Two Peculiar Fast Transients in a Strongly Lensed Host Galaxy

January 7, 2018

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A massive galaxy cluster can serve as a magnifying glass for distant stellar populations, as strong gravitational lensing magnifies background galaxies and exposes details that are otherwise undetectable. In time-domain astronomy, imaging programs with a short cadence are able to detect rapidly evolving transients, previously unseen by surveys designed for slowly evolving supernovae. Here we describe two unusual transient events discovered in a Hubble Space Telescope program that combined these techniques, with high-cadence imaging on a field with a strong-lensing galaxy cluster. These transients were faster and fainter than any supernova, but significantly more luminous than a classical nova. We find that they can be explained as separate eruptions of a luminous blue variable or a recurrent nova, or as an unrelated pair of stellar microlensing events. To distinguish between these hypotheses will require clarification of the cluster lens models, along with more high-cadence imaging of the field that could detect related transient episodes. This discovery suggests that the intersection of strong lensing with high-cadence transient surveys may be a fruitful path for future astrophysical transient studies.

The transients presented here are designated HFF14Spo-NW and HFF14Spo-SE and collectively nicknamed "Spock." As shown in Figure 1, the HFF14Spo events appeared in Hubble Space Telescope (*HST*) imaging collected as part of the Hubble Frontier Fields (HFF) survey [5], a multicycle program for deep imaging of six massive galaxy clusters and associated "blank sky" fields observed in parallel. One of these clusters was the MACS J0416.1-2403 cluster (hereafter

MACS0416), and the two HFF14Spo events appeared behind MACS0416 in separate images of the same strongly lensed galaxy at redshift $z = 1.0054 \pm 0.0002$. HFF14Spo-SE appeared 223 days after HFF14Spo-NW. Both transients reached peak luminosities of $\sim 10^{41}$ erg s^{-1} ($M_{AB} < -14$ mag) in $\lesssim 5$ rest-frame days, then faded below detectability in roughly the same time span.

Although recent surveys are beginning to discover progressively more categories of rapidly changing optical transients [1,2], most programs remain largely insensitive to transients with luminosities and timescales similar to the HFF14Spo events [3]. Such "peculiar" transients may be generated by the tumultuous atmospheres of massive stars or the interactions of close stellar binaries. These systems are valuable for understanding extreme outcomes of stellar evolution and the physical processes that lead to stellar explosions. Future wide-field observatories such as the Large Synoptic Survey Telescope [4] are expected to reveal many new examples of such astrophysical transients. *HST* is not an efficient wide-field survey telescope, but in the HFF program the combination of gravitational lensing magnification and a rapid observation cadence made it possible to catch intrinsically faint and rapidly evolving transient sources. In this way the HFF survey has provided a glimpse of the potential discovery space available to high-cadence imaging surveys in the future.

1 Results

To evaluate the impact of gravitational lensing from the MACS0416 cluster on observable properties of the two HFF14Spo events, we use seven independently constructed cluster mass models. These models indicate that the gravitational time delay between the HFF14Spo-NW location and the HFF14Spo-SE location is <60 days (Table 1). As shown in Figure 2, the observed 223 day span between the two events is inconsistent with the model-predicted time delays if one assumes that HFF14Spo-SE is a gravitationally delayed image of HFF14Spo-NW. However, if these were independent events, then a time delay on the order of tens of days between image 11.1 and 11.2 could have resulted in time-delayed events that were missed by the *HST* imaging of this field.

The models also predict absolute magnification values between about $\mu = 10$ and $\mu = 200$ for both events. This wide range is caused primarily by the close proximity of the lensing critical curve (the region of theoretically infinite magnification) for sources at $z = 1$. The lensing configuration consistently adopted for this cluster assumes that the arc comprises two mirror images of the host galaxy (labeled 11.1 and 11.2 in Figure 1) [6–14]. This implies that a single critical curve passes roughly midway between the two HFF14Spo locations. The location of the critical curve varies significantly among the models (Figure 3), and is sensitive to many parameters that are poorly constrained. We find that it is possible to make reasonable adjustments to the lens model parameters so that the critical curve does not bisect the HFF14Spo host arc, but instead intersects both of the HFF14Spo locations (see Supplementary Information). Such lensing configurations can qualitatively reproduce the observed morphology of the HFF14Spo host galaxy, but they are disfavoured by a purely quantitative assessment of the positional strong-lensing constraints.

1.1 Ruling Out Common Astrophysical Transients.

There are several categories of astrophysical transients that can be rejected based solely on characteristics of the HFF14Spo-NW and HFF14Spo-SE light curves, shown in Figure 4. Neither of the HFF14Spo events is *periodic*, as expected for stellar pulsations such as Cepheids, RR Lyrae, or Mira variables. Stellar flares can produce rapid optical transient phenomena, but the total energy released by even the most extreme stellar flare [15] falls far short of the observed energy release from the HFF14Spo transients. We can also rule out active galactic nuclei (AGN), which are disfavoured by the quiescence of the HFF14Spo sources between the two observed episodes and the absence of any of the broad emission lines that are often observed in AGN. Additionally, no x-ray emitting point source was detected in 7 epochs from 2009 to 2014, including *Chandra* X-ray Space Telescope imaging that was coeval with the peak of infrared emission from HFF14Spo-SE.

Many types of stellar explosions can generate isolated transient events, and a useful starting point for classification of such objects is to examine their position in the phase space of peak luminosity ($L_{\rm pk}$) versus decline time [20]. Figure 5 shows our two-dimensional constraints on $L_{\rm pk}$ and the decline timescale t_2 (the time over which the transient declines by 2 mag) for the HFF14Spo events, accounting for the range of lensing magnifications ($10 < \mu < 200$) derived from the cluster lens models. The HFF14Spo-NW and HFF14Spo-SE events are largely consistent with each other, and if both events are representative of a single system (or a homogeneous class) then the most likely peak luminosity and decline time (the region with the most overlap) would be $L_{\rm pk} \approx 10^{41}$ erg s^{-1} and $t_2 \approx 1$ day.

