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Evolution of Stars in Binary Systems: A Review

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ABSTRACT

In this report, I discuss binary star evolution and how this field of research has been developing in the last few decades. I summarize three theories for how multiple star systems form during the pre-main sequence phase of evolution (including two different types of fragmentation). I describe how stars evolving in multiple star systems follow different evolutionary tracks than single stars during the main sequence, with one major factor contributing to this difference is mass loss. I discuss some of the open questions the field has and the limitations that prevent progress. I conclude with what must be done to expand the frontier of our knowledge in binary star evolution.

Keywords: stars, binary sytems, stellar evolution

1. INTRODUCTION

Binary and multiple star evolution concerns the lives of two or more stars that are gravitationally bound, with separations within 0.1 parsecs. We have a clear theory for how single stars evolve, from fragmentation and collapse of proto-stellar clouds to post-main sequence life. However, binary star evolution is still a developing field; it is more difficult to model binary stars using computer simulations because such models should be three-dimensional to track factors like mass transfer and because as the number of stars in the system increases, so does the parameter space.

Historically, binary and multiple star systems and their effect on stellar evolution were not extensively studied, but this changed in the early 21st century as observations of stellar emission lines were not able to be explained by single star evolution models. Further studies showed that most stars were in multiple star systems, especially massive stars; as Figure 1 from Offner et al. (2023) shows, as primary mass increases, so does the multiplicity fraction, which is defined as

$$MF = \frac{B + T + Q + ...}{S + B + T + Q + ...}$$

S, B, T, Q are defined as the number of single stars, binary systems, triple systems, and quadruple systems respectively. About 40-50% of solar-mass stars have at least one companion, while about 95% of O-type stars have a companion. Considering these statistics, studying only single stars will not provide an accurate representation of the mechanics of stellar formation and evolution in the universe.

Studying binary stars is not only important for understanding phenomena that cannot be explained by single stars, but is also important for understanding exoplanet formation. Observations have shown that many main sequence stars have planets orbiting them, and planets in circumbinary orbits (orbiting both stars in the system) have been detected. As Offner et al. (2023) discusses, multiplicity (the number of stars in a system) has a strong influence with planet formation, affecting the raw material used for planets and the initial orbits of the planets. Understanding how binary stars form will assist in developing theories for exoplanet formation, which as implications in other fields of astronomy like astrobiology.

The rest of the review begins with a discussion of the state of the field: how did research into binary systems start and what were the initial challenges. Then, I continue with an explanation of the three main theories for multiple star formation, different types of mass transfer between binary stars, and how that may affect post-main sequence life. I conclude with open questions researchers have, why it is important to study binary systems, and what must be done in terms of theory (evolution simulations) and data (observatories) to further our understanding.

2. DISCUSSION

2.1. *The State of the Field*

In the past, binary and multiple star systems were not considered to be major factors in how massive star populations evolved. This began to change in the early 21st century, as shown when a paper, Shapley et al. (2003), observed stellar emission lines that could not be explained by single star stellar models (Eldridge &

Stanway 2022). Further studies with binary star evolution simulations explain the results of the Shapley paper. The idea that binary systems affected how massive stars evolved became more and more prevalent as observations showed that most massive stars formed and stayed on the main sequence with at least one other companion.

Studying the evolution of binary stars has historically had many challenges, both observationally and theoretically. For example, star-forming regions were difficult to study because high-resolution radio observations were needed to penetrate the dust in the region, and theoretical models needed to consider many complex factors, like mass transfer, turbulence, rotation, and magnetic fields (Offner et al. 2023). Now, with observatories like the Very Large Array and the Atacama Large Millimeter/submillimeter Array, and with new advancements in computational power, more observations and complex simulations can be carried out to further our understanding.

