The Formation and Coalescence of Binary Systems

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Abstract

Binary systems are pairs of astronomical objects, such as Black Holes (BHs) and Neutron Stars (NSs), that are loud sources of Gravitational Waves (GWs). This property determines them as perfect laboratories for Gravity Theories. Hence, understanding their evolution from formation to coalescence is vital to understanding gravity. Since their discovery, there have been many theories for the formation of such systems. In this paper, we explore and compare the hypotheses for the formation of binary systems, classify them into two categories based on the distance between the pairs they form (wide or close), and discuss the phases of coalescence of binary systems. It is found that close binary systems can form by fission, fragmentation, magnetic braking, or tidal capture. Moreover, wide binary systems can form by dynamical unfolding, cluster dissolution, or entrapment.

I. Introduction

Binary systems, also known as binaries, are pairs of astronomical objects that orbit their common center of mass (COM) due to the effect of their gravitational waves (GWs), which are ripples or disturbances in the curvature of spacetime that cause objects to orbit other objects [1], [2]. Binary systems differ depending on their particular pair of astronomical objects; there are Binary Stars (star-star), Binary Neutron Stars (BNSs), Binary Black Holes (BBHs), et cetera. All these combinations of astronomical objects have different masses and, hence, GWs, which means they behave differently and may have different detection techniques. There are systems of more than two astronomical objects, such as triples and quadruples, but this paper is not concerned with the formation or coalescence of such systems.

i. Binaries Usage in Testing Gravity Theories

Since the discovery of binary pulsars in 1974, studying binary systems became crucial in astronomy and astrophysics, as the compact binary systems' strong gravitational field made testing Gravity Theories easier than the solar system's weaker gravitational field [3], [4]. This pushed astrophysicists to understand binary systems, from their formation to their coalescence; many hypotheses were constructed regarding binary system formation, and some of these hypotheses were deemed unfavorable (i.e., fission) due to failing to predict specific properties of binary systems, such as the mass ratios of the pairs. However, it is not necessarily that one hypothesis is accurate, and the rest is false; it is such that binary systems form differently depending on factors, such as the particular combination of astronomical objects and the pairs' radius, mass, or distance between them.

iii. Coalescing Binaries

Coalescence is the process where objects merge (coalesce) into one, and thus, coalescing binaries are the gravitationally-bound compact binary systems.

Coalescing binaries serve a great purpose in astrophysics, as their strong source of GWs allows them to be test-beds for Gravity Theories, especially Einstein's General Relativity [2], [5]. This paper aims to explain how coalescing binaries are sources of GWs in addition to their three phases: the inspiral, merger, and ringdown.

II. Gravitational waves

Every massive object that accelerates produces Gravitational Waves (GWs). Space-time "ripples" known as GWs are produced by some of the Universe's most furious and intense phenomena. In 1916, Albert Einstein anticipated GWs in his general theory of relativity. According to Einstein's equations, massively speeding objects such neutron stars or black holes orbiting one another would cause space-time to be disrupted in a way that would cause 'waves' of undulating space-time to spread outward in all directions. With knowledge about their origins and hints about the nature of gravity itself, these cosmic ripples would move at the speed of light. [6] LIGO (The Laser Interferometer Gravitational-Wave Observatory) researchers have divided GWs, based on what causes them, into four categories: Continuous, Compact Binary Inspiral ,Stochastic , and Burst. [7]

i. Continuous Gravitational waves:

Ideally, a single rotating heavy object, such as a neutron star, might be able to continuously create GWs. As this star spins, any irregularities or faults in its spherical shape will cause GWs to be produced. The star's GWs will remain constant if the star's spin rate stays. Accordingly, the frequency and amplitude of the gravitational wave remain constant. That is why these are referred to as "Continuous Gravitational Waves." [7]

ii. Compact Binary Inspiral Gravitational Waves

Compact binary inspiral gravitational waves are generated when pairs of compact objects like white dwarfs (WDs), black holes (BHs), and neutron stars (NSs) start orbiting. There are further three subclasses of compact binary systems, which are Binary Neutron Star (BNS), Binary Black Hole (BBH), and Neutron Star-Black Hole Binary (NS-BH). Although the pattern of gravitational waves produced by each binary pair differs, they are always produced by the same mechanism termed inspiral. [7]

