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Electromagnetic evidence that SSS17a is the result of a binary neutron star merger

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11 hours after the detection of gravitational wave source GW170817 by the Laser Interferometer Gravitational-Wave Observatory and Virgo Interferometers, an associated optical transient, SSS17a, was identified in the galaxy NGC 4993. While the gravitational wave data indicate GW170817 is consistent with the merger of two compact objects, the electromagnetic observations provide independent constraints of the nature of that system. We synthesize the optical to near-infrared photometry and spectroscopy of SSS17a collected by the One-Meter Two-Hemisphere collaboration, finding that SSS17a is unlike other known transients. The source is best described by theoretical models of a kilonova consisting of radioactive elements produced by rapid neutron capture (the *r*-process). We conclude that SSS17a was the result of a binary neutron star merger, reinforcing the gravitational wave result.

The gravitational wave event GW170817 (1) was detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO) (2) and Virgo Interferometer (Virgo) (3). An electromagnetic counterpart, SSS17a, was subsequently identified 11 hours after the gravitational wave event (4). Combining the gravitational wave and electromagnetic signatures could inform models of the physical mechanisms involved in compact object mergers (5) and the rate at which compact object binaries produce heavy elements (6).

Two seconds after GW170817 and 11 hours before SSS17a was identified, the *Fermi* Gamma-ray Space Telescope (*Fermi*) and International Gamma-Ray Astrophysics Laboratory (INTEGRAL) detected a γ -ray burst (GRB), GRB 170817A, coincident with GW170817 (7, 8). It has long been hypothesized that short-duration GRBs (SGRBs) are the result of compact binary mergers involving neutron stars and/or black holes (9). Rapidly fading GRB afterglows and kilonova emission powered by the decay of heavy elements have been hypothesized as potential counterparts to compact binary mergers (5).

While the LIGO/Virgo collaboration analyze GW170817 and the information encoded in the waveform of the gravitational signal, as astrophysicists we seek to place stringent constraints on the nature and evolutionary behavior of the progenitor system by interpreting the electromagnetic properties of SSS17a

and its galactic environment. We take an agnostic approach motivated by the question: if we had no constraints from gravitational waves and SSS17a was discovered as part of a typical optical transient survey, what could we conclude about the nature of the progenitor system? Such considerations may be unavoidable in future events given that the LIGO and Virgo interferometers will undergo temporary off-line periods. In addition, deep, wide-field surveys, such as the Large Synoptic Survey Telescope, are expected to be more efficient at detecting SSS17a-like objects than targeted follow-up of LIGO/Virgo detections (10).

SSS17a was identified by the One-Meter Two-Hemisphere (1M2H) collaboration and the Swope Supernova Survey as part of a search for gravitational wave counterparts on 2017 August 17 (4). The discovery image revealed a transient source with *i*-band magnitude of 17.476 ± 0.018 mag approximately 10.6 arcseconds (") from the center of the S0-type galaxy NGC 4993 (4). We synthesize optical and near-infrared photometry of the transient source (11, 12), its environment (13), and our theoretical interpretation of these data.

Galactic environment in NGC 4993

We first consider the host galaxy of GW170817, and the location of SSS17a within it. The host galaxy morphology and mass provide information about its age, the populations of

stars that it contains, and their dynamical properties. Comparison between different classes of astrophysical transients and their host galaxies is therefore an indirect constraint on the properties of their progenitor systems.

The host galaxy of SSS17a is NGC 4993, an S0-type galaxy with prominent lanes of cosmic dust concentrated at its core and reaching out nearly to the projected position of SSS17a (13). We analyzed the surface brightness of NGC 4993 using a *Hubble Space Telescope* (HST) image (14), and found that it decreases with projected radius (R) and a scaling constant (k) as $\exp(-kR^{1/4})$. This profile is a de Vaucouleurs profile and is typical for S0-type galaxies. Assuming this profile, we find NGC 4993 has an effective radius $R_e = 3.3$ kpc (17").

Fitting stellar population models to 13-band photometry of NGC 4993 (14), we find a galactic stellar mass of $\log(M / M_\odot) = 10.49^{+0.08}_{-0.20}$, where M is the stellar mass of NGC 4993 and M_\odot is the mass of the Sun. This stellar mass is consistent with the host galaxies masses of SGRBs (15).

