Electromagnetic Counterparts of Advanced LIGO Binary Black Hole Mergers

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Abstract

The Advanced LIGO (Laser Interferometer Gravitational-Wave Observatory) detectors have successfully detected gravitational wave signals from four binary black hole (BBH) mergers, GW150914, LVT151012, GW151226, and GW170104. These discoveries have prompted follow-up campaigns to search for any electromagnetic (EM) counterparts to the gravitational wave transients, which have yielded no strong candidates, except for the detection of a weak gamma ray transient 0.4 seconds after GW150914 in the sky localization of this gravitational wave event. Our motivation for this project is therefore to study various models of binary black hole mergers to predict whether or not any EM emission should be expected, and if so, what kind, how much, and when. While we currently do not believe that BBH mergers produce EM counterparts, the results of this study will help assess the prospects of these campaigns given our current observing limitations and will ultimately be an important step forward for future work in multimessenger astronomy.

Introduction

LIGO's Role in Multimessenger Astronomy

While studying electromagnetic emission from cosmic sources is still an important endeavor in astronomy, recent technological developments have provided astronomers with various new ways of learning about our universe. It has been found that single cosmic events can produce multiple types of signals, or "messengers," and by combining our knowledge of all these messengers we can better understand the astrophysics at hand in producing them. In addition to electromagnetic signals, we can observe and learn from gravitational waves, neutrinos and cosmic rays, and at the intersection of all these research areas lies multimessenger astronomy. As the most sensitive gravitational wave detector currently operating, LIGO plays an important role in this field. The process by which multimessenger astronomers from these various fields collaborate is through EM follow up campaigns, where a search is conducted for any EM or neutrino counterpart after a gravitational wave (GW) signal is received.

A Curious Gamma Ray Transient

On September 14, 2015, LIGO detected for the first time the gravitational wave signal from a merger of two binary black holes (GW150914). This detection was an important step forward for the field of multimessenger astronomy, and as such it was soon succeeded by a follow-up campaign to search for any electromagnetic counterpart to the merger event. This campaign searched in a wide variety of energy bands, including radio, optical, near IR, X-ray, and gamma ray, in the localization of the GW signal following the LIGO trigger. The only potential counterpart found was a short gamma ray transient detected by the Fermi telescope about 0.4 seconds after the GW signal [1]. This transient was determined to be in the localization region of GW150914, but as it was not detected by any other instruments it was never definitively determined to be correlated. Since it is not currently believed that binary black hole (BBH) mergers produce EM emission, this detection was particularly interesting to multimessenger astronomers, as it would have large implications for our understanding of BBH merger dynamics if the two events were confirmed to be related.

Motivations

While this strange gamma ray transient is a source of confusion, it is also a compelling piece of evidence in the argument supporting the use of EM follow up campaigns for binary black hole merger events. Although the discovery of a confirmed counterpart for a BBH merger would of course make a campaign worthwhile, there are many other factors that must be taken into account when assessing the validity of these campaigns, including how difficult it will be to overcome some unavoidable logistical challenges.

So far, all the GW triggers detected by LIGO have been produced by the coalescence of two black holes. Due to our lack of understanding of BBH EM counterparts, protocol has been to conduct follow up campaigns anyway in the hopes that a counterpart could be caught if it existed. Since it is difficult to understand the likelihood of these campaigns being able to detect any counterparts after a BBH merger, we are motivated to study models of progenitor systems of LIGO events to help answer that question.

EM Counterparts of Neutron Star Mergers

We expect that certain types of astrophysical events within the sensitivity range of LIGO will have EM counterparts, such as binary neutron star (BNS) mergers, black hole-neutron star (BHNS) mergers, and supernovae. These events have been carefully studied and their respective EM counterparts have been thoroughly modeled, as shown in Figure 1 [4].

