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THE UNPRECEDENTED PROPERTIES OF THE FIRST ELECTROMAGNETIC COUNTERPART TO A GRAVITATIONAL WAVE SOURCE

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ABSTRACT

We discovered Swope Supernova Survey 2017a (SSS17a) in the LIGO/Virgo Collaboration (LVC) localization volume of GW170817, the first detected binary neutron star (BNS) merger, only 10.9 hours after the trigger. No object was present at the location of SSS17a only a few days earlier, providing a qualitative spatial and temporal association with GW170817. Here we quantify this association, finding that SSS17a is almost certainly the counterpart of GW170817, with the chance of a coincidence being $\leq 9 \times 10^{-6}$ (90% confidence). We arrive at this conclusion by comparing the optical properties of SSS17a to other known astrophysical transients, finding that SSS17a fades and cools faster than any other observed transient. For instance, SSS17a fades >5 mag in g within 7 days of our first data point while all other known transients of similar luminosity fade by <1 mag during the same time period. Its spectra are also unique, being mostly featureless, even as it cools. The rarity of "SSS17a-like" transients combined with the relatively small LVC localization volume and recent non-detection imply the extremely unlikely chance coincidence. We find that the volumetric rate of SSS17a-like transients is $\leq 1.6 \times 10^{4}$ Gpc^{-3} year^{-1} and the Milky Way rate is $\leq$0.19 per century. A transient survey designed to discover similar events should be high cadence and observe in red filters. The LVC will likely detect substantially more BNS mergers than current optical surveys will independently discover SSS17a-like transients, however a 1-day cadence survey with LSST could discover an order of magnitude more events.

Keywords: galaxies—individual(NGC 4993), stars: individual(SSS17a), stars: neutron, supernovae—general

1. INTRODUCTION

The transient sky is filled with dozens of different observationally distinct classes of explosive transients. Although most fall into three broad classes, Type Ia, Type II, and Type Ib/c supernovae (SNe Ia, II, and Ib/c, respectively), there are many additional classes of "exotic" or "peculiar" transients including Ca-rich SNe, luminous red novae, luminous SNe IIn, pair-instability SNe, SN impostors, SNe Iax, SN 2006bt-like SNe, and tidal disruption flares (e.g., Smith et al. 2007; Berger et al. 2009; Gal-Yam et al. 2009; Foley et al. 2010b, 2013; Perets et al. 2010; Gezari et al. 2012; Quimby et al. 2011). These classes have diverse observational properties with peak luminosities spanning >3 orders of magnitude, timescales ranging from about two weeks to >1 year, and spectra that bely significantly different compositions, ejecta velocities, and ionization states. Quite simply, the transient sky is extremely diverse.

Despite this diversity, known transients still do not fill the entire parameter space of peak luminosity–timescale–velocity space (e.g., Villar et al. 2017). Instead, there are clear correlations between these parameters that can be explained by most transients coming from a limited set of progenitor stars (generally white dwarfs or massive stars), energy sources (generally the decay of ^{56}Ni, H recombination, or interaction between a shock and circumstellar material), and emission mechanisms (thermal or synchrotron). Therefore new progenitors and/or energy sources are likely necessary to produce a transient with truly unique observational properties.

At 12:41:04 on 17 August 2017 (all times are UT), the advanced LIGO detector (LIGO Scientific Collaboration et al. 2015) at Hanford measured a gravitational-wave transient (later labeled GW170817 (Abbott et al. 2017)); the same event was then detected in the advanced LIGO detector data at Livingston and identified by the LIGO Scientific Collaboration and the Virgo collaboration (LVC) as a binary neutron star (BNS) merger (LIGO/Virgo collaboration 2017a). Nearly simultaneously, Fermi and INTEGRAL detected a short GRB (sGRB), GRB170817A, that was spatially coincident with GW170817 (INTEGRAL 2017). Later, the full preliminary three-instrument skymap using also the data of the Advanced Virgo detector (Acernese et al. 2015) was given (LIGO/Virgo collaboration 2017b) at 23:54:40 UTC. Only 10.9 hours after the LVC trigger, we discovered an optical transient, Swope Supernova Survey 2017a (SSS17a; also known as DLT17ck Yang et al 2017 and AT 2017gfo), spatially coincident with GW170817 (One-Meter Two-Hemisphere (1M2H) collaboration 2017; Coulter et al. 2017). For the following three weeks, we monitored SSS17a in the optical and near-infrared (Coulter et al. 2017; Drout et al. 2017; Shappee et al. 2017).