We detect no point source at the position of SSS17a in the pre-trigger HST image in the $F606W$ filter, with a V -band apparent magnitude limit of > 27.2 mag. This is equivalent to a limit on the absolute V -band magnitude $M_V > -5.8$ mag at 40 Mpc, which is the distance to NGC 4993 (14). This limit rules out the most luminous and massive progenitor stars, but is still consistent with the majority of massive stars (16) and with low-mass stars or compact binary systems, both of which are optically dim.

SSS17a is offset 10.6" from the center of NGC 4993, or 2.0 kpc in projection. This corresponds to an offset of $0.6R_e$, which is small compared to the typical offsets seen in population studies of SGRBs (17). The small offset is indicative of either a progenitor velocity less than the escape velocity of the galaxy (≈ 350 km s $^{-1}$ at the location of the transient; (13)) or a system that was recently kicked from the site where it formed. If the latter is true, then SSS17a must be close to the site where it formed.

It is thought that the progenitor systems of SGRBs are formed more frequently in globular clusters, which have high stellar densities and more dynamical interactions per star (6). There are > 100 likely globular clusters in HST imaging of NGC 4993, the closest offset by 290 pc in projection from SSS17a (13). Even if the progenitor system was ejected from the closest cluster with a relative velocity of 10 km s $^{-1}$, this corresponds to a travel time of 28 Myr, meaning that we cannot exclude the possibility that the SSS17a progenitor system originated in a globular cluster.

If the SSS17a progenitor system had received a large kick velocity of > 350 km s $^{-1}$, it would have become unbound and exited its host galaxy after a relatively short time (< 20 Myr).

Given the lack of recent star formation seen in NGC 4993, it is unlikely that the progenitor system could have been as young as 20 Myr. In addition, such large kicks are physically unlikely given that they tend to unbind a compact binary (18). Thus, it is more likely that the SSS17a progenitor was bound to its host and merged over a long timescale. This hypothesis also agrees with expectations of the progenitor systems of SGRBs in S0-type galaxies, which are thought to be systematically older and occur at lower redshifts (19).

The optical properties of SSS17a

For many known classes of transients there is sufficient observational evidence to connect them to specific progenitor systems. For instance, pre-explosion images of some supernovae reveal a massive star located at the precise position of the transient (16). Indirect evidence from optical light curves and spectroscopy also associate other transients (e.g., Type Ia and Ic supernovae) with either white-dwarf or massive star progenitors (16, 20).

SSS17a has different optical properties from other known astrophysical transient objects (10). Figure 1 shows the photometric light curves, in which optical emission rises in $\lesssim 1$ day, then fades rapidly, with a rapid color evolution to the red (11). The spectra shown in Fig. 2 exhibit similarly rapid evolution; 11 hours after the trigger the spectrum is blue and smooth, but it transitions within a few days to a redder spectrum with at least one clear spectral bump near 9000 Å (12). These optical spectra lack the numerous absorption features typically seen in the spectra of ordinary supernovae (10, 12).

Nearly every known class of astrophysical transients is inconsistent with at least one of the following properties of SSS17a: the rise time < 11 hours, subsequent fading at $\gtrsim 1$ mag day $^{-1}$, the color difference in V and H band magnitudes ($V - H$) that transitions from -1.2 to $+3.6$ mag over 4 days, and the nearly featureless optical spectra at all epochs (10–12). Among previously observed events dominated by thermal continuum emission, the most similar class is rapidly evolving blue transients (21), however these events have peak magnitudes too luminous, typically occur in star-forming galaxies, do not have the observed color evolution, and do not fade as quickly as SSS17a (10). Non-thermal relativistic sources such as GRB afterglows can produce rapidly fading transients, but are not expected to produce the quasi-blackbody spectra that are observed (Fig. 2) (12).

