MATTERS OF GRAVITY

The newsletter of the Division of Gravitational Physics of the American Physical Society

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Contents

Editor

David Garfinkle

Department of Physics Oakland University Rochester, MI 48309
Phone: (248) 370-3411
Internet: garfinkl-at-oakland.edu
WWW: http://www.oakland.edu/physics/Faculty/david-garfinkle

Associate Editor

Greg Comer

Department of Physics and Center for Fluids at All Scales,
St. Louis University, St. Louis, MO 63103
Phone: (314) 977-8432
Internet: comergl-at-slu.edu
WWW: http://www.slu.edu/arts-and-sciences/physics/faculty/comer-greg.php

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Editorial

The next newsletter is due December 2019. Issues **28-53** are available on the web at `https://files.oakland.edu/users/garfinkl/web/mog/` All issues before number **28** are available at `http://www.phys.lsu.edu/mog`

Any ideas for topics that should be covered by the newsletter should be emailed to me, or Greg Comer, or the relevant correspondent. Any comments/questions/complaints about the newsletter should be emailed to me.

A hardcopy of the newsletter is distributed free of charge to the members of the APS Division of Gravitational Physics upon request (the default distribution form is via the web) to the secretary of the Division. It is considered a lack of etiquette to ask me to mail you hard copies of the newsletter unless you have exhausted all your resources to get your copy otherwise.

David Garfinkle

Correspondents of Matters of Gravity

- Daniel Holz: Relativistic Astrophysics,
- Bei-Lok Hu: Quantum Cosmology and Related Topics
- Veronika Hubeny: String Theory
- Pedro Marronetti: News from NSF
- Luis Lehner: Numerical Relativity
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- Warren Johnson: Resonant Mass Gravitational Wave Detectors
- David Shoemaker: LIGO
- Stan Whitcomb: Gravitational Wave detection
- Peter Saulson and Jorge Pullin: former editors, correspondents at large.

Division of Gravitational Physics (DGRAV) Authorities

Chair: Gary Horowitz; Chair-Elect: Nicolas Yunes ; Vice-Chair: Gabriela Gonzalez . Secretary-Treasurer: Geoffrey Lovelace; Past Chair: Emanuele Berti ; Councilor: Beverly Berger Members-at-large: Lisa Barsotti, Theodore Jacobson, Michael Lam, Jess McIver, Alessandra Corsi, Henriette Elvang. Student Members: Belinda Cheeseboro, Alejandro Cardenas-Avendano.

we hear that ...

David Garfinkle, Oakland University garfinkl-at-oakland.edu

Clifford Will has been awarded the 2019 Albert Einstein Medal by the Albert Einstein Society in Berne, Switzerland.

Gabriela Gonzalez has been named the 2019 SEC Professor of the Year.

Bernard Schutz has been elected to the National Academy of Sciences.

Gabriela Gonzalez has been elected Vice-Chair of DGRAV. Alessandra Corsi and Henriette Elvang have been elected Members-at-large of the DGRAV Executive Committee. Alejandro Cardenas-Avendano has been elected Student Student Member of the DGRAV Executive Committee.

Hearty Congratulations!

Gravitational-wave Standard Sirens

Daniel Holz, University of Chicago holz-at-uchicago.edu
Maya Fishbach, University of Chicago mfishbach-at-uchicago.edu

Overview

Over thirty years ago Bernie Schutz pointed out that general relativity provides an exceedingly elegant way to determine the absolute distance to a source at cosmological distances [36]. By measuring the gravitational waves from the inspiral and merger of two compact objects, such as neutron stars or black holes, one can infer both the mass scale and the luminosity distance to the source. The scale, known as the chirp mass, comes from the frequency evolution, while the distance comes from the measured amplitude of the waveform in the detectors [see][24][for an introductory discussion]. These sources are the gravitational analog of "standard candles" such as Type Ia supernovae, which can be used to infer absolute distances through use of a cosmological version of the inverse square law. Because of this close correspondence, these binary sources have been dubbed "standard sirens" [23]. Unlike in the case of standard candles, standard sirens offer a direct and independent way to measure distances, completely obviating the need for a distance ladder. They are calibrated directly by general relativity.