The relatively low peak luminosities and the very rapid rise and fall of both HFF14Spo light curves are incompatible with all categories of stellar explosions for which a significant sample of observed events exists. This includes the common Type Ia SNe and core-collapse SNe, as well as the less well-understood classes of superluminous SNe [21], Type Iax SNe [22], fast optical transients [2], Ca-rich SNe [23], and luminous red novae [20].

The SN-like transients that come closest to matching the observed light curves of the two HFF14Spo events are the "kilonova" class and the ".Ia" class. Kilonovae are a category of optical/near-infrared transients that may be generated by the merger of a neutron star (NS) binary [24–26]. The .Ia class is produced by He shell explosions that are expected to arise from AM Canum Venaticorum (AM CVn) binary star systems undergoing He mass transfer onto a white dwarf primary star [27]. The HFF14Spo light curves exhibited a slower rise time than is expected for a kilonova event [28, 29], and a faster decline time than is anticipated for a .Ia event [30].

Another problem for all of these catastrophic stellar explosion models is that they cannot explain the appearance of *repeated* transient events. The kilonova progenitor systems are completely disrupted at explosion, as is the case for all normal SN explosions. For .Ia events, even if an AM CVn system could produce repeated He shell flashes of similar luminosity, the period of recurrence would be $\sim 10^5$ yr, making these effectively nonrecurrent sources. Models invoking a stellar merger or the collision of a planet with its parent star have a similar difficulty. In these cases the star may survive the encounter, but the rarity of these collision events makes it highly unlikely to detect two such transients from the same galaxy in a single year.

Dynamically induced stellar collisions or close interactions in a dense stellar cluster [16] could in principle produce a series of optical transients. Similarly, the collision of a jovian planet with a main sequence star [17, 18] or a terrestrial planet with a white dwarf star [19] could generate an optical transient with a peak luminosity comparable to that observed for the HFF14Spo events, although it is unclear whether the UV/optical emission could match the observed HFF14Spo light curves. These scenarios warrant further scrutiny, so that predictions of the light-curve shape and anticipated rates can be more rigorously compared to the HFF14Spo observations.

Although the two events were most likely not *temporally* coincident, all of our lens models indicate that it is entirely plausible for the two HFF14Spo events to be *spatially* coincident: a single location at the source plane can be mapped to both HFF14Spo locations to within the positional accuracy of the model reconstructions ($\sim 0.6''$ in the lens plane). This is supported by the fact that the host-galaxy colours and spectral indices at each HFF14Spo location are indistinguishable within the uncertainties (see Supplementary Figures 5 and 6 and Supplementary Tables 1 and 2). Thus, to accommodate all of the observations of the HFF14Spo events with a single astrophysical source, we turn to two categories of stellar explosion that are sporadically recurrent: luminous blue variables (LBVs) and recurrent novae (RNe).

1.2 Luminous Blue Variable.

The transient sources categorised as LBVs are the result of eruptions or explosive episodes from massive stars (> 10 $M_\odot$). The class is exemplified by examples such as P Cygni, η Carinae (η Car), and S Doradus [31, 32]. Although most giant LBV eruptions have been observed to last much longer than the HFF14Spo events [31], some LBVs have exhibited repeated rapid outbursts that are broadly consistent with the very fast HFF14Spo light curves (see Supplementary Figure 7). Because of this common stochastic variability, the LBV hypothesis does not have any trouble accounting for the HFF14Spo events as two separate episodes.

Two well-studied LBVs that provide a plausible match to the observed HFF14Spo events are "SN 2009ip" [33, 34] and NGC3432-LBV1 [35]. Both exhibited multiple brief transient episodes over a span of months to years. Unfortunately, for these outbursts we have only upper limits on the decline timescale, t_2, owing to the relatively sparse photometric sampling. Recent studies have shown that SN 2009ip-like LBV transients have remarkably similar light curves, leading up to a final terminal SN explosion [36, 37]. Figure 5b shows that both HFF14Spo events are consistent with the observed luminosities and decline times of these fast and bright LBV outbursts – though the HFF14Spo events would be among the most rapid and most luminous LBV eruptions ever seen.

In addition to those relatively short and very bright giant eruptions, most LBVs also commonly exhibit a slower underlying variability. P Cygni and η Car, for example, slowly rose and fell in brightness by $\sim$ 1–2 mag over a timespan of several years before and after their historic giant eruptions. Such variation has not been detected at the HFF14Spo locations. Nevertheless, given the broad range of light-curve behaviours seen in LBV events, we cannot reject this class as a possible explanation for the HFF14Spo system.

The total radiated energy of the HFF14Spo events is $10^{44} < E_{\rm rad} < 10^{47}$ erg (see Methods), which falls well within the range of plausible values for a major LBV outburst. From this measurement we can derive constraints on the luminosity of the progenitor star, by assuming that the energy released is generated slowly in the stellar interior and is in some way "bottled up" by the stellar envelope, before being released in a rapid mass ejection (see Methods). With this approach we a quiescent luminosity of $L_{\rm qui} \approx 10^{39.5}$ erg s^{-1} ($M_V \approx -10$ mag). This value is fully consistent with the expected range for LBV progenitor stars (e.g., η Car has $M_V \approx -12$ mag and the faintest known LBV progenitors such as SN 2010dn have $M_V \approx -6$ mag).

1.3 Recurrent Nova.

Novae occur in binary systems in which a white dwarf star accretes matter from a less massive companion, leading to a burst of nuclear fusion in the accreted surface layer that causes the white dwarf to brighten by several orders of magnitude, but does not completely disrupt the star. The mass transfer from the companion to the white dwarf may restart after the explosion, so the cycle may begin again and repeat after a period of months or years. When this recurrence cycle is directly observed, the object is classified as a recurrent nova (RN).

The light curves of many RN systems in the Milky Way are similar in shape to the HFF14Spo episodes, exhibiting a sharp rise ($<$ 10 days in the rest-frame) and a similarly rapid decline (see Supplementary Information and Supplementary Figure 8). This is reflected in Figure 5, where novae are represented by a grey band that traces the empirical constraints on the maximum magnitude vs. rate of decline (MMRD) relation for classical novae [38,39].

