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- PERSPECTIVE

ASTROPHYSICS

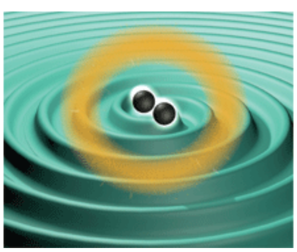
Seeing Gravitational Waves

Mansi M. Kasliwal

+ Author Affiliations

E-mail: mansi@obs.carnegiescience.edu

Gravity is responsible for the long-range order of the universe. Using Einstein's general relativity, we now think of gravity as the geometrical curvature of the four-dimensional fabric of space-time (*1*). Extreme cosmological events such as the merging of neutron stars or black holes induce ripples in the fabric of space-time (see the figure). However, these ripples, or gravitational waves, are extremely weak, and their detection has remained elusive. To measure the small signal, an interferometric detector is required that can detect strain to one part in 10^{21} (that is, a billionth of a nanometer for a kilometer-length interferometer). Such extreme gravity events are also rare, occurring only once every 10,000 years per galaxy (*2*). An advanced version of such a detector is designed to find gravitational waves on a regular basis (roughly tens of events annually) beginning in 2017 (*3*). This heroic experiment alone will be somewhat unsatisfying—gravitational wave interferometers will only be able to hear the wave and detect when something happens (literally "hear" as the operational frequency of tens to thousands of Hertz overlaps with the human auditory range). The interferometers will be blind to exactly where the merger occurs. To locate the source of the gravitational waves, collaboration between the physics and the astronomy communities together with extensive simulations are under way (*4*).



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Gravity wave detection.

Merging neutron stars or black holes induce ripples in the fabric of space-time. The decade ahead promises to witness the first gravitational wave detections: to "hear" the sound waves with advanced gravitational wave interferometers and "see" the gold halo (produced via nucleosynthesis) with a slew of panchromatic telescopes.

There is a lot of activity in three complementary camps: instrumentalists, theorists, and observers. Instrumentalists are striving to set up a global network of advanced interferometers to localize the gravitational wave signals: the longer the baselines, the tighter the triangulation. The first such triangle to come online will be the Laser Interferometer Gravitational Wave Observatory at Hanford (LIGO-Hanford) (*5*), LIGO-Louisiana (*5*), and VIRGO-Italy (*6*). Next will be LIGO-India (*7*) and Kagra-Japan (*8*). Median error regions of 50 (or 6) degrees2 can be achieved with three (or five) interferometers (*4*, *9*). The network will be sensitive to mergers out to 400 Mpc (or 750 Mpc) for three (or five) interferometers (*2*, *4*). Low-latency gravitational wave localization volumes can be constructed within minutes to alert the astronomers to search for the relevant electromagnetic counterpart (*4*).

Theorists are working out the expected electromagnetic signature from neutron star and black hole mergers; the luminosity, time scale, and spectral energy distribution. The predicted counterpart is expected to be fainter than a supernova (but brighter than a nova), last for a few hours to a few days, and have red colors (*10*–*12*). Nucleosynthesis in the neutron-rich ejecta is expected to give elements with mass numbers ranging between 120 and 200. Indeed, the majority of gold in the universe may be produced during neutron star or black hole mergers (*12*, *13*).

Observational astronomers are mobilizing large telescopes across the entire electromagnetic spectrum. For the tiny fraction of jets (<2.5%) beamed toward us, an all-sky gamma-ray monitor (such as the Fermi and Swift space-based telescopes) detecting contemporaneous emission would be the most straightforward identification. Radio astronomers have also recently brought online a wide array of low-frequency antenna arrays to look for a contemporaneous pulse and upgraded existing facilities (e.g., Jansky Very Large Array) to improve mapping speed.

Optical astronomers have the strongest arsenal to search wide areas efficiently to look for a counterpart to all gravitational wave events. Very wide-field cameras on all sizes of telescopes are being built: Zwicky Transient Facility (35 degrees^2, 1.2 m; 2015), Dark Energy Camera (3 degrees^2, 4 m; 2012), and HyperSuprimeCam (1.8 degrees^2, 8.2 m; 2012). Opacity calculations suggest that there may be an emission peak in the infrared (*12*). Unfortunately, the infrared sky doesn't have wide-field instrumentation at this time. Astronomers have proposed to build the Synoptic All-Sky Infrared telescope (SASIR; 0.2 to 1 degrees^2) on the ground and the Wide-Field Infrared Survey Telescope (WFIRST; 0.3 degrees^2) in space.

The biggest challenge ahead is that the transient sky is extremely dynamic, which results in a large number of false positives (*4*, *14*). Because of the small solid angle occupied by galaxies on the sky, spatial coincidence with nearby galaxies can reduce the false positives from hundreds to just a few (*4*, *14*). Unfortunately, we do not know the location of half of the galaxies within the relevant horizon. Efforts are under way to complete our galaxy catalog using H-α narrow-band imaging in the optical and HI imaging in the radio. Systematic surveys are characterizing all types of transient phenomena in the local universe and have recently found multiple new distinct classes of elusive transients (*15*).

A complete inventory of transients and a complete catalog of nearby galaxies will empower us to find these needles in the haystack. Thus, there is a surge of excitement as the era of routine gravitational wave detection draws near—this search may prove to be the 21st-century gold rush.

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