Contribution Prospectives 2020
Constraining Astrophysical Models and Populations using Gravitational Waves

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Abstract

The detection of gravitational waves from compact binary mergers by the Advanced LIGO and Advanced Virgo detectors has put the first constraints on compact binary formation scenarii. In this letter, we present different aspects of research in areas of astrophysics that we believe will be of crucial importance in the next 10 years and will only be feasible with GW detectors: (1) mass and spin distributions of compact binaries as a function of redshift (2) astrophysical formation scenarios (3) cosmological formation of compact binaries and seeds of supermassive black holes.

Overview

A major question raised after the first GW detections is “How did this binary form?” Currently, the formation through massive binary evolution the most likely scenario, although formation through N-body interactions in dense stellar environments such as clusters likely has a significant contribution to the merger rate as well (Abbott et al, 2016). The evolution of massive stars is still poorly understood as theoretical and observational progress is hindered by the fact that massive stars are rare and most live in binary (or multiple) systems (Sana et al. 2012). Several mass transfer phases, either through stable Roche Lobe overflow or the more dramatic common envelope phase results in the exchange of both matter and angular momentum, fundamentally changing the evolutionary process of the stars, and the binary itself (Tauris et al, 2006). If the system can remain bound throughout the entire evolutionary process, a compact binary can form. The nature of the compact objects (black hole, neutron star or white dwarf) depends on the initial masses of the stars and the binary interactions. The compact binary then evolves through GW emission, and, provided the binary separation is small enough, it will end its lifetime through the merger of the two compact objects. This phenomenon has been observed by the Advanced LIGO and Advanced Virgo detectors. As of the end of the second LIGO/Virgo observing run (O2), 10 binary black hole mergers and 1 binary neutron star merger have been observed (Abbott el at, 2019a).

Most evolutionary models of binary stellar systems are based on the coupled evolution of two single, isolated stars (Hurley et al, 2002, Belczynski et al, 2016). However, these evolutionary models are incomplete. While the mechanisms governing isolated stellar evolution are not fully understood, we know even less about the physical processes occurring in close binary systems. The most important outstanding questions are: (1) the common envelope phase. This can occur at different times, according to the changing sizes of the stars, and is crucial for sufficiently shrinking the binary orbit such that binary components eventually merge. At present, this is still both theoretically and observationally highly unknown. (2) the natal kick received during the supernova (SN). As the SN is not symmetric, the compact object receives a kick which may eject it from the binary, which impact on recently formed black holes is unconstrained. (3) metallicity. This plays an important role in the strength of the stellar winds, which can cause the star to lose much of its mass, and is crucial for explaining that higher than expected masses observed by the LIGO/Virgo detectors. Many of these uncertainties are relevant whether the progenitor stars were formed in binaries or in star clusters. Therefore, as the full evolution of merging compact binaries is not completely understood, the current population synthesis models for binary systems have a high degree of uncertainty.

Binary Astrophysics in the 2G/2G+ era

Compact Binaries

At the end of the second Advanced LIGO/Virgo observation run (Abbott el at, 2019a), 11 events were observed. These events have already allowed us to begin investigating the mass, spin and redshift parameter space for compact binaries (Abbott el at, 2019b). In the next five years, we expect the number of detections to increase dramatically. This will allow us to make more significant statistical statements on the redshift evolution of mass and spin distributions, and distinguish formation scenarios using spin measurements.

In order to accurately measure the intrinsic properties of compact binaries, the GW community uses Bayesian inference. A key component of Bayesian inference is the construction of parameter priors, i.e. a-priori information that can be motivated either by current observations or by our current lack of knowledge. At present, as we do not know the mass and spin distributions for compact objects, we have to use uninformative priors. We also assume a certain prior on luminosity distance coming from observations in the local universe and that our sources are distributed isotropically in the sky. As we move forward with more detections, we will slowly be able to swap out these priors for ones that are more astrophysically motivated and based on our detected populations, which will have a major effect on our ability to describe the detected binary.

The 11 events observed thus far have already allowed us to rule out some astrophysical models and call others into question. While not much can yet be said about the populations of Binary Neutron Stars (BNS) or Neutron Star - Black Holes (NSBH), the detected BBHs pose a number of questions. Two of the systems in question, GW151226 and GW170608, contain low mass black holes of $(13.7, 7.7)$ and $(10.9, 7.6)\, M_{\odot}$ respectively. Others have more moderate masses, i.e. $(~30,~25)\, M_{\odot}$, and one, GW170729, is the most massive yet detected with component masses of $(50.6, 34.3)\, M_{\odot}$. In the next few years, a major research focus will be to determine if all of these sources belong to the same population, or multiple populations with different formation channels, host galaxy types, metallicity etc. Such work will rely on good astrophysical models combined with reliable statistical analysis.

In April 2019, the third Advanced LIGO/Virgo science run (O3) began. This is the first science run in the era of open alerts. While no EM counterparts have yet been announced, the LIGO/Virgo collaboration has issued alerts for 33 potential GW candidates. While the majority of these systems are BBHs, a number of BNS and NSBH alerts have been sent. If confirmed as astrophysical, we are on the verge of making significant investigations into population models for these binary types. Within the next 5 years or so, we should be able to constrain population models and formation channels for BNS/NSBH systems in the local universe.