iii. Stochastic Gravitational Waves

The Universe is constantly being bombarded by many tiny GWs, which are randomly mixed. A "Stochastic Signal" is made up of these tiny waves coming from all directions. The term "stochastic" refers to a random pattern that can be statistically analyzed but cannot be precisely predicted. Although these GWs will be the tiniest and hardest to find, it is possible at least some of this stochastic signal came from the Big Bang. [7]

iv. Burst Gravitational Waves

Burst gravitational waves are the GWs that go bump in the night; they originate from short-duration unknown or unexpected sources. Supernovae and gamma-ray bursts are two examples of systems that have been theorized to produce burst gravitational waves, but not enough is known about these systems to predict the shape that these waves will take. These GWs are anticipated to make "pops" and "crackles." However, it is still hard to verify that because there is not much that can be inferred about their origin. [8]

v. Gravitational Lensing

The apparent variation in astrophysical objects' emissions caused by the gravitational field of the lens is one of the most significant effects of gravitational lensing. When the velocities of the observer, lens, and source's relative motions are high enough, their mutual location changes quickly. This effect can be seen for a considerable amount of time. [9]

For instance, it is possible to verify binary evolution hypotheses and look into the last stages of single-star evolution due to a complete set of data for compact object binaries and their statistical analysis. It was observed that just ten double WDs had been discovered in the past ten years, and during the course of 25 years, about 40 WD-NS pairs have been discovered. Additionally, this might aid in the discovery of binaries with neutron stars inside that have a weak magnetic field. It is possible to examine the specific cooling models for WDs and NSs, as well as the equation of state for the latter, by studying these systems in conjunction with ideas of double star evolution. [9]

III. Types of Binary Systems

Binary systems are diverse, and they can be classified into a lot of categories. However, they are mainly classified according to their way of detection. The following sub-topics discuss these types extensively.

i. Visual Binaries

As their name implies, visual binaries refer to observable binary systems that can be resolved using telescopes. Typically, these binaries are the very close ones to the Earth. However, there is a misconception when the naked eye observes these stars. They might appear as they orbit each other, but in reality, they are very distant and aren't even bounded together. They aren't considered true binaries. Instead, they are called optical pairs. In addition, a bunch of stars that appear to be a single system is orbiting other stars in binaries. A well-known example of these stars is The α Centauri system. It consists of two stars, α Cen A and α Cen B, at an orbital distance of around 23 AU [10]. The stars always orbit about the center of mass of the system, which is the focus of the line joining the two stars together. The more massive the star is, the closer it is to the center of mass, as shown in figure 1.

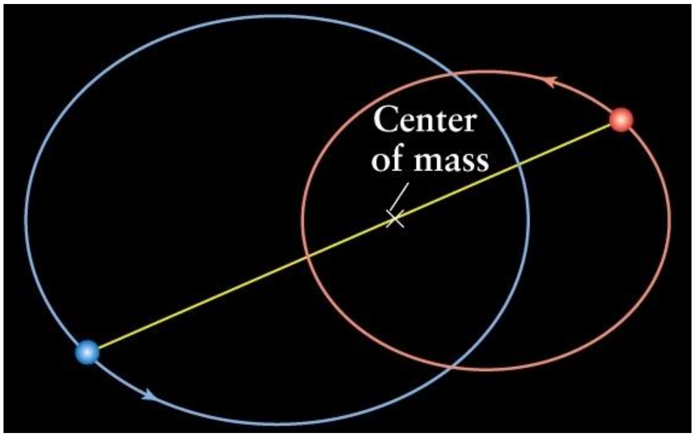

Figure 1: COM of a binary system. This image is taken from W.H. Freeman, 2011, [11, ch. 17, pp. 458].