SSS17a's observational properties suggest a different progenitor system. Various types of short duration transients have been theorized to come from white dwarf or massive star explosions, but none of these model predictions resemble SSS17a. For example, models of surface detonations on a white dwarf (22) could explain the peak luminosity and spectra dominated by thermal continuum emission. But this

model cannot explain the rapid rise time and color evolution of SSS17a detailed above. In particular, SSS17a's combination of luminosity, rise time, and red color implies a small ejecta mass ($< 0.1 M_{\odot}$) consisting predominately of high-opacity, radioactive material (10, 11). Therefore, we turn to models of other astrophysical transients to describe our observations.

Comparison with kilonova models

Kilonova models and ultraviolet to near-infrared photometry of SSS17a

The early evolution, colors, and ultraviolet (UV) to near-infrared (IR) luminosities of SSS17a are well-constrained by its light curve (11). Observations of the optical transient began roughly 11 hours after the LIGO/Virgo trigger (4), and within 1 day of discovery the spectral energy distribution of the transient had been determined from the far-UV (*Swift* W2 -band; 1928 Å) to the near-IR (Magellan/FourStar *K* -band; 21480 Å) (14).

Models of compact object mergers involving neutron stars predict that optical and IR emission should be produced by radioactively powered thermal emission (a kilonova) (5). This emission, which is produced by sub-relativistic ejecta thrown off from the neutron stars during or just after the merger, is thought to be observable in all directions. This physical mechanism contrasts with SGRBs, which are beamed along certain lines of sight.

Numerical simulations predict that neutron-rich material will be ejected from the system and assemble into heavy elements via rapid neutron capture (*r*-process) nucleosynthesis (23). The optical and IR appearance of kilonovae are distinguished by the unusual composition of the ejecta. Heavy *r*-process ejecta (atomic mass $A \gtrsim 140$) include a large fraction of lanthanide elements, which have complex f-shell valence electron structures, producing millions of bound-bound line transitions (24). This leads to a high optical opacity $\kappa \approx 5\text{--}10 \text{ cm}^2 \text{ g}^{-1}$, which causes the kilonova spectrum to peak in the IR and produces a red transient lasting for several days (25). Ejecta composed primarily of lighter *r*-process products (with mass number $A \lesssim 140$) can be relatively lanthanide-free and have lower opacities, leading to a bluer transient (26).

The peak luminosity, characteristic timescale, and spectral energy distribution of a kilonova is largely determined by the total ejecta mass (M_{ej}), characteristic ejecta velocity (v_k), and lanthanide fraction in the ejecta (X_{lan}). To test whether our data are consistent with a kilonova, and to constrain the model parameters, we analyze the UV, optical, and IR emission of SSS17a (11) using numerical kilonova models (27).

The UV to IR observations of SSS17a qualitatively match the numerical kilonova model (Figs. 1 and 2), and indicate

that the ejecta contained two distinct components. The longer-duration IR light curves require the high opacities of a lanthanide-rich component, while the short-duration UV/optical light curves require a lower-opacity, relatively lanthanide-free component. We model the panchromatic data by summing a red kilonova component with $M_{\text{ej}} = 0.035 \pm 0.15 M_{\odot}$, $v_k = 0.15 \pm 0.03 c$, $\log(X_{\text{lan}}) = -2.0 \pm 0.5$, and a blue kilonova with $M_{\text{ej}} = 0.025 M_{\odot}$, $v_k = 0.25 c$, and a gradient in the lanthanide fraction spanning $\log(X_{\text{lan}}) = -4$ to -6 (14). The blue kilonova reproduces both the UV luminosity and decline rate of SSS17a at early times. We do not attempt to tune the model parameters or compositional stratification.

Specific features in the data provide evidence for two-components of kilonova ejecta. The distinctive shape of the bolometric light curve – which declines at $\gtrsim 1 \text{ mag day}^{-1}$ at times $t < 3$ days, then plateaus from $t \approx 3\text{--}8$ days (11) – is naturally reproduced by the sum of blue and red kilonova components. Such a spectral energy distribution can be formed by the superposition of two quasi-blackbody sources of different temperatures, and was predicted to be a signature of two-component kilonovae (25).