We expect to see various kinds of emission, ranging from gamma ray bursts to radio waves, on vastly different time scales, such as seconds to years after the gravitational wave

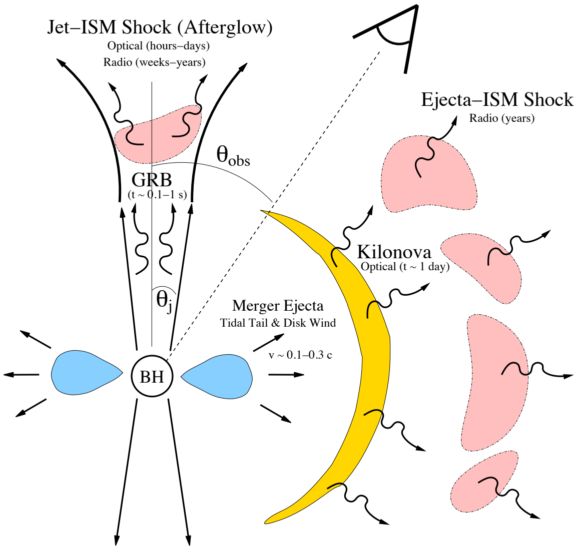

Figure 1: EM counterparts of binary neutron stars and black hole neutron star mergers. *Reproduced from Metzger & Berger 2012*

trigger, respectively. The energy of emission and timescale of arrival for each type of merger counterpart is highly dependent upon the progenitor system; however, in every merger model for which we expect an EM counterpart, there is some kind of matter present in the initial configuration of the system that remains visible after the GW emission takes place, and as far as we know this is NOT the case for BBH mergers. But, can we conceive of any black hole binary merger models with a source of matter that remains outside the Schwarzchild radius of the remnant black hole after the merger takes place? If so, it will be important to study these models to determine their chances of powering an EM counterpart and use them to try to comment on the astrophysics at hand in these mergers.

The Challenges of EM Follow Up Campaigns

Another reason why it is important to study different progenitor systems of binary black hole mergers is because electromagnetic follow up campaigns for these GW triggers face many challenges that are not easily remedied without further investigation. For example, given the short time delays that could occur for our receipt of EM counterpart emission, telescopes must act rapidly after the detection of a GW event to point at the localization region of the signal in order to hope to catch any counterpart. (We might naively assume that an EM counterpart would arrive at the same time as a GW signal since gravitational waves travel at the speed of light, but depending on the type of progenitor system it is reasonable to assume that there could be a time delay between the merger and the subsequent event which creates a counterpart.) However, the localization regions for these GW events are sometimes much too large to explore all at one time, as they can reach sizes as large as 1000 square degrees. Furthermore, in the case of BBH mergers, we don't fully understand what kind of emission to expect or when to expect it, so the detection of any counterpart will require the correct type of telescope to be lucky enough to point in the right direction at the right time. These challenges clearly present many barriers for detection of emission from a counterpart.

The Benefits and Goals of EM Follow Up Campaigns

Despite all these hardships, EM follow up campaigns stand to detect a crucial piece of information about the astrophysics at hand in the GW event. There are multiple reasons why we would like to detect an EM counterpart if possible, one of them being the fact that we get highly improved sky localization for our GW event when we factor in the localization of the counterpart. As shown Figure 2, if the gamma ray transient following GW150914 had been confirmed to be associated with this event, our localization area for the source would have drastically improved from an area of about 600 to about 200 square degrees. In particular, the detection of certain energy types of EM counterparts could help with localization so much that it could be possible to identify the host galaxy of the merger. With this information, we might even be able to conduct cosmological studies, so there are certainly significant scientific implications of detecting EM counterparts. Finally, in addition to all we can learn about where the signal came from, if an EM counterpart were detected for a BBH merger it would have a large impact on our understanding of the progenitor system of the black hole binary.

Methods

Progenitor Models of Binary Black Hole Mergers

There have been multiple models proposed to explain how the gamma ray transient seen after GW150914 could have been related to the GW event. For example, it has been suggested that this system started as a rapidly rotating, hypermassive main sequence star whose core collapsed into two dumbbell shaped clumps while leaving the outer layers of the star intact. Eventually these two clumps collapsed further into black holes, which later merged (emitting gravitational waves) and blew off the outer layers of the star as EM emission [3]. The validity of this model has been widely debated, and energy constraints for EM counterparts have been demonstrated for this model [2].

