Protostellar Outflows

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Abstract. The formation of massive stars differs from low-mass stars due to their rapid evolution, relatively low abundance, and their burial within molecular clouds, making observations more challenging. Moreover, the mechanisms give rise to the formation of O-type and B-type stars, in particular, differ from those responsible for the formation of low-mass stars. The paper presents an overview of the two main theories that have been proposed to explain the formation of massive stars: accretion and collision theories. The paper also investigates several mainstream theories of protostellar outflows during the massive star formation phase, and describe the model and their simulation of these theories. These results may provide useful references and guidance for future studies on the formation of massive stars.

Keywords: Star Formation, outflows, protostar.

1. Introduction

Since the early 20th century, the formation and evolution of stars have been a subject of great interest for astronomers. The first models of star formation were proposed by eminent astronomers such as James Jeans and Arthur Eddington, who posited that the collapse of interstellar matter under gravitational instability could result in the formation of stars. In the 1960s, researchers employed radio telescopes to observe molecular clouds, which led to the confirmation of the hypothesis that stars form from collapsing molecular clouds. The 1980s saw the development of more sophisticated observational technologies such as infrared and submillimeter telescopes, which enabled the observation of protostars, the nascent stages of star formation. Investigation of protostars has yielded crucial insights into the physical mechanisms governing the process, such as the formation of accretion disks and the influence of magnetic fields. Recent advancements in technology and observational techniques, exemplified by the ALMA, have allowed unprecedented views of star-forming regions, enabling a more comprehensive exploration of the details of the process. These observations have shed light on the impact of turbulence, magnetic fields, and feedback from young stars on their environment [1].

After more than half a century of research on stellar evolution, the mechanisms of star formation have been gradually understood. However, the forming process of massive stars ($M > 10\ M_{\odot}$) remains a mystery due to limited observational data and tiny evolutionary timescales. Previously, it was assumed by researchers that the mechanism of high-mass stars formation was similar to the low-mass stars.

However, in 1965, the Japanese astrophysicist Hayashi put forward the idea that stars of varying mass evolve at varying rates, with more massive stars taking only tens of thousands of years to reach the main sequence, whereas low-mass stars require a longer period of time [2]. In contrast to the research of low-mass stars, the traditional approaches to measuring the dynamical processes involved in massive star formation could be problematic due to the high luminosities. As a result, researchers have put forward various theories to explain the mechanism of massive stars formation, such as accretion and collision theories, but both of them have their limitations.

The process of outflow from massive star formation is a crucial factor that influences the surrounding environment and the formation of subsequent generations of stars. When a massive star forms, it emits intense radiation, which results in a pressure effect on the gas and dust surrounding it, leading to the creation of an outflow of material. These outflows are highly energetic, with observed

kinetic energies ranging from approximately 10^{43}-10^{47} erg [3]. Depending on the orientation of the accretion disk and the strength of the magnetic field, these outflows may take the form of either broad or collimated outflows. Due to the high levels of dust and gas extinction surrounding star-forming regions, the observation of the earliest stages of massive star is challenging. However, outflows provide researchers with a valuable tool for studying this early stage of formation because they can be traced back to the protostellar phase of massive stars.

Additional physics may be involved in the outflows from massive stars compared to low-mass stars. This paper discusses the accretion and collision theory in pre-main-sequence phase and introduce the mechanism and model of outflows. The reminder of the paper is organized as follows. In Section 2, there are two main theories to explain the formation. In Section 3, the description of the massive star outflow and in Section 4, three mainstream theories of protostellar outflow would be discussed. The comparison of those theories is presented in Section 5. Section 6 contains the limitation in the research of massive star origin and future prospect. Conclusion are presented in Section 7.

2. Two mainstream concepts

2.1. Collision Theory

According to the Collision Theory, massive stars are formed via the collision of smaller protostellar cores within a dense molecular cloud. The collision results in a rapid increase in mass and it could trigger the onset of nuclear fusion, which leads to the formation of a massive star. The process begins with the fragmentation of a molecular cloud, which gives rise to smaller protostellar cores. These cores are thought to be gravitationally unstable and collapse to form stars. As the protostellar cores continue to grow, they begin to interact with one another and eventually collide. The collision leads to the formation of a single giant star.

One of the most well-known simulation models, the Smoothed Particle Hydrodynamics (SPH) simulation, has shown that the collision plays an important role in the formation process. In a simulation conducted by Rowan et al. (2009), the author divided the simulation into three regions to obtain a more accurate quantitative description of the clump's evolution. This three-dimensional model was considered more reliable than the two-dimensional model, as it could avoid the enhancement of the additional mass of the clump. Over time, the clump's structure becomes more compact within the region, eventually leading to the collision of clumps and the simultaneous formation of stars, which verifying the collision theory [4].