An absolute distance measurement is of particular interest when coupled with a redshift measurement to the same source. This combination constrains the distance-redshift relation, which is a measure of the scale of the universe as a function of time. Measurements of this relation help determine interesting quantities such as the age and composition of the universe and the nature of the dark energy. At low redshift, this relation can be approximated by $cz = H_0 d$, with c the speed of light, z the redshift, H_0 the Hubble constant, and d the distance to the source. A standard siren provides d directly from the amplitude of the gravitational waves, and with a measurement of the redshift to the source one can directly infer the Hubble constant.

It is to be emphasized, however, that the redshift of the source cannot be straightforwardly determined from gravitational waves alone. There is a redshift degeneracy: a lower mass binary farther away will be redshifted to have an identical (modulo amplitude) waveform to a closer, more massive binary. The simplest way to address this is to find an electromagnetic counterpart to the gravitational-wave source, and measure the redshift using photons. We call this the "counterpart standard siren" approach [23], and short gamma-ray bursts have been thought to be a particularly promising counterpart source [14, 33, 32]. An alternate "statistical standard siren" approach is to identify potential host galaxies within the gravitational-wave localization volume, with each galaxy providing a potential redshift to the source [36, 28, 16]. Additionally, structure present in the population of sources, such as known features in the mass distribution, can be used in a similar manner [20, 42]. Finally, it may be possible to use properties of the source (such as knowledge of the equation-of-state of neutron stars) to extract frequency-dependent features in the waveform and thereby determine redshift directly [29, 17].

For thirty years after Bernie's original paper, a number of obstinate souls toiled at developing the standard siren approach to cosmology. In the absence of the detection of gravitational waves, much less the detection of a gravitational wave source with an associated electromagnetic counterpart allowing for a redshift determination, the field of standard siren science remained somewhat speculative and quixotic. This all changed in August of 2017.

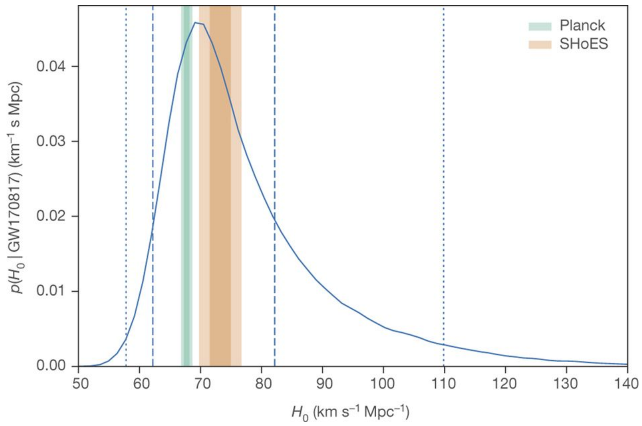

Figure 1: Posterior probability density for the Hubble constant given the gravitational-wave distance measurement from GW170817 and the redshift of its host galaxy (solid blue line). The dashed and dotted lines show minimal 68.3% and 95.4% intervals. For comparison, the shaded green and orange bands show the 1σ (dark shading) and 2σ (light shading) constraints from the CMB [6] and from Type Ia supernovae [35], respectively. Reproduced from [2]

