GRAVITATIONAL WAVES AND GAMMA-RAYS FROM A BINARY NEUTRON STAR MERGER: GW170817 AND GRB 170817A

The gravitational-wave signal GW170817 was detected on August 17, 2017 by the Advanced [LIGO] and [Virgo] observatories. This is the first signal thought to be due to the merger of two neutron stars. Only 1.7 seconds after the gravitational-wave signal was detected, the Fermi Gamma-ray Burst Monitor (GBM) and the Anticoincidence Shield for the SPectrometer for the INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL SPI-ACS) detected a short gamma-ray burst GRB 170817A. For decades astronomers suspected that short gamma-ray bursts were produced by the merger of two neutron stars or a neutron star and a black hole. The combination of GW170817 and GRB 170817A provides the first direct evidence that colliding neutron stars can indeed produce short gamma-ray bursts.

INTRODUCTION

Gamma-Ray Bursts (GRBs) are some of the most energetic events observed in Nature. They typically release as much energy in just a few seconds as our Sun will throughout its 10 billion-year life. They occur approximately once a day and come from random points on the sky. These GRBs can last anywhere from fractions of seconds to thousands of seconds. However, we usually divide them in two groups based roughly on their duration, with the division being at the 2 second mark (although more sophisticated features are also taken into account in the classification). Long GRBs (>2 seconds) are caused by the core-collapse of rapidly rotating massive stars. Now we have evidence that short GRBs (<2 seconds) are due to the merger of two neutron stars, and also perhaps (although not directly observed yet) a neutron star and black hole.

FIGURES FROM THE PUBLICATION

For more information on the meaning of these figures, see the full publication here.

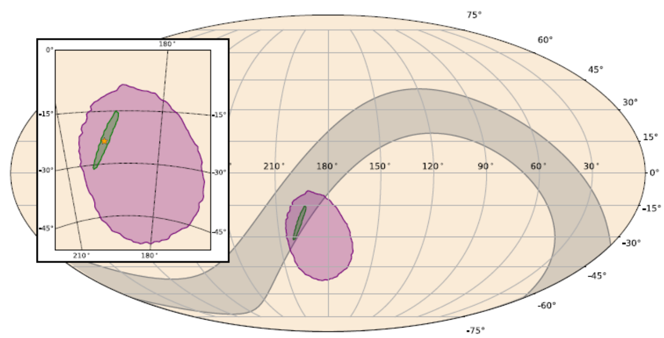

Figure 1: The final localization of the source which produced GW170817 and GW170817A. All contours are at 90% confidence. The contour for the skymap produced from LIGO-Virgo is shown in green. The Fermi-GBM targeted search localization is overlaid in purple. The annulus determined with Fermi and INTEGRAL timing information is shaded in gray. The zoomed inset also shows the position of the optical transient marked as a yellow star. The axes are Right Ascension and Declination in the Equatorial coordinate system.

THE GRAVITATIONAL-WAVE AND GAMMA-RAY BURST SIGNALS

The gravitational-wave observation: The two Advanced LIGO and the Virgo detectors observed the gravitational-wave signal GW170817 with a combined signal-to-noise ratio of 32.4, making it the loudest gravitational-wave signal recorded to date. Analysis of the gravitational-wave data revealed the signal to be consistent with the merger of two neutron stars, with masses between 0.86 and 2.26 times the mass of the Sun, over a hundred million light years away. This makes GW170817 the closest gravitational-wave event ever observed. The triangulation between the three detectors allowed the signal to be localized to within a 28 square degree patch of sky with 90% confidence; this is the smallest localization region LIGO-Virgo have ever reported and is shown in Figure 1. The time-frequency trace of GW170817 can be seen in the bottom panel of Figure 2.

The gamma-ray burst observation: The gamma-ray emission was detected independently by Fermi-GBM and INTEGRAL, two gamma-ray observatories orbiting the Earth. GRB 170817A was autonomously detected by Fermi-GBM in 3 out of 12 sodium iodide (NaI) detectors; the signal shows two apparently distinct components. The triggering observation, which lasts about half a second, shows characteristics typical of a short GRB and is shown in the second panel of Figure 2. This is then followed by a weaker emission at lower energy which lasts a few seconds, shown in the first panel of Figure 2. GRB 170817A is 3 times more likely to be a short GRB than a long GRB based solely on the GRB characteristics. Fermi-GBM localized GRB 170817A (at 90% confidence) to 1100 square degrees. The routine untargeted search for short transients by INTEGRAL SPI-ACS identified GRB 170817A, as shown in the third panel of Figure 2. Fermi-GBM and INTEGRAL SPI-ACS often jointly detect short GRBs; it has been confirmed to high confidence that the short GRB observed by Fermi-GBM is the same. Using the difference in the arrival time of GRB 170817A in INTEGRAL SPI-ACS and Fermi-GBM a joint localization can be made. This localization, as well as the Fermi-GBM search and LIGO-Virgo localizations, are presented in Figure 1.

Despite the overlapping sky localizations determined from the gravitational-wave detectors and the gamma-ray burst satellites, and the close time relation of the two signals, the question remains whether GW170817 and GRB 170817A originate from the same source. The probability that two unrelated signals would overlap this closely in space and time can be shown to be only 1 in 20 million. Therefore, it is extremely likely that the two signals are due to the same neutron-star merger.

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WHAT CAN THIS JOINT OBSERVATION TELL US?

The joint gravitational-wave and GRB observation provides an unprecedented opportunity to study the inner workings of short GRBs and allows us to probe a number of fundamental physics concepts, as well as the properties of the neutron stars that collided. All this is done by taking into account (1) the 1.7 second difference between GW170817 and GRB 170817A (2) the more than one hundred million light years both signals traversed and (3) when we expect each signal to be emitted during the neutron-star merger.

