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High Mass Star Formation - a (short) review

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ABSTRACT
Massive star formation is one of the most enigmatic topics in astrophysical research. It involves complex mechanisms such as accretion, competitive accretion, and stellar collisions. A comprehensive understanding requires multi-wavelength studies, as different phases of star formation emit distinct radiative signatures. Massive stars significantly influence their surroundings by forming HII regions and injecting energy into the interstellar medium (ISM) via stellar winds and ultraviolet radiation. This review explore the theoretical and observational perspectives on massive star formation, highlighting the challenges, processes, and their profound impact on galactic evolution.

Keywords: ISM, Massive Star formation

I. INTRODUCTION

Stars are the fundamental units of luminous matter in the universe, and they are responsible, directly or indirectly, for most of what we see when we observe it. They also serve as our primary tracers of the structure and evolution of the universe and its contents. Consequently, it is of central importance in astrophysics to understand how stars form and what determines their properties.

The study of the formation and early evolution of stars has become an ever-growing part of astrophysical research. It is a common perception that astronomy is one of the oldest occupations in human history. However, ancient views contain very little about the origins of stars. Their everlasting presence in the night sky made stars widely used as benchmarks for navigation. Though it always was, and still is, a spectacular event when a new light—a nova or a new star—appears in the sky, such new lights are either illuminated moving bodies within our Solar System, a supernova (the death of a star), or other phases in the late evolution of stars. A normal star is never truly ”born” in these cases. The birth of a star always occurs in the darkness of cosmic dust and is therefore not visible to the human eye. In fact, when a newborn star finally becomes visible, it is already in the final stages of its formation. Understanding the formation of stars requires the most modern observational techniques and the full accessible bandwidth of the electromagnetic spectrum.

In some sense, the evolution of stars is a cyclic process. A star is born from the gas and dust that exist between the stars, known as the Interstellar Medium (ISM). During its lifetime, depending on the star’s total mass, much of this material may be returned to the ISM through stellar winds and explosive events. Subsequent generations of stars can then form from this recycled material. Thus, the ISM can be considered both the source of star formation and the medium into which stars expel their material.

Massive stars are rare but have a profound impact on their environment. Their short lifetimes, intense radiation, and supernova explosions dominate the energy and chemical processes within galaxies. This review aims to provide a detailed exploration of massive star formation, focusing on the challenges, mechanisms, and their interactions with the environment.

This review focuses on massive star formation and is divided into four parts. The first part discusses the motivation for studying massive star formation, highlighting its significance in astrophysics. The second part provides an outline of the star formation mechanism, emphasizing the process of high-mass star formation and its importance. The third part describes the current understanding of massive star formation, including key challenges and recent advancements in the field. Finally, the review concludes with a summary of the findings and their broader implications.

II. MOTIVATION FOR THE STUDY

The formation of high-mass stars remains one of the most significant un- solved problems in astrophysics. These stars, with masses 10 times or more greater than that of the Sun, eventually explode as supernovae, producing most of the heavy elements in the universe. Through their stellar winds, ultraviolet (UV) radiation, and supernova explosions, massive stars domi- nate the energy injection into the interstellar medium. Observations of HII regions, created by massive stars, serve as a crucial tool for extragalactic astronomers to estimate star formation rates and measure chemical abun- dances in galaxies.

Massive stars also influence planet formation. Many low-mass stars are born in clusters containing massive stars, whose intense UV radiation can destroy protoplanetary disks, potentially disrupting the formation of planets.

The study of massive star formation is critical for several reasons:

1. Galactic Impact: Massive stars influence galaxy evolution by producing heavy elements through nucleosynthesis and enriching the ISM during supernovae.
2. Energy Dynamics: Through ultraviolet (UV) radiation and stellar winds, massive stars dominate the energy budget of the ISM.
3. Role in Star Formation: Massive stars can both trigger and inhibit the formation of new stars, shaping the structure of molecular clouds.