GW170817

GW170817 was detected shortly before 8am Chicago time on August 17, 2017 [5]. Less than a day later we were making the first standard siren measurement of the Hubble constant! This binary neutron-star merger was the first gravitational-wave source with a detected electromagnetic counterpart. Two seconds following the merger, the Fermi gamma-ray space telescope detected a short gamma-ray burst spatially coincident with the gravitational-wave localization error box on the sky [3]. While it was incredibly exciting to detect gamma-rays and gravitational-waves from the same source for the first time, the gamma-ray burst was poorly localized on the sky. Over the next day, an extensive multi-messenger campaign was launched [4], and eleven hours later, an optical transient was detected in the galaxy NGC 4993 [12, 40]. Further study revealed that this optical transient was a kilonova powered by r-process decay and unambiguously associated with the neutron star merger. It was now possible to associate a host galaxy with the gravitational-wave source, and thereby determine the redshift and make the very first standard siren measurement of the Hubble constant [2]. The resulting Hubble constant measurement is shown in Figure 1. With a single source, the Hubble constant is constrained to roughly $\sim 15\%$: 70^{+12}_{-8} km/s/Mpc. This first result agrees with the cosmic microwave background measurement from Planck [6] as well as the local distance ladder measurement using Type Ia supernovae from SHoES [35], which both lie near the peak of the posterior probability shown in Figure 1. As we discuss in the next section, combining this result with future standard sirens will tighten the gravitational-wave measurement and may help shed light on the current Hubble constant tension. We note that the broad distribution in Figure 1 is due in part to the distance-inclination degeneracy: a close edge-on binary will be detected with a similar amplitude to a more distance face-on binary [see, e.g.,][14, 38, 2]. Independent determinations of inclination would improve the measurement of H_0 [see, e.g.,][22, 25], at the (significant) cost of introducing potential astrophysical systematic errors.

The measurements discussed above presume that the theory of general relativity is correct. Alternatively, one can use the standard siren approach to constrain deviations from GR [31, 8, 7, 27]. For example, by comparing the measured amplitude of gravitational waves with the inferred luminosity distance through electromagnetic observations, it is possible to constrain the number of spacetime dimensions [34] and the running of the Planck mass [26].

GW170817 is the only gravitational-wave source with a counterpart thus far, and therefore provides the only existing counterpart standard siren measurement. As a proof of principle, we can pretend that we were unable to identify the kilonova, and thereby unable to determine the host galaxy of GW170817 and determine its redshift. In this case, we would be relegated to the statistical standard siren approach discussed above, where we use every galaxy in the GW170817 localization volume as a potential host galaxy. We followed this approach in [21], where we combined the gravitational-wave measurements with the GLADE galaxy catalog [15] to determine the Hubble constant. Since GW170817 is the closest and best-localized gravitational-wave detection, the galaxy distribution within the relatively small volume is dominated by a single group of galaxies (of which NGC 4993 is a member), with all of these galaxies at similar redshifts. As a result, the statistical standard siren measurement with GW170817 recovers the same distinct peak at $H_0 \sim 70$ km/s/Mpc which is seen in the counterpart result, with an error that is only roughly twice as broad, $H_0 = 76^{+48}_{-23}$ km/s/Mpc. For comparison, the statistical measurement for an "average" detected binary neutron star, at a typical distance and detected with a typical signal-to-noise ratio, would be expected to be ~ 3 times less informative than the counterpart measurement [11].

The first application of the statistical standard siren method to a "dark siren" was with the binary black hole merger GW170814. This source was the first signal detected by three gravitational-wave detectors, the two LIGO detectors as well as the Virgo detector, and for this reason it was relatively well-localized to $\sim$ 60 deg^2 on the sky. The localization region of GW170814 also happened to be in the middle of the footprint of the Dark Energy Survey, which means there happened to be a pre-existing relatively deep and complete catalog of galaxies. GW170814 was therefore an ideal dark standard siren, and we performed a statistical standard siren measurement of the Hubble constant using GW170814 and the DES galaxy catalog in [41]. The resulting measurement is only marginally more informative than the prior: $H_0 = 78^{+96}_{24}$ km/s/Mpc. The weaker constraint from GW170814 compared to Gw170817 is to be expected: because binary black holes are detected at greater distances with larger localization volumes and a significantly greater numbers of potential host galaxies, the Hubble constant measurement from a binary black hole standard siren is typically much less informative than the case of a binary neutron star, even if the neutron stars don't have a counterpart and are analyzed statistically [11].

The future of standard siren science

GW170817 heralds the birth of the field of standard siren cosmology, with this first measurement providing a $\sim 15\%$ determination of the Hubble constant. This is an impressive beginning, especially given that it is based on the detection of a single source. However, to make interesting contributions to cosmology, and shed light on the ongoing "tension" between early (CMB) and late (supernova) measurements of the Hubble constant, it will be necessary for standard siren measurements to improve to $\lesssim 3\%$ [18]. This precision is attainable with the gravitational-wave detection of ~ 30 binary neutron star coalescences [32, 11, 19]. Figure 2 provides an example of a 2% measurement of the Hubble constant from 50 binary neutron star detections with counterparts, based on mock data from the "First 2 Years" simulated gravitational-wave dataset [39].