Visual binaries are beneficial, as they allow us to determine the sum of the masses of the stars by using Kepler's third law as shown in equation 1 [11, ch. 4, pp. 75-77]:

$$M_1 + M_2 = \frac{a^3}{p^2} \qquad (1)$$

where $M_1 + M_2$ is the sum of the masses of the stars, a is the semi-major axis of one star's orbit around the other, and p is the orbital period in years [11]. However, it is sometimes difficult to determine the semi-major axis of a star except by using parallax. Moreover, by determining the relative sizes of the stars, the ratio of their masses can be determined too, and finally, by doing some algebra, the mass of each star can be calculated.

ii. Spectroscopic Binaries

Spectroscopy is the field of science that studies visible light or any electromagnetic radiations and analyzes these radiations to their spectra. Scientists detect spectroscopic binaries by splitting the spectrum components produced from a specific star. These stars are often very far that they cannot be resolved easily, as in the case of visual binaries. The spectrum produced from a spectroscopic binary must be a combination of different types of spectra due to the presence of two different star types. For instance, the spectrum of what appears to be a single star may have both powerful hydrogen lines (representative of a type A star) and powerful titanium oxide absorption bands (typical of a type M star). Such a star must be a binary system since a single star cannot have the distinct physical characteristics of these two spectrum groups. Another common technique widely used to detect binaries is the Doppler shift. This phenomenon takes place when two stars orbit each other, making the star nearer to Earth more likely to emit red light as the wavelength increases, and the other further star emits short wavelength blue light. The analysis of this spectral line shift concerning time lets the observers know the radial velocities of the system's stars.

However, there can be obstacles to this way of detection. For instance, the main factor that is taken into consideration while using this way is making sure that the stars' motion isn't perpendicular to our eyesight. As shown in figure 2, when the stars orbit each other in this orientation, there will be no doppler shifts. In addition, when the orbital distances between the two stars are large, then the periods will be too long, and their velocities will be slow. Otherwise, the star may be dim making it difficult to detect its spectral lines [10], [12].

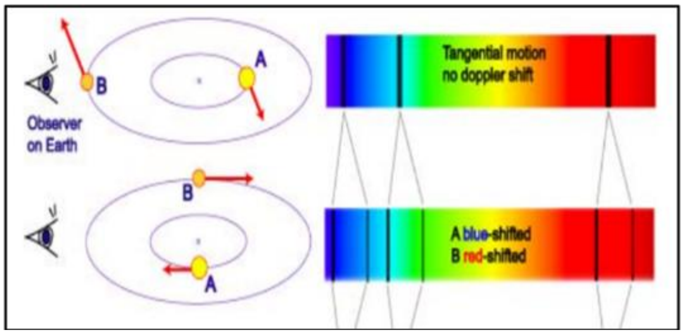

Figure 2: The Doppler shift cases. This image is taken from [10].

iii. Eclipsing

Some stars exhibit a periodic change in their apparent light intensity over hours, days, or years. These stars are almost orbiting other stars, and each one eclipses the other periodically. Unexpectedly, the first ever discovered binary star system was an eclipsing binary. The two stars were Alcor and Mizar. However, recent studies reveal that this is a sextuplet system, not binary. The most important technique used to analyze this type of binary is drawing the light curve of the two stars versus time, as shown in figure 3. Eclipsing binaries can occur in other types as well. A visual binary, for instance, can be an eclipsing binary, but the periods are just for a very short period. [13]

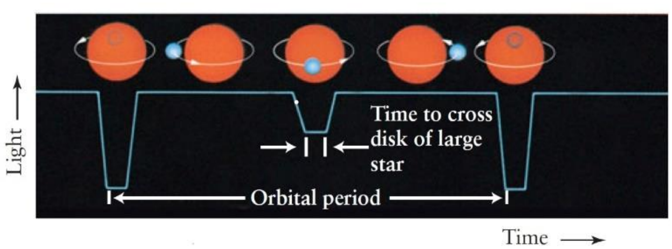

Figure 3: Eclipsing binaries. This image is taken from W.H. Freeman, 2011, [11, ch. 17, pp. 463].

One of the most challenging obstacles in detecting this type of binary is the inclination angle from our eyesight. The inclination angle can be defined as the angle of the star's orbit relative to a perpendicular plane to our eyesight on Earth, as shown in figure 4.