III. CHALLENGES

Despite the importance of massive star formation, relatively little is known about it. Observations are challenging because massive star-forming regions are heavily obscured by dust, making them invisible in optical and near- infrared wavelengths. These regions are also rare and typically located much farther from Earth than low-mass star-forming regions. Observing them re- quires high spatial resolution. Furthermore, massive star formation occurs in clusters with high stellar densities, necessitating even higher resolution to obtain a clear view of individual star-forming sites. Additionally, massive stars disrupt their surroundings by forming plasma in HII regions. Much of our current knowledge comes from observations of ultra-compact HII regions, which become visible only after star formation is nearly complete. At this stage, the massive star's radiation heats the surrounding nebula, causing it to glow and eventually leading to its destruction.

Massive star formation also presents significant theoretical challenges. Massive stars begin nuclear burning and radiate large amounts of energy while still accreting material. For stars above approximately $10M_\odot$ the radi- ation pressure on dust grains in the accreting material can exceed the grav- itational force pulling the material inward. This raises a critical question: how can a sufficiently high mass accretion rate onto the massive protostel- lar core be sustained despite the opposing force of radiation pressure on the accreting envelope?

Key questions in recent research on massive star formation include:

- What are the main phases of massive star formation, and how do they affect the surrounding environment?
- How does the energy injection mechanism influence the surrounding molecular cloud?
- What are the effects of massive stars on their associated HII regions?

A multi-wavelength observational approach is essential to addressing these questions, as different parts of the electromagnetic spectrum can probe dis- tinct regions of a star-forming environment. This is due to variations in the radiation emission mechanisms across the spectrum. By combining data from multiple wavelengths, researchers can uncover the diverse processes occurring within molecular clouds. Thus, a multi-wavelength study of high-mass star formation is crucial to solving the complex puzzle of massive star formation. Despite their significance, studying massive stars poses unique difficulties:

- Observational Challenges: Massive star-forming regions are often dis- tant and heavily obscured by dust, necessitating high-resolution in- frared and radio observations.
- Theoretical Barriers: The intense radiation pressure of massive proto- stars should theoretically halt accretion, yet massive stars continue to grow, defying simple models.

IV. THE STAR FORMATION PROCESS

Stars form from the gravitational collapse of clouds of gas and dust. Ini- tially, a molecular cloud is in a state of equilibrium when the inward gravi- tational pull is exactly balanced by the outward thermal pressure. However, when the gravitational force exceeds the thermal pressure, the gas cloud be- gins to collapse. During the collapse, the density and temperature of the cloud increase, with the highest values occurring at its center, where a new star will eventually form.

The object forming at the center of the collapsing cloud, destined to be- come a star, is called a protostar. Protostars are embedded within dense clouds of gas and dust, making them difficult to detect in visible light, as the surrounding material absorbs most of their emitted light. Only in later stages, when the protostar becomes hot enough for its radiation to clear away the surrounding material, can it be observed in visible light. Until this point, protostars can only be detected in the infrared. The infrared radiation arises because the protostar’s light warms the surrounding dust, which then radi- ates in the infrared. Infrared observations of star-forming regions provide valuable insights into the processes of star formation and, consequently, into the origins of our Sun and Solar System.

The idea that stars form through the gravitational condensation of diffuse matter in space is very old, dating back to Newton, who suggested it in 1921. However, it is only in the last half-century that compelling evidence has emerged showing that stars are currently forming in our Galaxy and others through the condensation of interstellar matter. Observations across multiple wavelengths, particularly in the radio and infrared regions, have greatly enhanced our understanding of star formation. Today, star formation is a major area of research, involving both extensive observational studies and theoretical work, supported by advanced computational simulations to clarify the underlying physical processes.