The RN model can provide a natural explanation for having two separate explosions that are coincident in space but not in time. However, the recurrence timescale for HFF14Spo in the rest frame is 120 ± 30 days, which would be a singularly rapid recurrence period for a RN system. The RNe in our own Galaxy have recurrence timescales of 10–98 yr [40]. The fastest measured recurrence timescale belongs to M31N 2008-12a, which has exhibited a new outburst every year from 2008 through 2016 [41, 42] Although this M31 record-holder demonstrates that very rapid recurrence is possible, classifying HFF14Spo as a

RN would still require a very extreme mass-transfer rate to accommodate the < 1 yr recurrence.

Another major concern with the RN hypothesis is that the two HFF14Spo events are substantially brighter than all known novae—perhaps by as much as 2 orders of magnitude. This is exacerbated by the observational and theoretical evidence indicating that rapid-recurrence novae have less energetic eruptions [43] (see Supplementary Information and Supplementary Figure 9). Although the RN model is not strictly ruled out, we can deduce that if the HFF14Spo transients are caused by a single RN system, then that progenitor system would be among the most extreme white dwarf binary systems yet known.

1.4 Microlensing.

In the presence of strong gravitational lensing it is possible to generate a transient event from lensing effects alone. In this case the background source has a steady luminosity but the relative motion of the source, lens, and observer causes the magnification of that source (and therefore the apparent brightness) to change rapidly with time. An isolated strong lensing event with a rapid timescale can be generated when a background star crosses over a lensing caustic (the mapping of the critical curve back on to the source plane). In the case of a star crossing the caustic of a smooth lensing potential, the amplification of the source flux would increase (decrease) with a characteristic $t^{-1/2}$ profile as it moves toward (away from) the caustic. This slowly evolving light curve then transitions to a very sharp decline (rise) when the star has moved to the other side of the caustic [44, 45]. With a more complex lens comprising many compact objects, the light curve would exhibit a superposition of many such sharp peaks [46, 47].

The peculiar transient MACS J1149 LS1, observed behind the Hubble Frontier Fields cluster MACS J1149.6+2223, has been proposed as the first observed example of such a stellar caustic crossing event [48]. Such events may be expected to appear more frequently in strongly lensed galaxies that have small angular separation from the centre of a massive cluster. In such a situation, our line of sight to the lensed background galaxy passes through a dense web of overlapping microlenses caused by the intracluster stars distributed around the centre of the cluster. This has the effect of "blurring" the magnification profile across the cluster critical curve, making it more likely that a single (and rare) massive star in the background galaxy gets magnified by the required factor of $\sim 10^5$ to become visible as a transient caustic-crossing event. On this basis the HFF14Spo host-galaxy images are suitably positioned for caustic-crossing transients, as they are seen through a relatively high density of intracluster stars (see Methods)—comparable to that observed for the MACS J1149 LS1 transient.

The characteristic timescale of a canonical caustic-crossing event would be on the order of hours or days (see Supplementary Information), which is comparable to the timescales observed for the HFF14Spo events. Gravitational lensing is achromatic as long as the size of the source is consistent across the spectral energy distribution (SED). This means that the colour of a caustic-crossing transient will be roughly constant. Using simplistic linear interpolations of the observed light curves (see Methods), we find that the inferred colour curves for both HFF14Spo events are marginally consistent with this expectation of an unchanging colour (Supplementary Figure 4).

In the baseline lensing configuration adopted above—where a single critical curve subtends the HFF14Spo host galaxy arc—these events cannot plausibly be explained as stellar caustic crossings, because neither transient is close enough to the single critical curve to reach the required magnifications of $\mu \approx 10^6$. Some of our lens models can, however, be modified so that instead of just two host images, the lensed galaxy arc is made up of many more images of the host, with multiple critical curves subtending the arc where the HFF14Spo events appeared (Figure 3). If this alternative lensing situation is correct, then similar microlensing transients would be expected to appear at different locations along the host-galaxy arc, instigated by new caustic-crossing episodes from different stars in the host galaxy.

1.5 The Rate of Similar Transients.

Although we lack a definitive classification for these events, we can derive a simplistic estimate of the rate of HFF14Spo-like transients by counting the number of strongly lensed galaxies in the HFF clusters that have sufficiently high magnification that a source with $M_V = -14$ mag would be detected in *HST* imaging. There are only six galaxies that satisfy that criterion, all with $0.5 < z < 1.5$ (Methods). Each galaxy was observed by the high-cadence HFF program for an average of 80 days. Treating HFF14Spo-NW and HFF14Spo-SE as separate events leads to a rough rate estimate of 1.5 HFF14Spo-like events per galaxy per year.

Derivation of a volumetric rate for such events would require a detailed analysis of the lensed volume as a function of redshift, and is beyond the scope of this work. Nevertheless, a comparison to rates of similar transients in the local universe can inform our assessment of the likelihood that the HFF14Spo events are unrelated. A study of very fast optical transients with the Pan-STARRS1 survey derived a rate limit of $\lesssim 0.05$ Mpc^{-3} yr^{-1} for transients reaching $M \approx -14$ mag on a timescale of $\sim$1 day [3]. This limit, though several orders of magnitude higher than the constraints on novae or SNe, is sufficient to make it exceedingly unlikely that two unrelated fast optical transients would appear in the same galaxy in a single year. Furthermore, we have observed no other transient events with similar luminosities and light-curve shapes in high-cadence surveys of five other Frontier Fields clusters. Indeed, all other transients detected in the primary HFF survey have been fully consistent with normal SNe. Thus, we have no evidence to suggest that transients of this kind are common enough to be observed twice in a single galaxy in a single year.

