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DISCOVERY OF AN UNUSUAL OPTICAL TRANSIENT WITH THE *HUBBLE SPACE TELESCOPE*[*]

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ABSTRACT

We present observations of SCP 06F6, an unusual optical transient discovered during the *Hubble Space Telescope* Cluster Supernova Survey. The transient brightened over a period of ~ 100 days, reached a peak magnitude of ~ 21.0 in both i_{775} and z_{850}, and then declined over a similar timescale. There is no host galaxy or progenitor star detected at the location of the transient to a 3σ upper limit of $i_{775} \geqslant 26.4$ and $z_{850} \geqslant 26.1$, giving a corresponding lower limit on the flux increase of a factor of ~ 120. Multiple spectra show five broad absorption bands between 4100 Å and 6500 Å, and a mostly featureless continuum longward of 6500 Å. The shape of the light curve is inconsistent with microlensing. The transient's spectrum, in addition to being inconsistent with all known supernova types, does not match any spectrum in the Sloan Digital Sky Survey database. We suggest that the transient may be one of a new class.

Key words: stars: variables: other

Online-only material: color figure, machine-readable tables (tar.gz)

1. INTRODUCTION

Supernova (SN) surveys are designed to detect the brightening of supernovae (SNe) over timescales of days to weeks. They often cover large areas at high sensitivity. As a result, they are able to discover unusual and rare transients with similar timescales. For example, in 2006, the Lick Observatory Supernova Search (LOSS) discovered an optical transient in the galaxy M85 (Kulkarni et al. 2007; Rau et al. 2007; Ofek et al. 2008) with a light curve plateau of ~ 80 days. It is suggested that the origin of this transient is a stellar merger and that an entire class of similar transients, *luminous red novae*, exists. Other recent discoveries of rare objects include a Type Ia SN with a super-Chandrasekhar mass progenitor (Howell et al. 2006) from the Supernova Legacy Survey (SNLS) and SN 2005ap, the most luminous SN ever observed (Quimby et al. 2007) from the Texas Supernova Search (TSS).

Here, we report the observations of the optical transient SCP 06F6 discovered during the course of the 2005–2006 *Hubble Space Telescope* (*HST*) Cluster SN Survey (P.I.: S. Perlmutter; K. S. Dawson et al. 2008, in preparation). The discovery was originally reported in a June 2006 IAU circular (Dawson et al. 2006). Its light curve rise time of ~ 100 days is inconsistent with all known SN types, and its spectroscopic attributes do not readily match with any known variable. We present photometry in Section 2 and spectroscopy in Section 3. In Section 4, we discuss constraints and summarize.

2. PHOTOMETRY

The optical transient was discovered on 2006 February 21 (UT dates are used throughout this paper) in images taken in the course of the *HST* Cluster SN Survey in a field centered on the galaxy cluster CL 1432.5+3332.8 (redshift $z = 1.112$; Elston et al. 2006). As part of the survey, this field was repeatedly imaged over nine epochs with the Advanced Camera for Surveys (ACS) Wide-Field Camera with a cadence of roughly 3 weeks. Each epoch consisted of four exposures in the $F850LP$ filter (hereafter denoted z_{850}; similar to z' from the Sloan Digital Sky Survey (SDSS)), totaling ~ 1400 s, and one exposure of ~ 400 s in the $F775W$ filter (hereafter denoted i_{775}; similar to SDSS i'). Table 1 gives a summary of the photometric observations. Cosmic ray rejection was performed on the z_{850} images, and each epoch was searched for SNe using a modified version of the image subtraction code developed by the Supernova Cosmology Project (Perlmutter et al. 1999) employing

* Based in part on observations made with the NASA/ESA *Hubble Space Telescope*, obtained from the data archive at the Space Telescope Science Institute (STScI). STScI is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under the NASA contract NAS 5-26555. The observations are associated with program GO-10496. Based in part on observations obtained at the European Southern Observatory under ESO program 077.A-0110. Based in part on observations collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan. Some of the data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and NASA.
[13] Luis W. Alvarez Fellow.

