RESEARCH ARTICLE

NEUTRON STAR MERGER

Swope Supernova Survey 2017a (SSS17a), the optical counterpart to a gravitational wave source

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On 17 August 2017, the Laser Interferometer Gravitational-Wave Observatory (LIGO) and the Virgo interferometer detected gravitational waves (GWs) emanating from a binary neutron star merger, GW170817. Nearly simultaneously, the Fermi and INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory) telescopes detected a gamma-ray transient, GRB 170817A. At 10.9 hours after the GW trigger, we discovered a transient and fading optical source, Swope Supernova Survey 2017a (SSS17a), coincident with GW170817. SSS17a is located in NGC 4993, an S0 galaxy at a distance of 40 megaparsecs. The precise location of GW170817 provides an opportunity to probe the nature of these cataclysmic events by combining electromagnetic and GW observations.

Merging binary compact objects such as black holes (BHs) and neutron stars (NSs) are expected to be gravitational wave (GW) sources in the 10-to-10^4–Hz frequency range (*1*) that can be observed using interferometers. The Laser Interferometer Gravitational-Wave Observatory (LIGO) recently used this method to detect several binary BH (BBH) mergers (*2*–*4*). These discoveries have unveiled a population of relatively massive BHs, tested the theory of general relativity, and led to insights regarding stellar evolution and binary populations (*5*, *6*). Although it is unlikely that BBH systems produce a luminous electromagnetic (EM) signature, detecting an EM counterpart to a GW event would greatly improve our understanding of the event by providing a precise location and insight into the merger products. Unlike BBH mergers, binary NS (BNS) mergers are expected to produce gravitationally unbound radioactive material that is visible at optical and infrared wavelengths (an event known as a kilonova) (*7*–*10*), and perhaps relativistic jets seen as short gamma-ray bursts (SGRBs) (*11*, *12*). BNS mergers should produce transient, temporally coincident GWs and light. As compared with the detection of GWs alone, this method has many advantages, such as possibly constraining the nuclear equation of state, measuring the production of heavy elements, studying the expansion of the universe, and generating a clearer picture of the merger event (*13*–*15*).

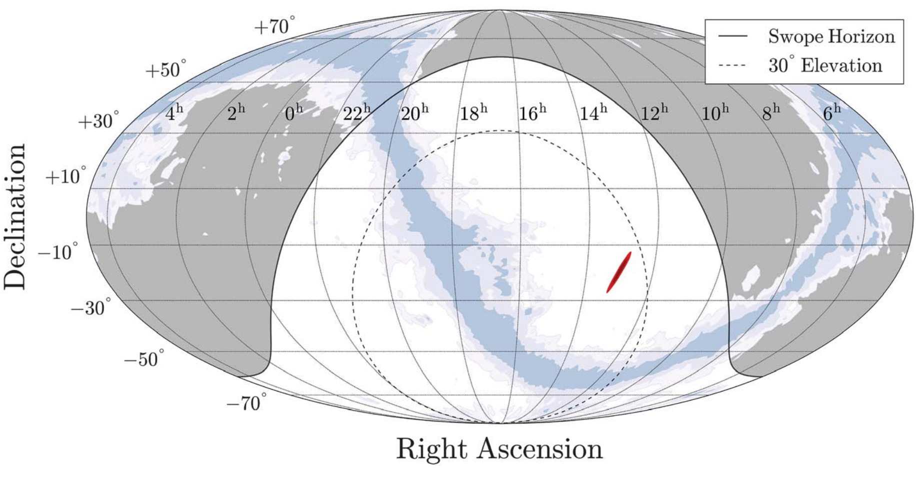

Fig. 1. Gravitational wave localization of GW170817. The outer edge of the red region represents the 90% confidence region as extracted from the revised BAYESTAR probability map. Also shown for context is the Milky Way (in blue), with the outermost blue contour corresponding to *V*-band extinction A_V = 0.5 mag (*34*). The thick solid line represents the horizon as seen from the Swope Telescope on 17 August 2017 at 23:33 UT, the time we observed SSS17a. The dotted line represents an elevation above the horizon of 30° (corresponding to an air mass of 2.0).

