Chapter 4

Astrophysics of Compact Binaries

This chapter is broken up into two sections. The first (section 4.1) presents evidence for the existence of compact objects (i.e., neutron stars and black holes). The second (section 4.2) presents predicted rates for the coalescence of binary compact objects based on observations and theoretical considerations.

4.1 Evidence for Neutron Stars and Black Holes

To date, there have been many observations of compact objects, which confirm the existence of neutron stars and strongly suggest the existence black holes. The theoretical maximum mass for an electron-degenerate star is given by the Chandrasekhar mass limit of $\sim$1.4 $M_{\odot}$. This limit is implicated in multiple types of stellar explosions, including Type Ia/b/c and II supernovae, in which either the mass of an electron-degenerate, white dwarf approaches this limit (Type Ia), or the core of a massive a star approaches this limit (Type 1b/c II). For the latter situation, the observations of the remnant object has been linked to compact object observations, as in the case of Cassiopeia A [87].

Compact objects with a tightly orbiting companion are good testing grounds for differentiating between neutron stars and stellar mass black holes. If the companion object is close enough, it fills its Roche Lobe, the boundary at which the gas of the companion object is no longer gravitationally bound to its parent star, and leaks onto the compact object. This gas then forms an accretion disk around the compact object as it is transferred. By measuring properties of the binary system as well as of the accretion disk, we can learn many things about the compact object. Studying the orbital parameters of the binary will tell us the mass of both the compact object and companion object. If the mass of the compact object is larger than the Chandrasekhar Limit, then the compact object must be either a neutron star or a black hole. If thermonuclear explosions are seen as matter falls onto the compact object, it is determined to be a neutron star. In the case of black holes, studying the profile of Fe-lines in the accretion disk can allow the spin of the black hole to be determined [88].

In addition, observation of binary pulsars such the Hulse-Taylor pulsar [89] have also yielded evidence for compact objects. The two objects, roughly 1.44 and 1.39 $M_{\odot}$, in this system are orbiting each other once every 8 hours, corresponding to a separation of $\sim$1 $R_{\odot}$. Additionally, this system is seen to lose orbital energy at the rate predicted by GW emission in general relativity. At this separation, if the objects were ordinary stars, there should be some other much stronger force causing them to depart from this prediction. Electromagnetic observations have also found no counterpart, which at a distance of 8 kpc, excludes these objects from being white dwarfs.

4.2 Predicted Compact Binary Coalescence Rates

In this section we summarize a number of different ways the rate of CBC are predicted. These methods are broken up into three categories, namely extrapolations from merging binary neutron star (BNS) observations (section 4.2.1), population synthesis of field binaries (section 4.2.2), dynamical simulations of star clusters (section 4.2.3), and extrapolations from short Gamma Ray Burst (GRB) observations (section 4.2.4) [90].

4.2.1 Extrapolations from Merging Binary-Neutron-Star Observations

Observations of binary systems involving pulsars that will coalesce within a Hubble time can be extrapolated in order to obtain a BNS merger rate. There are currently four known systems of binary pulsars that will merge within a Hubble time, and one more possible system, all in our galaxy. These systems are PSR B1913+16 (the Hulse-Taylor pulsar), PSR B1534+12, J0737-3039A, J1756-2251, and possibly J1906+0746.

In [91, 92], the authors use these binary pulsar systems to calculate a combined probability on the rate of coalescences in our galaxy. To do this they combine the number $N_{\rm tot}$ of observed Galactic pulsars, the fraction of Galactic pulsars with pulse and orbital characteristics similar to those of a particular type, the lifetime $\tau_{\rm life}$ of each of the observed systems, and the upward correction factor f_b^{-1} due to pulsar beaming. For each type of pulsar population, with the ratio α of the mean number of observed pulsars $\langle N_{\rm obs}\rangle$ to the total number of pulsars $N_{\rm tot}$ for that population

$$\alpha = \frac{\langle N_{\rm obs}\rangle}{N_{\rm tot}}\ , \tag{4.1}$$

they obtain a probability density function $P(R)$ for the rate given by

$$P(R) = \left(\alpha\tau_{\rm life} f_b\right)^2 R e^{-(\alpha\tau_{\rm life} f_b)R}\ . \tag{4.2}$$