Around 10–15 days after merger, the color temperature of SSS17a asymptotes to a value near 2500 K (11). This behavior can be naturally explained by the recombination of open f-shell lanthanides, which occurs around this temperature (24). However, at times > 10 day after merger the model *H*-band luminosity is fainter than the observations. This may reflect limitations in the radiation transport model calculations, which due to uncertainties in the atomic data inputs may poorly fit the observed *H*-band luminosities. This deviation is reflected in both the derived luminosity and temperature for SSS17a (11). Luminosities derived 12 days after merger assume that the temperature remains around 2000 K as we have no multi-band constraints beyond this point, although the model appears to match the *K* band data.

The characteristics of the blue kilonova are well-constrained by the early-time UV and optical detections of SSS17a. In BNS systems, it is thought that the merger scenario might involve two stars that collide violently; these dynamically expel hot polar ejecta that is neutrino irradiated and can produce a lighter *r*-process (lanthanide-free) blue kilonova (28). The early component of SSS17a could broadly match predictions of BNS kilonovae (25).

It is thought that kilonovae from black hole/neutron star (BH-NS) systems are generated in systems with relatively small mass ratios, that is, with neutron stars disrupted by relatively low-mass ($\lesssim 5 M_{\odot}$), high-spin ($\chi_{\text{BH}} > 0.8$) black holes (29). In this range, it is possible for tidal forces to eject a small

fraction of the neutron star material in tidal tails, and for additional disrupted material to assemble into a disk. If the mass ratio is too high, however, the neutron star would not be disrupted until it had already passed below the black hole's event horizon. The dynamical ejecta in these systems should produce a lanthanide-rich, red kilonova (23).

The photometry clearly exhibits a rapidly fading ($\gtrsim 1.5$ mag day⁻¹), blue kilonova in the far-UV *Swift* bands, where the transient was only detected within the first day of observations (Fig. 1). We find that SSS17a exhibits rapid color evolution from blue to red over the course of days (11), which contrasts with that of other known optical transients, which have characteristic timescales of weeks or months (10). This rapid transformation in color is consistent, however, with the kilonovae expected from BNS merger models.

We model the blue emission of SSS17a using a abundance gradient in the ejecta such that the lanthanide mass fraction is very low ($X_{\text{lan}} = 10^{-6}$) in the outermost layers, but increases inward to a higher, though still trace, fraction ($X_{\text{lan}} = 10^{-4}$) (14). A model with such a compositional gradient provides a better fit to the color evolution of SSS17a, and is consistent with the physical expectation that the fastest moving material may have experienced the highest neutrino irradiation.

Spectroscopy of SSS17a: Isolating kilonova features

As a check on the validity of our kilonova models, we overplot spectra of SSS17a (12) with the synthetic kilonova spectra from our model in Fig. 2. The observed spectra have been dereddened to remove the effects of dust obscuration, and the Doppler-shift caused by the recessional velocity of the host galaxy has been removed. There is qualitative agreement between the synthetic spectra and the optical emission from SSS17a, with a transition from blue at early times to red at later times (12). Given the high velocities associated with our synthetic spectra ($\geq 0.1c$) and the lanthanide features across the UV, optical, and IR, we are able to reproduce the smooth continuum shape of SSS17a with approximately the observed temperature at all epochs.

The presence of distinct blue and red thermal emission is especially apparent in the day 3–5 spectra. The spectra appear to be split into two smooth continua with a transition around 9000–10,000 Å, indicating that the spectrum can be divided into two components with $T > 3300$ K and $T < 2900$ K, which around day 3 each contribute roughly the same amount of flux.

Our kilonova model, which is the sum of distinct blue and red eject components, reproduces the general behavior of the observed color evolution, and reproduces the characteristic double-peaked spectral continuum observed at day 3.46. Quantitatively, however, the model evolution shows several

deficiencies. The blue kilonova component does not fade rapidly enough, such that the model over-predicts the optical flux at days 4.51 and 7.45. This suggests that the lanthanide gradient of the blue component of ejecta may be even steeper than assumed here, and the inner layers of ejecta even more lanthanide rich. This would result in a more rapid suppression of the optical flux over time. Thus, the time series of spectra provide insight into the layered compositional structure of the ejecta.

On the origin of r -process elements

Theoretical studies of nucleosynthesis have discerned the thermodynamic conditions required for the r -process (30). The specific astrophysical site, on the other hand, has not been unambiguously identified.