The progenitor model that I chose to focus on in this project is that of a hierarchical triple system, inspired by the system described in Rosswog et al. [5]. In this case, there are two black holes in a tight binary, and these two act as a single object in a much larger binary with a white dwarf star. The two black holes merge, emitting gravitational waves, and as they merge they are kicked towards the white dwarf star. Eventually, the white dwarf gets close enough that it becomes tidally disrupted and forms an accretion disk around the remnant black hole, which then acts as fuel for EM emission. In order for this system to be viable, the white dwarf star must be close enough that it can become tidally disrupted, but also far away enough that it does not have an impact on the gravitational waveform of the merger.

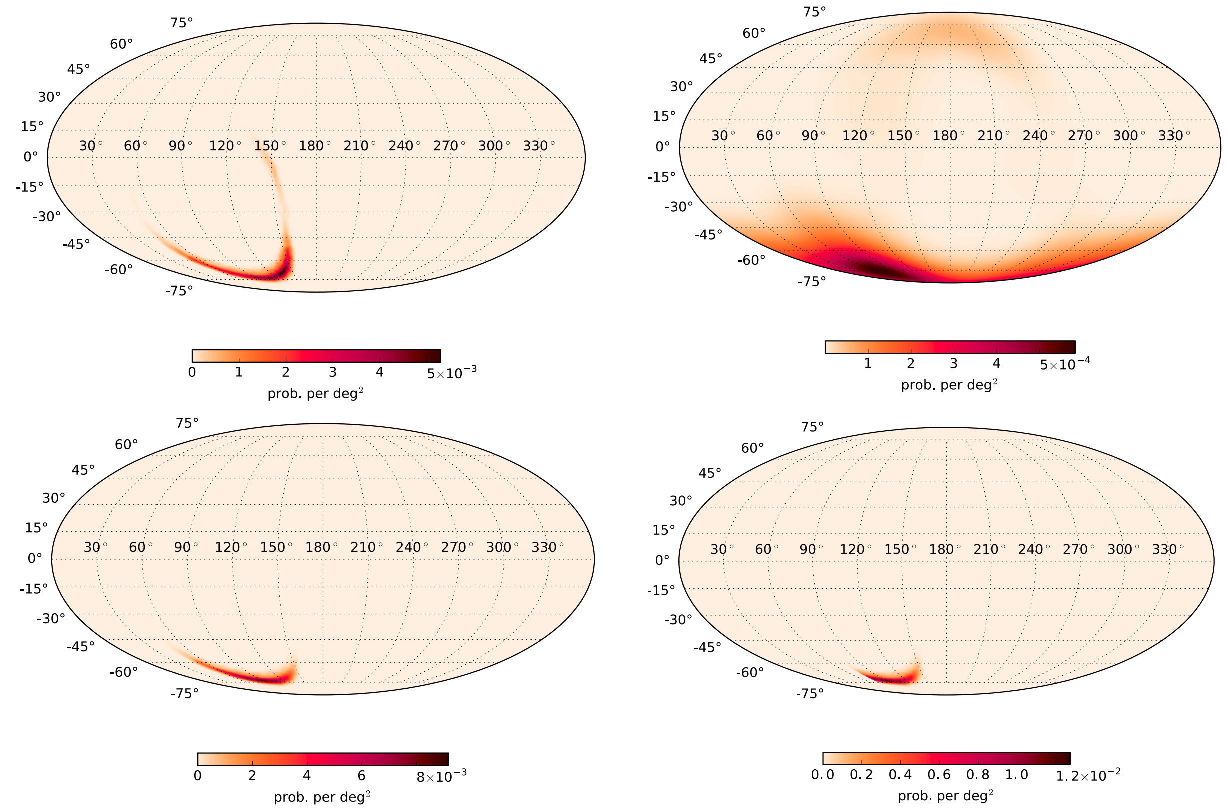

Figure 2: Original sky localization (top left) compared to improved sky localization for GW150914 (bottom right) assuming the Fermi gamma ray transient was indeed a counterpart. The gamma ray localization region is shown in the top right. *Reproduced from Connaughton et al. 2016*

