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# Detecting Massive Black Holes via Attometry: Gravitational Wave Astronomy Begins

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In their fall 2015 observing run the two detectors of the Advanced Laser Interferometer Gravitational-Wave Observatory (Advanced LIGO) simultaneously observed transient gravitational-wave signals. The detected waveforms indicated the inspiral and merger of pairs of massive black holes more than 1 billion years ago. These discoveries marked the first direct detections of gravitational waves and the first observations of binary black hole mergers. Interferometer-based attometry was key to these detections.

Gravitational waves can be thought of as ripples in the fabric of space-time, created in these instances by cataclysmic events that occurred long ago and far away. Einstein was the first to realize that a massive object, such as a star, warps the space around it. When such an object undergoes extreme acceleration in a close binary orbit, the warp becomes a swirling of space, forming waves that can propagate across the Universe. The strongest signal detected by the LIGO interferometers came from the merger of two black holes of roughly 30 solar masses each [1], which came together to form a final black hole of about 60 solar masses. In the last few tenths of a second, however, roughly three of those solar masses of energy were released as gravitational waves. During those last moments the gravitational wave "luminosity" was greater than the electromagnetic luminosity of the entire visible Universe.

The emitted waves traveled at the speed of light and decreased steadily in intensity just as light does, until 1.3 billion years later, they impinged upon the Earth with an amplitude so small as to seem immeasurable. The amplitude is most naturally described as a dimensionless strain, since the wave's effect can be regarded as alternating, transverse stretching and compressing of space that is proportional to the original spatial extent. That is, the change $\Delta L$ in distance between two affected objects is approximately $hL$, where $h$ is the dimensionless strain amplitude and $L$ the original, nominal separation. For the recycled, Fabry-Perot Michelson interferometers that form LIGO [2], the characteristic $L$ is 4 km, and the detected wave's strain amplitude was about $10^{-21}$, requiring a measurement precision of the distance between interferometer mirrors to better than an attometer at the wave's characteristic frequency of about 150 Hz. An important characteristic of gravitational waves is their quadrupolar spatial pattern; while space is stretched in one transverse dimension, it is simultaneously compressed in the orthogonal tranverse direction. This property makes a Michelson interferometer a natural detector, as it measures phase differences of its returning laser light to determine arm length differences.

The key to LIGO's measuring distance changes below the attometer level relies in part on exploiting the sheer number of laser photons ($\lambda$ = 1064 nm) circulating in the LIGO interferometers during the brief passage of the wave. The ~20 Watts of continuous, intensity-stabilized and frequency-stabilized laser power is amplified in two distinct ways. Each 4-km arm of the Michelson interferometer is itself a Fabry-Perot cavity with a power amplification of about 300, which ensures that the light bounces many times between the arm-defining mirrors, accumulating phase changes induced by a passing gravitational wave. In addition, a mirror between the laser and the Michelson beam splitter is adjusted so as to create a grand, nested Fabry-Perot cavity system, further increasing the laser power circulating in the arms to approximately 100 kW, reducing the statistical uncertainty on interference intensity due to shot noise statistics. Another important feature of the LIGO interferometers is isolation from ground motion. The mirrors are suspended in a quadruple-pendulum configuration, giving multiple stages of passive isolation for frequencies in the detection band (above ~30 Hz in the first data run). In addition, the pendula are supported on stages with active isolation servos using local accelerometer measurements. Further interferometer improvements now planned promise many new discoveries in the coming years.

References:

[1] B P Abbott *et al*, Phys. Rev. Lett. **116** (2016), p. 061102.
[2] B P Abbott *et al*, Phys. Rev. Lett. **116** (2016), p. 131103.

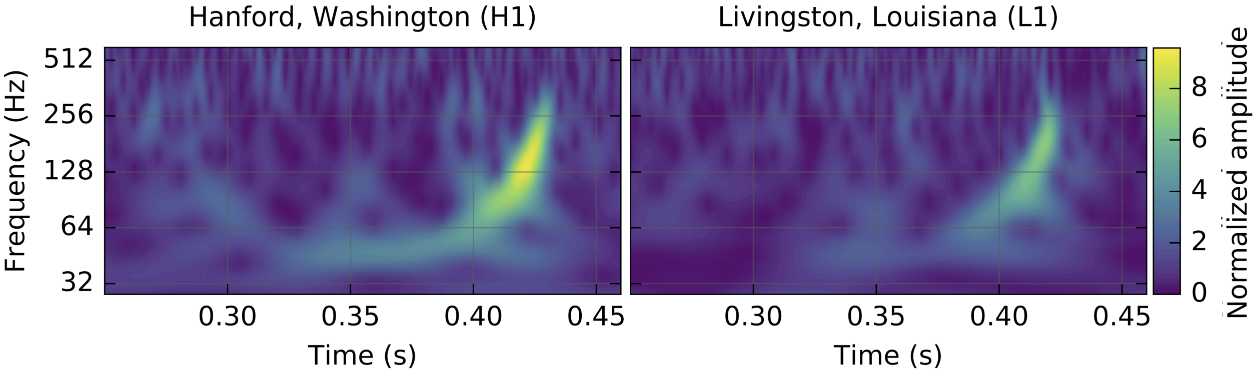

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**Figure 1.** Figure 1.The gravitational wave event GW150914 observed by the LIGO Hanford (H1, left panel) and LIGO Livingston (L1, right panel) detectors. The two plots show how the gravitational wave strain produced by the event in each LIGO detector varied as a function of time and frequency. Both plots show the frequency of GW150914 sweeping sharply upwards, from 35 Hz to about 150 Hz over two tenths of a second. GW150914 arrived first at L1 and then at H1 about seven ms later.

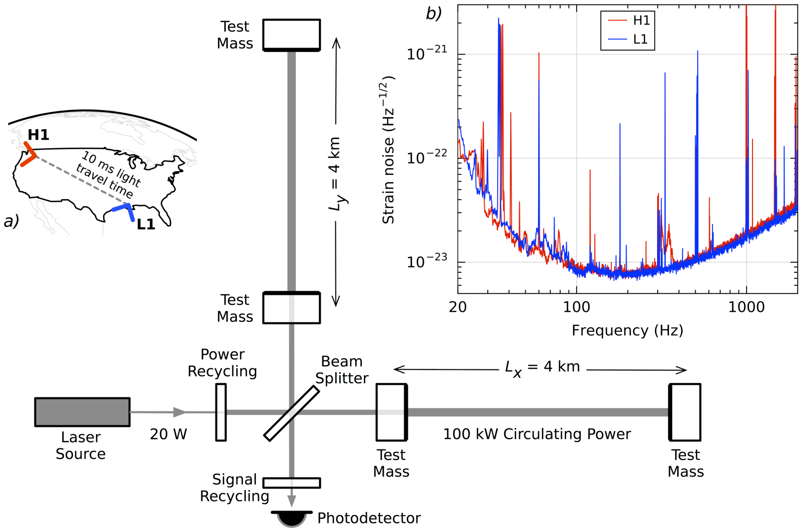

**Figure 2.** Simplified diagram of an Advanced LIGO detector (not to scale Inset (a), on the left, shows the locations and orientations of the two LIGO observatories, and indicates the light travel time between them. Inset (b) shows how the instrument strain noise varied with frequency in each detector near to the time of the event.