2 Discussion

We have examined three plausible explanations for the HFF14Spo events, but we cannot make a definitive choice between them, because of the scarcity of observational data and the uncertainty in the location of the lensing critical curves. If there is just a single critical curve passing between the two HFF14Spo locations, then our preferred explanation for the HFF14Spo events is that we have observed two distinct eruptive episodes from a massive LBV star. These would be extreme LBV outbursts in several dimensions, and should add a useful benchmark for the theoretical challenge of developing a comprehensive physical model that accommodates both the η Car-like great eruptions and the S Dor-type variation of LBVs.

If instead the MACS0416 lens has multiple critical curves that intersect both HFF14Spo locations, then our third proposal of a microlensing-generated transient would be preferred. Stellar caustic crossings have not been observed before, but the analysis of a likely candidate behind the MACSJ1149 cluster [48] suggests that massive cluster lenses may generate such events more frequently than previously expected [47, 48]. To resolve the uncertainty of the HFF14Spo classification will require refinement of the lens models to more fully address systematic biases and more tightly constrain the path of the critical curve. High-cadence monitoring of the MACS0416 field would also be valuable, as it could catch future LBV eruptions or microlensing transients at or near these locations.

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Acknowledgments The authors thank Mario Livio and Laura Chomiuk for helpful discussion of this paper, as well as Stephen Murray and Neil Gehrels for assistance with the *Chandra* and *Swift* data, respectively.

Some of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). Support for MAST for non-*HST* data is provided by the National Aeronautics and Space Administration (NASA) Office of Space Science via grant NNX09AF08G, and by other grants and contracts. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

Financial support for this work was provided to S.A.R., O.G., and L.G.S. by NASA through grant HST-GO-13386 from the Space Telescope Science Institute (STScI), which is operated by Associated Universities for Research in Astronomy, Inc. (AURA), under NASA contract NAS 5-26555. J.M.D. acknowledges support of projects AYA2015-64508-P (MINECO/FEDER, UE), AYA2012-39475-C02-01, and the consolider project CSD2010-00064 funded by the Ministerio de Economia y Competitividad. A.V.F. and P.L.K. are grateful for financial assistance from the Christopher R. Redlich Fund, the TABASGO Foundation, and NASA/STScI grants GO-14208, GO-14528, GO-14872, and GO-14922; A.V.F. is also grateful to the Miller Institute for Basic Research in Science (U.C. Berkeley). The work of A.V.F. was conducted in part at the Aspen Center for Physics, which is supported by NSF grant PHY-1607611; he thanks the Center for its hospitality during the neutron stars workshop in June and July 2017. R.J.F. and the UCSC group are supported in part by NSF grant AST-1518052 and from fellowships to R.J.F. from the Alfred P. Sloan Foundation and the David and Lucile Packard Foundation. C.G. acknowledges support by VILLUM FONDEN Young Investigator Programme through grant 10123. J.H. was supported by a VILLUM FONDEN Investigator grant (project number 16599). M.J. was supported by the Science and Technology Facilities Council (grant ST/L00075X/1) and used the DiRAC Data Centric system at Durham University, operated by the Institute for Computational Cosmology on behalf of the STFC DiRAC HPC Facility (`www.dirac.ac.uk`). M.J. was funded by BIS National E-infrastructure capital grant ST/K00042X/1, STFC capital grant ST/H008519/1, STFC DiRAC Operations grant ST/K003267/1, and Durham University. DiRAC is part of the National E-Infrastructure. R.K. was supported by Grant-in-Aid for JSPS Research Fellow (16J01302). M.O. acknowledges support in part by World Premier International Research Center Initiative (WPI Initiative), MEXT, Japan, and JSPS KAKENHI Grant Number 26800093 and 15H05892. J.R. acknowledges support from the ERC starting grant 336736-CALENDS. G.C. and S.H.S. thank the Max Planck Society for support through the Max Planck Research Group of S.H.S. The GLASS team and T.T. were funded by NASA through NASA/STScI grant GO-13459. L.L.R.W. would like to thank the Minnesota Supercomputing Institute at the

University of Minnesota for providing resources and support.

Author Contributions S.A.R. designed observations, processed the *HST* data, organised the analysis, and wrote the manuscript. M.B., T.B., G.B.C., G.C., J.M.D., A.H., M.J., R.K., M.O., J.R., K.S., S.H.S., L.L.R.W., and A.Z. contributed to the lensing analysis with construction and/or interpretation of a cluster lens model. I.B., G.B., C.G., S.H., B.M., A.M., P.R., K.B.S., J.S., and B.J.W. collected, processed, and/or analyzed data on the host galaxy and other galaxies in the cluster field. R.J.F., S.W.J., P.L.K., C.M., O.G., J.H., A.G.R., and L.-G.S. contributed to the evaluation of models of astrophysical transients. A.V.F. and T.T. assisted with the observational program design and editing of the manuscript.

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Competing Interests The authors declare that they have no competing financial interests.

Supplementary Information Supplementary figures, tables, and notes are available online.

Figure 1: The detection of HFF14Spo-NW and HFF14Spo-SE in *HST* imaging from the Hubble Frontier Fields. The central panel shows the full field of the MACSJ0416 cluster, in a combined image using optical and infrared bands from *HST*. Two boxes within the main panel demarcate the regions where the HFF14Spo host-galaxy images appear. These regions are shown as two inset panels on the left, highlighting the three images of the host galaxy (labeled 11.1, 11.2, and 11.3), which are caused by the gravitational lensing of the cluster. Two columns on the right side show the discovery of the two transient events in optical and infrared light, respectively. In these final two columns the top row is a template image, the centre row shows the epoch when each transient appeared, and the bottom row is the difference image.

Figure 2: Predictions for the reappearance episodes of both HFF14Spo-NW and HFF14Spo-SE caused by gravitational lensing time delays, as listed in Table 1. The top panel shows photometry collected at the NW position (host-galaxy image 11.2) where the first event (HFF14Spo-NW) appeared in January 2014. Optical measurements from ACS are in blue and green, and infrared observations from WFC3-IR are in red and orange. Each blue bar in the lower panel shows one lens model prediction for the dates when that same physical event (HFF14Spo-NW) would have also appeared in the SE location (galaxy image 11.1), due to gravitational lensing time delay. The lower panel plots photometry from the SE position (11.1). On the right side we see the second observed event (HFF14Spo-SE). The red bars above show model predictions for when the NW host image 11.2 would have exhibited the gravitationally delayed image of the HFF14Spo-SE event. The width of each bar encompasses the 68% confidence region for a single model, and darker regions indicate an overlap from multiple models.