Two main alternatives have been commonly discussed. The first attributed the production of r -process elements to the neutron-rich regions in the outer layers of a nascent neutron star in a core-collapse supernova explosion (31), while the second suggested the ejecta from a neutron star merger as a likely site (23). These two avenues are thought to eject different quantities of r -process material and the expectation is that such differences should be imprinted in the r -process enrichment pattern of stars in the Galactic halo (32).

Because both models imply that elements are synthesized in an explosive event, a strict lower limit for the dilution of such elements can be derived by calculating the mass swept up once the blast wave has lost most of its energy to radiation. The inferred minimum r -process mass per event as a function of explosion energy is shown in Fig. 3, which was derived using the r -process concentrations observed in low-metallicity stars in the Milky Way (14). Also shown are the constraints on the ejecta mass and kinetic energy we derive for SSS17a, which demonstrate that the ejecta in this event are consistent with the most stringent constraints on r -process production derived using low-metallicity stars.

The r -process abundance patterns in these stars (in particular elements with $A > 140$) closely follow that of the Solar System, suggesting that the rate of enrichment has been relatively constant over long periods of time in Galactic history (33). The large star-to-star r -process dispersions that are seen in Galactic halo stars probably suggest they formed in an early and nucleosynthetically unmixed Milky Way (32). These confined heavy element inhomogeneities are then expected to be washed out as more events take place and the merger products mix effectively throughout the host galaxy. This is the case for SSS17a, which will likely deposit all of its newly synthesized heavy element-rich ejecta into NGC 4993.

The rate of SSS17a-like events in the Galaxy is quite uncertain. Based on the observed properties of SSS17a, a conservative limit of the volumetric rate of SSS17a-like events, $\mathcal{R}_{\text{SSS17a}} \leq 9 \times 10^{-6} \text{ Mpc}^{-3} \text{ yr}^{-1}$ ($\leq 9 \times 10^3 \text{ Gpc}^{-3} \text{ yr}^{-1}$), has been

derived (10). Here we assume an average rate $\mathcal{R}_{\text{SSS17a}} \approx 3 \times 10^{-7} \text{ Mpc}^{-3} \text{ yr}^{-1}$ over the history of the local Universe. This value is consistent with rate limits derived from the first observing run performed by the Advanced LIGO Interferometer, although it is a factor of 3 smaller than predictions for what was necessary to detect a BNS merger during the second observing run (34). However, assuming 1 Milky Way-like galaxy per $(4.4 \text{ Mpc})^3$ (34), the assumed rate implies a Milky Way rate $R_{\text{MW}} = 25 \text{ Myr}^{-1}$, which is consistent with predictions from binary population synthesis (18).

Our estimates for SSS17a show that an average total mass of about $M_{r-p} \approx 0.06 M_{\odot}$ was ejected in the event. If this is representative of the average for BNS mergers, the cumulative mass of r -process elements ejected from all past SSS17a-like events over the Galactic history ($t_{\text{H}} \approx 10^{10} \text{ yr}$) is $M_{r-p} \mathcal{R}_{\text{SSS17a}} t_{\text{H}} \approx 10^4 M_{\odot}$.

This value is comparable to the present r -process mass inventory in stars in the Milky Way. We determine that the total mass of r -process elements per Milky Way-like galaxy is $X_{r-p} M_{\text{G}} \approx 10^4 M_{\odot}$, where $M_{\text{G}} \approx 10^{11} M_{\odot}$ is the total Galactic mass in stars and gas (35) and $X_{r-p} \approx 10^{-7}$ is the total mass fraction of r -process nuclei in the Solar System (36). This total mass of r -process elements consists of 78% light r -process elements ($A < 140$; likely powering the blue kilonova) and 22% in the main heavier component (33) ($A > 140$; likely powering the red kilonova). This indicates that BNS mergers such as SSS17a can produce sufficient r -process material to be a major source of r -process elements.