The inclination angle contributes significantly to determining the radial velocities of the stars. The radial velocity is considered the observed relative velocity of the star with respect to the observer on Earth. In other words, it is the rate of change of distance between two points as shown in equation 2:

$$V = \frac{dr}{dt} \qquad (2)$$

And the maximum velocity of the star can be calculated as shown in equation 3:

$$v_r = v. \sin i \qquad (3)$$

where i is the angle of inclination. [14], [15]

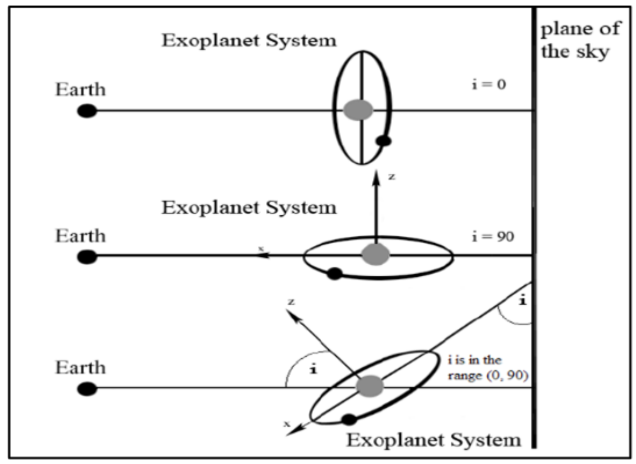

Figure 4: The inclination angle visualization. This image is taken from T. Camen, 2008, [15].

It can be concluded that the maximum velocity will be given if the inclination angle is 90^o, which is the maximum of the sin function. Thus, if the inclination is zero, there will be a radial velocity of zero because there is no change in the distance between the observer and the star. As a result, it can be concluded that to conduct experiments and data from the eclipsing star system, the radial velocity must be observed. Thus, the inclination angle should be parallel with our eyesight. However, eclipsing binaries with such properties is rare, so the inclination angle plays an important role in these stars' eclipsing binaries and determining many other properties. [16]

iv. Astrometric Binaries

In some cases, astronomers can determine one star's position without the other. This visible star can be a single system star, or it can be bounded to another one in a binary system. To predict the presence of another star, they must notice a gravitational attraction on the visible one that affects its proper motion periodically. So, in the long run, they predict that the star is in a binary system, as in the case of the Sirius star system [10]. Consequently, they developed a formula by which the observable quantities can represent the original orbital parameters. They observe the change in the position many times and measure the time intervals between each observation. This formula has the so-called Inverse formula. [17]

v. Exotic Binaries

The exotic type of binary systems does not represent a new category or way of detection, but it is very noticeable and fascinating to observe. Exotic binary systems can be binary pulsars or X-ray binaries, which will be discussed in the following sub-topics.

vi. Binary Pulsars

At the end of a massive star's life, it runs out of its fuel and collapses on itself, making supernovae explosions. Some of these stars turn into black holes, and others can generate neutron stars, extremely dense objects. A type of neutron star, pulsars are neutron stars that spin up hundreds of times per second, producing high-energy radiations, so they appear flashing, exhibiting a phenomenon called Lighthouse. An example of these pulsars is J0030 which revolves 205 times per second. It is estimated to have a mass of approximately the sun but a diameter of 26 km, which refers to how extremely these pulsars are dense [18]. When scientists were studying ordinary pulsars, they discovered a regular variation in the pulsing of the pulsar, so they predicted that there must be another companion for the pulsar that affects its pulsing which was a neutron star. This was the first discovery of a binary pulsar by the two scientists, Hulse and Taylor. Discovering such a system has made a revolution in the science of astrophysics. The binary pulsar system is dense with a very high spinning velocity, disturbing the fabric of space-time significantly and emitting high amounts of GWs. They also found that the orbital periods of this system decrease due to the energy loss in the system that is in the shape of GWs, which the General Relativity equations can calculate. In other words, binary pulsars came to confirm Einstein's theory, and the tests proved the theory's success. Hence, binary pulsars are described as an exotic type of binary system. [19]

vii. X-ray binaries

X-ray binaries are a special type of binary system as they are the most luminous things in X-rays in space ever. They can be detected a bit easier than other types because of these luminous X-ray radiations. Typically, the X-ray binary consists of a normal star or a white dwarf (companion) with a collapsed star which can be a neutron star or even a black hole (compact object). But in most cases, the collapsed star is a neutron star. The compact body accretes mass from the companion as a result of the great gravitational force exerted by the compact object. Due to the angular momentum of the incoming material, an accretion disc is formed as it spirals onto the compact star. The gas is heated to extremely high temperatures by the ferocious collisions between the particles of the inflowing materials. The incoming matter's gravitational potential energy is transformed into kinetic energy during this process and then into X-ray radiation. [20]