There are multiple theories for the pre-main sequence portion for a binary system's life. The mechanism for the formation of single stars is fragmentation: a perturbation causes a portion of a cloud of gas to collapse under its own gravity, and as regions within the cloud exceed Jeans mass, the regions start collapsing as well, eventually forming protostars. In simple single star models, fragmentation is an isothermal process that only involves gravity and pressure, but these conditions do not match those that are needed for multiple fragmentation. In contrast, there are three main ideas for binary formation: core/filament fragmentation, accretion disk fragmentation, and dynamical interactions.

Core and filament fragmentation occur when collapsing regions in the core or filament (which describe the shape of the region) overlap with each other, resulting in a binary or multiple star system where the stars are initially widely separated. A filament fragment will collapse if it exceeds the Bonnor-Ebert mass (Offner et al. 2023):

$$\begin{aligned} M_{BE} &\simeq 1.3\frac{c_s^4}{G^2\Sigma_{\rm fil}} \\ &\simeq 1.1\left(\frac{T}{10\rm K}\right)^2\left(\frac{M_{\rm l,crit}}{40M_\odot \rm pc}\right)^{-1}\left(\frac{W_{\rm fwhm}}{10^4\rm au}\right)M_\odot \end{aligned}$$

c_s is the speed of sound, G is the gravitational constant, $\Sigma_{\rm fil}$ is the ratio of the filament's mass-to-length value to its width, T is the temperature of the region, $M_{\rm l,crit}$ is the mass per unit length of an isothermal filament, and $W_{\rm fwhm}$ is the width of the filament. $M_{\rm l,crit}$ depends on the magnetic field around the filament, which suggests that magnetic fields have a strong role in the formation of multiples. However, this equation and others that have been developed make many assumptions, so it is not easy to predict multiplicity on a few properties of the filament or core.

Disk fragmentation is the process in which the disk around a protostar fragments into one or more additional stars because of instability caused by gravity overcoming thermal pressure and rotation. The instability criterion is:

$$Q = \frac{c_s\Omega}{\pi G\Sigma} \leq 1$$

Ω is the disk orbital frequency and Σ is the surface density of the disk. This does not represent whether the disk will actually fragment, but describes whether the disk is unstable.

Although both types of fragmentation can account for many of the observed binaries, they cannot account for the binaries with the smallest separations because multiple fragmentation would have been highly unlikely to have occurred. Instead, these binaries would have been formed post fragmentation, with one star capturing another star as it migrates within the first star's gravitational orbit. The second star would have migrated due to interactions with the cloud it was born in or with a disk.

On the main sequence, binary stars evolve differently than single stars as shown in Figure 1, due to the variable interactions between the stars, such as mass transfer. The two stars share a surface, named the Roche lobe, which is the region around the stars where orbiting material is gravitationally bound to the star. If a star expands beyond its Roche lobe or the Roche lobe shrinks into the star, mass could flow from one star to the other in a process called Roche lobe overflow (De Marco & Izzard 2017). There are three cases for Roche lobe overflow, depending on when in the stars' lifetime this process occurs. If mass flow happens when the donor star is on the main sequence, then it is a case A transfer. A case B transfer occurs when the donor has evolved off the main sequence onto the red giant branch and is burning hydrogen in a shell around the core. When mass loss happens as the donor star is on the asymptotic giant branch (after helium ignition), it is called case C transfer. The future of the system is determined by how the binary orbit is affected by the mass transfer. For example, if the gainer star cannot accommodate the mass that is transferred to it, the star will also expand past its Roche lobe, which may result in the two stars merging.

The presence of a stellar companion affects the life of a star as it evolves off the main sequence. For example, a white dwarf in a binary system may accrete so much mass from its companion that it crosses the Chan-