Star formation occurs due to the action of gravity on various scales, with different mechanisms opposing gravitational collapse depending on the scale:

1. Galactic Scales: On large scales, gravity pulls interstellar matter into star-forming regions, but this is counteracted by galactic tidal forces. Star formation occurs only where the gas becomes sufficiently dense for self-gravity to overcome these tidal forces, such as in spiral arms of galaxies.
2. Intermediate Scales (Giant Molecular Clouds - GMCs): Within GMCs, turbulence and magnetic fields are the primary forces counteracting gravity. Star formation at this scale often involves the dissipation of turbulence and weakening of magnetic fields, allowing the clouds to collapse.
3. Small Scales (Prestellar Cores): On the smallest scales, thermal pres- sure is the main force resisting gravity. This sets a minimum mass, called the Jeans mass, required for a cloud core to collapse and form stars. Once the collapse begins, centrifugal forces due to angular mo- mentum may play a role, potentially halting contraction and leading to the formation of binary or multiple-star systems.

As the central region of a collapsing core reaches stellar density, thermal pressure rises, halting the collapse and giving rise to a protostar. The proto- star continues to grow in mass by accreting material from its surroundings. Magnetic fields may influence this stage by mediating gas accretion and driv- ing bipolar jets, which are a common feature of newly forming stars. These jets mark the final stages of star formation and herald the birth of a new star.

Star formation begins with the collapse of molecular clouds under gravity.
The process involves the following stages:

- Initial Collapse: A molecular cloud collapses when gravity overcomes thermal pressure, forming dense cores.
- Protostar Formation: The core evolves into a protostar, surrounded by an accretion disk.
- Accretion and Feedback: The protostar grows by accreting material, while feedback from radiation and stellar winds begins to influence the surrounding environment.

V. MASSIVE STAR FORMATION

High mass stars, also called OB stars, have luminosities larger than, spec- tral types or earlier, and stellar masses roughly spanning the range From their birth to their death, high mass stars play a major role in the energy budget of galaxies via their radiation their stellar winds and through supernovae. Despite that, the formation of high mass stars remain an enigmatic process, less understood than the low mass stars. According to the initial mass func- tion, which give the total number of stars that form within a mass interval, the number of high mass stars is very low and it is very rare to observe also. Therefore, molecular clouds able to form high-mass stars are statistically more remote and than those of well studied low mass star forming regions.

Current observational studies of high mass star formation therefore suffers from the lack of high spacial resolution and from lack of basic knowledge of remote star forming regions.

High-mass stars, also known as OB stars, have luminosities exceeding $10L_{\odot}$, spectral types of O or early B, and stellar masses ranging from ap- proximately 10 $100M_{\odot}$. From their birth to their death, high-mass stars play a pivotal role in the energy budget of galaxies through their intense radiation, stellar winds, and supernova explosions.

Despite their significance, the formation of high-mass stars remains an enigmatic and less understood process compared to that of low-mass stars. According to the initial mass function (IMF), which describes the distribu- tion of stellar masses at birth, the number of high-mass stars is very small. As a result, it is rare to observe their formation directly. Molecular clouds capable of forming high-mass stars are statistically more remote than those forming low-mass stars, making them harder to study.

Consequently, current observational studies of high-mass star formation face two major challenges: the lack of sufficient spatial resolution to resolve fine details and the limited understanding of the remote environments in which these stars form. Overcoming these obstacles is critical to advancing our knowledge of high-mass star formation and its impact on the evolution of galaxies.

Over the past ten to fifteen years, there has been growing interest in ad- dressing the challenges of high-mass star formation from both theoretical and observational perspectives. This review presents the recent progress made in this field, highlighting key advancements and developments.

1. Theoretical Aspect of High mass star-formation

The formation of massive stars has become a topic of significant interest. Massive stars appear to form in exceptionally dense environments, with two primary competing hypotheses: formation through gas accretion or through stellar coalescence. Neither hypothesis can yet be definitively excluded. An intermediate possibility suggests that interactions between dense star- forming cores may also play a role. This scenario seems almost unavoidable. If accretion is the dominant process, the gas being accreted in a forming star cluster is likely clumpy and contains multiple forming stars. Conversely, if stellar coalescence occurs, the coalescing stars themselves would still possess massive gas envelopes, which would also influence the process.