Figure 3: Locations of the lensing critical curves relative to the positions of the two HFF14Spo sources. Panel (a) shows the *HST* Frontier Fields composite near-infrared image of the full MACS0416 field. The magnification map for a source at $z = 1$ is overlaid with orange and black contours [14]. The white box marks the region that is shown in panel (b) with a closer view of the HFF14Spo host galaxy. Panel (c) shows a trace of the lensing critical curve from the GRALE model, and panels (d)-(i) show magnification maps for the six other primary models, all for a source at the HFF14Spo redshift. The magnification maps are plotted with log scaling, such that white is $\mu = 1$ and black is $\mu = 10^3$. Panels j-m show the same magnification maps, extracted from the lens model variations (see Methods).

Figure 4: Light curves for the two transient events, HFF14Spo-NW on the left and HFF14Spo-SE on the right. Measured fluxes in microJanskys are plotted against rest-frame time at $z = 1.0054$, relative to the time of the peak observed flux for each event. The corresponding Modified Julian Date (MJD) in the observer frame is marked on the top axis for each panel. As indicated in the legend, optical observations using the *HST* ACS-WFC detector are plotted as circles, while infrared measurements from the WFC3-IR detector are plotted as squares.

Figure 5: Peak luminosity vs. decline time for HFF14Spo and assorted categories of explosive transients. Observed constraints of the HFF14Spo events are plotted as overlapping coloured bands, along the left side of the figure. HFF14Spo-NW is shown as cyan and blue bands, corresponding to independent constraints drawn from the F435W and F814W light curves, respectively. For HFF14Spo-SE the scarlet and maroon bands show constraints from the F125W and F160W light curves, respectively. The width and height of these bands incorporates the uncertainty due to magnification (we adopt $7 < \mu_{\rm NW} < 485$ and $7 < \mu_{\rm SE} < 185$; see Table 1) and the time of peak. In the left panel, ellipses and rectangles mark the luminosity and decline-time regions occupied by various explosive transient classes. Filled shapes show the empirical bounds for transients with a substantial sample of known events. Dashed regions mark theoretical expectations for rare transients that lack a significant sample size: the ".Ia" class of white dwarf He shell detonations and the kilonova class from neutron star mergers. Grey bands in both panels show the MMRD relation for classical novae. In the right panel, circles mark the observed peak luminosities and decline times for classical novae, while black "+" symbols mark recurrent novae from our own Galaxy. The large cross labeled at the bottom shows the rapid-recurrence nova M31N 2008-12a. Each orange diamond marks a separate short transient event from the two rapid LBV outburst systems, SN 2009ip [34] and NGC3432-LBV1 (also known as SN 2000ch) [35]. These LBV events provide only upper limits on the decline time owing to limited photometric sampling.

Table 1. Lens model predictions for time delays and magnifications at the observed locations of the HFF14Spo transients.

Model	$\|\mu_{\rm NW}\|$	$\|\mu_{\rm SE}\|$	$\|\mu_{11.3}\|$	$\Delta t_{\rm NW:SE}$ (days)	$\Delta t_{\rm NW:11.3}$ (yr)
CATS	196^{+140}_{-53}	46^{+2}_{-1}	$3.3^{+0.0}_{-0.0}$	$-1.7^{+2.0}_{-1.9}$	$-3.7^{+0.1}_{-0.2}$
GLAFIC	29^{+43}_{-10}	84^{+103}_{-38}	$3.0^{+0.2}_{-0.2}$	$4.1^{+5.5}_{-3.4}$	$-5.0^{+0.5}_{-0.6}$
GLEE	182^{+203}_{-83}	67^{+31}_{-16}	$2.9^{+0.1}_{-0.1}$	36^{+6}_{-7}	$-6.1^{+0.3}_{-0.2}$
GRALE	13^{+11}_{-6}	12^{+9}_{-5}	$3.1^{+2.2}_{-0.9}$	-10^{+1}_{-7}	$-2.5^{+1.0}_{-3.1}$
SWunited	38±8	13±1	2.9 ±0.1	···	···
WSLAP^{+}	35±20	30±20	···	-48±10	0.8
ZLTM	103^{+48}_{-40}	32^{+8}_{-10}	3.5±0.3	43^{+12}_{-10}	-3.7±0.3

Note. — Each lens model is identified by the name of the modeling team or tool. Time delays give the predicted delay relative to an appearance in the NW host image, 11.2. Positive (negative) values indicate the NW image is the leading (trailing) image of the pair. The observed time lag between the NW and SE events was $\Delta t_{\rm NW:SE} = 234 \pm 6$ days.

Methods

2.1 Discovery.

The HFF14Spo transients were discovered in *HST* imaging collected as part of the Hubble Frontier Fields (HFF) survey (HST-PID GO-13496, PI Lotz), a multicycle program observing six massive galaxy clusters and associated "blank sky" parallel fields [5]. Several *HST* observing programs have provided additional observations supplementing the core HFF program. One of these is the FrontierSN program (HST-PID GO-13386, PI Rodney), which aims to identify and study explosive transients found in the HFF and related programs [49]. The FrontierSN team discovered HFF14Spo in two separate HFF observing campaigns on the galaxy cluster MACS0416. The first was an imaging campaign in January 2014 during which the MACS0416 cluster field was observed in the F435W, F606W, and F814W optical bands using the Advanced Camera for Surveys Wide Field Camera (ACS-WFC). The second concluded in August 2014, and imaged the cluster with the infrared detector of *HST*'s Wide Field Camera 3 (WFC3-IR) using the F105W, F125W, F140W, and F160W bands.