However, the age of a star-forming region is typically between 10^6 and 10^7 years, and if low-mass stars were to collapse quickly and form a massive star, the core's density would be enormous. According to the simulation by Bonnell et al. (2002), a stellar number density of 10^8 pc^{-3} is required for effective collision and merger to occur in a 1 pc^3 space [5]. Although this theory seems perfect in simulations, there is still a lack of observational data to support it.

2.2. Accretion Theory

Accretion theory is a widely accepted mechanism for explaining the formation of massive stars in the universe. This theory postulates that mass accumulates in the central region of a collapsing cloud core, which eventually forms a protostar, and that accretion continues onto the protostar as it grows in mass. However, the radiation pressure may counteract the gravitational force and impede the accretion of matter. As a solution, researchers have proposed that gas outflow from the polar region could form a cavity, which is cleared out by a combination of radiation and the stellar wind. This process serves to mitigate the impact of radiation pressure and modify the geometry of the cavity. According to the study by H. Bondi (1951), the pressure effects could be neglected. The rate of accretion is represented by equation 1:

$$\frac{dM}{dt} = 2\pi\alpha(GM)^2V^{-3}\rho_\infty. \quad (1)$$

Where M is the mass of the star, thus dM/dt is the rate of accretion. α and G are constant. V is the relative velocity between the star and the interstellar medium. ρ_∞ is the density of the medium. Although the BHL equation has been shown to be a good approximation in many cases and is widely used in simulations of accretion onto protostars, it does not take into account the effects of magnetic fields, which could be significant in situations where the magnetic field is strong [6].

However, the theory did not consider the mass carried out by the jet of polar direction. What is more, according to the research of material outflows and jets [7], the relationship between outflow and accretion is still unclear which might challenge the accretion theory.

3. Outflow

It is widely believed that the outflow from massive stars is often driven by stellar winds emanating from the inner regions of accretion disks. There are several models for driving these outflows: Magnetohydrodynamics (MHD) jet model, bow shock model and stellar-wind model. Those models would be discussed in section 4.

The energetic and collimated outflow from the star has strong feedback effects on the protostar. The feedback has two distinct impacts on star formation. Firstly, the outflow carries away excess angular momentum from the accretion disk and strong radiation pressure from the original star, allowing material to continuously fall onto the surface of the original star which promoting the formation rate of the central star. On the other hand, the outflow also carries away a large amount of material from the central star, injecting a lot of kinetic energy into the parent molecular cloud, making the environment for star formation unstable and inhibiting the growth of the star.

Observational data indicates that all stars go through a highly energetic outflow phase. These outflows often exhibit collimation, with the most prominent instances being the cold molecular gas bipolar flows and narrow optical jets of massive stars. Nonetheless, a study by Arce et al. (2007) found no highly collimated outflows in regions of massive star formation beyond 10^5 $L_\odot$ (which is approximately equivalent to 25 $M_\odot$) [8]. This indicate that the formation of high-mass stars differs from low-mass star formation significantly and is not a mere upscaling of the latter. It is believed that the polar regions that house the stellar material and magnetic fields are cleared by the influence of intense stellar wind and radiation so the collimation of molecular outflows is negatively impacted which may support the MHD model [9]. The MHD model of outflow would be discussed in section 4. Zinnecker indicates that maybe the outflow from AFGL 2591 is influenced by the radiation. The AFGL 2591 is represented in Fig. 1.



Figure 1. The massive outflow in the vicinity of AFGL 2591 was examined using the Near InfraRed Imager (NIRI) at the Gemini North telescope. The imaging results revealed the presence of poorly collimated flows, loops, and cavities, which emanate from a central 20 $M_{\odot}$ star. The nebulosity that has been observed is believed to be a result of the scattering of light and is indicative of gas that has been excited by shock. It is likely that the counterflow, which is possibly obscured by a circumstellar disk with a high density, is deeply embedded. Both the flow and counterflow extend up to a distance of around 0.2 pc from the central source, indicating that the outflow is intrinsically bipolar. Original data from Zinnecker.

4. Mechanism of outflow

4.1. Magnetohydrodynamics (MHD) Jet model

Magnetohydrodynamics (MHD) is a theoretical framework that describes the dynamics of a plasma, a gas composed of charged particles, in the presence of a magnetic field which are commonly used in the research of young stellar objects (YSOs). The magnetic field of a massive star could drive the formation of an outflow, and the material in the outflow is subjected to magnetic constraints and heating, producing strong radiation and fluid dynamics effects.