Our current best theory of gravity, Einstein's General Theory of Relativity, predicts the speed of gravitational waves and gamma-rays or light to be identical. Taking just the time delay between the two signals allows us to test the difference between the speed of gravity and light. The fractional difference between the speed of gravity and light is very close to zero, between -0.000000000000003 and 0.0000000000000007!

We have also been able to further test the equivalence principle and Lorentz violation, two of the fundamental principles that underpin Einstein's theory.

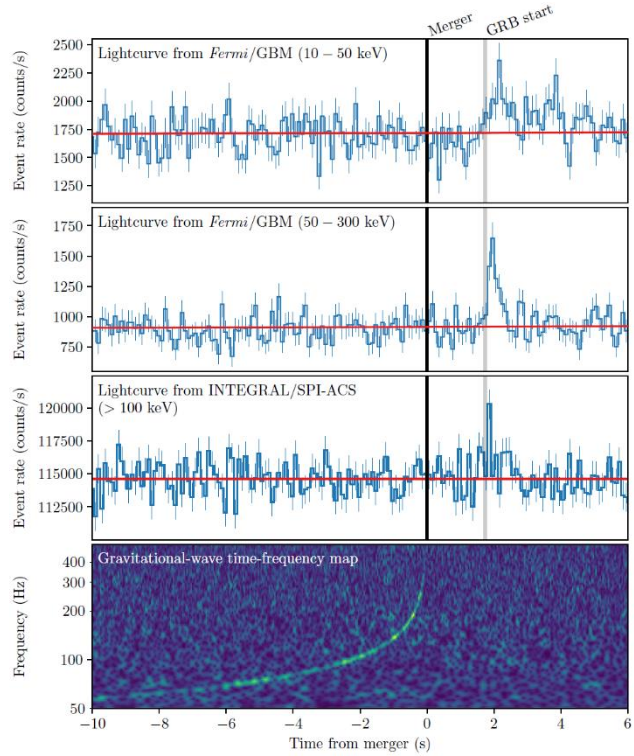

Figure 2*: The joint detection of GW170817 and GRB 170817A. First panel: The summed Fermi-GBM lightcurve for sodium iodide (NaIs) detectors 1, 2, and 5 for GRB 170817A between 10 and 50 keV, matching the 100 ms time bins of INTEGRAL SPI-ACS data. The background estimate is overlaid in red. Second panel: The same as the first panel but in the 50 - 300 keV energy range. Third panel: The INTEGRAL SPI-ACS lightcurve with the energy range starting approximately at 100 keV and with a high energy limit of least 80 MeV. Fourth panel: The time-frequency map of GW170817 obtained by coherently combining LIGO-Hanford and LIGO-Livingston data.*

HOW DOES GRB 170817A COMPARE WITH OTHER GRBS?

GRB 170817A is 100 times closer than typical GRBs observed by Fermi-GBM. It is also much dimmer or "subluminous" compared to the population of other long/short GRBs. This means GRB 170817A is less energetic. In fact, it is between 100 to 1,000,000 times less energetic than other short GRBs. Because gamma-ray emissions from GRBs are thought to be beamed, one possible explanation for the dimness of this GRB is that the Earth was on the edge of the beam. Another possibility is that the beam was not uniformly bright. Nevertheless, the observed dimness of GRB 170817A, given that it was relatively nearby, raises the following question: is there a population of similarly dim and nearby GRBs which have so far been missed (due to limited sensitivity of gamma-ray instruments), misinterpreted as more distant than they are (due to biases in determining the galaxy they came from), or simply because their distances are unknown (which is the case for most short GRBs)? Continued joint gamma-ray and gravitational wave observations will address these points directly.

HOW MANY JOINT OBSERVATIONS CAN WE EXPECT OVER THE COMING YEARS?

GRB 170817A is only the beginning of an era of joint gamma-ray and gravitational-wave observations that will help reveal the astonishing physics of neutron stars and gamma-ray bursts. LIGO and Virgo are currently being upgraded to further improve their performance. Given the expected sensitivity of these detectors in the next observing run (scheduled for late 2018), between 1 and 50 gravitational-wave signals from binary neutron star mergers are expected per year. In conjunction with Fermi-GBM, between 0.1 and 1.4 joint gravitational-wave and GRB observations are expected yearly. When the gravitational-wave detectors reach their design sensitivity (circa 2020), the expected number of detectable gravitational-wave signals rises to between 6 and 120 and the number of joint detections with Fermi-GBM to 0.3 - 1.7 per year.

The global network of gravitational-wave detectors and wide-field gamma-ray observatories, such as Fermi-GBM and INTEGRAL SPI-ACS, will be critical to the future of gravitational-wave-GRB astronomy.

FIND OUT MORE:

- Visit our websites: http://www.ligo.org, http://www.virgo-gw.eu
- You can read the full article, which has been accepted for publication in **The Astrophysical Journal**. You can read the paper here.

GLOSSARY

Gamma rays: Electromagnetic radiation at the highest energy on the electromagnetic spectrum.

Neutron star: Extremely dense object which remains after the collapse of a massive star. A typical neutron star has a mass half a million times that of the Earth but is only about 30 km across.

Black hole: A region of space-time caused by an extremely compact mass where the gravity is so intense it prevents anything, including light from leaving.

Signal-to-noise ratio: The ratio of the signal power to the noise power, used to compare the level of signal to the level of the noise. It measures the strength of the signal compared with the sources of noise that could potentially contaminate it.

Observing run: A period of observation in which gravitational-wave detectors are taking data.