Compact Object Mergers as Laboratories for Extreme Matter, Curved Spacetime, and Fundamental Physics By Dhruv Sharma

Abstract

With the detection of the first gravitational wave in 2015, and with the first detection of a binary neutron star merger with multi-messenger astronomy in 2017, compact object mergers have emerged as a leading probe of extreme astrophysics. This review discusses the key primary LIGO-Virgo-KAGRA Collaboration and related literature exemplifying one thesis, however limited: that compact binary mergers are laboratories for probes of strong-field gravity and dense matter as well as cosmology, with varying emphasis on each. The earliest observations constrained the equation of state of ultra-dense matter by measuring tidal deformability from neutron-star inspirals. Models consistent with the observations suggested relatively small neutron-star radii. The distance between these two values ranged between 11 and 13 km, depending on priors adopted, from the equation of state assumed, and whether observations from X-Rays and nuclear physics were mutually consistent. The second series of tests, using the compact-binary signals, tested predictions of general relativity in the strong-field, dynamical regime (and, with respect to Einstein's theory, the equality of light and gravity propagation speeds). Uncertainties in these null tests may arise from both the signal's amplitude and how the deviation is measured. For class three, the use of mergers as standard sirens within the distance ladder is limited by degeneracy between distance and inclination of the merger, low rate of electromagnetic counterpart detection, and lack of accurate galaxy catalogs. But combined with the first two classes, compact object merging gives very concrete observational prospects. At this point in time, GW170817 is the strongest evidence, as well as the clearest thorn in its side.

Background

Until recently, all astronomy made use of electromagnetic radiation, of all wavelengths from radio waves to X-rays to gamma-rays, as the messenger from the universe. Gravitational waves, however, are ripples of spacetime curvature first predicted by Einstein in 1916 because of his general theory of relativity, but they were not discovered until a century later. Because they interact so weakly with matter, gravitational waves propagate unaffected through events that do not emit electromagnetic radiation, including black hole mergers and neutron star mergers.

The main topics of this review are the remnants left when stars deplete their nuclear fuel and can no longer support themselves. A neutron star is a superdense object of a mass greater than that of the Sun, which is compressed into a sphere about the size of a city, with the density of atomic nuclei. A black hole is an object whose surface is so dense that not even light can escape it. General relativity predicts that if two such objects form a binary pair, they will spiral closer together as they lose energy to gravitational waves. The orbit speeds up as the objects come together, producing gravitational waves which have ever-increasing frequency and amplitude: a chirp. The frequency sweep is strongest at a combination of the two masses called the chirp mass; since this dominates the wave, it is almost always the best-measured property of

any detection. There is no unique frequency associated with the system, and the individual masses and spins are inferred from smaller features in the waveform. These signals are too weak to be detected by eye against the background noise in the data stream, and require matched filtering: cross-correlating data against banks of templates of theoretical waveforms calculated from general relativity and then identifying which template produces a statistically important correlation in the data stream (Krishnendu and Ohme). These sources may be classified as binary black holes, binary neutron stars, or binary neutron-star-black hole systems, with each source population illuminating a different corner of physics.

All of the sources cited here for the literature review mention some primary sources. A famous indirect detection was the discovery of the binary pulsar PSR B1913+16 by Hulse and Taylor in 1974, where a 30-year timing of orbital period decay agreed within 0.2% with the expected rate of energy loss due to gravitational radiation, winning them the 1993 Nobel Prize (Weisberg and Taylor). The September 2015 detection of gravitational waves from the merger of a 36 and 29 solar mass black hole at a distance of 1.3 billion light years (GW150914) with importance of greater than 5 sigma (Abbott et al., "Observation of Gravitational Waves"; Abbott et al., "Properties of the Binary Black Hole Merger GW150914") was followed by the August 2017 detection of the first binary neutron-star merger observed via gravitational waves and across the electromagnetic spectrum, inaugurating multi-messenger astronomy (Abbott et al., "GW170817: Observation of Gravitational Waves"). Since then the first such overlaps in the three types of thematic literatures reviewed below, indicating some overlap between the literatures.