Multimessenger Astronomy (MMA)

Much of the rich astronomy extracted from the BNS merger GW170817 was due to the follow-up by almost 80 facilities and satellites in the hours - weeks that followed the event (Abbott et al, 2017a). The difference between the time of arrival of GWs at Advanced LIGO/Virgo and the gamma rays at Fermi-GBM allowed a measurement of the speed of GWs with unprecedented accuracy (Abbott et al, 2017b). This single event has already ruled out a number of alternative theories of gravity and cosmology that required the speed of GWs to be different from the speed of light.

The kilonova light curves, the delay between the detection of gamma and x-rays, as well as the late-time emission of radio waves sparked a vast number of studies world-wide into the modelling of BNS mergers. While the merger itself, and the subsequent formation of a post-merger remnant, was not observed in GWs, this events has stimulated an unprecedented level of activity in numerical relativity simulations and EOS modelling.

Currently there is a conflict between measurements of Hubble's constant from the CMB and Type 1a supernovae. While it was possible to infer a value of H_0 from the observation of GW170817 (Abbott et al, 2017c), it was not accurate enough to resolve the conflict. However, with more events associated with an EM counterpart, the fact that we measure luminosity distance directly in GW astronomy without the need for a cosmic distance ladder, it is possible that GW measurements of H0 can resolve the tension between the two measurements in the next decade.

Binary Astrophysics in the 3G era

Einstein Telescope

Binary Black Holes (BBHs)

As we expect to be able to detect BBHs out to a redshift of $z \sim 10$ in the 3G era, we expect to be able to constrain the BBH merger rate as a function of redshift all the way to the beginning of reionisation. This will allow us to answer questions such as what is the correlation between the masses of the first metal-poor stars, metallicity and galaxy evolution. We expect to detect roughly a million BBH mergers per year. With such a large sample of events, we will be able to constrain BBH formation channels and probe the matter distribution of the universe. This is possible as stellar evolution binaries should track cosmic star formation, and more specifically metal-poor environments such as small galaxies, while primordial black holes should track the dark matter distribution.

As the expected signal-to-noise ratio of closer mergers will be high, precision measurements of mass, spins and distance will allow us to probe if these parameters evolve as a function of redshift. Furthermore, the precision measurement of masses will allow us to properly bound the potential mass gap between the maximum neutron star (NS) mass and minimum black hole mass as prediction from binary stellar evolution models. Properly determining this bound would allow us to constrain supernova mechanisms and NS equation of state (EOS).

As the merger frequency for a compact binary scales as the inverse of the total mass, a 3G detector with sensitivities down to 1Hz would allow us to probe the universe for intermediate mass black holes (IMBH) with masses of $10^2 - 10^3\,M_\odot$. The detection of multiple systems would allow us to not only constrain the formation channels of IMBHs, but also investigate the proposition that they act as "seeds" for the formation of supermassive black holes in galactic centers.

Binary Neutron Stars (BNS) / Neutron Star - Black Holes (NSBH)

While we observed the inspiral of a BNS with GW170817, the merger and production of a post-merger remnant were not seen. This was due to the fact that the merger took place at frequencies greater than 1 kHz, where the detector sensitivity is dominated by photon shot noise from the lasers in the interferometer. 3G detectors will have sufficient sensitivity at these high frequencies such that we will be able to determine whether the BNS promptly collapsed to a BH, or formed a supramassive or hypermassive NS that subsequently collapsed to a BH over timescales of tens of milliseconds to seconds. Measuring the post-merger GW signal will provide us with another way of constraining the NS radius, and hence the nuclear EOS.

A 3G detector would allow us to measure the BNS merger rate up to the star formation peak at $z \sim 2$. Precision measurements of the component masses will allow us to discriminate between different formation scenarios and models of mass ejection. This will be important as it determines the light curves of kilonovae and would allow us to constrain different models of mass ejection and electromagnetic emission. Given the high number of expected events, and the precision measurement of the binary parameters, discrimination between different EOS models should also be possible.

Multimessenger Astronomy (MMA)

MMA follow-ups of BNS/NSBH mergers will be vitally important in the 3G era. If we can identify the host galaxy for a sufficient number of events, we may also be able to trace the demographics of low mass compact objects out to redshifts of $z \sim 0.5$. MM observations will also be of utmost importance when it comes to investigating nucleosynthesis in BNS mergers. While the GW detection will determine source type, masses, spins, merger rates etc., the MMA observations of associated kilonovae should determine the r-process yields, and hence the abundance of heavy elements being produced in each merger. These observations would further allow us to determine how the r-process in BNS/NSBH mergers depends on host galaxy type and redshift, and may hence allow us to determine the formation of heavy elements over cosmic time.

