LIGO's Observation of Gravitational Radiation from a Binary Black Hole Collision

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ABSTRACT

On September 14, 2015, at approximately 09:50:45 UTC the two LIGO gravitational-wave antennas detected a signal of high significance later identified to be the gravitational radiation from the collision of a pair of stellar mass black holes. This observation, consisting of a mere 200 ms of data, has profoundly transformed our understanding of nature and launched humanity into a new area of strong field gravity research and gravitational astronomy.

INTRODUCTION

One hundred years ago, in 1916, Albert Einstein published a wave solution to the field equations of general relativity (GR) [1][2]. For many years it was debated whether this solution described real physical waves of spacetime or was merely a mathematical illusion resulting from ambiguous assignment of co-ordinates. It was finally decided that the solution described a real physical phenomenon and at about that same time the first attempts to detect these waves were carried out [3]. For the following five decades searches for gravitational waves (GWs) failed to yield positive results, although there were a few interesting null results during that time [4]. In the early part of this century, a network of kilometre-scale laser interferometer antennas began operation, including the GE600 [5] and Virgo [6] antennas in Europe, and the two LIGO [7] antennas in the United States. These antennas were constructed primarily to detect binary neutron star mergers. Because several binary neutron star systems within our galaxy are known to be orbiting tighly enough to collide within the age of the universe, collisions of pairs of neutron stars was expected to be the dominant source of signals in ground-based detectors [8]. In September of 2015, after a series of upgrades lasting several years, the Advanced LIGO antennas began their first astronomical observations, a period of data taking named "O1", and almost immediately detected GWs from the collision of a pair of high mass stellar black holes [9].

IMPLICATIONS

The observation of this signal immediately taught us many things about the Universe around us. We learned that high stellar mass black holes exist at all, that they occur in binaries, and that these binaries can have sufficiently tight orbits for the black holes to merge within the age of the Universe [10,11,12,13]. More profoundly, we learned that black holes behave as precited by GR and that gravitational waves propagate as predicted by GR, they are not dissipated into other energy forms, so that GW astronomy is, in fact, possible [14]. In August of 2015 the field of GW astronomy was struggling. NASA had cancelled its participation in LISA, the ESA continued to delay the mission's launch, the null results from pulsar timing were in tension with favoured galaxy formation models [15], and it was not unusual for one to encounter discussions about the implications of these null results on fundamental physics: what does it mean if Advanced LIGO doesn't see anything, could GR be wrong? In August of 2015 it was possible GR could be so wrong that GW astronomy was impossible, and in September 2015 with just 200 ms of data that question evaporated; we learned that our understanding of gravity in the strong field dynamical regime is more or less correct, and that sources exist in sufficient abundance for GW astronomy to be possible.

The event occurred very early, before the official start of science data collection at a time when the antennas were still undergoing final adjustments. Luckily we were running a low-latency burst detection code at the time that alerted the collaboration to the presence of a candidate of interest, and caused the planned observatory work to be postponed so that we could collect enough data to understand the statistical properties of the noise at the time and confirm the candidate's significance. Had the candidate not been identified until later, it's possible we would not have been able to satisfactorily establish its statistical signficance and while we still would have published the observation we might not have been able to claim a detection.

GW150914

Unfortunately we do not know very much about GW150914 itself. We know the masses of the two black holes that collided were $36^{+5}_{-4} M_{sun}$ and $29^{+4}_{-4} M_{sun}$ and we know the final black hole was left with a mass of $62^{+4}_{-4} M_{sun}$ with a dimensionless spin of $0.67^{+0.05}_{-0.07}$. We cannot constrain the spins of the original black holes very well, nor can we constrain the orbit inclination of the system. The latter means we cannot constrain the distance very well, which we determine from the amplitude of the waves, because we do not know if we were looking at the system edge on (and seeing relatively weak GW emission) or along the orbital axis (and seeing relatively strong GW emission). By bounding the amount of dispersion the signal experienced we can bound the mass of the graviton to be $\leq 1.2\times 10^{-22} eV/c^2$ (four orders of magnitude lower than the current bound on the mass of the photon).

Searches for high-energy neutrinos in association with GW150914 using the ANTARES and IceCube detectors yielded a null result [16]. Fermi GBM observations suggest a possible gamma-ray counterpart [17]. The implications of these observations have not yet been understood.

THE FUTURE

Advanced LIGO is expected to begin its second science data taking run in the late summer or early fall of 2016. It is hoped that Advanced Virgo will be ready to begin operations at that time. There is much science that LIGO alone cannot accomplish. Because the LIGO antennas are closely aligned with each other they are unable to determine the polarization state of the wave, which makes it essentially impossible to measure the orbit inclination of compact object collisions, which makes measuring their distances difficult. With a third, differently aligned, antenna it will be possible to better constrain the properties of the systems, their locations on the sky, and their distances, enabling more useful joint observations with non-GW observatories. With a fourth antenna we could probe additional properties of general relativity, for example we could test if the wave field really has only the two polarization states predicted by GR or if there is evidence of additional degrees of freedom. There is a great deal of knowledge that cannot be obtained with LIGO alone, therefore when they become operational KAGRA and LIGO India will play crucial roles in advancing our knowledge of fundamental physics and in expanding our understanding of the Universe around us.

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China, India, Japan, and Korea. The full list of current participants and their affiliations can be found online at https://roster.ligo.org/roster.php.

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