The progenitor system of SSS17a

SSS17a has been observed throughout the entire electromagnetic spectrum, providing clues to the nature of the progenitor system. The radiated γ -ray flux varies on time scales of $\sim 0.1 \text{ s}$ (7, 8), which demonstrates that the site producing γ -ray photons must be very compact. Estimates of the total emitted energy suggest that the event must have emitted $> 10^{50} \text{ erg}$ (37). Given the requirements of energy, outflow velocity and γ -ray compactness, it is unlikely that mass can be converted into outflow energy with efficiencies better than a few percent. As a result, the central source giving rise to GW170817/GRB170817A/SSS17a must process upwards of $10^{-2} M_{\odot}$ of material through a region which is not much larger than the size of a neutron star (38).

Based on these electromagnetic constraints, several questions remain regarding the central engine that triggered SSS17a. In particular, does the progenitor system involve a black hole and neutron star or two neutron stars? If so, can

we distinguish between the two?

The UV-to-IR observations of SSS17a do not strongly constrain the primary source of this radiated emission, rather they are signatures of secondary reprocessing by the radioactive decay of r -process elements. From this we can determine the properties of the binary merger only by a chain of less certain inferences. However, one such inference involves the properties of the dynamical ejecta, namely its mass and velocity. These properties are predicted to correlate primarily with the mass ratio of the compact binary (39).

Comparing our results with numerical simulations (14) in Figure S1, we estimate the mass ratio of the binary system to be ~ 0.75 , which is consistent with findings from the gravitational wave data alone (1). This conclusion is based on a specific set of simulations, but it is generally consistent with a BNS system progenitor where the mass ratio of the progenitor binary is more likely to be close to 1. However, these constraints on the mass ratio depend sensitively on general-relativistic effects and the equation of state of nuclear matter (40).

Conclusion

SSS17a was a peculiar optical transient with a luminosity, rise time, and rate of decline unlike known classes of optical transients (10–12). It occurred well within the effective radius of the massive, S0-type host galaxy NGC 4993. Either the progenitor star system was bound to its host galaxy, or there was a $< 20 \text{ Myr}$ delay time between the formation of the system and the optical transient. Given the morphology of the host and the lack of any obvious signs of star formation, we infer that the former is more likely.

The light curves of SSS17a are fairly well matched by kilonova models. Such models involve the merger of a compact binary system with at least one neutron star, ejecting and synthesizing r -process elements. From these models, we infer that SSS17a had an early blue kilonova component with $M_{\text{ej}} = 0.025 M_{\odot}$, $v_{\text{k}} = 0.25c$ and a longer-lasting red kilonova with $M_{\text{ej}} = 0.035 \pm 0.15 M_{\odot}$ and $v_{\text{k}} = 0.15 \pm 0.03c$. From this mass estimate, we find that the rate of r -process nucleosynthesis inferred from SSS17a is consistent with the production in our Galaxy as inferred from halo stars and the abundance of r -process elements in the Solar System.

From the properties of the dynamical ejecta as inferred from the UV, optical, and IR light curves of SSS17a, we infer a mass ratio of ~ 0.75 for the compact object binary progenitor. We therefore conclude that SSS17a is most consistent with a binary neutron star progenitor system.