To discover transient sources, the FrontierSN team processes each new epoch of *HST* data through a difference-imaging pipeline (`https://github.com/srodney/sndrizpipe`), using archival *HST* images to provide reference images (templates) which are subtracted from the astrometrically registered HFF images. For MACS0416, the templates comprise images collected as part of the Cluster Lensing And Supernova survey with Hubble (CLASH, HST-PID GO-12459, PI Postman) [50]. The resulting difference images are visually inspected, and any new transients of interest (primarily SNe) are monitored with additional *HST* imaging or ground-based spectroscopic observations as needed.

2.2 Photometry.

The follow-up observations for HFF14Spo included *HST* imaging observations in infrared and optical bands using the WFC3-IR and ACS-WFC detectors, respectively. Supplementary Tables 3 and 4 present photometry of the HFF14Spo events from all available *HST* observations. The flux was measured on difference images, first using aperture photometry with a $0''.3$ radius, and also by fitting with an empirical point-spread function (PSF). The PSF model was defined using *HST* observations of the G2 V standard star P330E, observed in a separate calibration program. A separate PSF model was defined for each filter, but owing to the long-term stability of the *HST* PSF we used the same model in all epochs. All of the aperture and PSF-fitting photometry was carried out using the `PythonPhot` software package (`https://github.com/djones1040/PythonPhot`) [51].

2.3 Host-Galaxy Spectroscopy.

Spectroscopy of the HFF14Spo host galaxy was collected using three instruments on the Very Large Telescope (VLT). Observations with the VLT's X-shooter cross-dispersed echelle spectrograph [52] were taken on October 19, 21, and 23, 2014 (Program 093.A-0667(A), PI J. Hjorth) with the slit centred on the position of HFF14Spo-SE. The total integration time was 4.0 hr for the near-infrared (NIR) arm of X-shooter, 3.6 hr for the visual (VIS) arm, and 3.9 hr for the UVB arm. The spectrum did not provide any detection of the transient source itself because it had faded below detectability. However, the spectrum did provide a redshift for the host galaxy of $z = 1.0054 \pm 0.0002$ from Hα and the [OII] doublet in data from the NIR and VIS arms, respectively. This is consistent with the photometric redshift of the host: $z = 1.00 \pm 0.02$ from the BPZ algorithm [53], and $z = 0.92 \pm 0.05$ from the EAZY program [54]. Both were derived from *HST* photometry of the host images 11.1 and 11.2, spanning 4350–16,000 Å.

Additional VLT observations were collected using the Visible Multi-object Spectrograph (VIMOS) [55], as part of the CLASH-VLT large program (Program 186.A-0.798; PI P. Rosati) [56], which collected ~ 4000 reliable redshifts over 600 arcmin^2 in the MACS0416 field [11, 57]. For the MACS0416 field the CLASH-VLT program collected 1 hr of useful exposure time in good seeing conditions with the Low Resolution Blue grism. Unfortunately, the wavelength range of this grism (3600–6700 Å) does not include any strong emission lines for a source at $z = 1.0054$, and the signal-to-noise ratio (S/N) was not sufficient to provide any clear line identifications for the three images of the HFF14Spo host galaxy.

The VLT Multi Unit Spectroscopic Explorer (MUSE) [58, 59] observed the NE portion of the MACS0416 field—where the HFF14Spo host images are located—in December 2014 for 2 hr of integration time (ESO program 094.A-0115, PI J. Richard). These observations also confirmed the redshift of the host galaxy with clear detection of the [OII] doublet. Since MUSE is an integral field spectrograph, these observations also provided a confirmation of the redshift of the third image of the host galaxy, 11.3, with a matching [OII] line at the same wavelength [14].

A final source of spectroscopic information relevant to HFF14Spo is the Grism Lens Amplified Survey from Space (GLASS; HST-PID GO-13459; PI T. Treu) [60, 61]. The GLASS program collected slitless spectroscopy on the MACS0416 field using the WFC3-IR G102 and G141 grisms on *HST*, deriving redshifts for galaxies down to a magnitude limit $H < 23$. As with the VLT VIMOS data, the three sources identified as images of the HFF14Spo host galaxy are too faint in the GLASS data to provide any useful line identifications. There are also no other sources in the GLASS redshift catalog (`http://glass.astro.ucla.edu/`) that have a spectroscopic redshift consistent with $z = 1.0054$.

2.4 Gravitational Lens Models.

The seven lens models used to provide estimates of the plausible range of magnifications and time delays are as follows.

- *CATS:* The model of [Ref. 7], version 4.1, generated with the `LENSTOOL` software (`http://projects.lam.fr/repos/lenstool/wiki`) [62] using strong lensing constraints. This model parametrises cluster and galaxy components using pseudo-isothermal elliptical mass distribution (PIEMD) density profiles [63, 64].

- *GLAFIC:* The model of [Ref. 65], built using the `GLAFIC` software (`http://www.slac.stanford.edu/~oguri/glafic/`) [66] with strong-lensing constraints. This model assumes simply parametrised mass distributions, and model parameters are constrained using positions of more than 100 multiple images.

- *GLEE:* A new model built using the `GLEE` software [67, 68] with the same strong-lensing constraints used in [Ref. 14], representing mass distributions with simply parametrised mass profiles.

- *GRALE:* A free-form, adaptive grid model developed using the GRALE software tool [13, 69–71], which implements a genetic algorithm to reconstruct the cluster mass distribution with hundreds to thousands of projected Plummer [72] density profiles.

- *SWUnited:* The model of [Ref. 12], built using the `SWUnited` modeling method [73, 74], in which an adaptive pixelated grid iteratively adapts the mass distribution to match both strong- and weak-lensing constraints. Time-delay predictions are not available for this model.

- *WSLAP+:* Created with the `WSLAP+` software (`http://www.ifca.unican.es/users/jdiego/LensExplorer`) [75]: Weak and Strong Lensing Analysis Package plus member galaxies (Note: no weak-lensing constraints were used for this MACS0416 model).

- *ZLTM:* A model with strong- and weak-lensing constraints, built using the "light-traces-mass" (LTM) methodology [76, 77], first presented for MACS0416 in [Ref. 6].