A key difference between the formation of high-mass and low-mass stars lies in the role of the radiation field of massive protostars. Massive protostars heat the surrounding gas, creating a plasma of protons and electrons known as an HII region. This intense radiation field generates significant radiation pressure, which can inhibit further accretion of matter. The critical luminos- ity beyond which radiation pressure prevents additional accretion is known as the Eddington Luminosity.

2. Scenarios of massive star formation

The currently accepted models of hight massive star formation are the following

1. Core Accretion

Massive stars grow in size through the accretion of material from their surroundings. However, accretion typically halts once the Eddington lumi- nosity is reached, where radiation pressure—generated by nuclear fusion and accretion—prevents further infall of material. The question of how accretion continues despite extreme radiation pressure, particularly above the Edding- ton limit, was first explored by Larson and Starrfield (1971) Hoare and Franco and Khan (1974) Kahn (1974).

A critical distinction between low-mass and high-mass star formation lies in the timescale for contraction to the main sequence. For massive stars, this timescale is significantly shorter than that for low-mass stars, and it is even shorter than the formation timescale for the stars themselves. Consequently, massive stars are likely still accreting material when hydrogen fusion begins in their cores. As the mass increases, the combined luminosity from fusion and accretion generates significant radiation pressure on dust grains within the infalling cloud. In a spherically symmetric treatment, Khan deduced that this radiation pressure would limit the mass of a star formed via accretion to approximately $40M_{\odot}$. However, adopting more realistic dust parameters eliminates this strict limit, though it requires very high infall rates to main- tain sufficient ram pressure to counteract radiation pressure.

Another approach to explaining high-mass star formation involves rec- ognizing that the cores of massive stars are not supported by thermal pressure but rather by a combination of turbulence and magnetohydrodynamic (MHD) waves. Bernasconi and Maeder (1996) Bernasconi and Maeder (1996) found accretion rates as high as $10^{-4}M_{\odot}yr^{-1}$ for the most massive stars. McKee and Tan (2003) McKee and Tan (2003) developed a turbulent core model, which predicts accretion rates about an order of magnitude higher, at $10^{3}M_{\odot}yr^{1}$. This model justifies such high rates by observing the elevated pressures in massive star-forming cores, which require larger line widths than predicted by the usual Larson relations. Although the Larson relations are often applied to estimate increasing accretion rates over time, direct evidence of their applicability to massive star-forming clumps remains limited.

The spherical accretion rates in the turbulent core model are sufficient to overcome radiation pressure. Moreover, the time-dependent accretion rates make the star formation timescale relatively independent of the stellar mass, enabling the formation of seemingly coeval clusters containing a wide range of stellar masses. The model also predicts a radial density distribution on large scales approximating r^{-4} onsistent with observations of several mas- sive star-forming regions. This density gradient is typically interpreted as evidence of infall during rapid star formation scenarios, in which the entire region undergoes collapse.

In the McKee and Tan model, the turbulent core is envisioned as a quasi- equilibrium structure supported by turbulence over extended periods. Obser- vations of massive young stars strongly suggest that they form via accretion through a disk rather than spherical infall. Bipolar outflows, a common feature of luminous embedded sources, provide indirect evidence of this disk-mediated accretion process.

Accretion through a disk plays a crucial role in overcoming radiation pressure in several ways:

1. Limited Interception of Radiation: Stellar radiation is isotropic, and the disk intercepts only a small fraction of the total luminosity.
2. Enhanced Accretion Rates: Concentrating infall through a thin disk amplifies the effective accretion rate.
3. Self-Shielding Effects: The disk’s midplane material is shielded by the upper layers, enabling accretion to persist even under intense radiative forces.

As material rains down on the accretion disk, radiation bubbles periodically blow out perpendicular to the disk plane and subsequently collapse, but overall accretion continues. These processes yield accretion rates of the order of , and a consensus appears to be emerging around these rates for massive star formation.

