes of 0.3–1 pc, masses 20–1000 $M_\odot$, and mean stellar densities 1–10^3 $M_\odot$ pc^{-3}. The 'SF efficiency' (SFE) is the ratio of the mass of stars to the total mass of the original cloud and is 10–30%. It is this unused gas that provides the gravitational glue that binds the cluster. Most clusters lose their gas in the first 5 Myr which leads to the disruption of clusters called 'infant mortality'. Barely 4% of the clusters survive beyond 100 Myr.

It is very important to study these objects in the early phase of their formation to understand their spatial and temporal distribution, stellar, planetary companions, environments, etc.

Embedded clusters can be identified by making systematic searches of molecular clouds in infrared bands, say K band (2.2 μm). Often, most members are obscure and the densities may not be significantly higher than the background. Other methods are surveys of signposts of SF like outflows, luminous IRAS sources, Herbig AeBe stars, etc. We also use surveys using all the sky data of 2MASS [5], DENIS which can give good methods of statistical subtraction of stars in clusters and field areas to map over densities.

For young embedded clusters with ages < 3 Myr, at least half of the members will have circumstellar discs [6]. Observations using

Figure 8. This composite image of NGC 281 contains X-ray data from Chandra in purple, with infrared observations from Spitzer in red, green, blue. (Image credit: X-ray: NASA/CXC/CfA/S.Wolk; IR: NASA/JPL/CfA/S.Wolk).

the Spitzer Space Telescope[2] at wavelengths 3–70 μm have been very useful to study discs around stars [7]. For discless stars, a very effective method is the observations in the X-ray wavelength, as young stars emit X-rays at levels 10^2–10^4 times that of normal stars, particularly during the first 10 Myr of their lives [7] (see *Figure* 8).

5. Some Important Aspects of Star Formation

5.1 *Initial Mass Function (IMF)*

The distribution of mass amongst the stars born from the same parent cloud is called the 'initial mass function' (IMF). The IMF is often stated in terms of a series of power laws, where $N(M)$ the number of stars of mass M within a specified volume of space is proportional to $M^{-\alpha}$ where α is a dimensionless exponent. The form of the IMF for stars with $M > 1$ M$_\odot$ was discovered by Salpeter [8], who found that $\alpha = 2.35$.

5.2 *Multiplicity*

It was earlier believed that most stars are born in multiples [9]. It has been also found that there is a linear relation between the mass of a star and the number of multiples. *Figure* 9 shows the relation between the frequency of multiple systems and the companion frequency MF and CF, respectively, to the mass of the star. For M type stars [3] 66–67% stars are single. Recent studies of the IMF, show that the IMF breaks from a single power law near 0.5M$_\odot$ and has a broad peak between 0.1–0.5 M$_\odot$ [10]. On either side of this peak, the IMF falls rapidly. The peak of the IMF lies around M type stars, and it has been estimated that 73–78% of all stars are M type. Therefore, two-thirds of (main sequence) stars currently residing in the galactic disc are single stars [11]. However, it is found that there is a decline in multiplicity as we go from Class 0 to Class I, II, and III stars, implying that all single stars may not have been born single.

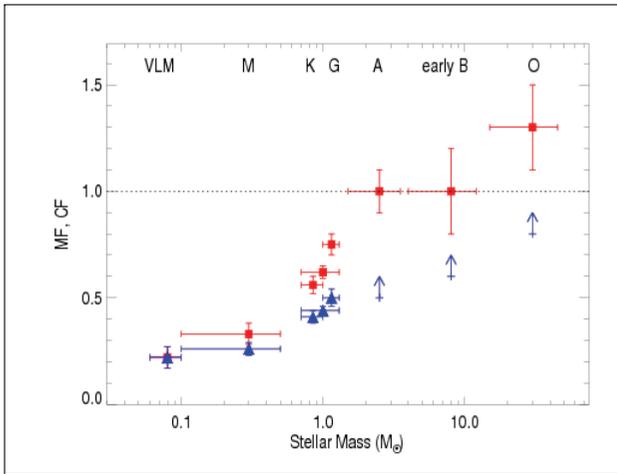The questions that follow are – Is this how stars are formed? In-

Figure 9. Dependency of CF (red squares) and MF (blue triangles) with primary mass for MS stars (Image credit: [12]).

dividually? Or do stars form in binaries and multiples which later disrupt? Then, how do we explain the dependence of stellar multiplicity on mass? Or does increased cloud turbulence in massive dense cores lead to efficient core fragmentation and higher incidence of binary stars?

5.3 *Mass Segregation*

Mass segregation is the spatial distribution of stars according to their masses. It is observed that there is a concentration of high-mass stars near the centre and the low-mass ones away from the centre. This can take place as a result of dynamical interactions between stars in the clusters, or could be primordial. The variation of the MF of clusters in different regions of the clusters has been studied [13].

6. Conclusion

Stars are forming in our Galaxy at a rate of $1–4$ $M_\odot$ yr^{-1}. In contrast to elliptical galaxies, star formation is still going on in spiral galaxies because of their reservoirs of molecular gas which is the fuel for new stars.

The optically dark molecular clouds are nurseries of stars, where the enigmatic process of SF takes places under the grip of gravity.

Many unsolved problems of this process continue to puzzle astronomers like – How and why are stars clustered when they form? What causes stars to form with different masses? Is there a different process of SF for low and high mass stars? What brings the SF process within a molecular cloud to a halt? How do stars form in diverse environments? How do massive stars influence the formation of low mass stars? How coeval is SF?

New observations and further research is required in these areas to answer some long-standing questions about the universe in which we live, and to decipher the secrets in the starlight in darkness.

Acknowledgement

Suggested Reading

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