White Dwarf Stars

The first step in testing the validity of this model was to conduct further research on the properties of white dwarf stars with the hope of better understanding their size and structure. The equation which describes how the outward internal pressure P of the star is balanced by its inward gravitational pull, called the equation of hydrostatic equilibrium, is

$$\frac{dP}{dr} = -\frac{G}{r^2}\rho(r)m(r), \tag{1}$$

where $m(r)$ describes the mass of the star as a function of radius and $\rho(r)$ describes the density of the star as a function of radius. We can also write the derivative of the mass function of this object as

$$\frac{dm}{dr} = 4\pi r^2 \rho(r). \tag{2}$$

Using these two differential equations along with the equations of state (EOS) of a Fermi gas, which we can take to be a model for our white dwarf star, we can find numerical solutions for the relationship between mass, radius, pressure, and density. There are two polytropic equations of state that I have used to accomplish this, one non-relativistic and one relativistic. The non-relativistic version is

$$P = K_1 \rho^{\gamma_1}$$

where γ_1 is a constant value for which we have chosen 5/3, and

$$K_1 = \tfrac{\hbar^2}{15\pi^2 m_e}(\tfrac{3\pi^2}{n m_n})^{5/3},$$

where n=2. The relativistic version is

$$P^{-2} = (K_1\rho^{\gamma_1})^{-2} + (K_2\rho^{\gamma_2})^{-2}$$

where K_1 and γ_1 are the same as before, but

$$K_2 = \tfrac{\hbar c}{12\pi^2}(\tfrac{3\pi^2}{n m_n})^{4/3}$$

and $\gamma_2 = 4/3$.

First, I used an RK4 integration technique to solve (1) and (2) numerically with the non-relativistic equation of state, and was able to produce Figure 3. This shows how the internal pressure, density, and mass scale from r=0 to the final radius of the white dwarf. Next, I ran this simulation many times using a variety of central pressures and recorded the resulting mass and radius of each simulation. By looking at all these data points as a whole, one can plot the range of possibilities for white dwarf mass and radius relationships, as shown in Figure 4.

Since this result was obtained numerically, I wanted to compare it to the answers I obtained analytically when looking at the two different equations of state. In order to do this, I found an order of magnitude estimate for how radius scales with mass for each

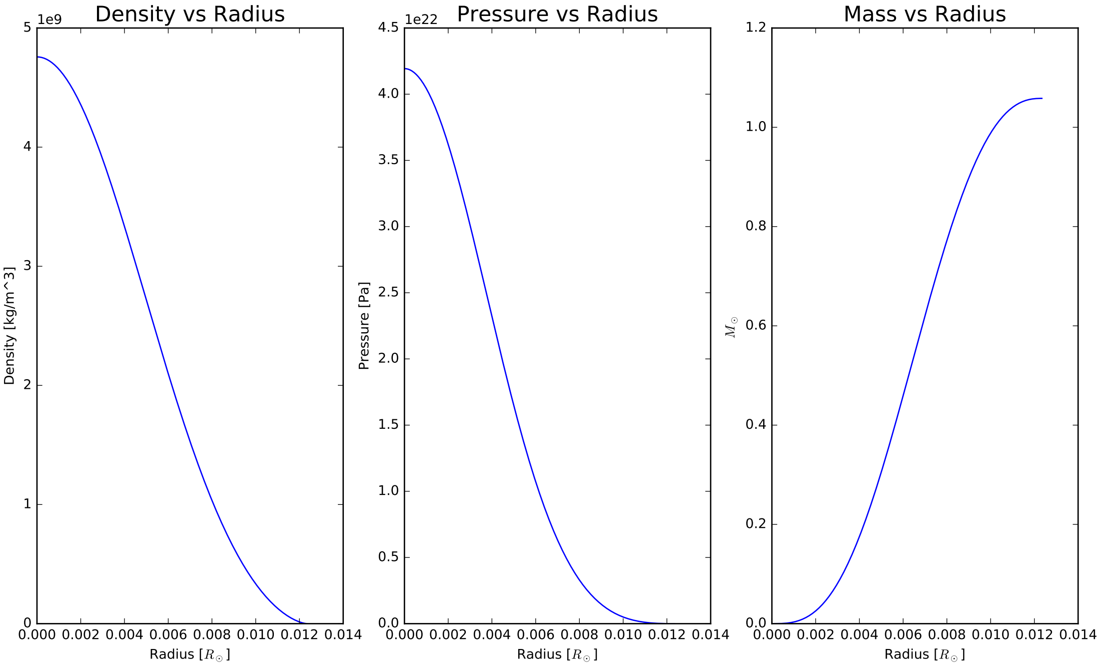

Figure 3: Solutions to the equation of hydrostatic equilibrium for a white dwarf with central pressure 4.2e22 Pa