The third LIGO/Virgo observational run commenced this past April, and is expected to

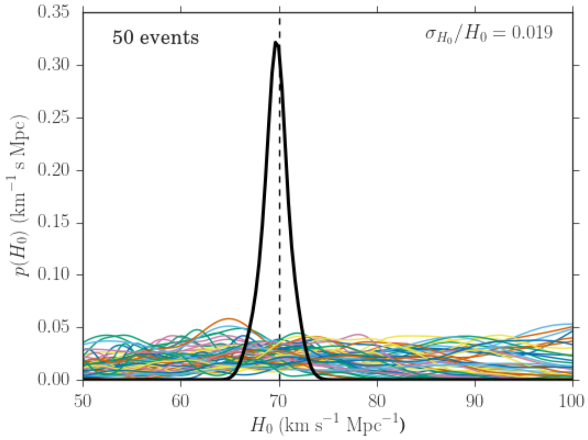

Figure 2: Posterior density on the Hubble constant from 50 simulated binary neutron star events with an associated counterpart (colored lines) together with the combined posterior (black line). The injected value, $H_0 = 70$, km/s/Mpc is shown as the dashed vertical line. With 50 events, we expect to attain a $\sim 2\%$ measurement on the Hubble constant.

last ~ 1 year and produce a few detections of binary neutron stars. The detectors will then be upgraded, and roughly a year later a fourth observational run will commence at the design sensitivity, which is expected to be a $\sim 50\%$ improvement in distance over the current configuration [1]. After one year of observation with this improved network, neutron-star standard sirens may constrain the Hubble constant to $\sim 2\%$ [11]; the precise constraint will depend on a number of factors, including the detection rate and the fraction with electromagnetic counterparts and associated redshifts. Roughly speaking, the precision on H_0 will scale as $\sim 15\%/\sqrt{N}$, where N is the number of detected binary neutron-star sources with counterparts. Without counterparts, the statistical standard siren method yields $\sim 40\%/\sqrt{N}$ for binary neutron stars, and upwards of $\sim 100\%/\sqrt{N}$ for binary black holes, depending on the galaxy catalog completeness and the binary black hole mass function. Some neutron star-black hole mergers are also expected to have counterparts and, depending on the merger rate, may contribute significantly to the standard siren measurement [43].

Farther in the future, next generation ground-based networks such as the Cosmic Explorer and the Einstein Telescope will detect standard siren sources to very high redshift [9, 30, 44]. In addition, the space-based LISA gravitational-wave detector will enable revolutionary standard siren measurements of cosmology [37, 13, 10].

After thirty years of development, standard sirens are now poised to become an important new tool in our exploration of the universe. It will be exciting to see what the next thirty years will bring.

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Hartlefest

Gary Horowitz, University of California Santa Barbara horowitz-at-ucsb.edu

On June 7, 2019, approximately 70 physicists gathered at the KITP in Santa Barbara for a one-day celebration of Jim Hartle's 80th birthday. There were seven talks: Kip Thorne and Gary Gibbons reviewed Jim's many contributions to physics and astrophysics going back to the 1960s; Neil Turok and Thomas Hertog discussed various aspects of the Hartle-Hawking no-boundary wave function; Sean Carroll and Mark Srednicki discussed aspects of probability in quantum cosmology and complexity; and a philosopher, Simon Saunders, discussed the many worlds view of quantum mechanics. Many distinguished relativists attended this event, including Bob Wald, John Friedman, Jim Bardeen, and many others (including three of Jim's former students: Paul Anderson, David Craig and Peter Morse). For a complete list of participants and links to the talks and pictures, see the conference website: `http://web.physics.ucsb.edu/ HartleFest/`

After dinner, there were reminiscences and remarks about how kind and helpful Jim has been to generations of students and postdocs by a number of people including Wald, Bardeen, Isaacson, Zurek, and a couple of Jim's former students. It was a special event honoring a very special person.