GW151226: OBSERVATION OF GRAVITATIONAL WAVES FROM A 22 SOLAR MASS BINARY BLACK HOLE COALESCENCE

A few months after the first detection of gravitational waves from the black hole merger event GW150914, the Laser Interferometer Gravitational-Wave Observatory (LIGO) has made another observation of gravitational waves from the collision and merger of a pair of black holes. This signal, called GW151226, arrived at the LIGO detectors on 26 December 2015 at 03:38:53 UTC.

The signal, which came from a distance of around 1.4 billion light-years, was an example of a compact binary coalescence, when two extremely dense objects merge. Binary systems like this are one of many sources of gravitational waves for which the LIGO detectors are searching. Gravitational waves are ripples in space-time itself and carry energy away from such a binary system, causing the two objects to spiral towards each other as they orbit. This inspiral brings the objects closer and closer together until they merge. The gravitational waves produced by the binary stretch and squash space-time as they spread out through the universe. It is this stretching and squashing that can be detected by observatories like Advanced LIGO, and used to reveal information about the sources which created the gravitational waves.

GW151226 is the second definitive observation of a merging binary black hole system detected by the LIGO Scientific Collaboration and Virgo Collaboration. Together with GW150914, this event marks the beginning of gravitational-wave astronomy as a revolutionary new means to explore the frontiers of our Universe.

THE SIGNAL

Just like the first detection, GW151226 was observed by the twin instruments of Advanced LIGO situated in Hanford, Washington and Livingston, Louisiana. **Figure 1** shows the data as seen by the two instruments during the final second before the merger took place. The animation alternates between showing the raw detector data and the data after the best-matching signal has been removed, making it easier to identify. Even then, and unlike the first detection (where the signal of the event was very obvious against the background 'noise' of the instruments), in this case it is not immediately clear that there is a gravitational-wave signal embedded in the data. This is because GW151226 has a lower signal strength (referred to as the measured gravitational-wave strain). It is also harder to see as the signal is spread over a longer time, lasting 1 second compared to 0.2 seconds for the first detection. Despite the difficulty in spotting this event by eye, our detection software was able to find the signal in the data.

HOW WAS THE DETECTION MADE?

The first indication of the signal came from an online search method, which looks at detector data almost in real time as it is recorded. **Figure 2** shows the results of one of the search methods. This analysis had identified GW151226 as a gravitational wave candidate within 70 seconds of its arrival at the Earth. About a minute later the first, rough estimates of the candidate's source properties had been calculated. These initial searches used a technique known as *matched filtering* to identify possible gravitational-wave signals. In this method, the data are compared to many predicted signals ('waveforms') in order to find the best match. If both detectors' data match a signal at the same time, then we have a gravitational wave candidate. Matched filtering was essential for both the detection and analysis of GW151226 due to its smaller signal strength compared with the first detection (GW150914).

The initial search analyses could only give approximate estimates for the properties of the source — including the masses of the two compact objects, their rotation rates and their orientation, distance and position on the sky. To determine these properties (known as 'parameters') more accurately, we used a different technique: we tested many different parameter combinations and each time checked how well the predicted waveform for that combination matched the signal we had seen. This approach allows us to build up a map of the different sets of parameters which could explain our observation, and figure out the probability of each set being the correct one. **Figure 3** shows the excellent agreement between the reconstructed gravitational-wave signal (as observed by the Livingston detector), generated using a range of the most probable parameters, compared with a signal calculated from a numerical solution of Einstein's equations of general relativity.

HOW CAN WE BE SURE THIS WAS A REAL EVENT?

Just as we did for the first detection, many checks were carried out on the detectors to ensure that no environmental or instrumental effects could have caused the signal. These effects could be anything from misbehaving refrigerators to far-away lightning strikes! During the time of the event, there were no such disturbances large enough to explain GW151226, so we concluded that the signal must have had an astrophysical origin.

FIGURES FROM THE PUBLICATION

For more information on how these figures were generated and their meaning, see the main publication at Physical Review Letters.