It has been assumed that SSS17a is the electromagnetic (EM) counterpart to GW170817. Here we determine the uniqueness of SSS17a compared to other known transients. In Section 2, we compare the optical light curves and spectra of SSS17a to other known transients. In Section 3, we determine the likelihood of SSS17a being associated with GW170817. We discuss SSS17a in the context of current and future surveys in Section 4 and conclude in Section 5.

In this Letter, we assume the Tully-Fisher distance to NGC 4993, the host galaxy of SSS17a, of D = 39.5 Mpc (Freedman et al. 2001) and no host-galaxy reddening for SSS17a (consistent with non-detection of Na D absorption; Shappee et al. 2017). We assume $H_0 = 73.2$ km s^{-1} Mpc^{-1} (Riess et al. 2016), $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. PHOTOMETRIC AND SPECTROSCOPIC COMPARISONS

Immediately after the discovery of SSS17a (Coulter et al. 2017), we initiated a follow-up campaign to obtain near-nightly 14-band ultraviolet/optical/NIR photometry (Coulter et al. 2017; Drout et al. 2017) and optical spectra (Shappee et al. 2017). Kilpatrick et al. (2017) analyze these data in the context of kilonova models. Here we compare to other known transients with no model assumptions.

Figure 1 presents our g- and i-band absolute magnitude (M_g and M_i, respectively) light curves. Also displayed are the absolute magnitude light curves (in similar bands) of representative SNe Ia, low-luminosity SN 1991bg-like SNe Ia, and SNe Ic, IIP, and IIb. SSS17a is clearly very different from these classes, being less luminous at peak ($M_{g,\ \rm peak} = -16.0$ mag; $M_{i,\ \rm peak} = -15.7$ mag) and fading much faster than all typical classes. We also display SN 1987A, which is low luminosity but very slow, the "typical" SN Iax 2005hk (Phillips et al. 2007), the low-luminosity SN Iax 2008ha (Foley et al. 2009, 2010a), the Ca-rich SN 2005E (Perets et al. 2010), three fast-evolving, blue Drout et al. (2014, hereafter D14) transients, and several sGRB afterglows. SSS17a has a peak luminosity somewhat similar to SN 1987A, Ca-rich SNe, and SNe Iax, and is lower luminosity than the D14 transients and significantly fainter than sGRBs. While SNe 2005E, 2008ha, and the D14 transients all fade quickly relative to common SNe, none fades nearly as rapidly as SSS17a. On the other hand, all three short-GRB afterglows, GRB130603B, GRB070707 and GRB051221A (Berger et al. 2013; Piranomonte et al. 2008; Soderberg et al. 2006), decline extremely rapidly during the time they are visible and are significantly faster than SSS17a.

Although SSS17a is associated with GRB170817A, it is inconsistent with being an afterglow (Drout et al. 2017). Its broadband spectral-energy distribution (SED), and its evolution, are consistent with a rapidly cooling thermal spectrum (Drout et al. 2017) and its detailed spectral evolution is inconsistent with a synchrotron spectrum (Shappee et al. 2017). As no other sGRB is known to have a non-thermal optical SED, SSS17a is clearly not simply a GRB afterglow. Furthermore, significantly more energy is radiated from SSS17a than originally from GRB170817A (Murguia-Berthier et al. 2017), even making the phrase "afterglow" a misnomer. Therefore, we focus our subsequent comparisons on other transients that are discovered by optical surveys.

