Comparison the Massive Star Formation Theorem of Collision and Accretion

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Abstract. Massive star ($M \geq 10\ M_\odot$) is so luminous that the radiation pressure has negative effects to the formation itself. There are several mainstream theories could explain how massive star form in this particular surrounding. The collision theory and accretion would be discussed in this paper. Compared to the collision case, star is more likely to form massive by the accretion process. The simulation of collision case seems to work well. However, there is no evidence that astrophysicists have been found in the observation that supports this theory. The paper summarizes the simulation of two mainstream theories and the limitation for the research of high-mass star formation. The paper also proposes a possible method by analyzing the geometry of Wolf-Rayet star. With the development of models of gas distribution, hydrodynamical and mathematics work, it is necessary to calculate the gas structure in order to speculate the history of protostar in the center. These results could also provide reference and guidance for investigation of star formation.

Keywords: Star formation; radiation; stellar accretion; protostar.

1. Introduction

Before the telescope were invented, scholars show great interest in the distribution of star to understand the universe. In twenty centuries, the research of star is promoted by the Einstein's mass-energy relation. Astrophysicists tend to understand the evolution of star. The evolution of massive star is valuable to research because it will have types Ib or Ic supernovas. It might form to a stellar black hole and some massive star has strong stellar winds which lose several times the mass of the sun every year. The foundation of galaxy-sed-fitting is based on the star formation history. The research of star formation is also significant to improve the cosmological models. For some high redshift galaxy, it could help to predict and find out first generation star which is massive but be short-lived.

Star is origin from the area where stellar matter is relatively concentrated. Gravitational influence would dominate and cause the nebula collapse into a denser area if mass and gravity is available which may be triggered by close supernova or galaxy dynamic effect. For an intermediate mass star, its formation is typical: the block mass which is separated from a nebula has a temperature less than 2000K and a diameter of about 500 million $R_\odot$. There is no energy accumulation in the core and the temperature rises slowly because of scattered core. When the stellar matter shrinks to $1000 R_\odot$ [1], the temperature rises faster and the rate of shrinkage is gradually slowed down by thermal pressure. However, even if radiation in the central area is strong, for a solar-mass star, it could not resist the gravitational effect of falling matter. Eventually, a newborn star is created.

However, in 1965, a Japan astrophysicist Hayashi indicated that stars of different mass evolve at different rate. Massive star could only spend tens of thousands of years to reach main sequence, while low-mass star takes more time [2]. Unlike the research of Low-mass star, the traditional method might be problematic to measure the dynamical process of massive star formation because of large luminosities. That is to say, the core of the protostar, before the process of main sequence, has high radiational pressure which is origin from the gravitational potential energy released by shrinkage process. When star reaching a mass of $10\ M_\odot$ and a few $10^3\ L_\odot$, the radiation barrier is so strong that limiting the falling of surrounding gas (stellar material) [3].

As a result, there are several kinds of theories to explain how they form. One is collision theory. Before the massive star form, there are numbers of low-mass star cluster orbit around the protostar. They orbit in the accretion disk, closer with each other and tend to collide which improve the formation of central star (to resist the negative influence) [4]. Another is accretion theory. Star formed by accretion process through a circumstellar disk. A large number of photons could be released from protostar's polar side which reduce the radiation pressure in the center [5]. Beside the reduction of dust opacity also help to form a massive star. This makes sure the star could grow larger than standard theoretical limitation.

In order to understand how the stellar formation avoids the problem of radiational influence, this paper discusses the theory and simulation of accretion and collision case in pre-main-sequence phase. The reminder of the paper is organized as follows. In Section 2, there are 2 main theories to explain why do not radiation effects influence the star formation. In Section 3, the observational analyze for collision theory and in Section 4, the observational analyze for accretion theory would be discussed. The comparison of two theory 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

There are two cases of gas and star that need to be discussed: collision and accretion.