These probability distributions can be combined (Appendix A of [93]) to obtain the most probable rate of $R \approx 71$ MWEG^{-1} Myr^{-1} and a 90% confidence interval of ∼15–240 MWEG^{-1} Myr^{-1} [94] without the inclusion of J1906+0746 and a factor of 2 larger with its inclusion, where an MWEG is a Milky Way Equivalent Galaxy. This can be converted to 7.1×10^{-1} Mpc^{-3} Myr^{-1} using a galaxy number density of 10^{-2} MWEG Mpc^{-3}.

4.2.2 Population Synthesis of Field Binaries

Population synthesis simulations have been used to estimate the rate of binary coalescences for BNS, binary black-hole neutron-star (BHNS), and binary black hole (BBH) systems in the binary evolution scenario (i.e., stars formed as binaries during their stellar formation). These simulations start with stars distributed according to an initial mass function. These systems are then evolved keeping track of their evolutionary details. At the end of the simulation, observational constraints can be imposed on the results such that the results are consistent with the observed sample of merging Galactic BNS, wide Galactic BNS, white dwarf–neutron star binaries, the observed rate of Type Ib/c, Type II supernovae, etc.

With these constraints imposed, the final rates can be can be obtained by looking at the number of BNS, BHNS, and BBH with orbits tight enough to merge within a Hubble time. Results suggest that the range of merger rates are 1–10^3 MWEG^{-1} Myr^{-1} for BNS [91, 92], 5×10^{-2}–1×10^2 MWEG^{-1} Myr^{-1} for BHNS [95], and 4×10^{-2}–1×10^2 MWEG^{-1} Myr^{-1} for BBH [96] systems.

4.2.3 Dynamical Simulations of Star Clusters

In this section we summarize arguments of [97, 98, 99, 100] for predicting the CBC rate from different types of star clusters. Star clusters may provide the necessary breeding ground for BBH due to their increased star formation rate and their increased density. Studies have shown [101] that in such an environment, mass segregation occurs through dynamical interactions within the cluster, driving the higher mass objects toward the center, increasing the possibility of forming stellar mass BBH systems.

For a cluster of mass $M_{\rm cl}$, since stars form according to a power-law mass distribution [102], the number of stars that are massive enough to form black holes after supernova (i.e., those with masses greater than 20 $M_\odot$) is roughly $3 \times 10^{-3}(M_{\rm cl}/M_\odot)$. These objects undergo rapid evolution forming their black holes quickly (on a timescale of about $t_{\rm SN} \sim (M)^{-2.5} \times 10^{10}$ yr). Then, since these are the most massive objects, they tend to sink toward the center with a timescale of

$$t_{\rm relax} \simeq t_{\rm cross} \times 0.1N/\ln N \ , \tag{4.3}$$

where $t_{\rm cross}$ is the typical crossing time of the cluster [103]. This happens through a mechanism known as equipartition, which is a statistical tendency for objects undergoing two-body interactions to equilibrate their kinetic energy. This tendency causes the lower mass object to leave a two-body interaction with a larger average speed than the higher mass object, thus causing the higher mass object to sink further in the potential well of the cluster.

Another effect that occurs in the mass segregation process is the accumulation of high mass binaries. When a binary interacts with a third object, the two most massive objects tend to leave the interaction as a binary [104]. In these interactions, the binding energy of the binary tends to increase. These interactions thus favor the formation of tight binaries from the highest mass objects in the cluster.

The combination of mass segregation and binary exchanges continue until the recoil speed from the three-body interactions is large enough such that even the BBH systems receive a recoil larger than the escape velocity of the cluster [105, 106]. At that point, the binary has hardened enough that even though it leaves the cluster, the time until merger due to gravitational radiation is less than a Hubble time.