GW170817 and the One-Meter Two-Hemispheres Collaboration

On 17 August 2017, LIGO and Virgo detected a strong GW signal consistent with a BNS merger, GW170817 (*16*). A preliminary analysis of the GW data suggested that the two component masses were small enough to be a BNS system. This event had a low false-alarm rate of one per 10,000 years, a 90% chance of being localized to an area of 31 square degrees (Figs. 1 and 2), and a distance D = 40 ± 8 megaparsecs (Mpc) (*16*, *17*). Contemporaneously, the Fermi and INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory) gamma-ray telescopes detected a SGRB both spatially and temporally coincident with the GW event, GRB 170817A. However, the Fermi-INTEGRAL localization area was larger than the LIGO-Virgo localization area (*18*, *19*).

Our One-Meter Two-Hemispheres (1M2H) Collaboration uses two 1-m telescopes, the Nickel Telescope at Lick Observatory in California and the Swope Telescope at Las Campanas Observatory in Chile, to search for EM counterparts to GW sources. Our strategy involves observing previously cataloged galaxies whose properties are consistent with the GW data to search for new sources. This strategy is particularly effective for nearby events with a small distance uncertainty, which reduces the surface density of viable targets (*20*). We observe in either *i*′- or *i*-band filters (Nickel

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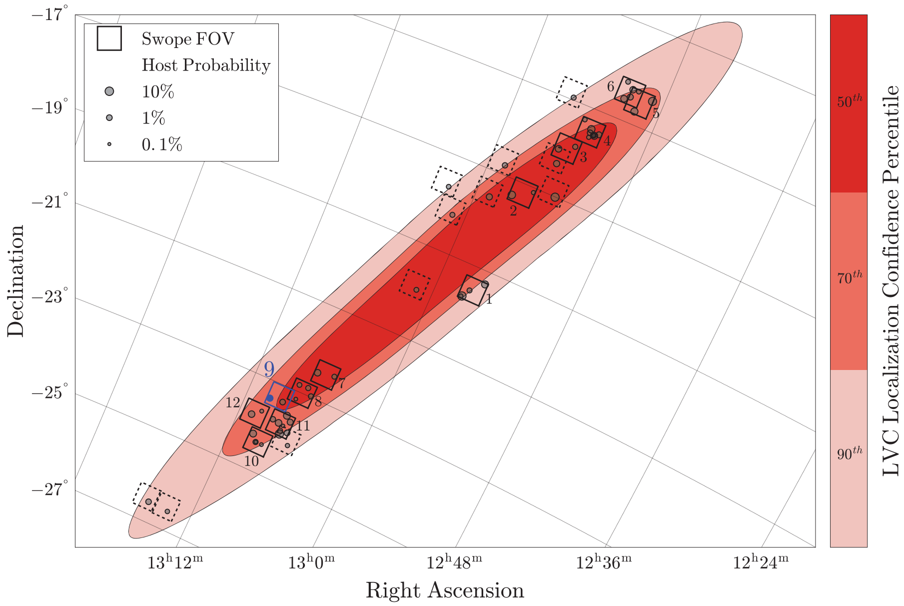

Fig. 2. Sky region covering the 90% confidence region for the location of GW170817. The 50%, 70%, and 90% contours are shown, with contours extracted from the same probability map as Fig. 1. Gray circles represent the locations of galaxies in our galaxy catalog and observed by the Swope Telescope on 17 to 18 August 2017 to search for the EM counterpart to GW170817. The size of the circle indicates the probability of a particular galaxy being the host galaxy for GW170817. The square regions represent individual Swope pointings, with the solid squares specifically chosen to contain multiple galaxies (and labeled in the order in which they were observed) and the dotted squares being pointings that contain individual galaxies. The blue square labeled "9" contains NGC 4993, the location of which is marked by the blue circle, and SSS17a. FOV, field of view.

and Swope, respectively) because those are the reddest bands available on those telescopes and theoretical models predicted that kilonova light curves would be particularly red (*10*).

Because the center of the localization region was in the Southern Hemisphere and relatively close to the Sun, the Nickel Telescope could not observe the GW170817 localization region. For GW170817, we were able to also use both Magellan telescopes as part of the search (*21*), allowing a multiwavelength campaign covering the *giH* bands. At the time of the trigger, the local time in Chile was 9:41 a.m. (when the Sun was above the horizon), so observations could not begin for more than 10 hours. Because of the GW position, the majority of the 90% localization region was expected to be accessible only for the first 2 hours after civil twilight that evening (Fig. 1).