2.1. Collision

Although the radiation pressure halts the process of material accretion, collision of young star and gas have positive effects to star formation. Pre-main-sequence phase are always found in the central regions of an area which is full of stellar material. Because of the dense region, there are several low-mass stars have already form through the collapse of the core of molecular cloud. Cluster formation occurs simultaneously with massive star formation. The falling of newborn star and gas would contribute the formation. Once the core form enough to expel the remaining gas, the collision would be halted. There is no doubt that the condition of stellar merger is that the collision time must be shorter than the timescale of central star formation. The collision time is depending on the stellar velocity dispersion, v_{rms}, the stellar density, n_{star}, the cross section σ_{grav} and the radius at which mergers occur, R_{min}. The stellar collision time per star is represented by equation 1:

$$\tau_{coll} = \frac{1}{n_{star}\sigma_{grav}v_{rms}} = \left[4\sqrt{\pi}n_{star}v_{rms}(R_{min})^2\left(1+\frac{2GM_*}{R_{min}V_{rms}^2}\right)\right]^{-1} \tag{1}$$

Which is based on the collision of equal mass object. In addition, the equation has been extended in recent year to include the case of nonequal mass collision. It is a good way to calculate and compare the collision time and the initial cluster crossing time in order to compare the process of collision and accretion [4]. The comparison would be discussed in Section 5.

2.2. Accretion

Apparently, the accretion luminosity will be larger with the higher mass of the protostar. The accretion luminosity is represented in equation 2:

$$L_{acc} = \eta G M_* \dot{M}/R_* \tag{2}$$

Where the η is the fraction of the accretion energy radiated, $\dot{M}$ is the mass accretion rate, M_* and R_* is the mass and radius of protostar. The equation 2 shows that the accretion luminosity is sensitive to the mass of protostar [6]. For the massive star, high accretion luminosity means high radiation pressure. However, the radiation pressure does not halt matter accretion because gas outflow from polar side creates a polar cavity which is evacuated by the incorporation of radiation and the stellar wind in order to reduce the effects of radiation pressure and change its geometry. According to the Keto's research, the motion of H66α recombination line indicated that the pressure of accretion flow has a negative impact on the bubbling HII region so that it allows the protostar continue to grow [7]. The radiative acceleration of dusty also leads to radiation-driven bipolar winds, and ionizing radiation could escape through the wind-blown cavities [5]. Furthermore, the decreasing of dust opacity could also reduce the effects of radiation pressure. Surrounding gas could be repelled from the protostar if opacity is too high. As a matter of fact, the ratio of the force of radiation and gravitation is in direct proportion to the opacity.

3. Simulation of collision theory

A SPH (smoothed particle hydrodynamics) simulation proposed by Rowan J. Smith indicates that the collision would dominate in the process of formation. It contains a 10^4 $M_\odot$ cylindrical cloud with a radius of 3 pc and a length of 10 pc which is consist of 15.5 million SPH particles. A barotropic equation of state designed in order to mimic a cooling evolution and is represented in Equation 3.

$$P = k\rho\gamma \tag{3}$$

Where $\gamma = 0.75$ when $\rho \leq \rho_1$; $\gamma = 1.0$ when $\rho_1 \leq \rho \leq \rho_2$, $\gamma = 1.4$ when $\rho_2 \leq \rho \leq \rho_3$; $\gamma = 1.0$ when $\rho > \rho_3$, Besides, in this simulation, $\rho_1 = 5.5 \times 10^{-19}$g cm^{-3}, $\rho_2 = 5.5 \times 10^{-15}$g cm^{-3} and $\rho_3 = 2\times10^{-13}$g cm^{-3}. At densities above ρ_3, sink particles are used to model star formation provided the region is bound and collapsing [8]. During the simulation, the author considers three region and name these cluster Alpha, Beta and Gamma. Compared to the two-dimensional model, three-dimensional model could be more reliable to describe the evolution of the clumps more quantitatively and avoid enhancive additional mass of clump.