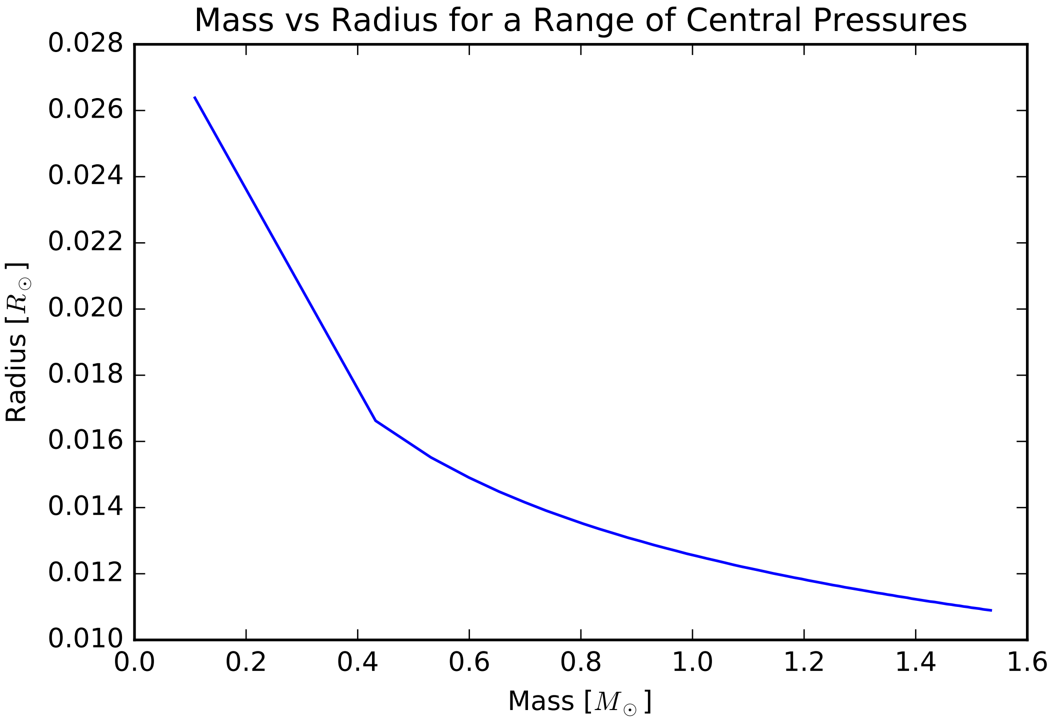

Figure 4: The range of possibilities for mass and radius of a white dwarf star

condition (relativistic and non-relativistic) and plotted these against the numerical result, scaling them appropriately. As can be seen in Figure 5, the numerical simulation is nearly identical to the order of magnitude estimate obtained with the non-relativistic equation of state, while the relativistic estimate is very different from the numerical simulation. In fact, the relativistic estimate shows that there is a limit to how massive a white dwarf star can be, which is just over 1.4 solar masses. This is the Chandrasekhar mass limit, and doing this simulation gives us a good constraint on how massive and how large any white dwarf in a hierarchical triple system might be. Once we know this, we can study how far away the star would need to be in order not to influence the coalescence of the central black holes and estimate how this distance compares to the radius of the white dwarf itself.