The decline of transients are often described by the magnitude decline from peak over 15 days, Δm_{15} (Phillips 1993). However, SSS17a faded so quickly in the optical that we have no measurements near 15 days after peak. Instead, we use Δm_7, finding $\Delta m_7(g) > 5.2$ and $\Delta m_7(i) = 3.90 \pm 0.18$ mag (with the assumption that our first data point corresponds to peak in each band). Figure 2 displays the peak luminosity and Δm_7 for SSS17a and all other transients with sufficient data in the Open Supernova Catalog (Guillochon et al. 2017). We note that we do not correct the peak absolute magnitude of these objects for host-galaxy extinction. Although this is a biased sample that depends on which objects were followed, it is still informative and peculiar transients are over-represented relative to a magnitude-limited sample. The median decline rates for all comparison transients are $\Delta m_7(g) = 0.31$ mag and $\Delta m_7(i) = 0.18$ mag, respectively. The second-fastest transient in i-band, after SSS17a, is PS1-11qr, a D14 transient with $\Delta m_7(i) = 0.94$ mag. Figure 2 is a striking representation of how unique SSS17a is relative to previously observed transients, including those previously described as "exotic."

In addition to the fast fading of SSS17a, its color also evolves extremely quickly. Figure 3 displays $g-r$, $r-i$, and $g-i$ color curves of SSS17a and comparison objects. At peak SSS17a has colors very similar to those of other transients. However, only a few days later, SSS17a has significantly redder colors, with its $r-i$ color changing from -0.26 mag at peak to 1.12 mag 4.0 days later. This dramatic color evolution is consistent with the overall temperature evolution showing that SSS17a cooled from $\sim$10,000 K at peak to 5100 K a day later, to about 2500 K about a week after peak (Drout et al. 2017). Such color/temperature evolution has never been seen in any other transient.

Shappee et al. (2017) performed a detailed comparison of the SSS17a spectral sequence to other transients. The earliest spectra are blue and featureless, similar to several other young transients. However, SSS17a already has distinct spectra 1 day later. Figure 4 displays the +4.5-day spectrum of SSS17a compared to other transients at similar phases. SN 2002bj is the fastest evolving SN of the comparison transients. However, there are prominent He and C lines superimposed on a blue continuum (Poznanski et al. 2010) at 5.73 days after B-band maximum. The color and luminosity of SSS17a are somewhat similar to those of SN 1987A, but the evolutionary timescale of its spectral and photometric properties is orders of magnitude shorter. All transient spectra, except for that of SSS17a, exhibit relatively narrow spectral features. SSS17a has a very broad "feature" from $\sim$8000–10,000 Å, which may be the result of combining physically distinct ejecta components (Shappee et al. 2017). Regardless, SSS17a has spectra that are significantly different from those of other previously known transients.

3. LIKELIHOOD OF SSS17A BEING ASSOCIATED WITH GW170817

SSS17a has truly unique observational properties relative to all other known transients. Qualitatively, the unprecedented nature of SSS17a combined with the spatial and temporal coincidence provides strong evidence that SSS17a is the EM counterpart to GW170817. Here we quantify this association and update our initial estimates (Foley 2017).

To perform this calculation, we must first determine the relative rate of transients similar to SSS17a and other transients in transient surveys. We note that in the surveys relevant for this calculation, no GRB afterglow has been detected (although see Cenko et al. 2015). Each survey observes to a limiting magnitude, which provides a volume in which a particular transient can be discovered. Since SSS17a fades so quickly, we must be careful to determine the volume in which a survey would detect SSS17a on at least two separate epochs. For these calculations, we follow the procedure outlined by Foley et al. (2013).

One of the most prolific transient surveys is the Lick Observatory Supernova Search (LOSS; Filippenko et al. 2001a), which has performed a galaxy-targeted SN search for two decades. Leaman et al. (2011) presented a sample of 726 LOSS-discovered SNe. Although their cadence varied over the entire survey, the closest galaxies were generally observed at a cadence of $\sim$5 days.