In an MHD jet model, the magnetic field plays a crucial role in launching, collimating, and accelerating the outflow. The outflow is assumed to be ionized and have a low resistivity so that it could be treated as a fluid that responds to the magnetic field. According to the simulation by C. Zanni et al (2007), the resistivity has a significant effect on the jet acceleration process. In the case of low resistivity, magnetic field lines efficiently extract energy from the disk and transfer it to the jet, resulting in a highly collimated and energetic jet. In contrast, high resistivity leads to tangled and disordered magnetic field lines that reduce the efficiency of energy extraction, resulting in a weaker and more diffuse jet [10]. In addition, the jet is typically assumed to be axisymmetric, with the magnetic field and plasma velocity aligned along the axis.

The MHD equations governing the plasma dynamics include the conservation of mass, momentum, and energy, as well as the induction equation, which describes how the magnetic field evolves. The equations could be solved numerically to obtain a self-consistent model of the jet. The MHD algorithms is represented by equation 2 to equation 5:

$$\frac{D\rho}{Dt} + \rho\nabla \cdot v = 0, \tag{2}$$

$$\rho\frac{Dv}{Dt} = -\nabla p + (\nabla \times B \times B)/4\pi, \tag{3}$$

$$\rho \frac{D}{Dt}\frac{e}{\rho} = -p\nabla \cdot v - \Lambda + H, \tag{4}$$

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B). \tag{5}$$

Equations (2) ~ (5) describe the dynamical evolution of a nonrelativistic magnetized jet. In mathematical terms, Equation (2) expresses the principle of mass conservation, whereas equations (3) and (4) describe the principles of momentum and energy conservation, respectively. Equation (5) represents the evolution of the magnetic field. In these equations, the convective derivative "D/Dt" represents the rate of change of a quantity as it moves with the fluid [11].

In addition, James M. Stone et al (2000) conducted a simulation to investigate the behavior of a jet. Their findings revealed that strong cooling at the front of the jet results in most of the shocked gas accumulating in a dense shell located in front of the mach disk. Once the jet has propagated a distance of approximately 20 R_j, it begins to expand due to the absence of magneto hydrostatic balance. This expansion leads to the head of the jet becoming filamentary and growing laterally. The simulation results also depicted the detailed structures at the head of the jet, as shown in Figure 2. The figure displayed the temperature, velocity divergence, and velocity vectors at the end of the simulation.

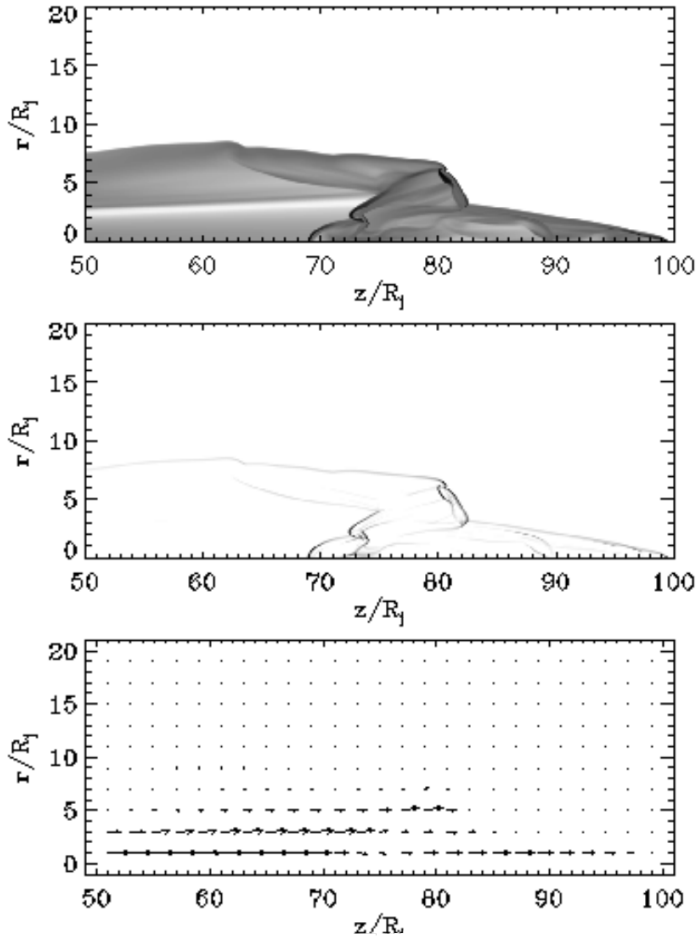


Figure 2. Detailed structures at the head of the jet. Logarithm of the temperature is on the top panel, the divergence of velocity is on the middle panel, and the velocity vectors is on the bottom panel. Original data from James M. Stone [11].