Clump Alpha and clump Gamma are 3.4 times and 1.8 times over-bound, clump Beta appears unbound. The clump Beta tend to collapse during the simulation because of the largely gas velocities. The evolution of the center of clumps is represented in Fig. 1. The top row shows the central region of clump Alpha at 0.75, 1 and 1.25 dynamical times (which equals to the 470,000 years). The filamentary geometry of clump Alpha make it collapse into a compact object. The bottom row shows the central region of clump Beta and Gamma, which formed by several shock fronts intersecting. Over time, the structure of clump becomes more compact in the region. Eventually, they collide with each other and form simultaneously as the stars are formed which verify the collision theory.

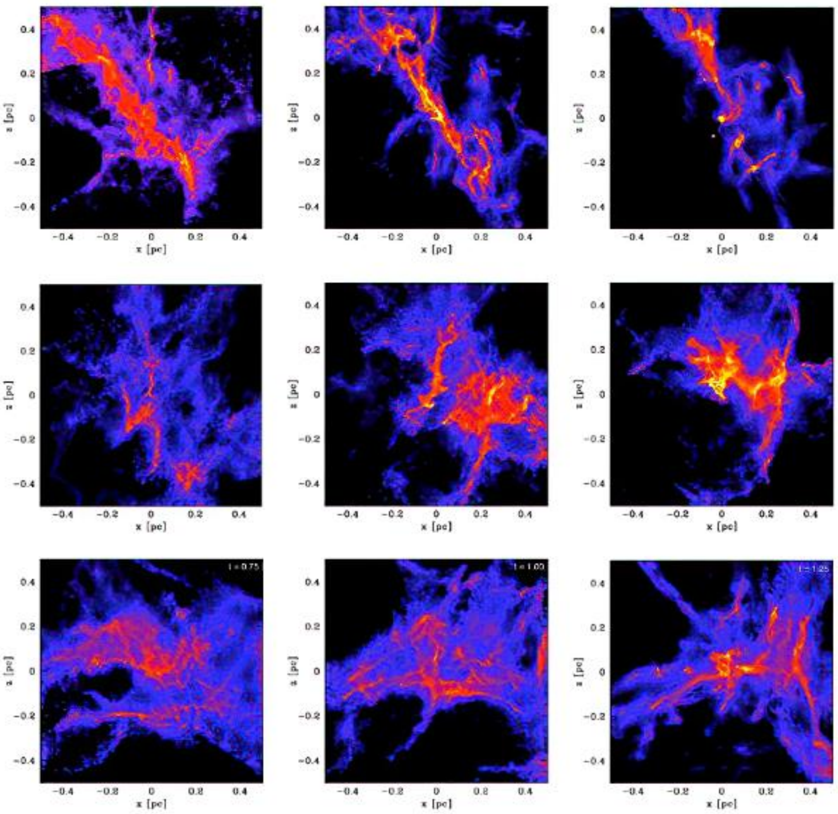

Fig. 1 The clump of Alpha, Beta and Gamma in the SPH simulation. The yellow region in the center is the place where star formation occurring. It has a column density above 1 g·cm^{-2}.

4. Simulation of accretion theory

A two-dimensional model to simulate a protostar could only accreted less than 40 $M_{\odot}$. Three-dimensional radiation-hydrodynamic simulations to research the formation of massive star ($M \geq 20\ M_{\odot}$) is necessary. It contains a primary nebula which has an initial mass of 100 $M_{\odot}$, a radius of 0.1pc and a temperate of 20 K. This simulation passes through several difference stages: A central protostar is formed 3,600 years after the gas collapse. During the process, an accretion disk is formed and the protostar grow bigger and heavier. After almost 25,000 years, the radiation pressure force is large enough to compete with the gravity. So, gas began to gather and stuck on the wall of a thin bubble but it does not halt accretion in the simulation as the gas moves along the edge of center and then continue to accrete onto the protostar.

