Compact Binaries as Sources of Gravitational Radiation

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Abstract. With current terrestrial gravitational wave detectors working at initial design sensitivities, and upgrades and space missions planned, it is likely that in the next five to ten years gravitational radiation will be detected directly from a variety of classes of objects. The most confidently expected of these classes is compact binaries, involving neutron stars or black holes. Detection of their coalescence, or their long-term orbits, has the potential to inform us about the evolutionary history of compact binaries and possibly even star formation over the past several billion years. We review what is currently known about compact binaries as sources of gravitational radiation, as well as the current uncertainties and what we expect to learn from future detections of gravitational waves from these systems.

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INTRODUCTION

Ground-based gravitational wave detectors are now operational and taking data in many laboratories. The current maximum sensitivity is such that a double neutron star inspiral could be detected out to ~ 20 Mpc, more than the distance to the Virgo cluster of galaxies. The next generation of improvements, expected in less than a decade, will enhance sensitivity to the point that regular detections of many events are likely. In addition, the planned launch in the next decade of space-based gravitational wave detectors such as LISA will allow a complementary view of the lower frequency gravitational wave universe, which is inhabited by thousands of known sources and will likely prove to be an important and precise probe of strong gravity.

Gravitational wave sources are typically divided into four categories: binary inspirals, continuous sources such as spinning neutron stars, burst sources such as supernovae, and stochastic sources such as turbulence in the early universe. Of these categories, binaries are the best-understood astrophysically. They have therefore received close attention, in terms of optimal frequency ranges for detection, data analysis and waveforms, and astrophysical rate estimates and scenarios.

Here we discuss binary sources of gravitational waves, for both ground-based high-frequency detectors and space-based low-frequency detectors. In § 2 we discuss double neutron star binaries. In addition to reviewing rate estimates and uncertainties, we discuss the information that will be obtained about the masses and spins of neutron stars, as well as about their evolutionary histories and their possible link to short gamma-ray bursts. In § 3 we examine binaries involving a stellar-mass black hole and either a neutron star or another black hole. In § 4 we turn to more massive black holes, in the

$M > 10^2 M_\odot$ range, and their observability in binary inspirals in either relatively local star clusters or in dark matter halos in the crucial $z \sim 5-30$ epoch of structure formation. In § 5 we survey the remarkable recent progress in numerical relativity made by many groups, and we present our conclusions in § 6.

NS-NS BINARIES

The discovery and observation of the double neutron star binary PSR 1913+16 by Hulse and Taylor [36], plus similar systems, demonstrates that these orbits decay at a rate that is within 0.1% of the prediction of general relativity. With several such systems now known that will spiral together within a few billion years or less, it is possible to make informed estimates of the rate of such inspirals per Milky Way Equivalent Galaxy, or MWEG. Several groups have made such calculations [62, 39, 20], with rates ranging from a few to a few hundred per million years per MWEG. When combined with the volume expected to be probed by second-generation ground-based detectors such as the advanced Virgo and LIGO instruments, this suggests detection rates of tens per year. There is still substantial uncertainty in this number, because among other things it is necessary to guess the number of sources below current thresholds of radio detection.

When double neutron star mergers are detected, they will yield a number of astrophysical returns. One obvious yield will be a far larger number of high-precision neutron star masses than exist currently. Radio observations of the current handful of binary pulsar systems suggest that the neutron stars in these systems occupy a relatively narrow band in masses, from $1.25 M_\odot$ (pulsar “B" in the PSR J0737–3039 system; [44]) to $1.44 M_\odot$ (the pulsar in the first binary pulsar system PSR 1913+16; [36]). Other observations, notably of the NS-WD system PSR J0751 [59] and of X-ray timing from neutron star low-mass X-ray binaries [86, 5, 6, 7] suggest that some neutron stars have masses on the order of $2 M_\odot$, but statistical and systematic uncertainties, respectively, prevent any definitive conclusions at this time.

Measurement of tens of pairs of neutron star masses will increase the sample dramatically, although it will still be possible that it is the evolutionary history of such systems, rather than fundamental nuclear physics, that funnels the masses into a narrow range. If radius measurements are possible along with the masses, this will place strong limits on the properties of dense matter regardless of what the masses are [41]. Neutron star angular momenta might also be measured via their frame-dragging effects, but known double neutron star sources and binary evolution theory both suggest that the dimensionless spin $j \equiv cJ/GM^2$ will be much less than 0.1 and thus difficult to detect.