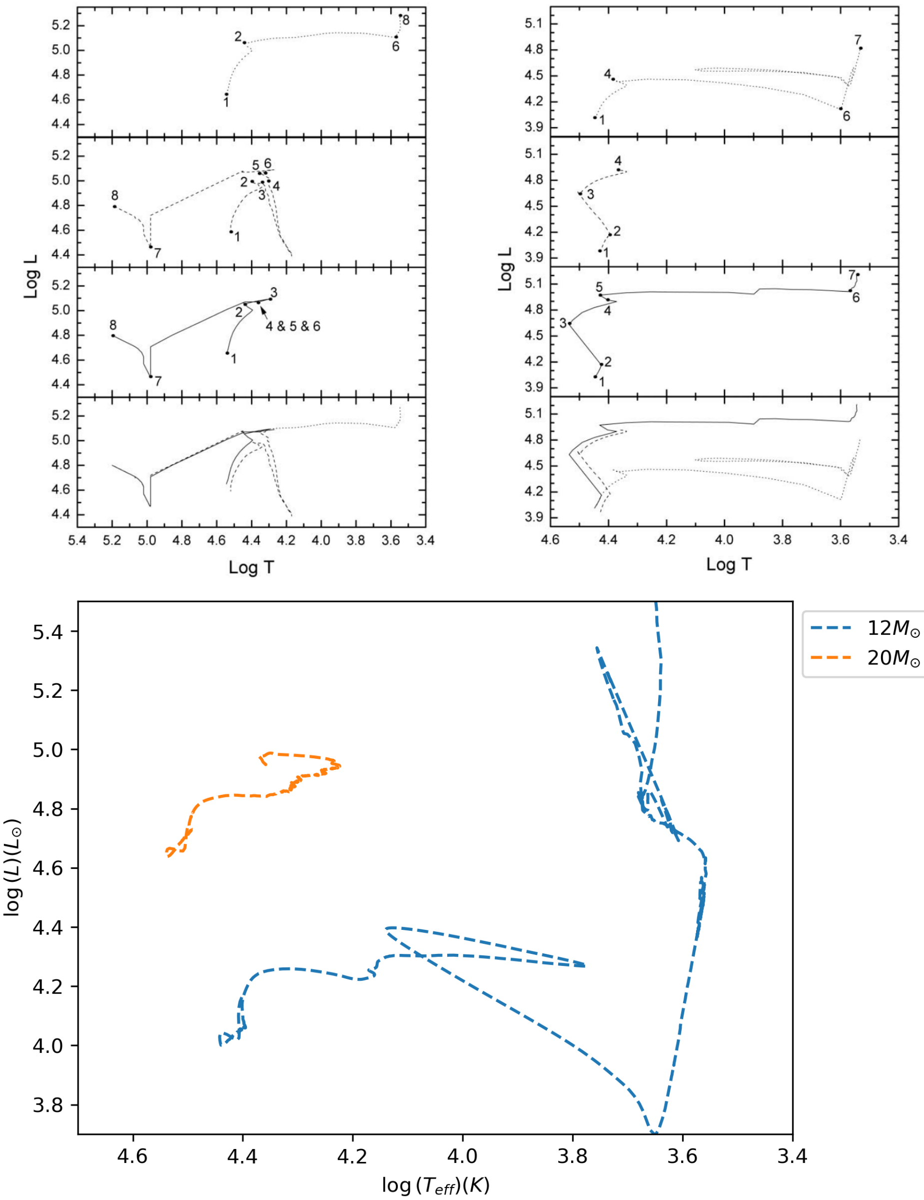

Figure 1. Comparison of Binary Evolution Models with Single Star Models *Top Panel:* Taken from Dionne & Robert (2006), where the left panel shows the evolutionary track for $20M_\odot$ star and the right panel shows the track for $12M_\odot$ star from various simulation codes. *Top to bottom:* Single star track from the Geneva group; primary/secondary star track from de Loore & Vanbeveren; primary/secondary star track based on modified tracks; superposition of all three tracks. *Bottom Panel:* Single star tracks for a $20M_\odot$ and $12M_\odot$ star that I calculated using the MESA-Web interface Jermyn et al. (2023).

drasekhar limit, igniting the carbon in the carbon and causing a runaway nuclear chain reaction, resulting in a Type Ia supernova. Type 1b and 1c supernovae are also linked to binaries because these kinds of explosions are a result of mass loss; however, stellar wind can also cause significant mass loss in large single stars, so mass transfer between binary stars is not the only cause of 1b and 1c supernovae.