This paper is not a standard review, but a survey of especially influential primary literature and associated reviews. These papers in science of neutron-star matter, strong field gravity, and standard-siren cosmology are cited repeatedly by other articles. The paper is therefore useful as a conceptual synthesis, but it does not try to provide a thorough coverage of other studies nor a formal statistical ranking of evidence. The question is not whether compact object mergers in each of these domains are valuable in their own right (this is well understood by the community), but whether, and how, the same events and the same data analysis pipelines really bring the two domains together. It is worth noting that this is an important caveat, because the review risks overweighting convergence if a few spectacular detections (most notably GW170817) are treated as a mature population.

My main thesis is that mergers of compact objects should be seen as a single physical laboratory rather than as a set of disjoint phenomena. I re-stress the idea because, from the perspective of using mergers as an observation platform, the scientific payoff varies markedly for different subjects within the field. They have enabled the strong-field gravity test, detailed formation and population of black-hole mergers, allowed dense-matter inference from the one neutron-star merger, and placed constraints on X-ray and nuclear physics. So far, they have not yet measured fast enough to yield a value of the Hubble parameter for standard siren cosmology. The rest of this paper reviews this discussion, including recent results in the equation of state of dense matter, general relativity in the strong field, and the cosmological expansion rate.

Compact Mergers as Probes of Ultra-Dense Matter

The purpose behind the papers in this first collection is to use the tidal interaction of inspiraling neutron stars to constrain the equation of state (EOS) of matter at supernuclear density. This regime is inaccessible to Earth-based experiments. This mechanism can be stated tidally, as it is what transforms the merger into a nuclear physics instrument. As these neutron stars approach each other the tidal force each invariant mass exerts on the other raises a tidal bulge on that star much as the Moon raises a tidal bulge on Earth. The degree to which a star can be deformed by this tidal force can be expressed by a dimensionless number, the tidal deformability, which is determined by the equation of state. The stiffness of the equation of state is, loosely speaking, a measure of the star's resistance to being compressed: an equation of state representing large stars which are weakly distorted has a high deformability. This deformation depletes some of the orbital energy faster than if the stars were point-like masses, so the gravitational wave phase is slightly advanced in the point-mass case. The offset can then be measured and used to determine the deformability and properties of matter that would otherwise remain out of reach.

The first results came from the LIGO-Virgo Collaboration's analysis of GW170817, where it was reported that the first binary neutron star merger had been detected and put an upper limit on the system's combined tidal deformability (Abbott et al., "GW170817: Observation of Gravitational Waves"). By taking a more advanced approach, an inference of about 222 under a uniform-mass prior was obtained, which changed the upper limit from 700 to 800 at this epoch (Abbott et al., "Properties of the Binary Neutron Star Merger GW170817"). When a joint analysis of the data with a common equation of state for both stars was performed, the common radius was found to be about 10.8 km with a range between 8.9–13.2 km (Abbott et al., "GW170817: Measurements of Neutron Star Radii"). These findings are important to this thesis, since they suggest a direct transition of waveform phase to nuclear physics.

It is important to note that the translation is not model-free. The tidal signal in GW170817 is inferred informative, but not precise enough to unambiguously determine the equation of state. The radius, however, changes when we vary the mass ratio, change the waveform model, change the spins, or change the parametrization of the tidal deformability. Going from 700 to 800 is not a crisis. Rather it is a warning that even headline numbers will change, as many choices in our analysis and source model are systematically revisited in this still young field. As illustrated by the literature on dense matter, the information that gravitational waves can provide is simultaneously powerful and limited. Although they are capable of placing a new constraint on the size of neutron stars, the information content requires a network of assumptions for interpretation and corroboration.

Several other works also self-consistently combine the gravitational-wave measurements with other astrophysical constraints. Most and colleagues argued that if the equation of state allows a two-solar-mass star (as required by the radio pulsar measurements) this severely constrains the possible range of radii for neutron stars. As such, these authors found that the radius of a 1.4-solar-mass neutron star lay between approximately 12.0 and 13.5 km (Most et

al.). This work is related to the thesis because it shows that the merger laboratory does not stand alone. However, its findings become stronger when combined with pulsar mass measurements, and are a limitation of the strongest version of the thesis. In the most constraining case, mass measurements from outside the merger, nuclear theory, and, eventually, X-ray observations are required. The merger provides an important pillar for multi-messenger inference, but is not a stand-alone laboratory, as the inferences are otherwise not as straightforward.