Early versions of the *SWUnited*, *CATS*, *ZLTM*, and *GRALE* models were originally distributed as part of the Hubble Frontier Fields lens modeling project (`https://archive.stsci.edu/prepds/frontier/lensmodels/`), in which models were generated based on data available before the start of the HFF observations to enable rapid early investigations of lensed sources. The versions of these models applied here are updated to incorporate additional lensing constraints. In all cases the lens modelers made use of strong-lensing constraints (multiply imaged systems and arcs) derived from *HST* imaging collected as part of the CLASH program [50]). These models also made use of spectroscopic redshifts in the cluster field [11, 14, 78, 79]. Input weak-lensing constraints were derived from data collected at the Subaru telescope [80, 81] and archival imaging.

Variations of these lens models, developed specifically for analysis of the HFF14Spo transients, are described in the Supplementary Information.

2.5 X-ray Nondetections.

The MACS0416 field was observed by the *Swift* X-Ray Telescope and UltraViolet/Optical Telescope in April 2013. No source was detected near the locations of the HFF14Spo events (N. Gehrels, private communication). The field was also observed by *Chandra* with the ACIS-I instrument for three separate programs. On June 7, 2009 it was observed for GO program 10800770 (PI H. Ebeling). It was revisited for GTO program 15800052 (PI S. Murray) on November 20, 2013 and for GO program 15800858 (PI C. Jones) on June 9, August 31, November 26, and December 17, 2014. These *Chandra* images show no evidence for an x-ray emitting point source near the HFF14Spo locations on those dates (S. Murray, private communication).

The *Chandra* observations that were closest in time to the observed HFF14Spo events were those taken in August and November 2014. The August 31 observations were coincident with the observed peak of rest-frame optical emission for the HFF14Spo-SE event (on MJD 56900). The November 26 observations correspond to 44 rest-frame days after the peak of the HFF14Spo-SE event. If the HFF14Spo events are UV/optical nova eruptions, then these observations most likely did not coincide with the nova system's supersoft x-ray phase. For a RN system the x-ray phase typically initiates after a short delay, and persists for a span of only a few weeks. For example, the most rapid recurrent nova known, M31N 2008-12a, has exhibited a supersoft x-ray phase from 6 to 18 days after the peak of the optical emission [82].

2.6 Light-Curve Fitting.

Owing to the rapid decline timescale, no observations were collected for either event that unambiguously show the declining portion of the light curve. Therefore, we must make some assumptions for the shape of the light curve in order to quantify the peak luminosity and the corresponding timescales for the rise and the decline. We first approach this with a simplistic model that is piecewise linear in magnitude vs. time. Supplementary Figure 3 shows examples of the resulting fits for the two events. For each fit we use only the data collected within 3 days of the brightest observed magnitude, which allows us to fit a linear rise separately for the F606W and F814W light curves of HFF14Spo-NW and the F125W and F160W light curves of HFF14Spo-SE. To quantify the covariance between the true peak brightness, the rise time, and the decline timescale, we use the following procedure.

1. Make an assumption for the date of peak, $t_{\rm pk}$.

2. Measure the peak magnitude at $t_{\rm pk}$ from the linear fit to the rising light-curve data.
3. Assume the source reaches a minimum brightness (maximum magnitude) of 30 AB mag at the epoch of first observation after the peak.
4. Draw a line for the declining light curve between the assumed peak and the assumed minimum brightness.
5. Use that declining light-curve line to measure the timescale for the event to drop by 2 mag, t_2.
6. Make a new assumption for $t_{\rm pk}$ and repeat.

For further details, see the discussion of Supplementary Figure 3 and in the Supplementary Information.

At any assumed value for the time of peak brightness this linear interpolation gives an estimate of the peak magnitude. We then convert that to a luminosity (νL_ν in erg s^{-1}) by first correcting for the luminosity distance assuming a standard ΛCDM cosmology, and then accounting for an assumed lensing magnification, μ. The range of plausible lensing magnifications ($10 < \mu < 100$) is derived from the union of our seven independent lens models. This results in a grid of possible peak luminosities for each event as a function of magnification and time of peak. As we are using linear light-curve fits, the assumed time of peak is equivalent to an assumption for the decline time, which we quantify as t_2, the time over which the transient declines by 2 mag.

2.7 LBV Build-up Timescale and Quiescent Luminosity.

To explore some of the physical implications of an LBV classification for the two HFF14Spo events, we first make a rough estimate of the total radiated energy, which can be computed using the decline timescale t_2 and the peak luminosity $L_{\rm pk}$:

$$E_{\rm rad} = \zeta t_2 L_{\rm pk}, \tag{1}$$

where ζ is a dimensionless factor of order unity that depends on the precise shape of the light curve [31]. Note that earlier work [31] has used $t_{1.5}$ instead of t_2, which amounts to a different light-curve-shape term, ζ. Adopting $L_{\rm pk} \approx 10^{41}$ erg s^{-1} and $t_2 \approx 1$ day (as shown in Fig. 5), we find that the total radiated energy is $E_{\rm rad} \approx 10^{46}$ erg. A realistic range for this estimate would span $10^{44} < E_{\rm rad} < 10^{47}$ erg, owing to uncertainties in the magnification, bolometric luminosity correction, decline time, and light-curve shape. These uncertainties notwithstanding, our estimate falls well within the range of plausible values for the total radiated energy of a major LBV outburst.

The "build-up" timescale [31] matches the radiative energy released in an LBV eruption event with the radiative energy produced during the intervening quiescent phase,

$$t_{\rm rad} = \frac{E_{\rm rad}}{L_{\rm qui}} = t_2 \frac{\xi L_{\rm pk}}{L_{\rm qui}}, \qquad (2)$$

where $L_{\rm qui}$ is the luminosity of the LBV progenitor star during quiescence.