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SUPPLEMENTARY MATERIALS

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Fig. S1
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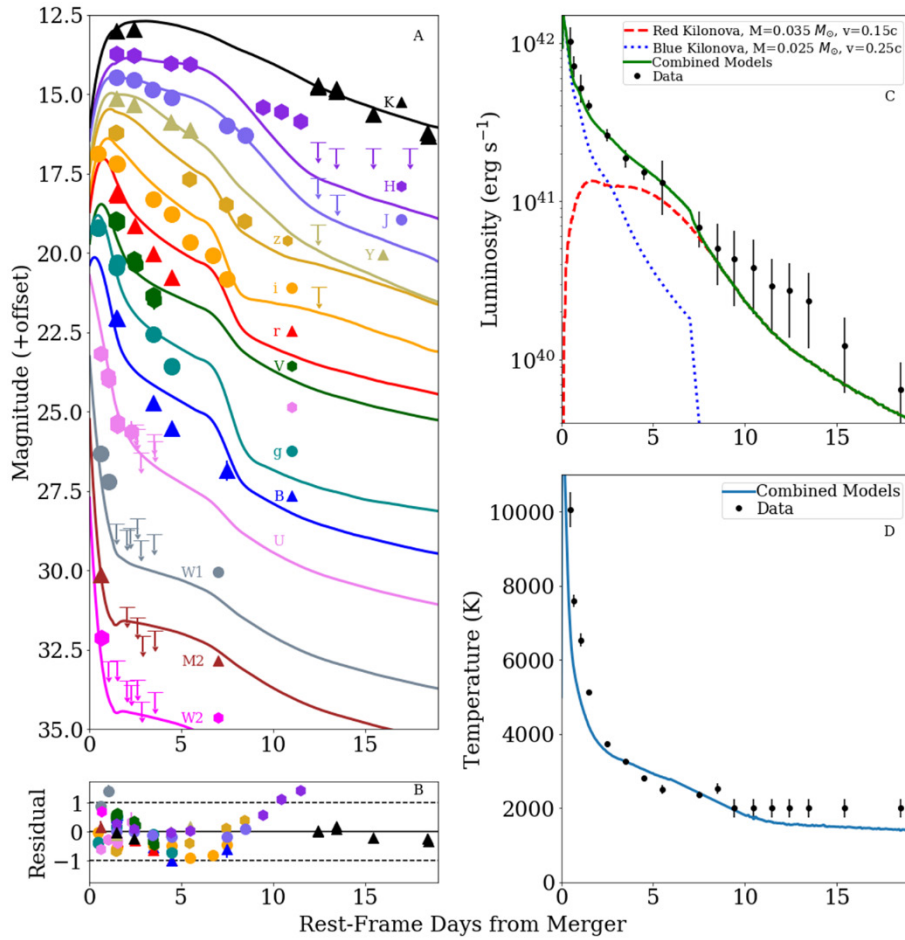


Fig. 1. Photometry of SSS17a compared to fitted kilonova models. A: UV to NIR photometry of SSS17a from 10.9 hours after the BNS merger to +18.5 days (11). Overplotted lines are our best-fitting kilonova model in each band. B: Residuals (in magnitudes) between each photometry measurement and our best-fitting model. C: The integrated luminosity of our best-fitting kilonova model compared with the total integrated luminosity of SSS17a (11). We also show the luminosity of the individual blue and red components of our kilonova model. D: The derived temperature of our kilonova model compared with the temperature derived by fitting a blackbody SED to each epoch (11).