MHD jet models could explain a variety of observed phenomena, such as the collimation of outflow, the formation of shocks and knots, and the production of emission lines. They also predict observable quantities such as the jet velocity, density, and magnetic field strength, which could be compared to observations to test the validity of the model.

4.2. Bow Shock model

Bow shocks are formed when the outflowing material interacts with the surrounding medium. In the case of stellar outflows, the bow shock model proposes that the outflowing material creates a region of energetic, compressed plasma as it collides with the surrounding interstellar medium. This region of compressed plasma then produces a shock wave that propagates upstream and forms a characteristic bow-shaped structure. This bow shock acts as a barrier, preventing the material from escaping perpendicular to the jet axis, and instead, directing it along the jet direction. This results in a highly collimated outflow that is accelerated to high velocities.

Raga et al. (1993) and Masson et al. (1993) both concluded that the bow shock model is a plausible explanation for the formation of molecular outflows from young stars, and that it could explain many of the observed properties of these outflows. Raga analyzed high-resolution images of molecular outflows and found that they often have a bow shock shape, which could be explained by the interaction of the jet with the surrounding gas [12]. What is more, Masson analyzed a sample of molecular outflows and found that their properties are consistent with the predictions of the bow shock model [13].

Observational studies have supported the bow shock model by identifying the key features predicted by the model in molecular outflows from young stars. These features include the highly collimated structure of the outflows, the high velocities of the material and the presence of a low-velocity component that is likely driven by a wide-angle wind from the central star. The simulation by Eve C. Ostriker et al. (2001) reveal that the effects of various parameters, such as jet velocity and density, influence the shape and size of the shell depend strongly on these parameters, and the presence of a magnetic field could also affect the structure of the shell. The physical characteristics of a bow shock would be represented by equation 6:

$$\frac{width}{length} = 0.012 \left(\frac{t}{10^4\ yr}\right)^{-2/3} \left(\frac{\beta c_s}{32\ km\ s^{-1}}\right)^{1/3} \left(\frac{R_j}{100\ AU}\right)^{2/3} \left(\frac{v_s}{100\ km\ s^{-1}}\right)^{-1}. \quad (6)$$

Where R_j is the radius of working surface, the isothermal sound speed at the initial temperature of the outflow is defined by c_s and v_s is the velocity of shock [14].

In addition, the bow shock model has also been used to explain a number of other phenomena associated with young stars, such as the formation of jets themselves and the creation of Herbig-Haro objects (HH objects) which are small, bright knots of material that are found along the axis of molecular outflows and caused by shocks in the material as it collides with the surrounding gas. According to the bow shock model, the origin of these shocks could be attributed to the interaction of the jet with the surrounding cloud, and the HH objects are a creature of the formation of the molecular outflow.

4.3. Stellar Wind model

The stellar wind model proposes that a massive star generates a stellar wind during its evolution, due to the high temperature and pressure on its surface, which could carry away the surrounding material and form an outflow. The model suggests that the stellar wind has a large transverse momentum compared to the transverse pressure in the shock wave shell surrounding the star.

As a result, the stellar wind transfers its transverse momentum to the surrounding gas and sweeps out a large shell-like structure. This process is similar to a snowplow, where the stellar wind acts as a "snowplow" and the surrounding gas is "swept" away to form a broad outflow [15]. Li et al. (1996) and Matzner et al. (1999) indicated that the accretion disk generates the stellar wind has a density stratification, with density decreasing as the radius increases. They suggested that this density stratification could explain the observed properties of broad outflows, such as their size and morphology [16] [17].

According to a study conducted by John Bally (2016), two models could be used to explain the mechanisms underlying outflows. One is the X-wind model. The X-wind model describe the

magnetohydrodynamic (MHD) winds that are launched centrifugally from open field lines that form a part of a stellar magnetosphere. Moreover, the disk-wind model could also explain the mechanisms underlying outflows which describes the open field lines which crossing the accretion disk.