They can be classified concerning the mass of the companion (mass of the losing star) into High Mass X-ray Binaries (HMXBs) and Low Mass X-ray Binaries (LMXBs). The companion star's mass in HMXBs is usually at least ten solar masses. The stellar wind works as the way for the matter in the companion to transfer to the compact star, then this matter is directed to the two magnetic poles of the neutron star and produces these high-energy X-ray radiations. Thus, there is no distinct accretion disk in HMXBs, as opposed to LMXBs, which have accretion due to the companion's relatively small mass, around one solar mass. The accretion of LMXBs occurs by filling the Roche lobe of the star and transferring the matter into the compact star. In addition, there is a distinct accretion disk from which most X-rays are scattered from the center of this accretion disk. [20]

viii. Contact Binaries

As the name implies, contact binaries are binary stars or systems that are very near each other to a distance smaller than their combined radii and rotate around their common COM. As a result of their touching (approximately), an essential process is the mass exchange. The system usually consists of two different stars in mass and temperature. When the two stars are near each other until a specific limit, they also begin exchanging mass and energy. This limit is the so-called Roche lobe of each star, as shown in figure 5 [21]. The most common example of these contact binaries is the W Ursae Majoris (W Uma) variable stars designation. Variable stars are the stars whose brightness is changed periodically (eclipsed) from an external stimulus, mostly because of their presence in binary systems. Ursae Majoris is a constellation or a group of stars forming a specific shape in the sky. This constellation is the most common one that comprises variable stars. Around 95% of the known eclipsing binaries in the solar neighborhood are from W Uma [21]. Contact binaries can be any other type of binary like eclipsing, spectroscopic or exotic except for the wide binaries far apart.

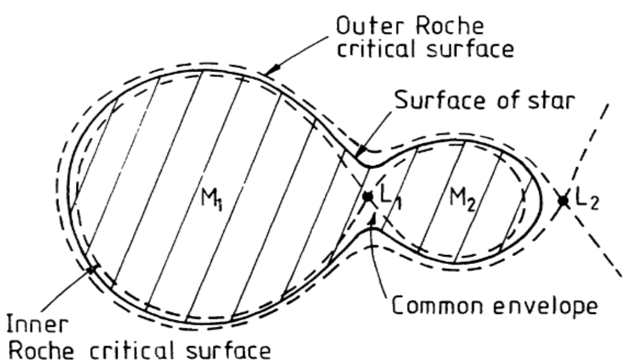

Figure 5: The Roche lobe of binary systems. This image is taken from R.C Smith, 1984 [21].

IV. Formation of Close Binary Systems

i. Fission

According to the fission theory, the formation of close binary systems is due to the breakup of a single mass caused by the dynamical result of the contraction of a revolving, self-gravitating fluid mass. While the fundamental concept still appeals to some, the detailed development of the theory has run into several obstacles that have led some people to doubt its validity. Darwin [22] and Jeans [23] explored a general secular increase in angular momentum with uniform density. The original mass was considered to have contracted due to gravity, and the viscosity was high enough to maintain a constant angular velocity throughout the mass. The mass initially assumes the shape of an oblate spheroid at low angular momentum values; as angular momentum increases, this form becomes unstable, and an ellipsoid with three unequal axes develops, which is stable initially. [24]

However, the theory has run into several problems that have led astrophysicists to doubt its plausibility. It has some special presumptions that there must be uniform density (which is not the case for stellar structure) and constant angular velocity. In addition, the longest diameter perpendicular to the rotation axis elongates as the angular momentum increases until it is nearly three times the length of the shortest diameter. At this point, the form becomes secularly unstable and does not transform into any other secularly stable figure. [24], [25]