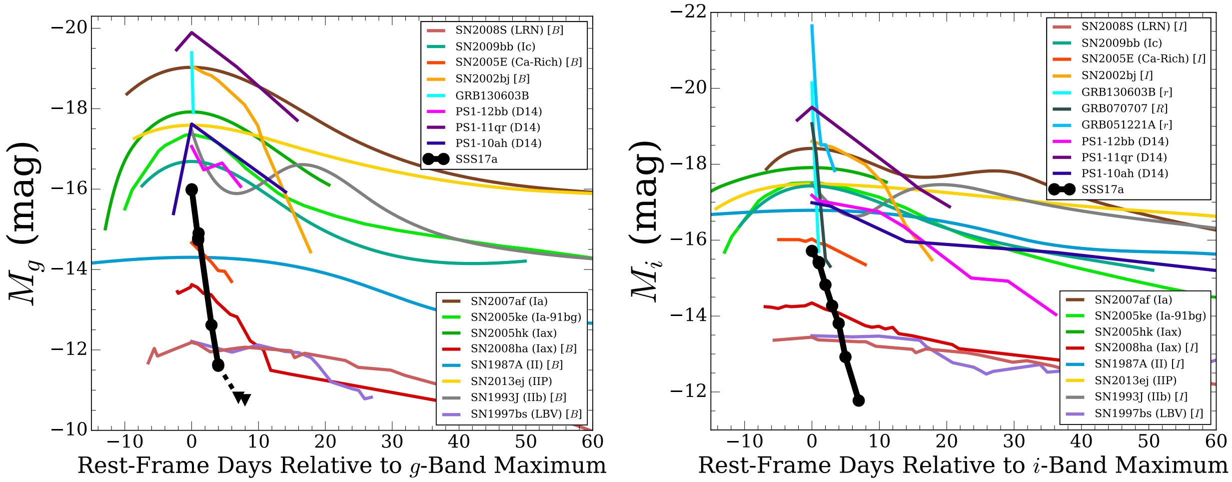

Figure 1. Absolute magnitude light curves of SSS17a (black curves) in g (left panel) and i (right panel) bands. Also shown for comparison are representative light curves for SNe Ia (both typical-luminosity and a representative of the SN 1991bg-like class), Ic, IIP, and IIb, as well as peculiar transients, SN II 1987A, SN Iax 2005hk, SN Iax 2008ha, Ca-rich SN 2005E, fast-evolving SN Ib 2002bj (Poznanski et al. 2010), luminous red nova SN 2008S (Prieto et al. 2008; Botticella et al. 2009), multiple members of the D14 sample of fast-evolving, blue transients, and several sGRBs. All light curves are presented in the observer frame. SSS17a evolves significantly faster than any non-GRB comparison object. SSS17a is slower than sGRB afterglows and significantly less luminous at peak. We use the B and I-band light curves for all comparisons except SN 2013ej, SN 2005ke, GRB and D14 objects (where we use g/i). Luminosities for SN 2002bj, SN 2005E, GRB and D14 objects assume Hubble distances while the rest are independently measured.