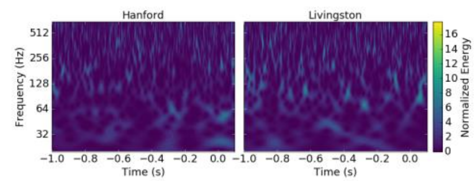

Figure 1: *(Adapted from figure 1 of our publication). The gravitational wave event GW151226 as observed by the twin Advanced LIGO instruments: LIGO Hanford (left) and LIGO Livingston (right). The images show the data recorded by the detectors during the last second before merger as the signal varies as a function of time (in seconds) and frequency (in Hertz or the number of wave cycles per second). To be certain that a real gravitational wave has been observed, we compare the data from the detectors against a pre-defined set of models for merging binaries. This allows us to find gravitational wave signals which are buried deep in the noise from the instruments and nearly impossible to find by eye. This signal is much more difficult to spot by eye than the first detection GW150914!*

(To see an animated version of this figure visit our website)

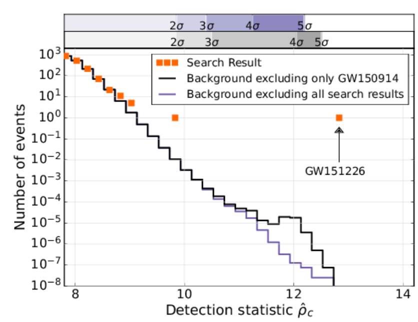

Figure 2: *(Adapted from figure 2 of our publication). Results from our search for gravitational wave sources similar to GW151226 (and the previous detection GW150914) showing the significance of this detection compared to a background of false 'events' caused by noise from the LIGO instruments. We see that GW151226 is detected well above the level of the background.*

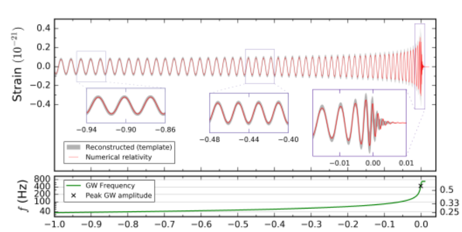

Figure 3: *(Adapted from figure 5 of our publication). The top panel shows a comparison of the reconstructed gravitational-wave strain signal over time as seen by the Livingston detector (gray) with a signal calculated from a numerical relativity simulation. The time is counting down in seconds leading up to the merger of the two black holes at zero. The lower panel shows how the frequency of the gravitational waves changes with time. The frequency increases as the black holes spiral together. This can also be related to the orbital velocity v, shown on the right hand side of the lower panel in units of the speed of light c. The black cross marks the point where the amplitude of the signal was largest, which is also approximately the time at which the black holes merged.*

SO WHAT DID WE SEE?

By comparing millions of predicted signals to the data, we can find which combinations of the binary parameters are able to describe the signal. **Figure 4** shows the distribution of probable combinations of masses for the binary inferred by this method. From this figure we can tell with 99% certainty that the mass of the smaller object cannot be less than 4.5 times the mass of the Sun, which is well above the largest theoretical mass of a neutron star. Therefore we can be confident that we have observed a binary black hole! The distribution of the mass combinations for the two black holes are centered at about 14 and 8 times the mass of the Sun respectively. After the merger, the resulting black hole has a mass of about 21 times the mass of the Sun.

The black holes can be spinning as they orbit each other — just like the Earth rotates on its own axis. This rotation can be tilted at different angles compared to the orbital motion; for the Earth this tilt gives us different seasons. How quickly the black holes are rotating (the spin magnitude) and how much they are tilted (the spin misalignment) will also affect the length of the observed signal. If the spins are large and rotating in the same direction as the black holes are orbiting each other, then the two black holes can get very close to each other before they merge. If on the other hand, the black holes are spinning in the opposite sense to their orbital rotation, then they will merge at a greater separation, thus giving rise to a shorter gravitational-wave signal. When the spins and the orbit rotations are not aligned, the whole binary will be wobbling as it spirals towards merger (this is called spin-precession).

Figure 5 shows the combination of spin magnitudes and misalignments which can describe the data. We find that the primary black hole (the more massive of the two) is more probable to be spinning in the same direction as the orbital motion. However we cannot tell how it is tilted. This figure also shows that we are unable to put any significant constraint on the spin of the less massive black hole.

After the merger the final black hole is also rotating. We find that this new black hole is spinning at 70% of its maximum possible value.

The final black hole mass is lower than the sum of the two initial black holes as some mass is converted directly into gravitational-wave energy during the inspiral and merger. The mass difference is equivalent to converting about the mass of our Sun into energy radiated as gravitational waves. At its peak, the gravitational-wave power emitted from the binary was greater than the combined light power (what astronomers call luminosity) of all the stars and galaxies in the observable Universe!

We can also tell that this merger took place at a distance of around 1.4 billion light-years — so these gravitational waves have travelled a similar distance as those which came from the first detection, GW150914.