There are still many unknowns in the mechanics of the evolution of binary stars. Offner et al. (2023) posits a few open questions. Which one of the star formation methods is more common in multiple star systems, core fragmentation or disk fragmentation? How do the initial conditions of the environment affect multiplicity? Do high-mass star systems evolve in a significantly different way than low-mass star systems? How do the properties of disks in multiple star systems differ from those in single star systems?

Current stellar evolution codes are getting more and more powerful as technological advancements are made and the community's understanding of the field grows. BINSTAR (Siess et al. 2011) is one such example; it is built upon a single-star evolutionary model that considers magnetic fields and mixing of material within the star, but also takes into account mass transfer and tidal interactions (De Marco & Izzard 2017). However, it is difficult to create a model that takes all parameters into account; many single-star simulations are one-dimensional, but binary simulations should be three-dimensional to track factors such as magnetic fields. Additionally, the parameter space grows as another star is added to the model; single-star evolution can be simplified to only depend on the star's initial mass and composition, but that simplification cannot be made for binary and multiple star systems. Currently there is no code that considers all initial conditions and interactions because of the sheer scale of the parameter space.

2.2. *The Way Forward*

It is important to study binary and multiple star systems because it is evident that single star-only stellar populations cannot explain observations of early galaxies, but stellar populations that include binary systems and all their evolutionary paths can (De Marco & Izzard 2017). Many stars have one or more companions, so it is not enough to study single stars to draw an accurate picture of the galaxy and the wider universe. More interestingly, a number of exoplanets have been found orbiting both stars in a binary system; Kepler-47 is one such system with three planets, one of them orbiting in the habitable zone of the stars. Studying how binary stars form will assist in models for planet formation in multiple star systems, and how the exoplanets affect the evolution of the stars.

To make progress, more powerful telescopes are needed. The next-gen Very Large Array (ngVLA) will provide data with higher resolutions and more sensitivity than the current VLA, which makes the ngVLA better suited to study multiplicity in younger star-forming regions where the protostars are very close together, and in more distant, high-mass star-forming regions (Offner et al. 2023). To study the youngest regions, data is needed from both far-infrared space-based telescopes and millimeter/submillimeter ground-based observatories. Telescopes that have been proposed for these purposes include the Origins Space Telescope and Fred Young Submillimeter Telescope.

Additionally, theoretical simulations need to become more efficient and calculate to higher orders of magnitude, as well as consider more factors. For example, as Offner et al. (2023) states, current models do not take into account the separation distance between binary stars and how the distance changes over time; rotation is another factor that is not considered when modeling binary stars (Eldridge & Stanway 2022). Current simulation results are compared with observed statistics, but these comparisons are inaccurate for extremely young stars.

3. CONCLUSIONS

There is still much to study in this field of research, with many broad and narrow questions to be answered. The current theories for multiple stellar formation are core/filament fragmentation and disk fragmentation, which can account for many observed binaries, and post-formation gravitational capture which explains binaries with the closest separations. During the post-formation lifetime of a star with companions, there are multiple types of mass transfer: transfer that happens when the donor is on the main sequence, transfer that occurs when the donor is burning hydrogen in a shell, and transfer when the donor is on asymptotic giant branch. When this mass transfer happens and how much mass is transferred between the two stars will determine their fate; the stars may merge because they expand past their Roche lobe, or they may become supernova as they cross the maximum mass limit.

There are still many open-ended questions, like which form of fragmentation is more common and how do high-mass star systems evolve differently than low-mass star systems. To answer these questions, more powerful stellar evolution codes that account for parameters specific to multiple star systems must be developed. Additionally, space and ground-based telescopes with higher resolutions must be built. With currently operating observatories like ALMA and JWST, significant progress can be made with understanding multiple star systems.

Software: matplotlib, numpy, pandas, MESA-Web (Jermyn et al. 2023)

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