This limitation was highlighted by the second possible BNS merger discovery, GW190425, which had a mass of roughly 3.4 $M_\odot$, had no obvious EM counterpart, and no mechanism for breaking multi-messenger degeneracies with respect to counterparts. This made it less useful for much of the cross-domain analyses described in this review. It also raised questions about whether the Galactic sample is representative of the population observed by GW observatories. GW190425 thus gets in the way of a simple story about slow convergence. We can help, but the information that different detections yield is not the same. Some events sharpen the equation of state picture. Others simply test how complete the population picture is.

The third, most-complete, multi-messenger analysis includes gravitational-wave tidal deformability measurements, X-ray astrophysics from NASA's NICER, and nuclear physics. Both Miller et al. and Riley et al. independently measured the pulse profile of pulsar PSR J0030+0451 and claimed that concurrent mass-radius measurements were possible. Both experiments found a radius of about 13 km for a 1.4 solar mass star (Miller et al., "PSR J0030+0451"; Riley et al., "A NICER View of PSR J0030+0451"). The independent, pulse-profile based NICER analyses of the heavier PSR J0740+6620 in particular were important, because the star's mass is nearly two solar masses, requiring equations of state supported by higher central densities (Miller et al., "The Radius of PSR J0740+6620"; Riley et al., "A NICER View of the Massive Pulsar"). Raaijmakers et al. found canonical radii for neutron stars, combining and adapting GW170817, GW190425, NICER, radio timing, and nuclear theory, of about 12 km, depending on the equation of state parametrization. Similarly, using the reanalysis of NICER as well as modern insight on chiral effective-field theory, Rutherford et al. argued that the radius of a canonical neutron star is between 11.7 and 13.1 kilometers (Rutherford et al.).

Taken together the body of evidence is persuasive, but should not be overstated. The convergence at 11–13 km is one of the strongest results presented here, but is a convergence of overlapping credible intervals and compatible modeling frameworks, and is not a direct measurement in the sense that one would usually expect. It carries some genuine weight, but cannot exclude the possibility of a systematic error, or unify very soft equations of state, although it cannot ultimately distinguish between a diverse crust or core mixture and one containing some kind of exotic ingredient (hyperons, deconfined quark matter, etc.). The most honest conclusion is that compact mergers have made dense-matter physics observationally accessible, but have not fully solved the microphysical identification problem.

While most of the other work in the group looks at what happens inside the neutron star, the neutron-star merger produced a material that was ejected from the neutron stars at

GW170817 underwent r-process nucleosynthesis. A rapid sequence of neutron capture that has long been thought to produce about half of the elements heavier than iron, including the gold and platinum. The radioactive decay of freshly created material powered a kilonova, which was detected about eleven hours after the merger in the host galaxy NGC 4993. Pian et al. interpreted the color and decay rate of the kilonova, which was consistent with r-process material on the basis of the spectroscopic evidence of the kilonova, as direct evidence for the formation of heavy elements in a neutron-star merger. This essentially extends the merger laboratory, with the same event responsible for dense matter constraints also explaining the cosmic origin of heavy elements. However, the r-process interpretation is the most widely held. More detailed constraints on the element-by-element yields are more uncertain and depend on details of radiative-transfer modeling, ejecta geometry, and opacities.

The Compact Mergers as Tests of General Relativity

The second category of tests uses mergers to test general relativity in the strong-field, dynamical regime in a way that no previous test could. The classic tests of general relativity (bending of starlight, precession of Mercury, binary-pulsar timing tests described above) are tests of the weak-field limit or tests of systems moving slow with respect to the speed of light. On the other hand, as noted, during the final stages of a compact binary merger, the orbital separation is only a few kilometers, but relativistically large velocities and highly curved spacetime are involved. If GR fails anywhere in the region reachable from the Earth, it would be one of the first places where such failure would show.

The most relevant tests were on the third gravitational wave transient catalogue using the Collaboration's standardized battery of tests. Using multiple internal consistency checks (inspiral consistency test, merger-ringdown consistency test, anomalous dispersion test, additional polarizations), no statistically important deviation from general relativity was found (Abbott et al., "Tests of General Relativity with GWTC-3"). As a concrete example of what is made possible, an upper bound on the graviton mass can be obtained, less than about 1.27×10^{-23} eV/c², which is tighter than the corresponding Solar System limit. This result is relevant for the thesis of the paper, because all the equations which predict the mass, tidal deformability and distance of the binary also give rise to testable predictions.