The explanation is that although accretion disk beam radiation to the direction of polar, it does not reduce the angular momentum of gas and thus it could still fall into the center. Around 35,000 years, a secondary star which accreting enough material formed in the accretion disk and orbit around the primary protostar. The accretion disk tends to fragment with slow rate. Moreover, a third star would born in the accretion disk but eventually be accreted and destroyed by protostar. There is always a binary system during the formation of massive star. The process of simulation is presented in Fig. 2 (A→E). Eventually, the mass of two orbiting star is 32.4 $M_{\odot}$ and 46.9 $M_{\odot}$ (standard simulation predicts that $M \geq 10\ M_{\odot}$ is unavailable), the mass of accretion disk is 4.0 to 5.7 $M_{\odot}$ and 4.5 to 9.1 $M_{\odot}$ [9]. Subsequently, halting the simulation because of the constant infalling rate of process. The flowing of radiation has not influenced the angular momentum. Thus, during the simulation, the efficiency of star formation is not influenced by radiation. The cavities tend to change the geometry of the radiation pressure bubbles or prevent them from forming together. According to the research of compact cluster (e.g., NGC1333 [10]), gas outflows tend to maintain turbulence. Thereby, it limits the collapse rate and the formation rate while the formation would not be halted.

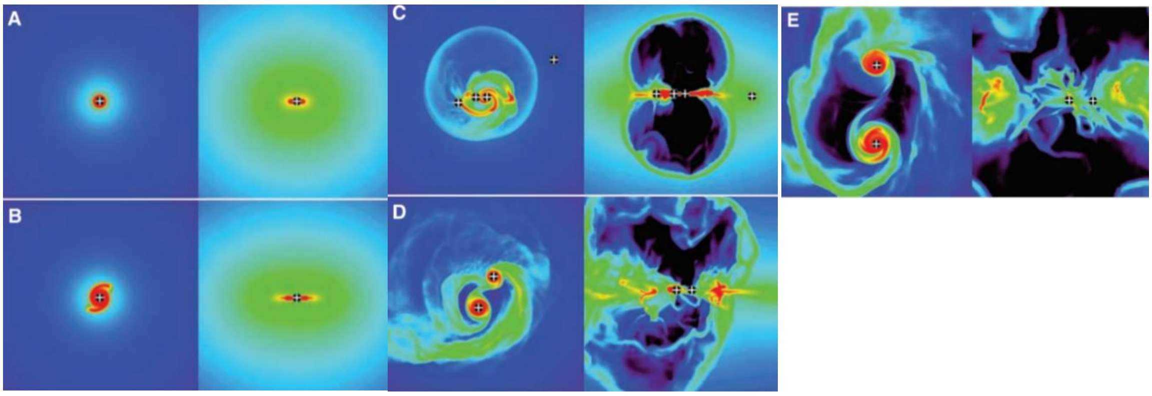

Fig. 2 Simulation snapshots. A: 17500 years, B: 25000 years, C: 34000 years, D: 41700 years, E: 55900 years. The first column on the left shows the column density which is vertical to the rotation axis. The right column shows the volume density along the rotation axis.

5. Comparison

In collision theory, although it seems perfect in simulation, there are still lack of observational data to support it. What is more, due to the observation, the age of star-forming area is usually 10^6~10^7 years. If low-mass star collapse with each other and form to a massive star in a short time, the density of core would be tremendous: almost 10^6 young stars per cubic light year [11]. However, during the calculation of accretion time and crossing time of material, the collision would become dominant to increase the mass of central star. That is: a simulation of the crossing and accretion timescales for a cluster with an initial radius of 0.1 pc which contains 100 stars is represented in Fig. 3 [4]. It should be noted that the timescale of collision is tend to decrease and eventually smaller than the timescale of accretion. As a result, the collision become dominant compare to the accretion process.