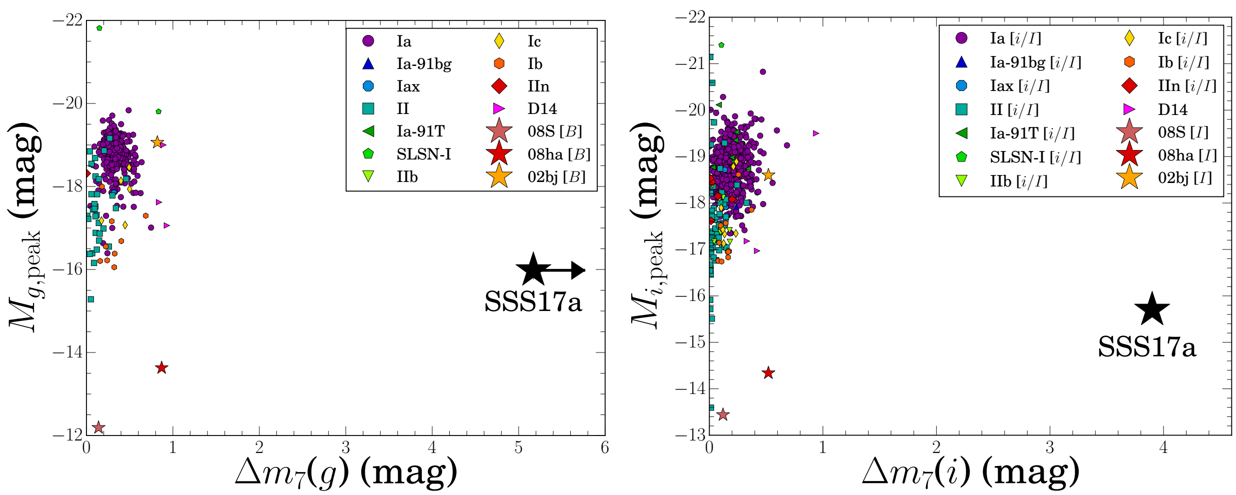

Figure 2. Comparison between peak luminosity and the magnitude decline after 7 days from peak (Δm_7) in the g (left panel) and i/I (right panel) bands for SSS17a (black star) and other transient objects. Transients of a particular class are shown with a similar color. We correct for Milky Way extinction, but not for any host-galaxy extinction. While SSS17a declines by >5.17 mag in g within the first 7 days after peak, no other transient declines by more than 1 mag. Luminosities assume either Hubble distances for $z > 0.015$ or independently measured distances for closer objects.

LOSS has an unfiltered search, but its CCD response is similar to R band (Filippenko et al. 2001b). With a typical limiting magnitude of 18.5, LOSS would detect SSS17a only to a distance modulus of $\mu_{\rm max} = 30.9$ mag (roughly 15 Mpc). There are only 12 SNe in the Leaman et al. (2011) sample within this volume. However, since 2008, which marks the end of the Leaman et al. (2011) sample, an additional 46 SNe were detected within this volume. While many of these objects may have been detected by low-cadence (>7 days) surveys, new surveys tend to have higher cadence (<3 days) than LOSS (∼5 days). We therefore use a total sample of 58 SNe as

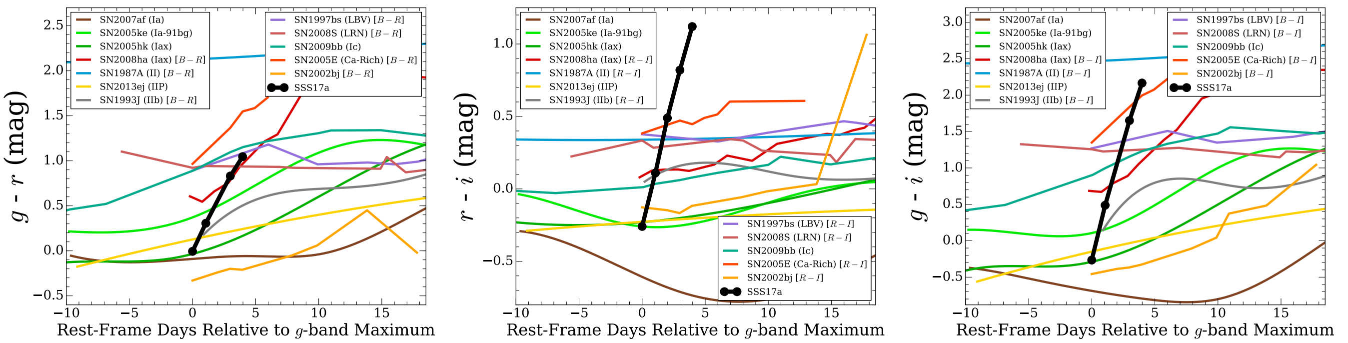

Figure 3. Color curves of SSS17a (black curves) in $g - r$ (left panel), $r - i$ (middle panel), and $g - i$ (right panel). Also shown are comparison objects from other transient classes. See Figure 1 for details. We correct for Milky Way extinction, but not for any host-galaxy extinction. While SSS17a has a similar $g - r$ color evolution as many objects, its dramatic $r - i$ color evolution is unprecedented, where it starts with a color near 0.1 mag at peak and quickly evolves to $r - i \approx 1.2$ mag only 4 days later.

occurring within the SSS17a detection volume as part of surveys that could have detected a transient similar to SSS17a.