Mergers of two neutron stars also have a prospect of being electromagnetically bright, perhaps producing short gamma-ray bursts (GRB; see [50] for a recent comprehensive review). If so, coincident observations of a short gamma-ray burst and gravitational waves from the event will establish their nature immediately. The rate per volume is difficult to establish due to many uncertainties, but even a single such event would have major implications. It has been pointed out [40] that if, as expected, the gamma rays come from the orbital axis, the strength of the observed gravitational wave signal will be greater than average. The same considerations apply if short GRBs are caused instead by mergers of neutron stars with stellar-mass black holes, which we discuss in the next section.

BH-NS AND BH-BH BINARIES

No stellar-mass black holes are known in binaries with neutron stars or other black holes. As a result, there is a lack of observational guidance about the expected merger rate, and indeed the formal lower limit could be zero. This can be turned around to note that detections via gravitational waves will thus open up new understanding for us about the evolutionary history of such systems.

Incidentally, unlike for NS-NS systems, mergers in globular clusters might contribute significantly to the BH-NS and BH-BH rates. The argument against their contribution to the NS-NS rate is straightforward (see [62] for an early version). The Galaxy has roughly 100 globular clusters. Suppose that each cluster has 200 neutron stars (probably an overestimate), and that every one of them pairs with another neutron star and merges within a Hubble time (certainly a gross overestimate). The rate is then $R = 100 \times 100/10^{10}$ years, or $R \approx 10^{-6}$ yr^{-1}. The estimated rate in the disk per MWEG is $\sim$ few $\times\, 10^{-5}$ yr^{-1} [39], so globulars are far down in the total rate. Even for ellipticals, where the specific frequency of globulars is an order of magnitude larger than for spirals, the extreme upper limit is still less than the rate in the main portion of the galaxy, and a realistic value is orders of magnitude less. In contrast, since no BH-NS or BH-BH systems are known, it is possible that the dominant contribution comes from the complex dynamical interactions possible in dense stellar systems such as globulars.

Despite the uncertainty, there is optimism that the observed BH-NS or BH-BH merger rates could be larger even than the NS-NS rates, simply because the higher system mass allows detection out to several times the distance of detectable NS-NS mergers, hence a volume of (several)^3 times larger. As with NS-NS mergers, if a BH-NS merger is detected coincident with a short GRB it will settle the issue of the central engine of these events, and will also settle the issue of whether black holes swallow neutron stars whole or whether they spit out enough matter to produce strong electromagnetic signals (for analytical and numerical explorations in full general relativity, see [52, 22, 74]). Resolution of this issue from the theoretical side will require a full no-approximation treatment of general relativistic magnetohydrodynamics (MHD). Encouragingly, independent groups have recently written and tested such codes, so answers to these and other strong-gravity MHD question may not be far off. This will also help determine whether either NS-NS or NS-BH mergers can eject nucleosynthetic products with unique signatures (due to the extreme neutron richness of the star), and if so, whether those products can enrich significantly the interstellar or even intergalactic medium [42, 68, 37, 75, 71].

BLACK HOLES ABOVE $\sim 10^2\,M_\odot$

Black holes above stellar mass certainly exist in the universe, but there are many fundamental questions remaining about them. For example, there is a clear link between the kinematical properties of galactic bulges and their central supermassive black hole, but the origin of this link and its role in galaxy formation is still being debated. There is also strong but not yet conclusive evidence of intermediate-mass black holes in the $\sim 10^2 - 10^4 M_\odot$ range, which might be forming at the present epoch as well as at higher redshifts. The maximum characteristic frequency of a gravitational wave is $\sim$ few $\times 10^3$ Hz$(M_\odot/M)$ for the inspiral portion, depending on the spin, and a comparable frequency $\sim 10^4$ Hz$(M_\odot/M)$ for the ringdown. Therefore, black holes of mass $< 10^3 M_\odot$ might be observable with ground-based detectors (with assumed frequency range $\sim 10 - 2000$ Hz), but more massive black holes can only be seen with space-based low-frequency detectors (e.g., LISA, with a range $\sim 10^{-5} - 10^{-1}$ Hz). We will thus separate these and discuss supermassive black holes first, followed by intermediate-mass black holes.