Detection of SSS17a

We used a catalog of nearby galaxies and the three-dimensional (3D) GW localization of GW170817 (*21*) to create a prioritized list of galaxies in which the source of the GW event could reside (table S1). Our prioritization algorithm includes information about the stellar mass and star-formation rate of the galaxy. We examined the positions of the 100 highest-priority galaxies to determine whether multiple galaxies could fit in a single Swope image (field of view of 29.7 arc min by 29.8 arc min) so that we could cover the probable locations as efficiently as possible. We were able to combine 46 galaxies in a total of 12 images (Fig. 2). The remaining galaxies on the initial list were sufficiently isolated to require their own images. We designed an observing schedule that allowed us to initially observe the 12 positions covering multiple galaxies, followed by individual galaxies in order of their priority while they were ~19.5° above the horizon (corresponding to an air mass of 3.0).

Starting at 23:13 UT, when nautical twilight ended (Sun >12° below the horizon), which was 45 min after sunset and 10 hours after the GW trigger, we began observing the GW170817 localization region with an *i*-band filter. The 60-s exposures had a point-source

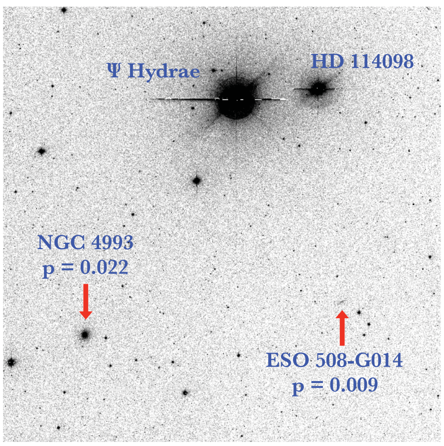

Fig. 3. Full-field Swope Telescope *i*-band image containing NGC 4993. For the location of NGC 4993, see field 9 in Fig. 2. The bright stars Ψ Hydrae and HD 114098 are labeled. The galaxies NGC 4993 and ESO 508-G014, which had probabilities of hosting GW170817 of 0.022 and 0.009, respectively (table S1), are labeled and marked with red arrows.

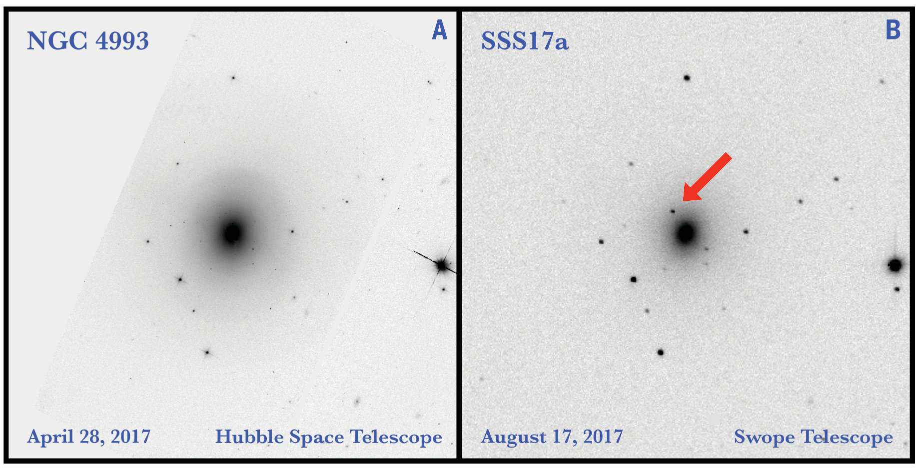

Fig. 4. Images centered on NGC 4993, with north up and east left. Image dimensions are 3 arc min by 3 arc min. (**A**) Hubble Space Telescope F606W-band (broad *V*) image captured 4 months before the GW trigger (*25*, *35*). (**B**) Swope image of SSS17a. The *i*-band image was obtained on 17 August 2017 at 23:33 UT by the Swope Telescope at Las Campanas Observatory. SSS17a is marked with the red arrow. No object is present in the Hubble image at the position of SSS17a (*25*, *35*).

