Gravitational-Wave Astrophysics as a Probe of Fundamental Physics

Contributors:

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Einstein's General Relativity has passed all laboratory, Solar-System, and binary-pulsar tests with flying colors. These observations constrain gravity in regions where the gravitational field is relatively weak and typical velocities are much smaller than the speed of light. Gravitational waves (GWs) from the inspiral and merger of compact objects will test gravity in regimes where gravitational fields are strong and Einstein's theory is fully dynamical. These tests will answer outstanding questions in theoretical physics, such as:

1) Are the massive objects at galactic centers the rotating (Kerr) black holes of Einstein's theory?

Most astronomers believe that the massive compact objects observed in galactic centers are Kerr black holes. Evidence for the ”Kerr paradigm” is only indirect, because it is hard to image these objects to sufficient precision. Tests of the the no-hair theorems and of the cosmic censorship conjecture will be possible by observing GWs from the inspiral of stellar mass compact objects into central galactic objects, which provide a precise map of the central bodys space-time. Similar tests are also possible by observing the ”ringdown” radiation produced from the final coalescence of the black-hole binaries that form following the merger of two galaxies. For massive black holes, ringdown waves can be observed to large redshifts, testing the Kerr nature of astrophysical black holes even at early epochs in the evolution of the universe, when first-generation black holes began to merge.

2) Do Einstein's equations fully and accurately describe gravitational dynamics?

Einstein's theory might have to be modified to explain cosmological observations and to make it compatible with quantum mechanics. Proposed modifications include additional fields that mediate gravity, parity-violating corrections, or new higher-order terms in the action to make the theory renormalizable. Such modifications can be compatible with current tests, yet alter (sometimes strongly) the late inspiral and merger of compact objects. Some modifications yield ”floating orbits,” in which inspiral is halted altogether by a new interaction; others predict that the graviton has a small mass and up to six different polarizations. Direct observations of GWs can thus identify or stringently constrain new physics. Multiple observations at different positions and redshifts would allow us to build ”constraint maps,” testing the fundamental assumption that the laws of gravity are independent of location and age of the universe.

3) How precisely can we map the cosmography of the universe?

The discovery of cosmic acceleration has motivated a program to measure cosmic distances precisely across a range of redshifts. GWs have the potential to add particularly well-calibrated points to this program. GW measurements of an inspiraling binary directly determine the binary's luminosity distance. They cannot, however, determine redshift, since it is degenerate with measured mass parameters. If it is possible to combine a GW measurement of a binary with an electromagnetic determination of its redshift, we could determine the redshift-distance relationship with very high precision for some sources. For sources that are in band long enough and measured with high enough signal-to-noise ratio, it may even be possible to observe the change of a source's redshift as it evolves in the Hubble flow. These measurements would be challenging: precise GW positions are needed for the redshift-distance relationship, and very high amplitude sensitivity for the redshift evolution.

Gravitational waves are outstanding tools for addressing these questions; answering any of them will sharpen our understanding of the fundamental laws of physics, especially in the dynamical and non-linear regime. Determining the feasibility of these measurements and the technology it would take to achieve them is a task for the next few decades.