Supermassive black holes

For our purposes, a supermassive black hole (or SMBH) is the central, most massive, black hole of a galaxy or dark matter halo. The mass range is therefore large in principle, from perhaps $\sim 10^3 M_\odot$ for halos containing the first stars to $\sim 10^{10} M_\odot$ in the largest galaxies today. In the process of hierarchical structure formation, as halos merge their central black holes may as well, leading to LISA-detectable signals from the $z \sim 5 - 30$ era of the first galaxies. The rate and properties of these mergers have been calculated by a large number of researchers (e.g., [48, 84, 80, 38, 72, 70]). The rate estimates span some five orders of magnitude, from a minimum of ~ 0.1 yr^{-1} to $> 10^4$ yr^{-1}, with the most recent and comprehensive models typically in the ballpark of tens per year. The prime reason for such uncertainty appears to be that it is currently unknown what halo masses can produce massive black holes; since there are more low-mass than high-mass halos, efficient production of black holes in the $M_{\rm halo} < 10^8 M_\odot$ range would imply higher rates and also a higher redshift start to such mergers.

There are additional uncertainties related to the effectiveness of dynamical friction on halos in the early universe [76], and to the role of kicks in black hole mergers in the early universe [49, 12, 34, 45, 85, 81, 43, 51] and for intermediate-mass black holes [77, 55, 56, 57, 58, 54, 30, 31, 60]. Kicks are an especially current topic because recent progress in numerical relativity has yielded dramatic advances in understanding of the strong gravity contribution to kicks (see below), which complements more accurate post-Newtonian calculations of the kick during the inspiral portion of coalescence. The net result is that LISA observations of these early-universe mergers will encode unique information about key aspects of early structure formation. This is especially true because the mass range to which LISA will be most sensitive ($\sim 10^4 - 10^6 M_\odot$) is extremely difficult to observe electromagnetically due to the low mass and luminosity of the associated galaxies and the small range of influence of the black holes.

Intermediate-mass black holes

We define intermediate-mass black holes (IMBHs) to be black holes of mass greater than could form from a single star in the current universe (thus $M > 10^2 M_\odot$) that are not the central black holes of galaxies or dark matter halos (and hence probably have masses $M < 10^{4-5}\,M_\odot$; see [54, 78] for overviews). It has been proposed that these could be the remnants of massive Population III stars [46], and an already massive black hole with initial mass $M_{\rm init} > 10^2\,M_\odot$ might be able to grow over billions of years via collisionless interactions in dense stellar clusters [77, 55, 56, 57, 58, 30, 31, 60]. In my opinion, however, the currently most promising origin for these objects is as the result of runaway stellar collisions in young massive stellar clusters whose relaxation time for the most massive stars is less than their $\sim 2\times 10^6$ yr main sequence lifetime [21, 65, 63, 33, 60, 32, 28, 27, 26]. After becoming black holes, they may acquire stellar companions in the cluster by exchange or tidal interactions and the resulting accretion events could explain at least some of the ultraluminous X-ray sources.

Mergers of stellar-mass black holes are likely to be rare enough and distant enough that their detection rate with LISA is discouragingly low [82]. However, some recent simulations suggest that for young dense stellar clusters with realistic initial binary fractions $f_b > 0.1$, more than one IMBH could form in a given cluster via collisional runaways [32, 26]. If so, the IMBHs will merge with each other within a few million years. It has also been proposed that, since massive young clusters are themselves clustered, a cluster-cluster merger could lead to the mergers of their IMBHs [1]. Either scenario leads to signals potentially detectable to redshifts $z \sim 1$, which is far enough to probe some features of active star formation that are not easily observable in other ways [26].

Yet another possibility is that if a cluster with an IMBH forms close enough to the center of its host galaxy, the cluster spirals in to the center in less than a few billion years. The cluster will be dissolved by the tidal forces in the galactic nucleus, and the IMBH can then merge with the SMBH. Such an event would lead to an extreme mass ratio inspiral (EMRI; for example, $\sim 10^3\,M_\odot$ with $\sim 10^6\,M_\odot$), but one with a much stronger signal than traditional $10\,M_\odot$-$10^6\,M_\odot$ EMRIs. This could lead to especially precise and model-independent probes of the spacetime around rotating SMBHs. Rate estimates are difficult because of many uncertainties, but initial analytical [53] and numerical [64, 47] explorations suggest that LISA rates of a few to tens per year are plausible.