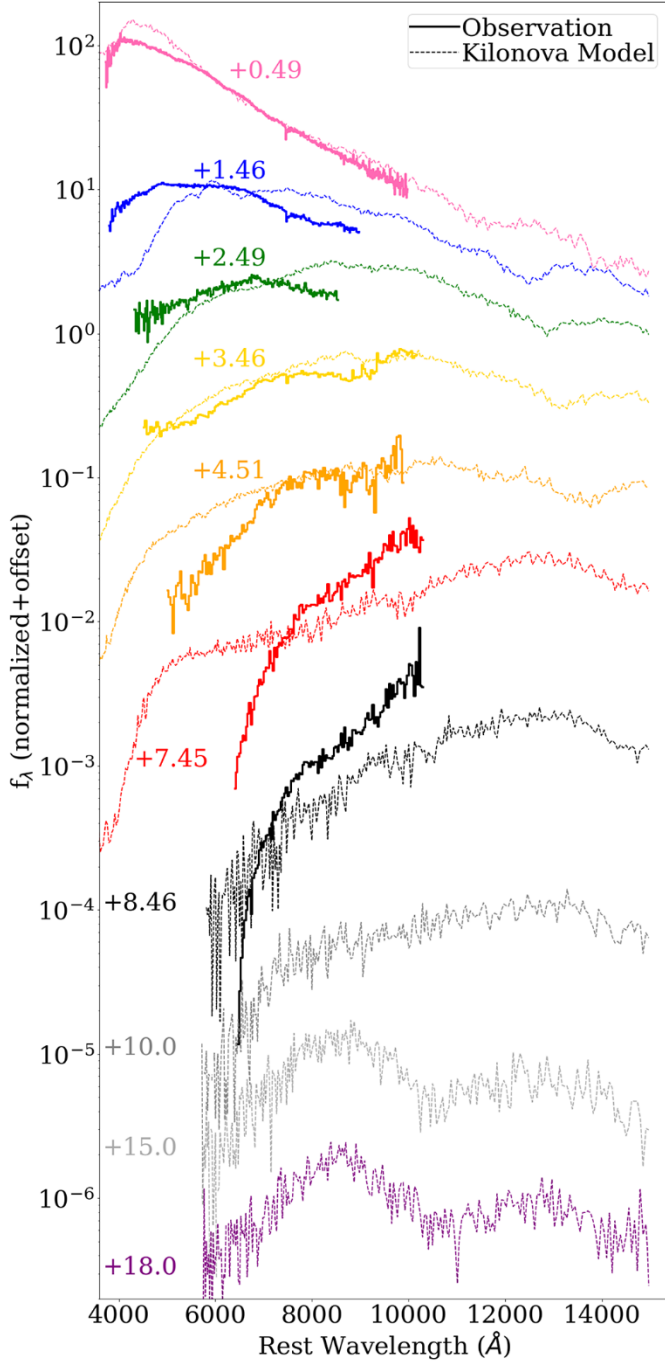


Fig. 2. Fig. 2. Spectral series of SSS17a and kilonova models. Our flux-calibrated Magellan spectra of SSS17a (12). Each spectrum is labeled with the epoch in rest-frame days since the BNS merger. We overplot our best-fitting kilonova model at each corresponding epoch.

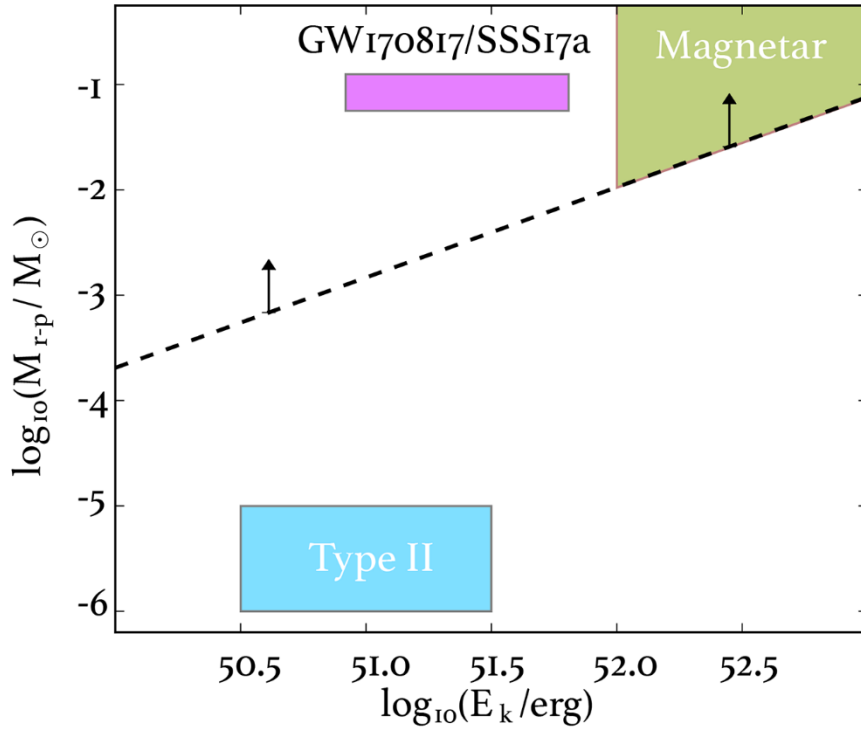


Fig. 3. Mass of r -process elements and kinetic energy in dynamical ejecta. Strict lower limit on the mass (M_{r-p}) and kinetic energy (E_k) of r -process ejecta derived from the r -process content of low metallicity stars (dashed line) (14). This argument provides a range for any viable model to be tested, for example, from magnetars and Type II supernovae (14) and illustrates that SSS17a-like mergers satisfy the mass and energy ejecta constraints required for viable scenarios.

Electromagnetic evidence that SSS17a is the result of a binary neutron star merger

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