It is important to stress, however, that these are null tests: the null result is only up to the sensitivity of the instruments, the quality of the signals observed and the specific alternative effect being tested. Therefore, one cannot claim that all modified gravity theories have been ruled out. Most of those tests in the catalog relate to the loudest and most easily parameterized tests of general relativity (as in binary black hole mergers), while the remainder, contrasting dense matter and bright siren cosmology, relate mostly to neutron-star mergers with electromagnetic counterparts. Thus, while the general relativity literature is closely related to these tests, it is less closely related to their evidence base.

The second branch of the field relates to the measurement technique. Krishnendu and Ohme review the field, and argue that gravitational waves provide qualitatively new ways to test

gravity, which can be divided into those due to the wave generation, those due to the wave propagation, and those arising from the merger remnant (Krishnendu and Ohme). The upshot of this section is that gravitational-wave tests are not merely quantitatively stronger versions of the Solar System or binary-pulsar tests; they test different regimes and different parts of the theory. The other implication is that, since all the tests above are cast in terms of parametrized deviations from general relativity, a theory producing deviations weak enough that they fall through the crack between parametrizations will be difficult or impossible to detect with any of the methods above.

GW170817 combined with the electromagnetic counterpart provides the most stringent limit of this kind. In this event, the gravitational-wave burst and the gamma-ray burst GRB 170817A were seen nearly simultaneously. The small difference in arrival time, 1.74 seconds after 130 million years of travel, constrains the difference between the speed of gravity and the speed of light to within a few parts in a thousand trillion (Abbott et al., "Gravitational Waves and Gamma-Rays"). GW170817 exemplifies the single merger event, with a variety of astrophysical applications: from constraining dense matter physics, testing gravity by measuring propagation speed and, by the distance and the redshift of the host galaxy, helping to constrain cosmology models.

Nevertheless, even though this is a strong propagation test, it must be said that this is not a complete test of general relativity. The travel time from GW170817 to Earth of the gravitational wave and photon emitted by the merger strongly constrains most modified gravity theories, particularly those predicting different propagation speeds for gravitational waves. However, it does not directly constrain other predictions of these theories, e.g. the detailed nonlinear black-hole ringdown dynamics or the properties of the interior of neutron-star matter. The conclusion is therefore balanced: compact mergers have made general relativity testable in a previously inaccessible regime, and all the studies we have critically reviewed are consistent with general relativity. There is confidence in this conclusion, but it is possible that more exotic signals might change this picture and test more deviations.

Compact Mergers as Cosmological Standard Sirens

All of the other works reviewed estimate the value for the Hubble constant, the rate of expansion of the universe, using mergers as standard sirens without utilizing the cosmic distance ladder. All the works reviewed conclude absolute distance can be determined from the gravitational-wave amplitude, a possibility provided by general relativity. Standard sirens can be measured directly from gravitational wave observation, which differ in their sources of uncertainty from both the early-universe measurement of the expansion rate from the cosmic microwave background and the late-universe measurement of the expansion rate from the distance to a distant supernovae determined by Cepheid-variable stars. Standard sirens can therefore provide an independent consistency check.

The theoretical basis of this method predates the detectors themselves. Schutz proposed in 1986 that gravitational-wave observations can determine the Hubble constant because the

gravitational-wave signature of a compact binary contains information about both the chirp mass and the luminosity distance (Schutz). The waveform amplitude measures the distance, just as the chirp mass determines the frequency sweep. This has the advantage that it can give the distance without the usual ladder of calibrated standard candles, but the distance is not enough. The redshift needs to be found. This may be either by direct detection of the host galaxy, or by association with a galaxy in the localization volume. It is at this stage that the method becomes observationally difficult.