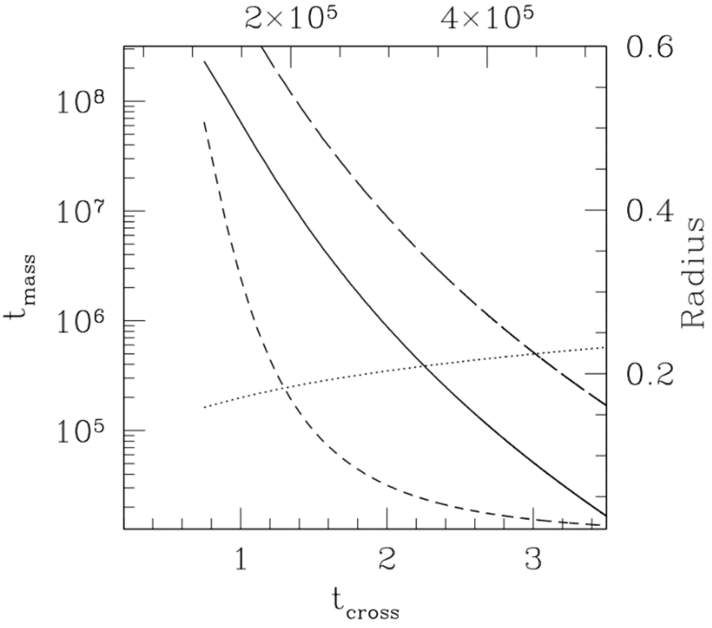

Fig. 3 the crossing and accretion timescales for a cluster with an initial radius of 0.1 pc which contains 100 stars. The timescale for doubling the mass of the star by collision (solid and long dashed lines) or by accretion (dotted line) is plotted versus time in units of the initial crossing time, $t_{cross} = 1.5\times10^5$ years.

In accretion theory, it also has a problem that the theory did not consider the mass carried out by the jet of polar direction. In addition, according to the research of material outflows and jets [12], the relationship between outflow and accretion is still unclear which might challenge the accretion theory.

Recently, more and more observational data indicated that the outflows of massive star is larger than the outflows in the area of the low-mass star formation. It seems like that massive star have the same mechanism as low-mass stars, but it is hard to prove the relation between outflows and massive star formation. This is crucial to the reliability of accretion theory. However, the observational data such as infrared radiation from the ejection and optically light is tremendous. Those observational work also progress the accretion theory.

6. Limitations & Prospect

There are still some limitations in the research of massive star formation: the lacking of high resolution data. It is hard to observe the dynamic process in the dense center of stellar matter. The number of massive stars is tiny in the universe and its short life make observational work more difficult. Unlike the intermediate-mass, the accretion disk (form in protostellar phase) would disappear rapidly when people find a new-born massive star. In addition, Jeans Creterion seem to forbid massive star form in a dense area. According to the theory, jeans mass is represented by equation 4:

$$M_J \equiv \frac{\pi}{6}\rho\lambda_J^3 = \frac{\pi}{6}v_s^3\sqrt{\frac{\pi^3}{G^3\rho}} \cong 1.2\times 10^5 M_\odot \left(\frac{T}{100K}\right)^{3/2}\left(\frac{\rho}{10^{-24}g\ cm^{-3}}\right)^{-1/2}\mu^{-3/2} \qquad (4)$$

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. Thus, the fundamental theory and common sense (massive star form in dense region) is contradictory. A possible explanation is that it might form several low-mass stars near the nebula center in the beginning. They start to heat the surrounding and increase the temperature which make the jeans mass increased too. However, there is no evidence about those tiny stars exist. Astrophysicists still need more observational data.

Although the lacking data prevent the progress of astrophysics, scientists still have method to research the stellar origin of massive star. It is a good way to observe and analyze the structure of Wolf-Rayet star in order to calculate the dynamic process before the main-sequence phase. Owing to the clearly structure in the interstellar, infrared image is valuable to research, optical light could also see the layer of Wolf-Rayet star. The different filter of optical image in Fig. 4 shows the dust distribution of WR-136. OIII narrow-band emission shows a faint structure around the nebula which was formed by the stellar wind after the period of red supergiant. H-alpha narrow-band emission shows a filamentary and clumpy structure. In the future, with the development of models of gas distribution, hydrodynamical and mathematics work might help to understand the origin of WR star formation [13]. Moreover, it still needs to build larger telescope. A large telescope could not only collect photon as much as possible, it could focus those photons into a high-resolution image which is valuable for astrophysics.