We can use the difference in arrival time of gravitational waves at each detector to 'triangulate' the position of a gravitational-wave source on the sky. However, with only the two LIGO detectors our estimate of the sky position is typically very crude. For GW151226 we could localize its position to within 850 square degrees on the sky — about 4000 times the area of the full moon. The precision of this triangulation method will be greatly improved with the addition of more gravitational-wave detectors in future; for more details see this article.

GW151226 spent about 1 second in the detectors' sensitive band of frequencies, making it a much longer signal than the first detection which lasted only 0.2 seconds. This longer duration is due to the lower mass black holes in this binary system: more of the inspiral phase of the event could be seen in the LIGO detectors' sensitive band. A longer inspiral also means that GW151226 can be used to place better constraints on any violations of general relativity. We do not find any hints that Einstein was wrong.

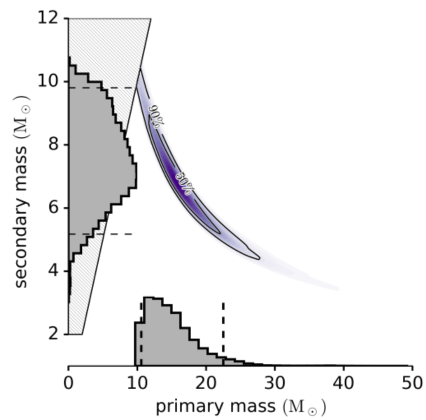

***Figure 4**. (Adapted from figure 3 of our publication). This image shows the combinations of the black hole masses (in units of the solar mass) which are able to describe the data we have observed. We label the more massive black hole as the primary and the less massive as the secondary. Darker regions correspond to more probable combinations of masses, where we measure a 90% probability of GW151226 having masses within the black contour labelled '90%'.*

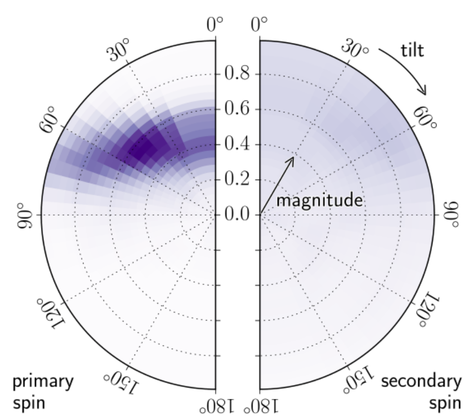

***Figure 5**. (Adapted from figure 4 of our publication). This image shows the possible spin magnitude (how quickly it is rotating) and misalignment (the tilt with respect to the orbital motion) for the two black holes. We label the more massive black hole as the primary and the less massive as the secondary. Each block in the semi-circle represents a different combination of the magnitude and misalignment, where the darker shading indicates combinations with greater probability. We can place some constraints on the spin magnitude and misalignment for the primary black hole, however we are unable to place any restrictions for the secondary.*

WHAT DOES IT MEAN FOR ASTROPHYSICS?

GW151226 is the first direct observation of a binary black hole in this range of masses. As binary black holes are not expected to emit any light, the gravitational waves which they emit allow us to find new binary black hole systems which could not be observed directly by any other means. That said, we can compare our results against other types of observations.

Binary black holes can form in a number of ways. They could have originated as two massive stars which were born together and evolved together to become a pair of black holes at the end of their lives. Alternatively, in areas of the Universe where individual stars are more densely packed, a black hole binary could be formed from two individual objects interacting with each other to become a binary system later in their lives. The properties of GW151226 are consistent with both of these formation scenarios, so for the moment we cannot favour one of them over the other.

However, both GW151226 and GW150914 indicate there could be many more stellar-mass binary black holes in the Universe than previously expected. These initial detections are an important first step towards understanding more about the population of these binaries, which until now has been completely hidden from us.

KEY POINTS

The LIGO Scientific Collaboration and Virgo Collaboration have observed another merging binary black hole system, detected by Advanced LIGO. The observations of GW151226 and GW150914 together indicate a population of binary black holes in the Universe. Gravitational-wave observations have, therefore, been able to confirm the existence of black holes and provide a new view into the mysteries of the Universe. The era of gravitational-wave astronomy has truly begun!

Visit our website at http://www.ligo.org/

READ MORE

LIGO Scientific Collaboration homepage (includes link to our publication in Physical Review Letters) : www.ligo.org

Advanced Virgo homepage: http://public.virgo-gw.eu/language/en/

Background information on the technology of the Advanced LIGO upgrades: http://tinyurl.com/ALIGO-upgrades-pdf

LIGO Open Science Center (with access to GW151226 data): https://losc.ligo.org