Liapounoff [26] and Jeans [23] showed that the new figure was secularly unstable, so there was no other way to store the angular momentum except by fission. Poincaré [27] had shown that the ellipsoids with three unequal axes developed a furrow at one end when they became secularly unstable. However, it was required to assume ordinary stability for fission into two detached masses moving in an almost circular relative orbit to be possible, as otherwise, the changes would not be slow, and viscosity would not be enough to maintain uniform angular velocity. This presumption was disproved by Cartan, who demonstrated that the ellipsoids became ordinarily unstable at the same time that they became secularly unstable. As a result, fission in the sense of binary star formation cannot occur through this process. [24]

ii. Fragmentation

Both turbulent fragmentation and disc fragmentation are major hypothesized formation processes for numerous stars. These techniques produce different distributions of companion separations; close binaries and wide (separation > 500 AU) binaries naturally arise through turbulent fragmentation and disc fragmentation, respectively. Although originally close binaries can become wide binaries due to dynamical processes such as three-body interactions, radial migrations, and interactions with cluster members. Therefore, it is important to witness protostellar binary or multiple systems that are younger than 0.5 Myers (Million years), the duration of the embedded protostellar phase, and can therefore expose their initial configurations to prove formation through turbulent fragmentation. [28]

According to a survey of protostars in the Perseus molecular cloud, companion separations have a bimodal distribution with peaks at 75 AU and 3000 AU. Therefore, both of the processes of binary creation are supported by evidence. New high-resolution data isolate specific targets to support each formation method. A triple protostellar system originating in a shared protostellar disc provided convincing proof of disc fragmentation. A triple condensation system, on the other hand, was found, and the authors claimed that it is developing into a stellar system with a wide separation; nevertheless, this system has thus far produced only one protostar, and its end state is unknown. [28]

Even though the systems with greater separations are likely candidates for turbulent fragmentation, this theory needs more support, specifically regarding the misalignment of the rotation axis of the stars, discs, and outflows. Binaries with misaligned rotation axes are produced by turbulent fragmentation because the angular momentum distribution in a turbulent core is unpredictable. On the other hand, binaries with aligned rotation axes are anticipated when the secondary member forms in a sizable co-rotating huge disc or ring around the primary or when it does so by fragmentation fueled by centrifugal force in a flattened cloud core. Although protostellar rotational axes are challenging to quantify, a star-disk system's bipolar outflow can be utilized to evaluate the alignment of angular momentum in the system. Outflow investigations, however, are hampered by environmental factors or interactions between different outflows. A stronger indicator is the misalignment of the disc rotation axes; however, wide binaries' disc rotation axes have only been observed in the T-Tauri stage, which is more developed than the protostellar stage and is subject to the impacts of tidal evolution. [28]

iii. Magnetic Braking

In contact binary stars, magnetic braking contributes significantly to angular momentum loss. When a magnetic field develops in a companion star, the impact of differential rotation in binary systems can be crucial. Interestingly, the created magnetic field typically slows down the current rotation rate. [29]

The compact star is the source of the field that surrounds the braking star in a magnetic massive variable system. Within the binary system, a closed field area forms that does not participate in magnetic braking. The overall braking rate is influenced by centrifugal forces based on the size of this zone and the open flow. It is discovered that, in the case of two interacting dipoles, the orientations of the dipoles with respect to the spin axis and one another matter, causing variable quantities of open flux and, consequently, magnetic braking due to various centrifugal effects on closed field areas. [30]

The magnetic braking of the secondary is significantly reduced by the white dwarf's field, though, under conditions consistent with observations and dynamo theory. This result is qualitatively similar to those previously found for two anti-aligned dipoles perpendicular to the orbital plane. The 'cut-off' in magnetic braking is less sudden when the two dipole axes are inclined in the plane that joins them rather than parallels the orbital plane, and this effect becomes more pronounced as the inclinations rise. The braking increases with the strength of the white dwarf field only under the most extreme circumstances when the two dipole axes are aligned in the orbital plane. [30]

iv. Tidal Capture

In 1975, Fabian et al. first proposed the “Tidal Capture” hypothesis for how close binary systems form could form [31]. This happens when two unbound objects have a close encounter; as they get near, their tidal forces affect each other to excite oscillations between them [32]. Fabian et al. explained how only very close binary systems could form by tidal capture, as the final stages of close binaries tend to be rapid in movement and non-linear tidal interactions, which causes the mass exchange to happen to bound them together. They also proposed that tidal capturing creates binaries that are sources of X-rays in globular clusters. LMXBs are often formed by tidal capture, and it was found that their number density goes along with their background stellar density [33].

