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

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On 2017 August 17, the Laser Interferometer Gravitational-Wave Observatory (LIGO) and the Virgo interferometer detected gravitational waves emanating from a binary neutron star merger, GW170817. Nearly simultaneously, the *Fermi* and INTEGRAL telescopes detected a gamma-ray transient, GRB 170817A. 10.9 hours after the gravitational wave 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 gravitational-wave observations.

Merging binary compact objects such as black holes (BHs) and neutron stars (NSs) are expected to be gravitational wave (GW) sources in the 10–10^4 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 black holes, tested 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 (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. This has many advantages in comparison to detecting GWs alone, 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*).

On 2017 August 17, LIGO/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 1 per 10,000 years, a 90-percent chance of being localized to an area of 31 deg^2 (Figs. 1 and 2), and a distance of $D = 40 \pm 8$ megaparsecs (Mpc) (*16*, *17*). Contemporaneously, the *Fermi* and INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) gamma-ray telescopes detected a SGRB both spatially and temporally coincident with the GW event, GRB170817A. However, the *Fermi*/INTEGRAL localization area was larger than the LIGO/Virgo localization area (*18*, *19*).

Our One-Meter, Two-Hemisphere (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 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*).

As 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 multi-wavelength 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. Due to the GW position, the majority of the 90-percentile localization region was expected to only be accessible for the first 2 hours after civil twilight that evening (Fig. 1).

Using a catalog of nearby galaxies and the three-dimensional GW localization of GW170817 (*21*), we created 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 see if multiple galaxies could fit in a single Swope image (field of view of 29.7×29.8 arcminutes), 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 first observed the 12 positions covering multiple galaxies, followed by individual galaxies in order of their priority while they were approximately 19.5 degrees above the horizon (corresponding to an airmass of 3.0).

Starting at 23:13 UT, when nautical twilight ended (Sun > 12 degrees below the horizon), which was 45 min after sunset and ten 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 limiting magnitude of 20.0 mag, corresponding to an absolute magnitude M_i of −13.0 mag at a distance of $D = 40$ 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 $i = 17.476 \pm 0.018$ 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 $13^h09^m48^s.085 \pm 0.018$, declination $-23°22'53''.343 \pm 0.218$ (J2000 equinox). SSS17a is offset 10.6 arcseconds (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*). NGC 4993 was the twelfth most likely host galaxy based on our algorithm, with a 2.2% probability of being the host galaxy (see 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 Coordination Network (GCN) circular [(*27*), see (*21*)] for details]. We quickly confirmed SSS17a in a Magellan image, 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 two-dimensional GW localization probability. Comparing to Swope images obtained 18–20 days after the trigger, we found no transient objects other than SSS17a in either set of images. Most galaxies are about ~7 arcminutes from the edge of a Swope image (1/4 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 found by SN searches, making it an unusual discovery if unassociated with an extraordinary event such as GW170817. Additionally, known SN rates imply we would expect only 0.01 SNe year^{-1} in the LVC localization volume. The combination of all available data further indicates that SSS17a is physically associated with GW170817, with a probability of a chance coincidence of $\sim 10^{-6}$ (*30*, *31*).

Our observations were made with a 1-m telescope with an approximately quarter square degree field-of-view camera. 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*). While wide-field imagers might be necessary to discover an EM counterpart in a larger localization error region or in a low-luminosity galaxy, such instrumentation was not necessary for the case of GW170817/SSS17a. Nearly every optical observatory has an instrument suitable for our strategy; even some amateur astronomers have sufficient instrumentation to perform a similar search. While 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 scientifically fruitful sources like GW170817/SSS17a, the more import factors are telescope location and observational strategy.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/cgi/content/full/science.aap9811/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S6
Tables S1 and S2
References (*36*–*65*)

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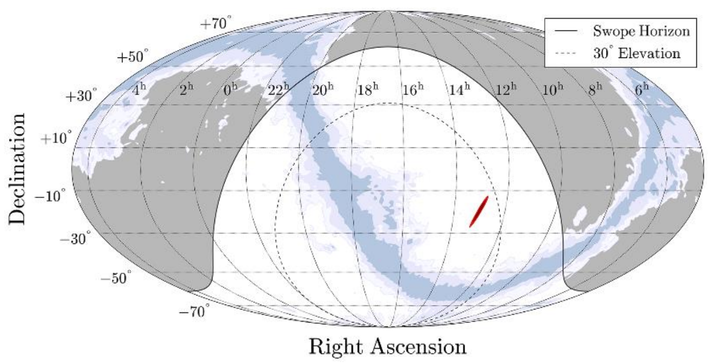


Fig. 1. Gravitational-wave localization of GW170817. The outer edge of the red region represents the 90th-percentile confidence region as extracted from the revised BAYESTAR probability map. Also shown is the Milky Way in blue for context, with the outermost blue contour corresponding to V-band extinction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