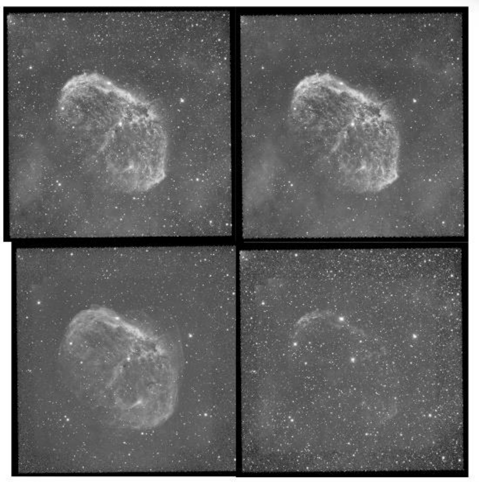

Fig. 4 The structure of WR- 136. The top left panel shows the combination of 3 narrow-band emission. The top right panel photographed by Hα filter. The bottom left photographed by OIII filter and the bottom right photographed by SII filter. All of them located in optical light. Original data from Telescopelive.

7. Conclusion

In conclusion, the paper investigated collision theory and accretion theory in star formation and both have their advantages and disadvantages. It seems like that the accretion theory is more reliable because of confirmed evidence. The formation process in the central area is complicated so that it is necessary to use both methods in some case. The research of the formation of massive star still stagnant and slow because new born massive star is hard to observe and its life span is short. Astrophysicists tend to use simulation to predict the process in dense core. Nevertheless, those simulations still have problem: some of them still fail to distinguish the evolution case in the innermost region of protostar. Besides, they tend to ignore the mass of outflows to explain how star form massive. In the future, high resolution data from new observatory might help to address those problems and improve two mainstream theories. The summary of simulation and the comparison of the results offer a guideline for further exploration of the theorem of star formation.

References

[1] Su Yi. Introduction to Astronomy (the 4th version). Science Press (Chinese), 2009.

[2] Xiang Shouping. Introduction to Astrophysics. University of Science and Technology Press, 2008.

[3] Motte F, Bontemps S, Louvet F. High-mass star and massive cluster formation in the Milky Way. Annual Review of Astronomy and Astrophysics, 2018, 56: 41-82.

[4] Bonnell I A, Bate M R, Zinnecker H. On the formation of massive stars. Monthly Notices of the Royal Astronomical Society, 1998, 298(1): 93-102.

[5] Zinnecker H, Yorke H W. Toward understanding massive star formation. Annu. Rev. Astron. Astrophys., 2007, 45: 481-563.

[6] Hartmann L, Herczeg G, Calvet N. Accretion onto pre-main-sequence stars. Annual Review of Astronomy and Astrophysics, 2016, 54: 135-180.

[7] Keto E, Wood K. Observations on the formation of massive stars by accretion. The Astrophysical Journal, 2006, 637(2): 850.

[8] Smith R J, Longmore S, Bonnell I. The simultaneous formation of massive stars and stellar clusters. Monthly Notices of the Royal Astronomical Society, 2009, 400(4): 1775-1784.

[9] Krumholz M R, Klein R I, McKee C F, et al. The formation of massive star systems by accretion. Science, 2009, 323(5915): 754-757.

[10] Bally J. Protostellar outflows. Annual Review of Astronomy and Astrophysics, 2016, 54: 491-528.

[11] Jiang Y, Yang Q. Massive star formation: theory and observations. Physics (Chinese), 2006, 35(7):5.

[12] Cesaroni R, Felli M, Churchwell E, et al. Massive star birth: A crossroads of Astrophysics. Massive Star Birth: A Crossroads of Astrophysics, 2005, 227.

[13] Rubio G, Toalá J A, Jiménez-Hernández P, et al. Unveiling the stellar origin of the Wolf–Rayet nebula NGC 6888 through infrared observations. Monthly Notices of the Royal Astronomical Society, 2020, 499(1): 415-427.