V. Formation of Wide Binary Systems

Wide binary systems' formation cannot be explained by the hypotheses for close binary systems' formation because their separation often exceeds the size of collapsing clouds [34], which means they cannot form by fragmentation, fission, or magnetic braking. This section will dive deep into the proposed hypothesis for wide binaries' formation.

i. Dynamical Unfolding of Triple Systems

Reipurth and Mikkoa [34] first proposed "unfolding" as a way that wide binary systems (15,000 AUs separation distance) could form. Dynamical unfolding is when compact unstable triple systems "unfold" into a wide binary system. The evidence for this hypothesis is that wide binaries are commonly part of triple systems. These triple systems are compact initially, but over millions of years, one of the three objects gets scattered away while the two other objects shrink, resulting in what is called an extreme "hierarchical architecture." The explanation for this dynamical unfolding, scattering, and shrinking of the orbits is that in compact triple encounters, energy and momentum are exchanged, causing the object with the smaller mass to break up from the system, which creates a stable binary [35], [36]. Eccentricity also plays a role in the dynamical unfolding of triple systems. Eccentricity is the shape of an object's orbit, and it ranges from 0 (circular) to 1 (a straight line) [11, ch. 4, pp. 74]. In a triple system, the outer orbit is very eccentric (near 1). This high eccentricity makes the system destabilize and experience perturbations, which are deviations in the motion. These perturbations eventually lead to the break-up (unfolding) of the system [36].

ii. Cluster Dissolution

According to Moeckel and Bate's research [36], the dense simulated cluster's expanding halo contains several wide binaries with 104 < s < 105 AU (s is separation distance) after 10 Myrs of dynamical evolution. Half of these binaries are triple or higher-order multiples, which are wider than the 104 AU original cluster size. There were 15±7 binaries, or 1.7% of the 900 stars in the cluster, with s > 104 AU. According to Kouwenhoven et al. [37], each cluster often generates a wide binary with s > 10^4 au. Such couples occur in the field with a 2% frequency. A typical cluster should have about 50 stars if the cluster dispersal process created all of the field-wide pairs. [38]

However, in the BPMG (the name of a star), the frequency of couples with s > 10^4 AU is 7/49 = 0.14±0.05, which is much higher than in the field. Neither cluster breakup nor the unfolding mechanisms can account for such a high percentage of wide pairs. A similar conclusion was found by Joncour et al. regarding wide pairs in Taurus. [38]

iii. Entrapment

The development of very wide pairs from unrelated stars that are unintentionally trapped into common motion in the galactic potential was considered by Makarov. In theory, such couples have a lengthy lifespan. However, because of their chaotic motion and ease of dissolution, they are not Keplerian structures. According to Makarov, this process is too ineffective to account for wide pairs. Furthermore, wide binaries are less resistant to smooth Galactic potential than passing stars or molecular clouds. Therefore, the enormous Jacoby radius of 1.8 pc is not important for their survival. [38]

VI. Coalescence of Binary Systems

Naturally, any binary system can collide together by the effect of their gravitational forces on each other. However, typically, the most important types that are common to scientists are the neutron stars' binaries and black holes binaries. They are essential as they are nearly the most massive and dense objects in the universe that spin at speed closer to the speed of light. Hence, objects with these characteristics can fold the fabric of space-time significantly and cause distortion. When this process occurs, a huge amount of angular momentum and energy is liberated from the system in the shape of the so-called "Gravitational Waves" [39]. Every massive object in the universe that has an acceleration causes disturbance in space-time fabric but at different levels.