The first observational measurement was from GW170817. The Collaboration and its partners viewed the gravitational wave signal, and located its optical counterpart in the host galaxy NGC 4993. They found $H_0 = 70$ km/s/Mpc (with an asymmetric uncertainty of roughly +12/−8) (Abbott et al., "A Gravitational-Wave Standard Siren Measurement"). The result was important because it does not depend on either the distance ladder or the cosmic microwave background. However, this uncertainty is too large to resolve the Hubble tension, and the main statistical problem is the distance-inclination degeneracy, whereby a relatively face-on system at one distance could be confused with a more inclined system at a different distance, and the gravitational-wave amplitude cannot always break the degeneracy.

Radio jet observations of GW170817 used to constrain the viewing angle showed the usefulness of electromagnetic data. The Hubble constant is now inferred to be 68.9 km/s/Mpc, with a much smaller uncertainty compared to the standard siren (Hotokezaka et al.). The ability to use electromagnetic data to constrain the Hubble constant makes mergers an even better cosmological tool. On the other hand, it shows a possible weakness of using mergers for cosmology. The best measurements are obtained if the gravitational-wave signal can be combined with a detailed electromagnetic model of a known nearby event. This means bright-siren measurements are informative, but not the most accurate ones, which require astrophysical modeling of the known events above.

Thus, the definition of a bright siren differs in the literature: a bright siren as GW170817 has an electromagnetic counterpart, from which both a unique host galaxy and a unique redshift can be inferred. Events like this are rare, and a dark siren does not have a counterpart, as is the case for most binary black hole mergers. The problem is statistical: the galaxies in the localization volume can give a possible redshift. A stack of many events strengthens the cosmological signal. In Fishbach et al. 's case, they excluded GW170817's host galaxy, and their result had a large uncertainty, but not less overall value being about 77 (the true error was not shown in their paper). This shows how well large catalogs and complete surveys will improve to make dark sirens competitive with standard sirens (cases that measure the distance and the electromagnetic redshift).

As such, this section provides the strongest test of the paper's unified-laboratory thesis. Strongly, standard sirens make compact mergers of cosmological tools. On the other hand, the literature on cosmology is less mature than that of dense matter or general relativity, statistically more difficult to study. For instance, the Planck Collaboration is able to determine the expanding rate of the Universe, based on the cosmic microwave background, as 67.4 kilometers per second

per megaparsec. Riess et al. get an expansion rate nearer to 73.0, yielding a five-sigma disagreement (Planck Collaboration; Riess et al.). Current standard siren distances do not have enough precision to discriminate between these poles. Their importance is not that they have solved the Hubble tension but that they are an independent line of inquiry that may well provide the resolution as more siren events are detected, and as the counterpart/galaxy catalog data grows.

Conclusion

Although the three literatures I have considered in this paper belong to the fields of nuclear physics, of gravitational theory, and of observational cosmology respectively, yet taken together they show an amazing structural isomorphism. A class of astrophysics observation, the gravitational wave (GW) events, shows directly that all three portions are possible. The gravitational waveform of a neutron star merger can be used to constrain the tidal deformability of the star, while the EM counterpart can be used to constrain the speed of gravity and the properties of the host galaxy. The distance-redshift relation can be used to make a standard siren measurement of the Hubble constant. This remains the strongest evidence for compact object mergers as a unified laboratory.

So the lesson is easily stated. While the unity is real, it is certainly incomplete. The detailed matter literature is moving forward. The last details will need NICER, gravitational wave observatories, the masses of radio pulsars, the modeling of kilonovae, and the nuclear theory behind these phenomena. The event sample is the largest in the relativity literature because all the available information is present in a single binary black hole merger. The only limitation for null tests is determined by the sensitivity of the measurements and the size of the deviation. By contrast, the standard-siren result is comparatively more conceptually straightforward (no distance ladder), but less precise, and does not resolve the Hubble tension. In addition, the same merger events may not necessarily carry all three domains along in the same way or to the same degree.

There are some common trends between different subfields, as the literatures are starting to interlace: gravitational-wave catalogs, electromagnetic counterparts, the era of modeling X-ray pulse profile, nuclear theory. Second, GW170817 is the most extreme case of and most cautionary tale for the field, but it also shows the huge potential of a multimessenger event to probe dense matter, gravity and cosmology. But it also shows that because it is currently the only such case, any general statements about compact mergers still rest on a very small number of especially informative observations. Third, each of these three disciplines has uncertainties: the composition of the densest stable stars, the relative validity of general relativity in the strong field, and the value of the Hubble constant.

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