The HFF14Spo events are not resolved as individual stars in their quiescent phase, so we have no useful constraint on the quiescent luminosity. Thus, instead of using a measured quiescent luminosity to estimate the build-up timescale, we assume that $t_{\rm rad}$ for HFF14Spo corresponds to the observed rest-frame lag between the two events, roughly 120 days (this accounts for both cosmic time dilation and a gravitational lensing time delay of $\sim$40 days). Adopting $L_{\rm pk} = 10^{41}$ erg s^{-1} and $t_2 = 2$ days (see Figure 5), we infer that the quiescent luminosity of the HFF14Spo progenitor would be $L_{\rm qui} \approx 10^{39.5}$ erg s^{-1} ($M_V \approx -10$ mag).

2.8 RN Light-Curve Comparison.

There are ten known RNe in the Milky Way galaxy, and seven of these exhibit outbursts that decline rapidly, fading by 2 mag in < 10 days [40]. We compared the declining phase of these nova outbursts against the HFF14Spo transients by normalizing the nova light curves to the observed peak flux of the HFF14Spo light curves. As shown in Supplementary Figure 8, this comparison demonstrates that the rapid decline of both of the HFF14Spo transient events is fully consistent with the eruptions of known RNe in the local universe.

2.9 RN Luminosity and Recurrence Period.

To examine the recurrence period and peak brightness of the HFF14Spo events relative to RNe, we rely on a pair of papers that evaluated an extensive grid of nova models through multiple cycles of outburst and quiescence [43,83]. We assume that the HFF14Spo events represent two outbursts of the same RN source, correct for the gravitational lensing time delay predicted by our lensing models, and derive the recurrence period from the observed separation in time between HFF14Spo-NW and HFF14Spo-SE. The nova recurrence models indicate that a recurrence period as fast as one year is expected only for a RN system in which the primary white dwarf is both very close to the Chandrasekhar mass limit (1.4 $M_\odot$) and also has an extraordinarily rapid mass-transfer rate ($\sim 10^{-6}$ $M_\odot$ yr^{-1}). The models of [Ref. 43] suggest that such systems should have a very low peak amplitude (barely consistent with the lower limit for HFF14Spo) and a low peak luminosity ($\sim$ 100 times less luminous than the HFF14Spo events). This comparison is presented in Supplementary Figure 9 and the physical implications are discussed in the Supplementary Information.

2.10 Intracluster Light.

To estimate the mass of intracluster stars along the line of sight to the HFF14Spo events, we follow the procedure of [Ref. 48] and Morishita et al. (in prep). This entails fitting and removing the surface brightness of individual galaxies in the field, then fitting a smooth profile to the residual surface brightness of intracluster light (ICL). The surface brightness is then converted to a projected stellar mass surface density by assuming a Chabrier [84] initial mass function and an exponentially declining star-formation history. This procedure leads to an estimate for the intracluster stellar mass of $\log(\Sigma_\star/(\mathrm{M}_\odot\,\mathrm{kpc}^{-2})) = 6.9 \pm 0.4$. This is very similar to the value of $6.8^{+0.4}_{-0.3}$ inferred for the probable caustic-crossing star M1149 LS1 [48].

2.11 Colour Curves.

At $z = 1$ the observed optical and infrared bands translate to rest-frame ultraviolet (UV) and optical wavelengths, respectively. To derive rest-frame UV and optical colours from the observed photometry, we start with the measured magnitude in a relatively blue band (F435W and F606W for HFF14Spo-NW and F105W, F125W, F140W for HFF14Spo-SE). We then subtract the coeval magnitude for a matched red band (F814W for HFF14Spo-NW, F125W or F160W for HFF14Spo-SE), derived from the linear fits to those bands. To adjust these to rest-frame filters, we apply K-corrections [85], which we compute by defining a crude SED via linear interpolation between the observed broad bands for each transient event at every epoch. For consistency with past published results, we include in each K-correction a transformation from AB to Vega-based magnitudes. The resulting UV and optical colours are plotted in Supplementary Figure 4. Both HFF14Spo-NW and HFF14Spo-SE show little or no colour variation over the period where colour information is available. This lack of colour evolution is compatible with all three of the primary hypotheses advanced, as it is possible to have no discernible colour evolution from either an LBV or RN over this short time span, and microlensing events inherently exhibit an unchanging colour.

If these two events are from a single source then one could construct a composite SED from rest-frame UV to optical wavelengths by combining the NW and SE flux measurements, but only after correcting for the relative magnification. Figure 4 shows that the observed peak brightnesses for the two events agree to within $\sim 30\%$. This implies that for any composite SED, the rest-frame UV to optical flux ratio is approximately equal to the NW:SE magnification ratio, and any extreme asymmetry in the magnification would indicate a very steep slope in the SED.

2.12 Rates.

To derive a rough estimate of the rate of HFF14Spo-like transients, we first define the set of strongly lensed galaxies in which a similarly faint and fast transient could have been detected in the HFF imaging. The single-epoch detection limit of the HFF transient search was $m_{\mathrm{lim}} = 26.7$ AB mag, consistent with the SN searches carried out in the CLASH and CANDELS programs [86,87]. For a transient with peak brightness $M_V > -14$ mag to be detected, the host galaxy must be amplified by strong lensing with a magnification $\mu > 20$ at $z \approx 1$, growing to $\mu > 100$ at $z \approx 2$. Using photometric redshifts and magnifications derived from the GLAFIC lens models of the six HFF clusters, we find $N_{\rm gal} = 6$ galaxies that satisfy this criterion, with $0.5 < z < 1.5$ (Supplementary Figure 10).

We then define the *control time*, t_c, for the HFF survey, which gives the span of time over which each cluster was observed with a cadence sufficient for detection of such rapid transients. We define this as any period in which at least two *HST* observations were collected within every 10 day span. This effectively includes the entirety of the primary HFF campaigns on each cluster, but excludes all of the ancillary data collection periods from supplemental *HST* imaging programs. The average control time for an HFF cluster is $t_c = 0.22$ yr (80 days). Treating each HFF14Spo event as a separate detection, we can derive a rate estimate using $R = 2/(N_{\rm gal}\, t_c)$. This yields $R = 1.5$ events galaxy^{-1} yr^{-1}.

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request. All *HST* data utilised for this work are available through the Mikulski Archive for Space Telescopes (MAST).

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