3. Competitive accretion

In this scenario, several stellar embryos build up their mass within a common cloud, often referred to as a protocluster. The accretion rate of protostars depends significantly on their location within the cloud. It is stronger at the cloud’s center, where the gas density is highest, and weaker near the cloud’s edge, where less gas is available. Furthermore, accretion is influenced by the mass of the protostars, as more massive stars can attract larger amounts of gas, thereby expanding their accretion domain.

The key distinction between competitive accretion and monolithic col- lapse lies in the timing of gas collection relative to star formation. In the competitive accretion model, the gas is not assumed to be assembled into a single structure before star formation begins. Instead, competitive accretion serves as the primary mechanism for gathering material during the process.

In this framework, high-mass stars predominantly form at the center of protoclusters. The gravitational force of the protocluster, where stars are undergoing competitive accretion, attracts a significant fraction of the gas and stars toward the cluster’s center. This central accumulation facilitates the formation of massive stars, which continue to grow by accreting gas from their surroundings in this dynamic and competitive environment.

4. Alternative Scenarios

1. Stellar collisions and merges

In this scenario, massive stars form through the coalescence of a large number of low-mass protostars. The original motivation for proposing stellar collisions as a formation mechanism for massive stars was to bypass the radiation pressure effect, which can inhibit accretion in traditional models. Additionally, this mechanism helps explain the large number of massive stars found in dense stellar clusters, where the high stellar density increases the likelihood of stellar collisions and mergers.

2. Interaction of massive stars with the surroundings

Massive stars play a crucial role in the evolution of galaxies, as they are the primary source of metals and dominate the turbulent energy input into the interstellar medium (ISM) through their intense and fast stellar winds, ultraviolet radiation, and supernova explosions. Young massive stars emit copious amounts of Lyman continuum photons that excite their surround- ings, creating dense, small regions of ionized gas known as ultra-compact HII regions. These regions are characterized by high emission measures, making them very bright at radio wavelengths. Therefore, probing high-mass star formation at radio wavelengths provides valuable insights into the properties of UC HII regions. Surveys at radio wavelengths have revealed the existence of a large number of UC HII regions in our galaxy.

As these stars have short lifetimes, typically only a few million years, HII regions serve as indicators of star formation sites and are key targets for measuring the current star formation rate in a galaxy. Additionally, the emission line spectrum produced by the ionized gas allows for the accurate determination of the chemical composition of the gas in a galaxy. Although the physical processes of line excitation are well understood, and accurate atomic data are available, spectral analysis of HII regions remains an essential tool for studying the evolution of galaxies.

5. Recent Studies and Results

1. Multi wavelength study of Massive star forming regions

Guido-Garay et al. (1999) conducted a multi-wavelength study of 18 lu- minous IRAS (Infrared Astronomical Satellite) objects using the ATCA. In this study, they found that the HII regions in the sample, most of which lie at the center of massive and dense molecular cores, are excited by stars with UV photon outputs typically around 3 $10^4 S^{-1}$. They concluded that the main mechanism for confining compact HII regions is the high density and large turbulent pressure of the surrounding molecular gas. They also suggested that if the sample is representative of Galactic IRAS sources with compact region colors, then this greater number of HII regions would account for the large rate of massive star formation in the galaxy. In their study of the dust environment, they found that the massive, dense cores are centrally condensed, and the UC HII regions detected with ATCA toward the IRAS sources are usually projected at the peak position of the 1.2 mm dust con- tinuum emission, suggesting that massive stars form at the center of these centrally condensed, dense cores.

2. Massive Star formation studies of IRCs

M.S.N. Kumar et al. (2010) studied the infrared counterparts (IRCs) of high-mass protostellar objects using the Spitzer Space Telescope (SST). They examined the IRCs for clustering to investigate the sequence of low- and high-mass star formation. They found clustering around high-mass pro- tostellar objects, suggesting that low-mass stars form prior to high-mass stars in a clustered environment. A comparison of the driving engines with those of outflows indicates that massive stars likely form through accretion, similar to low-mass stars. However, the detailed mechanism may differ significantly and requires further study.