Since we do not have detailed logs of each survey, it is difficult to precisely determine the correction factor necessary to account for the difficulty of observing SSS17a. Such a factor is necessary to account for the fact that while SSS17a could be detected within the volume determined above, doing so requires no significant reddening, no long periods of bad weather, and the transient occurring when it is not behind the Sun (other nearby SNe can be discovered in this volume over many months). Sun constraints and weather alone reduce the efficiency of discovering the most-distant SSS17a-like objects by a factor of ∼2. To account for unknown inefficiencies in different surveys, we choose a conservative correction factor of 4, which means that for every 4 SSS17a-like objects that occur in the volume, we would only detect 1. As a comparison, Foley et al. (2013) used a correction factor of 2 for the closest SNe Iax.

Using Poisson statistics, we determine the rate of SSS17a-like transients necessary such that 90% of the time, we would have expected to detect at least one SSS17a-like transient in previous surveys, finding that the SSS17a-like transient rate is at most 0.16 that of all other SNe. That is, if the fraction of SSS17a-like objects were higher than $f_{\rm SSS17a} = 0.16$ (16%) that of overall SN population with at least its luminosity, we would have expected LOSS or other surveys since 2008 to be more likely to detect at least one SSS17a-like object with 90% confidence.

The LVC localizes the source at a luminosity distance of 40±7 Mpc within a sky region of 31 deg^2 (at 90% confidence) (Abbott et al. 2017), corresponding to a volume of 104 Mpc^3. Using the Li et al. (2011b) total volumetric SN rate, we expect a SN rate in the LVC localization region of $R_{\rm LVC} = 0.010$ SNe year^{-1}.

Finally, we note that there was no detection of a transient at the location of SSS17a $t_{nd} = 2.0$, 21.0, and 111.8 days before its detection by ASAS-SN, DLT40, and *Hubble Space Telescope* (Shappee et al. 2014; Kochanek et al. 2017; Cowperthwaite et al 2017; DLT40 2017; Foley et al. 2017; Pan et al. 2017). Although it is unclear how bright SSS17a could have been two days before detection, it would likely be detectable in the ASAS-SN image if we simply extrapolate back from the time of detection. Ignoring the ASAS-SN data, SSS17a was at most 21.0 days old at the time of discovery. These non-detections indicate that SSS17a was relatively young when discovered.

We can combine the above individual measurements to determine the frequency of SSS17a-like objects in a volume consistent with the LVC localization and within a specific time frame,

$$P_{\rm chance} \leq f_{\rm SSS17a} \times R_{\rm LVC} \times t_{\rm nd}, \qquad (1)$$

where $P_{\rm chance}$ is the probability that SSS17a is a spatial and temporal chance coincidence with GW170817. Using the values calculated above, we find $P_{\rm chance} \leq 9 \times 10^{-6}$ at 90% confidence (or 1×10^{-4} using the DLT40 non-detection) . Therefore, it is extremely unlikely that SSS17a is unassociated with GW170817 and SSS17a is almost certainly the optical/NIR counterpart to GW170817. Adding further confidence that SSS17a is the counterpart to GW170817, Coulter et al. (2017) detected no other transients in its search covering 2 weeks after the trigger and covering 95.3% of the probability region (when combined with galaxy properties).