Tidal Forces

In this scenario, our white dwarf has to be just far enough away that it doesn't impact the merger of the two black holes but somehow can still be brought close enough to the resulting black hole that it becomes tidally disrupted. Therefore, it is important to know at what point tidal forces come into play, or how close the white dwarf has to be to the central object before it starts to really feel tidal forces. To find this value, I compared the hypothetical gravitational force felt by the white dwarf on its side closest to the black hole to the force felt on the exact opposite side of the star. To do this mathematically, I calculated the difference in the forces felt by these two points, given by

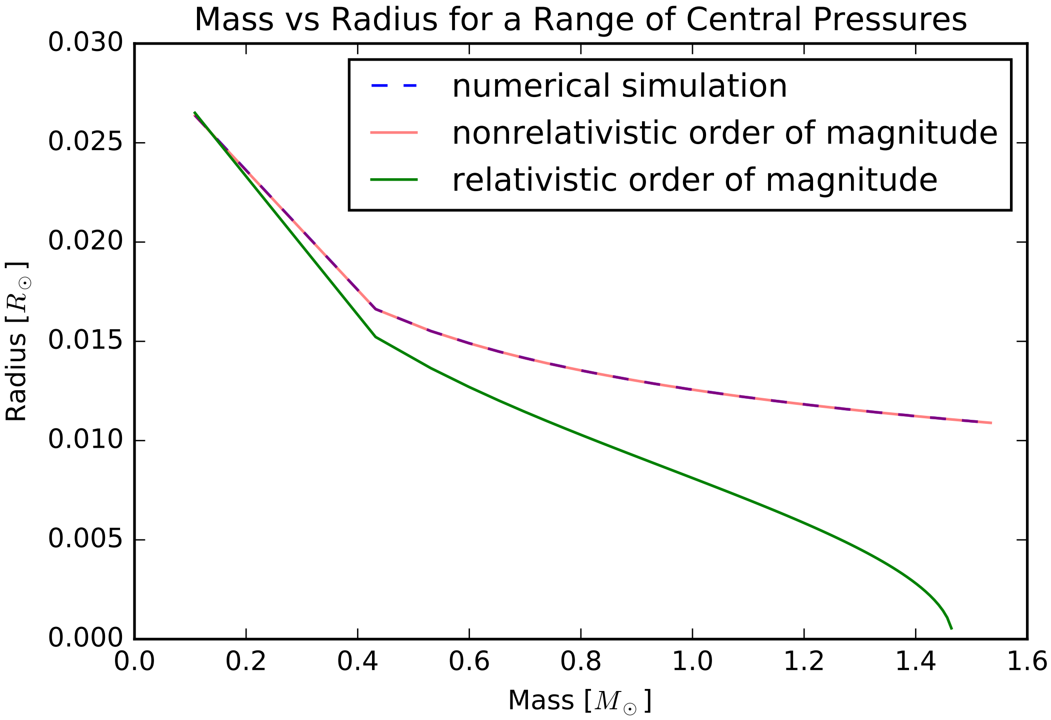

Figure 5: Numerical simulation vs analytic order of magnitude estimates for white dwarf mass and radius possibilities using both relativistic and non-relativistic equations of state