These arguments have been applied to globular clusters in [98]. They find that the rate of mergers from globular clusters is given by $\sim g_{\rm cl} g_{\rm evap}$ Mpc^{-3} Myr^{-1}, where $g_{\rm cl}$ is the fraction of total star formation that occurs in clusters and $g_{\rm evap}$ is the fraction of cluster-forming mass that possesses the birth conditions necessary for this process to occur.

These arguments have also been applied to nuclear star clusters both in the presence of a supermassive black hole (SMBH) [99], and not [100]. In [99], they found a wide range of merger rates in the presence of a SMBH with rates varying between 1.5×10^{-6} and 2×10^{-4} Myr^{-1} per galaxy (not Milky Way equivalent galaxy) depending on the model chosen. In [100], they argue for merger rates in the absence of a SMBH of a few times 10^{-3} Mpc^{-3} Myr^{-1}.

4.2.4 Extrapolations from Short-Gamma-Ray-Burst Observations

Here we present arguments used in [107] for estimating the rate of mergers of dynamically formed BNS and BHNS systems in globular clusters from short GRB observations. Short GRBs are theorized to originate in the merger of two compact objects forming a black hole surrounded by an accretion disk [108, 109, 110, 111]. In order for an accretion disk to form, there must be matter present in the system from either one or both objects, which excludes the possibility of short GRB coming from BBH systems.

BNS and BHNS systems can form in one of two ways. The objects were originally binary stars that both underwent core collapse forming a binary of compact objects, or the objects separately underwent core collapse and then dynamically formed through companion capture and possible exchange interactions. The former we will refer to as "primordial" systems, which can be found in the field. Results from population synthesis have shown that primordial systems that will merge within a Hubble time do so soon after their formation, thus the redshift associated with such systems should closely follow the star formation rate of the universe [112, 113, 114]. On the other hand, dynamically formed systems will be delayed by the relaxation time t_{relax} of the cluster, which can be on the order of a Hubble time.

Using this time delay, the short GRB rate can be calculated from the star formation rate history using

$$R_{GRB}(z) \propto \int_0^{t(z)} R_{\mathrm{SFR}}(t-\tau)P(\tau)d\tau \;, \tag{4.4}$$

where $R_{\mathrm{SFR}}(t)$ is the star formation rate at time t, $P(\tau)$ is the distribution of time delays τ before merger, which goes as $P(\tau) \sim 1/\tau$ for primordial systems [115, 116] while it increases for increasing time delays for dynamically formed systems [117].

Using equation (4.4) and the distribution of observed luminosities for short GRB, [107] calculate the local rate of events to be 1.3×10^{-3} and 4.0×10^{-3} Mpc^{-3} Myr^{-1} assuming all observed events come from primordial or dynamically formed systems respectively. Given the observed distribution of redshifts associated with short GRB, the best fit of the data comes from a 60% contribution from dynamically formed systems. Reducing the contribution from dynamically formed systems such that the Kolmogorov-Smirnov probability that the observed distribution comes from the expected distribution reaches a value of 0.1, the contribution from dynamically formed systems is found to be at least 10%. These two combinations yield a local event rate of 2.9×10^{-3} and 1.6×10^{-3} Mpc^{-3} Myr^{-1} for 60% and 10% fraction of dynamically formed mergers respectively.

The above rate calculations have only taken into account the observed rate, which ignores the effects of beaming at the source. In [118] and [119], the authors have estimated the beaming factor to be on the order of $f_b^{-1} \sim 100$, where f_b is the fraction of the total solid angle within which the GRB is emitted. Taking this into account, the beaming-corrected rates are found to be $2.9(f_b^{-1}/100) \times 10^{-1}$

and $1.6(f_b^{-1}/100) \times 10^{-1}$ Mpc^{-3} Myr^{-1} for 60% and 10% fraction of dynamically formed mergers respectively.