The X-wind model is a type of broad-angle stellar wind model that proposes that the magnetic fields observed in some young stars could drive a broad-angle stellar wind that would sweep out a shell-like structure. On the other hand, the disk-wind model proposes that the outflows are driven by the accretion disk around the central region rather than by a broad-angle stellar wind. In this model, the accretion disk generates a wind that is collimated by the magnetic fields and flows along the rotation axis of the disk [18]. Both models are types of broad-angle stellar wind models because they propose that the outflows are driven by a large-scale wind rather than by local processes. The broad-angle stellar wind model is a more general term that encompasses both models.

5. Comparison

Magnetohydrodynamics (MHD) jet model, bow shock model, and the stellar wind model are three different models used to explain the outflows from young stars. These models have been developed based on observations and theoretical calculations, and each model has its advantages and disadvantages.

One of the advantages of the MHD jet model is that it could explain the collimated morphology and the high velocities observed in some outflows by analyzing observational data. A study by Bally (2007) shows that the HH 30 jet, which is one of the best-studied MHD jets, has a well-defined collimated structure and a velocity of around 400 km/s. However, the MHD jet model does not explain the wide-angle outflows that are observed in some case. On the other hand, the bow shock model could explain the structure of jets and account for variations in jet properties. For example, the L1551-IRS5 outflow has a collimated jet that is well-explained by the model. However, the bow shock model could not explain the wide-angle outflows in most of the case too [19]. In addition, the stellar wind model could explain the wide-angle outflows that are observed in some sources. The numerical simulation results of the wide-angle star-driven model are in good agreement with the observations of large-scale and aged outflows.

These models are not mutually exclusive and are likely to interact to form the complex structure of outflows from massive stars. To better understand the mechanism of the formation, a combination of multiple model and observational techniques is needed.

6. Limitations & Prospect

The research is still subject to certain limitations, including the scarcity of high-resolution data which could accurately depict the dynamic processes taking place in the dense central regions of such stars. Moreover, given the relatively small number of massive stars in the universe and their comparatively short lifespan, observing them is a difficult task. Unlike intermediate-mass stars, new-born massive stars tend to lose their accretion disks quickly, making them even harder to detect. Furthermore, the application of the Jeans Criterion, which stipulates that massive star formation is unlikely to occur in dense regions, adds another layer of complexity to the study of massive star formation. According to the theory, jeans mass is represented by equation 7:

$$M_J \equiv \frac{\pi}{6}\rho\lambda_j^3 = \frac{\pi}{6}v_s^3\sqrt{\frac{\pi^3}{G^3\rho}} \cong 1.2\times10^5 M_\odot \left(\frac{T}{100K}\right)^{3/2}\left(\frac{\rho}{10^{-24}g\ cm^{-3}}\right)^{-1/2}\mu^{-3/2} \quad (7)$$

Where M_J is jeans mass, ρ is the density of the cloud and T is the temperature. The core of molecular cloud collapse depends on whether $M>M_J$. However, M_J and ρ are inversely correlated which means that in the dense region, M_J is extremely light. Making low-mass star easy to form. The fundamental theory and common sense suggest that massive stars form in dense regions, but this is

contradictory. One possible explanation is that in the beginning, several low-mass stars may form near the center of the nebula. These stars would then heat up the surrounding area and increase the temperature, causing the Jeans mass to increase as well. However, there is currently no evidence of these small stars existing, and astrophysicists require additional observational data.

According to the research by C. Goddi et al. (2005), the results of multi-epoch observational data of water masers and continuum emission towards the AFGL 5142 (which is a star-forming region) using the VLBA and VLA telescopes reveal that the collimated outflow and the clump of dense cloud around the young stellar object (YSOs) could be traced by the water maser emission. The VLBA provided improved high-resolution data, resulting in the detection of more maser outflow features and their proper motions which give support to the models of accretion [20].

7. Conclusion

In this paper, the outflow of star formation and its models, including the magnetohydrodynamics (MHD) jet model, bow shock model, and stellar wind model, were investigated. Each model has its advantages and limitations, and interactions between models may be necessary to form the complex structure of outflows from massive stars. The formation of massive stars is not simply a scaled-up version of the formation of low-mass stars, so their mechanisms of formation and outflows need to be discussed independently. The collision and accretion theories proposed in this paper suggest that both methods may be necessary in some cases, despite they have limitations. The research is still slow because of their tiny time-scale and difficulty of observation, with a lack of high-resolution data still being a problem for astrophysicists. However, some methods such as water maser emission from outflow and extended green object could be used to research the dynamics of central protostars. In summary, the outflow simulations and discussion of the three mainstream models provide a guideline for further exploration of the theory of star formation.

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