Core Collapse Supernovae (CCSN)

It is expected that 3G detectors will observe CCSN in both single and binary stellar systems. The observation of a CCSN in a binary system may provide important information on the natal kick of the remnant and hence the probability of the binary remaining bound after the SN. This information is important for both the detailed modelling of individual binary systems, as well as population simulations. While the emitted GW signal from a CCSN is expected to be weak, a coincident detection of neutrinos with a very clear timestamp would dramatically allow us to improve the GW search for such a weak signal. If we were able to detect the GW signal, it would allow us to measure the mass of the progenitor and constrain the core spin.

LISA

LISA will be a space-based GW detector operating in from 0.01mHz to 1Hz in the mid 2030s. LISA will be of great interest for cosmology and the study of supermassive black holes, as is detailed in a paper led by S. Babak in this prospective. LISA will also detect compact binaries with periods below 1 hour in the Milky Way and possibly nearby galaxies. Given the distribution of stellar masses at birth, the signal will be dominated by double white dwarfs, which stem from stars below 8 Msun. LISA will effectively detect every white dwarf binary with a period below 10 minutes, thus providing a complete and unbiased sample. Lower frequency binaries will create un unresolved foreground, informing on global star formation rate of the Milky Way. Of order 10 000 systems will have an individual frequency measurement, and about a third of them will have a chirp mass estimate within 10% (Nelemans+02, Lamberts+19). This sample will enable statistical studies to constrain the common envelope mechanism for lower mass stars and determine the local Type Ia supernova rate from WD mergers. Different binary types will likely have different spatial distributions in the Milky Way, and provide a new probe for the study of the Milky Way, which is very complimentary to large electromagnetic surveys. Nearby WDs will also be detectable in the optical (and sometimes X-rays), these multimessenger observations will enable detailed studies of mass transfer in low mass binaries. LISA will also detect up to a few tens of binaries with neutron stars and/or black holes (Belczynski+10). However, chirp mass measurements will only be possible for binaires with a measurable frequency derivative (a chirp), which makes the identification unlikely for many of these massive systems. However, the identification and localisation of even a few systems may enable the detection of electromagnetic counterparts and enable the study of binary evolution in specific environments of the Milky Way. LISA's ability to provide good enough sky localisation for EM follow-up and robust mass estimates strongly depends on the integration time. As such, most of the galactic science cases call for an extended mission of at least 10 years. As the mission is currently being planned, this aspect should be emphasized and supported by a broader community.

French Perspectives

The initial stages of GW astronomy are primarily driven by the LIGO/Virgo Collaboration (LVC), which is composed of 1300 members. As a result, its objectives and methodologies are beyond national interests and "habits". Currently the LVC analysis of the mergers is limited to parametrised astrophysical distributions, intended to be model-independent. This allows support from a large collaboration but can be problematic for more astrophysically motivated analyses. The development of improved astrophysical priors for the analysis of 2G+ data may be hindered by this methodology. The continuous development of the detector and data analysis methods for GWs is a long-standing effort at IN2P3. However, the astrophysical interpretation of the detections, as well as multimessenger follow-up now calls for much closer interactions between IN2P3 and INSU. Regular interactions between scientists with different expertise should be encouraged. The interpretation of future detections will rely both on astrophysical knowledge and understanding of Bayesian statistics. Similarly, the success of the Galactic science case of LISA strongly depends on inputs of the astrophysical community. In comparison with other countries of comparable size, a more extended global French GW astronomy community of is still lacking. While day-to-day scientific interactions with colleagues within the same working group of the LVC or LISA (or any other collaboration) are often smooth and fruitful, a better understanding of the funding and hiring practices of both institutes would be helpful for scientists and decision-makers at different levels. It is currently clear that scientists working in GW and multimessenger astronomy no longer fit within the clear framework defined by the 01 or 17 commissions, but actually straddle both. The success of the field will be highly dependent on an understanding of this fact by both IN2P3 and INSU when hiring new recruits.

References

Abbott el at, 2019a, *GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs*, Phys. Rev. X 9, 031040

Abbott el at, 2019b, *Binary Black Hole Population Properties Inferred from the First and Second Observing Runs of Advanced LIGO and Advanced Virgo*, Astrophys. J. Lett. 882, L24

Abbott et al, 2017a, *Multi-Messenger Observations of a Binary Neutron Star Merger*, Astrophys. J. Lett. 848, L12

Abbott et al, 2017b, *Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A*, Astrophys. J. Lett. 848, L13

Abbott et al, 2017c, *A gravitational-wave standard siren measurement of the Hubble constant*, Nature 551, 85

Abbott et al, 2016, *Astrophysical implications of the binary black hole merger GW150914*, APJL, 818, L22

Belczynski et al, 2016, Nature, 534, 512

Hurley et al, 2002, *Evolution of binary stars and the effect of tides on binary populations*, Mon.Not.Roy.Astron.Soc. 329, 897

Lamberts et al, 2018, *Predicting the binary black hole population of the Milky Way with cosmological simulations*, MNRAS, 480, 2704

Sana et al, 2012, *Binary interaction dominates the evolution of massive stars*, Science, 337, 444

Tauris et al, 2006, *Formation and evolution of compact stellar X-ray sources* in *Compact stellar X-ray sources* Edited by Walter Lewin Michiel van der Klis. Cambridge Astrophysics Series, No. 39., Cambridge University Press