4. DISCUSSION

SSS17a is a truly unique object. Since similar objects have not yet been discovered through searches unguided by a GW alert, it is difficult to determine the rate of such objects. Nevertheless, we have placed a limit on

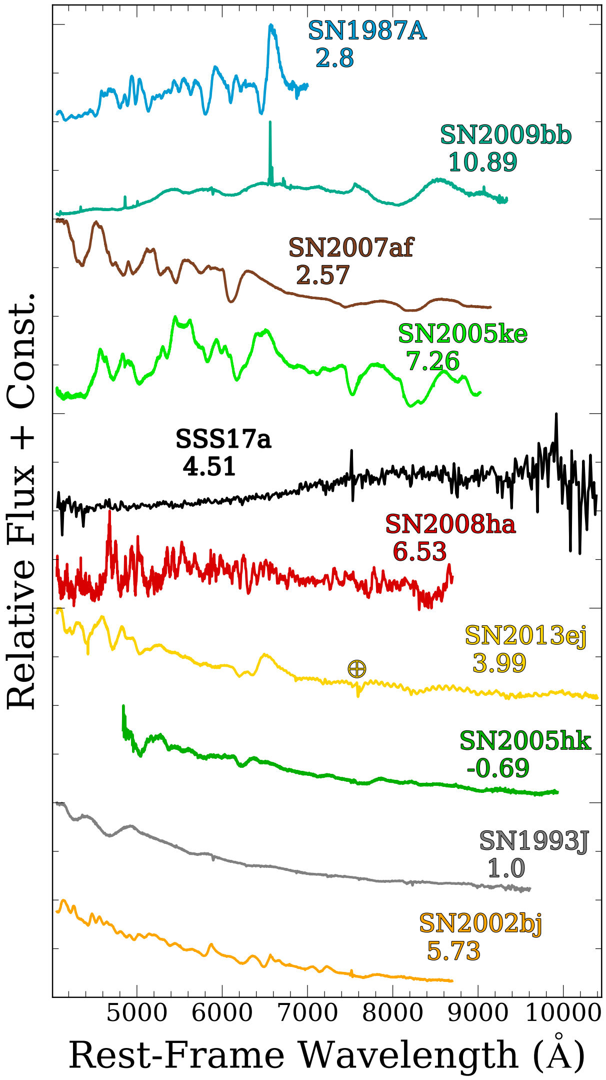

Figure 4. Optical spectrum of SSS17a (black curve) 4.5 days after the LVC trigger. Spectra of other transient objects are shown for comparison. Telluric absorption features are marked with an '⊕' symbol. No other SN has spectra similar to SSS17a at +4.5 days, and while there are some objects with spectra similar to SSS17a at +11 hours, none evolves nearly as quickly as SSS17a.

the rate of SSS17a-like objects relative to the SN rate in a volume-limited survey, $f_{\rm SSS17a} \leq 0.16$. Using the Li et al. (2011a) volumetric SN rate, we determine the rate of SSS17a-like events to be $\leq 1.6 \times 10^5$ Gpc^{-3} year^{-1} and a rate in the Milky Way of $\leq$0.46 SSS17a-like transients per century.

Current population synthesis models predict the BNS merger rate in the Milky Way to be 0.0024 per century (Chruslinska et al. 2017), two orders of magnitude below our estimate. The upper limit on the volumetric BNS merger rate from the LIGO O1 observing run is 12.6×10^3 Gpc^{-3} year^{-1} (Abbott et al. 2016b), comparable to our current estimate using independent data.

However, all values above required a GW alert. If we want to determine an independent measurement of the rate of BNS mergers and kilonovae from EM observations alone, we must have a survey that independently discovers such objects. Based on the observational properties of SSS17a, we can suggest a survey design to maximize their detection and thus the rate determination.

SSS17a fades quickly, so a high-cadence (<3-day) survey is key. Since SSS17a faded by >1 mag in g between 0.5 and 1.5 days after the LVC trigger, but only 0.3 mag during the same time in i, with $g - i \approx 0.6$ mag at +1.5 days, a survey in a redder band is clearly preferred. In fact, SSS17a "only" faded by 2.3 mag between +1.5 and +8.5 days in z band, indicating that a z-band search has distinct advantages over bluer bands.