3. Triggered Star Formation by Massive Stars

HT lee et alLee and Chen (2007) have studied about the star formation triggered by massive star formation. Given proper conditions, a massive star can play a constructive role in producing next generation stars, thereby sustaining the star formation activity in giant molecular clouds. A supernovae shock would have even greater influence, inducing star formation out to hun- dreds of parsecs.

4. Triggered Star formation associated with HII regions

Katsuo Ogura (2010) studied star formation regions associated with HII regions. Two well-known mechanisms of triggered star formation linked to HII regions were examined. The first is the collect-and-collapse process, where shells of gas accumulate around expanding HII regions and subse- quently collapse to form stars. The second is radiation-driven implosion (RDI) of bright-rimmed clouds (BRCs), which originate from pre-existing cloud clumps. In his study, Ogura presented recent observations on RDI- induced star formation in BRCs. Additionally, he proposed a third possible triggering mechanism, which involves the formation of elephant trunk-like structures caused by hydrodynamical instabilities at ionization fronts.

VI. CONCLUSION

Massive star formation remains a less understood phenomenon in astro- physics. While the stages of stellar evolution for low-mass stars are well- documented, the formation mechanisms for massive stars are still under in- vestigation. The primary proposed mechanisms include accretion through a disk and stellar coalescence. Massive stars significantly influence their sur- rounding environment, playing a crucial role in the formation of other stars and contributing vast amounts of energy to the interstellar medium (ISM). Understanding massive star formation and its impact on the surrounding en- vironment requires high spatial resolution observations.

REFERENCES

[1]. Bernasconi, P.A., Maeder, A., 1996. About the absence of a proper zero age main sequence for massive stars. Astronomy and Astrophysics, v. 307, p. 829-839 307, 829–839.

[2]. Carroll, B.W., Ostlie, D.A., 2017. An introduction to modern astrophysics.

[3]. Cambridge University Press.

[4]. Chen, W.P., 2010. Star formation influenced by ob stars, in: Interstellar Matter and Star Formation: A Multi-wavelength Perspective, ASI Conference Series, 2010, Vol. 1, pp 11-17 Edited by DK Ojha.

[5]. Garay, G., Lizano, S., 1999. Massive stars: their environment and formation.

[6]. Publications of the Astronomical Society of the Pacific 111, 1049.

[7]. Garay, G., Mardones, D., Brooks, K.J., Videla, L., Contreras, Y., 2007. A multiwavelength study of young massive star forming regions. ii. the dust environment. The Astrophysical Journal 666, 309. Hoare, M., Franco, J., . Massive Star Formation. Springer Netherlands. p. 61–82. URL: http://dx.doi.org/10.1007/978-1-4020-5425-9$_4$, doi : 10.1007/978 − 1 − 4020 − 5425 − 9_4.Kahn, F., 1974.Cocoonsaroundearly − typestars. AstronomyandAstrophysics, vol.37, no.1, Dec.1974, p.149 − 162.37, 149 − −162.

[8]. Larson, R., Starrfield, S., 1971. On the formation of massive stars and the upper limit of stellar masses. Astronomy and Astrophysics, Vol. 13, p. 190-197 13, 190–197.

[9]. Lee, H.T., Chen, W., 2007. Triggered star formation by massive stars. The Astrophysical Journal 657, 884.

[10]. McKee, C.F., Tan, J.C., 2003. The formation of massive stars from turbulent cores. The Astrophysical Journal 585, 850.

[11]. Ogura, K., 2010. Triggered star formation associated with hii regions, in: Interstellar Matter and Star Formation: A Multi-wavelength Perspective, ASI Conference Series, 2010, Vol. 1, pp 19-26 Edited by DK Ojha.