It is estimated that the most influencing things on this fabric that produce noticeable GWs are BBHs and BNSs. The coalescence process has three main phases, and each phase can be analyzed by different approaches [40]. As shown in figure 6, the first and the longest period is the inspiral stage. This stage includes the beginnings of the black holes approaching together, spinning faster than usual, causing the orbital periods to decrease, and their frequency is in exponential form. This can be explained easily by utilizing classic Post-Newtonian works in gravity. Then, in the merger state, the BHs get nearly in contact, and a very strong GWs produced in this stage with very high frequencies. Newton's works cannot explain this stage in gravity. Fortunately, Einstein found a different approach through his general relativity equations that he predicted the existence of these GWs. Then, after the merger, the final fate of the two coalescing BHs is now a single spinning black hole that depresses much energy. This state is called the "Ringdown" [39].

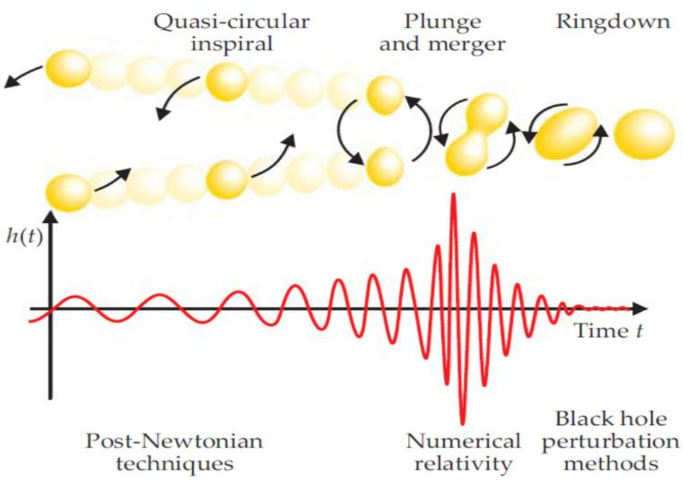

Figure 6: Coalescence stages. This image is taken from S. Philipp, 2017, [40, ch. 2, 28].

VII. Conclusion

Binary systems are pairs of objects that have been useful in Gravity Theories since their discovery in 1974. However, binary systems are yet to be understood fully, as they are still part of a fast-moving field in astrophysics and gravitational-wave astronomy. In this paper, we investigated GWs, the types of binaries, how close and wide binaries could form, and the coalescence of binaries. Since there are various GWs, the most detectable ones are continuous and inspiral compact binaries. The continuous provides sustainable production of GWs like the spinning of neutron stars. However, the inspiral compact has a more significant influence on the distortion of the fabric of space-time because it is a coalescence of two massive and fast objects. The most detectable of the types of binaries is the eclipsing binaries, as they are the most abundant in our solar neighborhood. In addition, they are the first detected types of binaries ever. Coalescence of binary systems has three distinct phases: inspiral, merger, and, finally, rundown. The merger stage has the greatest potential for gas production. Furthermore, they are a fundamental challenge to investigate more in the future. Because studying the nature of this process will be the clue for most of the controversies in the science of astrophysics and, especially, gravitational-wave astronomy.

For close binaries' formation, the fission hypothesis is unfavorable because of its presumptions and errors. On the one hand, fragmentation (both disk and turbulent) is favorable and deemed the most likely way binary systems form in the world of stellar astrophysics, especially for close binaries. However, it still has space for more investigation. For example, the frequency of binary systems through fragmenting is still uncertain as all the studies regarding this had a small sample. This makes formation through fragmentation have space for future research. Magnetic braking is another possible method of formation of binary systems, but it is still a newly hypothesized one that needs more investigation by scholars and computer simulations. Tidal capture is the fourth hypothesis and has been investigated heavily since its proposal in 1975, making it supported. However, it occurs less often than fragmentation, as it is only possible on rare occasions of two objects having an extremely close encounter. For wide binaries' formation, dynamical unfolding is the most likely and investigated out of all the formation hypotheses. However, cluster dissolution and entrapment still make great candidates with supporting evidence. Nevertheless, the formation of wide binary systems is not figured out as close binaries. This is because of the need to consider numerous aspects of factors that come with great separation distance. In short, understanding wide binary systems formation is fast-moving, and future research would be practical.

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