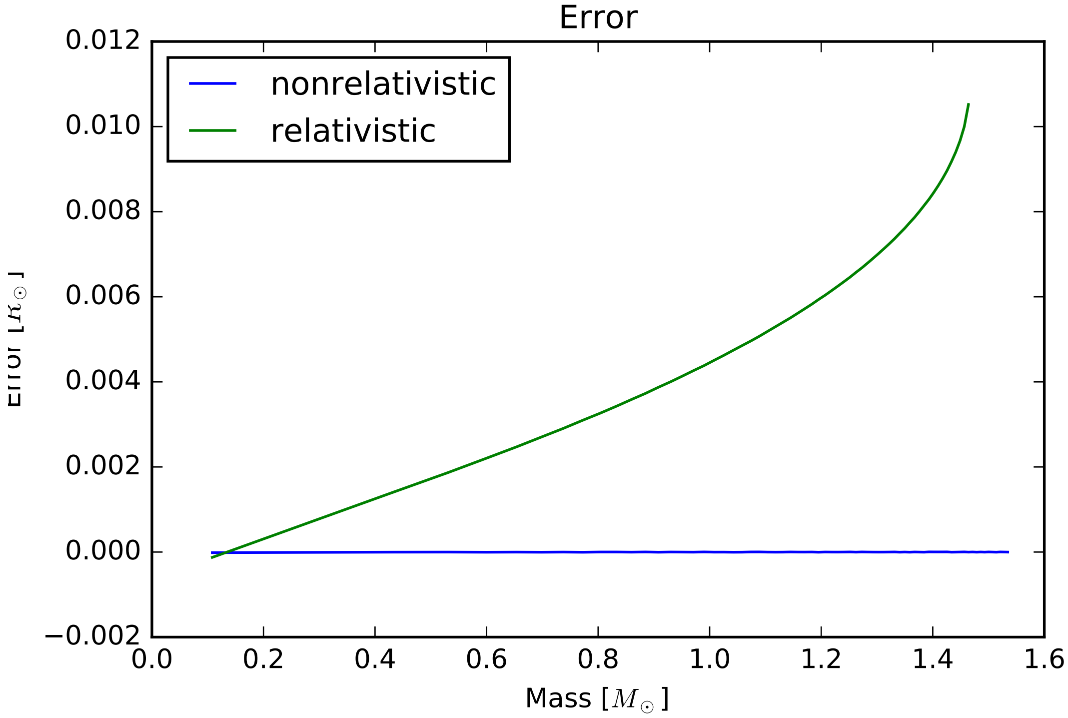

Figure 6: Error in order of magnitude calculations compared to non-relativistic numerical simulation

$$\Delta F(R) = -GM_1M_2[(R - r_{WD})^{-2} - (R + r_{WD})^{-2}]$$

where r_{WD} is the radius of the white dwarf, somewhere on the order of 7000 km as given by our simulation. This function can be expanded in a Maclaurin series to find the first nonzero term, and in doing so one can find the radius R when these tidal forces come into play. After doing this exercise, I found that this value is about 1.3 million km, which is several orders of magnitude larger than the radius of our white dwarf star. This is a good sign, since it means that we can't rule out this model based on an issue of size compatibility.

Driving an EM Counterpart

The next step in determining whether this is a viable system will be to model the tidal disruption of the white dwarf star. The surface of equipotential between the two objects (the remnant black hole and the white dwarf) is called the Roche lobe, and in order for any mass transfer to occur, the white dwarf star must overflow the Roche lobe through the Lagrange point L1. In Figure 7, I show the Roche potential and Roche lobe of a system composed of a 60 solar mass black hole and a 1 solar mass white dwarf star. In each frame, the binary separation decreases, and one can see the change in the potential and the size of the Roche lobe as the objects move closer together. The Roche potential is given by

$$\phi(\vec{r}) = -\frac{GM_1}{|\vec{r} - \vec{r_1}|} - \frac{GM_2}{|\vec{r} - \vec{r_2}|} - \frac{1}{2}(\Omega \times \vec{r})^2. \tag{3}$$

Goals and Future Work

Modeling Updates

First, I will have to study how black hole kicks can bring the remnant black hole and white dwarf star together, and obtain an estimate for how long this might take. I also hope to expand this model of Roche lobe overflow to a 3D system in order to better understand at what point Roche lobe overflow starts to occur. In addition, I will need to model the formation of an accretion disk around the black hole and eventually how this accretion disk powers an EM counterpart.

Statistical Analysis

Once I determine whether or not this system does indeed produce an EM counterpart, it will be important to conduct a statistical analysis to assess what the likelihood of an event like this occurring is. From my model, I aim to obtain a posterior distribution of amounts of expected EM emission, and I will use this distribution to compare to the gamma ray transient seen after GW150914. I will have to take into account in my priors the likelihood of a system such as this one even existing. Ultimately, I would like to use this project to place upper limits on the amount of emission that one can expect from such a merger, and assess the capabilities of present day telescopes to detect such levels of emission.