PROGRESS IN NUMERICAL RELATIVITY

Focusing now on mergers between two black holes of comparable mass, the coalescence process has typically been divided into the stages of inspiral (from large separations down to the point of dynamical instability), merger (from dynamical instability to the overlap of horizons), and ringdown (in which the merged and lumpy common horizon settles into a Kerr state). The ringdown phase has been understood for some time using perturbation theory, and substantial analytical progress has been made on the inspiral via post-Newtonian (e.g., [10]) and effective one-body [13] approaches. The merger phase, however, is not accessible analytically with any precision, because it involves strong nonlinearities. This stage can therefore only be treated with full numerical solutions of Einstein's equations. This is particularly tricky because even though in physical terms the equations do not have a preferred gauge, gauge choice makes a significant difference in the stability of numerical evolutions. In addition, the presence of a physical singularity and of the coordinate singularity at the horizon pose significant challenges.

Prior to 2005, although formal mathematical progress had been made in casting the equations in well-behaved ways [73, 8], numerical evolutions were still tantalizingly difficult. This all changed in the summer of 2005, with Frans Pretorius' stable evolution of two equal-mass nonspinning black holes over two full orbits, including the merger and ringdown [66, 67]. Multiple other groups followed with results in short order with their own equal-mass nonspinning coalescences [14, 15, 2, 16, 3, 79] and initial results have now been reported for unequal-mass nonspinning mergers [35, 4, 29] and for mergers of spinning equal-mass black holes [17, 18]. It is encouraging to note that the specifics of these numerical methods differ significantly from each other, suggesting that many robust paths to solution have been discovered, and that agreement between the methods provides a strong test of the reliability of the waveforms. In particular, it seems that at present there is clear understanding of the waveform of the last $\sim$orbit of the merger of two equal-mass nonspinning black holes, based on cross-comparison of results. Progress continues to be rapid, and it will be interesting to see whether numerical template banks can be constructed that span a reasonable range of spins, orientations, and mass ratios.

From the astrophysical standpoint, the most interesting output from such calculations is the recoil produced by the gravitational radiation emitted during a merger with some asymmetry (such as unequal masses or spins). This is particularly relevant to the redshift $z \sim 5-30$ universe, when hierarchical merging of dark matter halos is expected to lead to mergers of their central massive black holes. If the black hole mergers produce a strong enough kick to eject the remnant from the merged halo, then the halo will, for a time, be without a central black hole. Recent numerical simulations (e.g., [35, 4, 29]) bolster earlier analytic suggestions that the presence of a central black hole can have a major influence on galactic development, hence gravitational radiation kicks at this stage can have a key effect on galactic evolution.

There have, therefore, been a large number of analytic calculations of the recoil produced by radiation during the inspiral phase [61, 9, 24, 25, 69, 83], and some recent estimates of the contribution from the merger as well [23, 11, 19]. However, since the majority of the kick is in the strong-gravity regime, once again numerical calculations are necessary to get values that are precise enough for astrophysical purposes. Progress in this realm has also been rapid, with the first fully numerical calculations [35, 4, 29] suggesting that, for example, two nonspinning black holes in a mass ratio of 1.5:1 will produce a net kick of ≈ 90 km s^{-1}, which is consistent with analytic calculations and is reliable to $\sim$10%, sufficient for astrophysical applications. There is still a great deal to explore about kicks; in particular, it will be necessary to map out the dependence of kick speed on mass ratio and also on black hole spins.

CONCLUSIONS

The current rapid progress in gravitational wave instrumentation as well as numerical relativity make it realistic to think that within a decade detections of the gravitational radiation from compact object inspirals will become routine, and that the results will be interpreted with confidence in a physical and astrophysical framework. For some of the sources, such as double stellar-mass black hole mergers, there will be no electromagnetic counterpart, and hence gravitational radiation will provide our only glimpse at these events. For others, such as double neutron star or NS-BH mergers, there could well be spectacular EM counterparts such as gamma-ray bursts, and simultaneous EM and GW detections will provide profound and complementary information about some of the most luminous events in the universe. Either way, the era of gravitational wave detections is likely to bring unanticipated discoveries to the realm of compact object astrophysics.

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