limiting magnitude of 20.0 mag, corresponding to an absolute magnitude M_i of −13.0 mag at a distance D = 40 Mpc (uncorrected for foreground Milky Way extinction). We immediately transferred, reduced, and examined each image by eye. In the ninth image (Fig. 3), which was initiated at 23:33 UT and contained two high-priority targeted galaxies, we detected an i = 17.476 ± 0.018 mag source that was not present in archival imaging (Fig. 4). We designate the source as Swope Supernova Survey 2017a (SSS17a); it is located at right ascension $13^h09^m48^s.085$ ± 0.018 and declination −23°22′53″.343 ± 0.218 (J2000 equinox). SSS17a is offset 10.6 arc sec (corresponding to 2.0 kpc at 40 Mpc) from the nucleus of NGC 4993, an S0 galaxy at a redshift of 0.009680 (*22*) and a Tully-Fisher distance of 40 Mpc (*23*). On the basis of our algorithm, NGC 4993 was the 12th most likely host galaxy, with a 2.2% probability of being the host galaxy (table S1).

After confirming that SSS17a was not a previously known asteroid or supernova (SN), we triggered additional follow-up observations (*24*–*26*) and disseminated our discovery through a LIGO-Virgo Collaboration (LVC) Gamma-ray Coordinates Network (GCN) Circular [(*27*), see (*21*) for details]. We quickly confirmed SSS17a in an image from the Magellan Clay telescope, which was performing a similar galaxy-targeted search (*21*, *28*). Several other teams also detected the presence of the new source after our original discovery image [see (*29*) for a complete list]. We observed an additional 45 fields after identifying the new source, acquiring 54 images over 3.5 hours and covering 95.3% of the total probability (as determined by our algorithm) and 26.9% of the 2D GW localization probability. When we compared our findings with Swope images obtained 18 to 20 days after the trigger, we found no transient objects other than SSS17a in either set of images. Most galaxies are ~7 arc min from the edge of a Swope image (one-quarter of the size of the field of view), corresponding to ~80 kpc at 40 Mpc. For these regions covered by our images, we can exclude another luminous transient from being associated with GW170817 at the 95.3% confidence level (*21*). SSS17a is unlike any transient previously detected by SN searches, making it an unusual discovery if not associated with an extraordinary event such as GW170817. Additionally, known SN rates imply that we would expect only 0.01 supernovae per year in the LVC localization volume. The combination of all available data further indicates that SSS17a is physically associated with GW170817, with a chance coincidence probability of $\sim 10^{-6}$ (*30*, *31*).

Our observations were made with a 1-m telescope with a camera that had a ~0.25–square degree field of view. This is in contrast to the strategy of using wide-field cameras, often on larger-aperture telescopes, to observe the entire localization region, unguided by the positions of known galaxies (*32*, *33*). Although wide-field imagers might be necessary to discover an EM counterpart in a region with a larger localization uncertainty or in a low-luminosity galaxy, such instrumentation was not necessary for the case of GW170817 and SSS17a. Nearly every optical observatory has an instrument suitable for our strategy; even some amateur astronomers have sufficient instrumentation to perform a similar search. Although aperture and field of view are key capabilities in the EM follow-up of future GW sources at the LIGO-Virgo detection limits, when it comes to finding the closest and most scientifically fruitful sources, such as GW170817 and SSS17a, the more important factors are telescope location and observational strategy.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/358/6370/1556/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S6
Tables S1 and S2
References (*36*–*65*)

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Swope Supernova Survey 2017a (SSS17a), the optical counterpart to a gravitational wave source

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Photons from a gravitational wave event

Two neutron stars merging together generate a gravitational wave signal and have also been predicted to emit electromagnetic radiation. When the gravitational wave event GW170817 was detected, astronomers rushed to search for the source using conventional telescopes (see the Introduction by Smith). Coulter *et al.* describe how the One-Meter Two-Hemispheres (1M2H) collaboration was the first to locate the electromagnetic source. Drout *et al.* present the 1M2H measurements of its optical and infrared brightness, and Shappee *et al.* report their spectroscopy of the event, which is unlike previously detected astronomical transient sources. Kilpatrick *et al.* show how these observations can be explained by an explosion known as a kilonova, which produces large quantities of heavy elements in nuclear reactions.

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