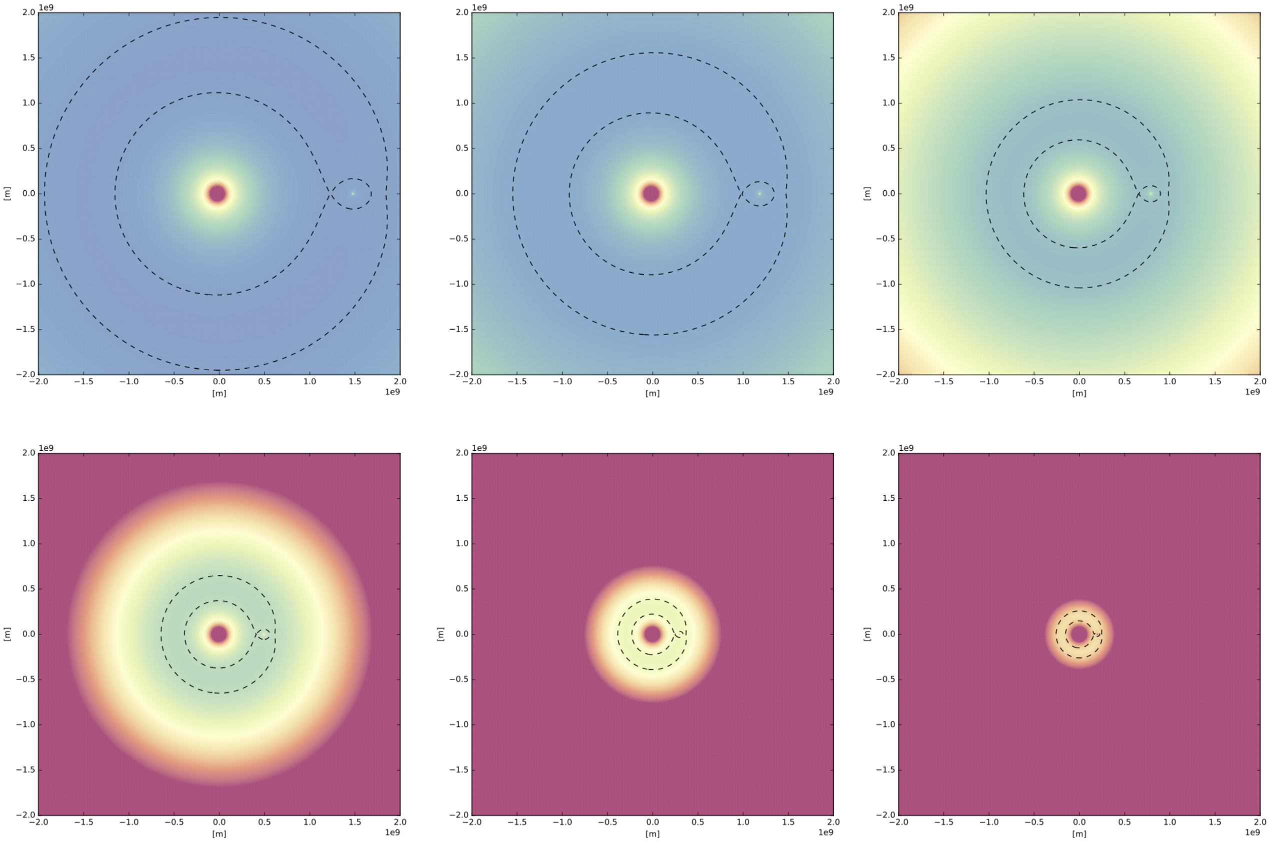

Figure 7: The Roche potential as the binary separtation decreases between a 60 solar mass black hole and a 1 solar mass white dwarf star. The Roche lobe, or the surface of equipotential between the two objects, is shown in the dashed line.

Conclusion

LIGO sits at the forefront of multimessenger astronomy as the most sensitive gravitational wave detector in operation, and as such it plays a crucial role in the effort to detect electromagnetic counterparts of cosmic events which produce gravitational wave signatures. Since all of the gravitational wave signals detected by LIGO thus far have been the result of binary black hole mergers, it is important to understand the capabilities of BBH progenitor systems to produce EM counterparts, not only in the interest of science, but in the interest of conducting searches for these counterparts effectively. While it is too early to say whether the hierarchical triple system model could be a viable progenitor for GW150914, it cannot be ruled out yet, and further research must be conducted to determine its viability.

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