In principle, one can now use the kilonova rate to determine the BNS merger rate. If one wants to discover a comparable number of kilonovae with an optical survey as LVC will discover BNS mergers, the optical survey must cover the same volume–time as LVC. In 2018-2019 advanced LIGO and Advanced Virgo are expected reach BNS ranges of 120-170 Mpc and 65-115 Mpc (Abbott et al. 2016a) respectively, corresponding to a maximum volume of 0.021 Gpc^3. Assuming a 50% duty cycle, LVC should survey 0.010 Gpc^3-year every year of operation. An optical survey might miss only ~10% of all possible kilonovae to weather/instrument failures if it has an adequately deep, high-cadence survey. While LVC will monitor the entire sky (although to varying distances depending on sky position), an optical search would likely only survey ~35% of the sky at any time because of the Sun, declination limits, and the Milky Way. Given these constraints, the optical survey must reach a distance of ~200 Mpc, or a distance modulus of $\mu = 36.5$ mag, to have the same volume–time as LVC. Thus, a nightly, "all sky" z-band (i-band) survey would need to reach a limiting magnitude of 21.1 mag (21.3 mag) to be competitive with LVC. Depending on the specifics of the telescope, site, and camera, an i-band survey may be more efficient than a z-band survey.

Currently, no survey reaches this goal. The most comparable are ATLAS (Shanks et al. 2015), which generally reaches a o-band (roughly $i + z$) limiting magnitude of 19.5 and covers a large fraction of the sky on a few-day cadence, and soon the Zwicky Transient Facility (Bellm 2014), which will reach a limiting magnitude of 20.4 in r band (where the limiting magnitude needs to be 21.4 to be competitive with LVC).

Interestingly, LSST is expected to have a limiting magnitude of 23.3 in z for a 30-second exposure (LSST

Science Collaboration et al. 2009). For such a deep exposure, one could potentially run a survey to 550 Mpc ($z = 0.11$), which would probe a volume–time that is a factor of 24 larger than LVC at design sensitivity. If SSS17a is typical for all BNS mergers, LSST should be able to produce a significantly more constraining BNS merger rate than LVC until GW detectors have a BNS horizon of $\sim$470 Mpc.

5. CONCLUSIONS

We have compared the optical properties of SSS17a, the first EM counterpart to a gravitational wave source, to other known transients. While its luminosity is similar to some SNe and other transients, all other properties of SSS17a are distinct from known classes of transients. In particular, SSS17a fades significantly faster than all non-relativistic transients, has a dramatic blue to red color evolution in only a week, and has relatively featureless spectra, even after it has cooled significantly. We conclude that SSS17a is unique among all known transients.

Based on the uniqueness of SSS17a and its spatial/temporal coincidence with GW170817, we determine that there is $\leq 9 \times 10^{-6}$ chance that SSS17a and GW170817 are physically unrelated at 90% confidence. Therefore, SSS17a is almost certainly the EM counterpart to GW170817.

As no transient discovered by an optical survey is similar to SSS17a, we can limit the relative rate of SSS17a-like transients, finding that they have a rate at most 16% that of all other SNe combined. We also limit the volumetric and Milky Way rate of SSS17a-like events to be $\leq 1.6 \times 10^4$ Gpc^{-3} year^{-1} and $\leq$0.19 per century, respectively. While our limits are not competitive with population synthesis expectations, they are comparable to previous constraints from LIGO.

Because SSS17a-like transients are relatively faint, fast fading, and relatively rare, it is unlikely that any current surveys will be able to detect more such events than LVC will be able to detect BNS mergers. However, LSST, if it performed a 1-day cadence search, could detect an order of magnitude more SSS17a-like events than GW detectors would detect BNS mergers. Such a survey would produce the tightest constraints on the BNS merger rate unless GW detectors significantly improved their sensitivity.

Now that we have measured the optical properties of the EM counterparts of a BNS merger, we can appropriately design observing programs to both follow-up GW detections and to discover such events without a GW trigger. Future discoveries will unveil the diversity of EM counterparts to BNS mergers. With a sample of such events, we will be able to determine if SSS17a is also unique among its peers.

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