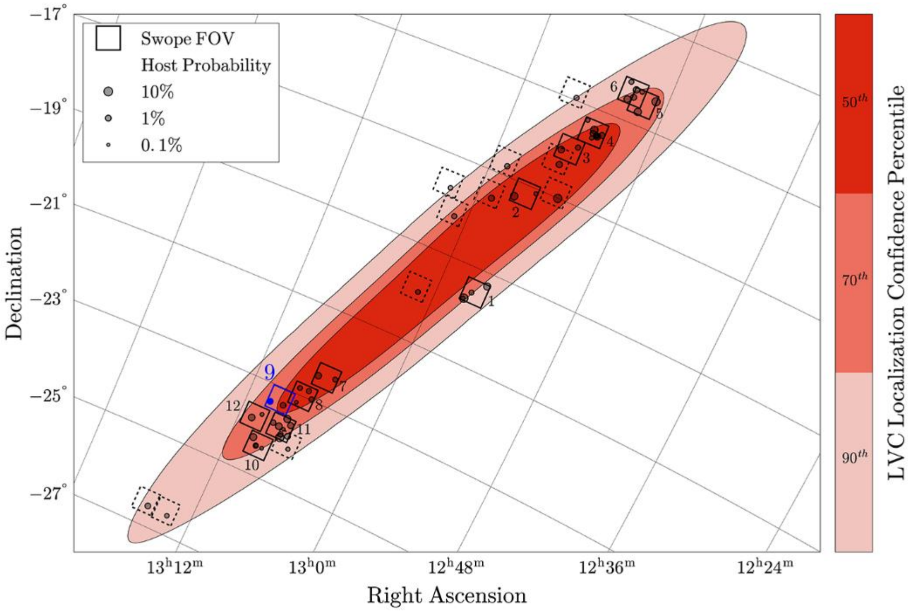
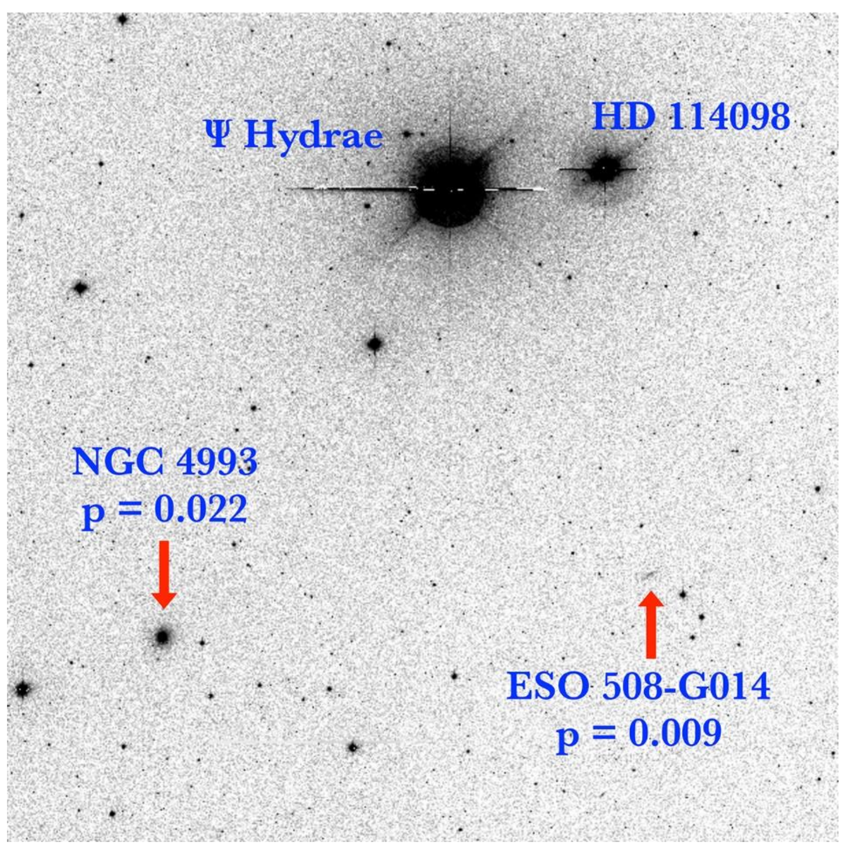


Fig. 2. Sky region covering the 90th-percentile confidence region for the location of GW170817. The 50th, 70th, and 90th-percentile contours are shown, with contours extracted from the same probability map as Fig. 1. Gray circles represent the locations of galaxies in our galaxy catalog and observed by the Swope telescope on 2017 August 17–18 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 that they were observed) and the dotted squares being pointings which contained individual galaxies. The blue square labeled "9" contains NGC 4993, whose location is marked by the blue circle, and SSS17a.

Fig. 3. Full-field Swope telescope *i*-band image containing NGC 4993 (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.



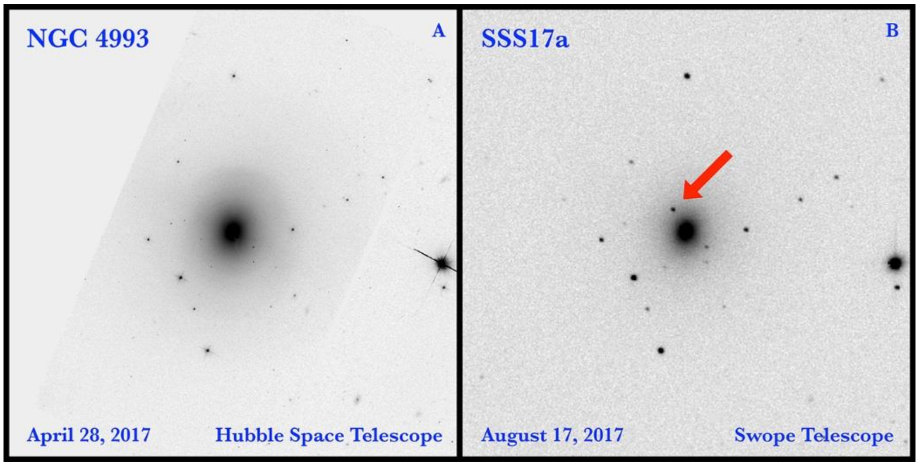


Fig. 4. 3×3 arcminute images centered on NGC 4993 with North up and East left. (**A**) *Hubble Space Telescope* F606W-band (broad *V*) image from 4 months before the GW trigger (*25*, *35*). (**B**) Swope image of SSS17a. The *i*-band image was obtained on 2017 August 17 at 23:33 UT by the Swope telescope 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*).

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

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