earlier epochs as a reference. The transient was discovered in the fourth epoch and is located at $\alpha = 14^{h}32^{m}27^{s}.395$, $\delta = +33^{\circ}32'24''.83$ (J2000.0), corresponding to galactic coordinates $l = 55^{\circ}.528943$, $b = 67^{\circ}.345346$, and ecliptic coordinates $\lambda = 13^{h}24^{m}9^{s}.067$, $\beta = 45^{\circ}21'46''.06$. This position has a statistical uncertainty of $0''.01$ relative to the *HST* Guide Star Catalog 2.3.2, which has an overall systematic uncertainty of $0''.3$. The angular separation from the cluster center is $35''$, corresponding to a projected physical separation at the cluster redshift of 290 kpc. There is no prior detection of a source at the transient's location in the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) at 1.4 GHz to the survey's 5σ detection limit of 2.5 mJy/beam. There is no X-ray detection at this location in a 5 ks exposure in the *Chandra* Telescope XBootes survey (Kenter et al. 2005) to the detection limit of 7.8×10^{-15} erg cm^{-2} s^{-1} in the full 0.5–7 keV band.

The transient is consistent with a point source in each of the six ACS detection epochs to the extent we can determine. We performed aperture photometry on drizzled ACS images (Fruchter & Hook 2002), using 3.0 pixel ($0''.15$) radius apertures for i_{775} and 5.0 pixel ($0''.25$) radius apertures for z_{850}. Aperture corrections were taken from Table 3 of Sirianni et al. (2005). The systematic error due to the known color dependence of z_{850} aperture correction (see Sirianni et al. 2005) is estimated to be less than 0.015 mag.

After the transient had left the visibility window of *HST*, it remained visible from Mauna Kea for several months. Three additional photometry points were obtained with the Faint Object Camera and Spectrograph (FOCAS; Kashikawa et al. 2002) on the Subaru telescope on 2006 June 28, 2006 August 23, and in the next year on 2007 May 18. The June observations suffered from poor weather conditions (seeing $\geqslant 2''$). All observations were cosmic ray rejected using 120 s exposures. We performed aperture photometry using a $1''.04$ radius aperture and estimated photometric errors, as described by Morokuma et al. (2008). In order to express magnitudes in the ACS filter system, we determined the Subaru image zero points by cross-correlating the photometry of nine surrounding stars in the ACS and Subaru images. The Subaru FOCAS i' and z' filters are similar enough to ACS i_{775} and z_{850}, respectively, such that there is no significant trend with stellar color.

A deep stack of the first three epochs in z_{850}, totaling 4400 s (Figure 1), and the first two epochs in i_{775}, totaling 550 s, provides limits on the magnitude of a possible progenitor star (if galactic) or host galaxy (if extragalactic). No progenitor star is detected in a 3.0 pixel radius aperture centered at the position of the transient (known to within 0.2 pixels) to a 3σ upper limit of $i_{775} > 26.4$ and $z_{850} > 26.1$ (Vega magnitudes are used throughout this paper.) There is no sign of a host galaxy in the 1 $arcsec^{2}$ surrounding the transient to a surface brightness 3σ limit of 25.0 mag $arcsec^{-2}$ and 25.1 mag $arcsec^{-2}$ in z_{850} and i_{775}, respectively. However, there is a 6σ detection in a 3.0 pixel radius aperture of a ~ 25.8 mag object, $1''.5$ southwest of the transient's position in z_{850} (Figure 1, lower left). If the transient is extragalactic, this might represent a faint host galaxy.

The transient increased in brightness in each of epochs 4 through 8 before finally declining in the ninth epoch, resulting in a rise time of approximately 100 days (Figure 2). A fit to the five brightest ACS z_{850} photometry points gives a date of max of 2006 May 17.3 (MJD 53872.3). The declining part of the light curve, although sparsely measured, is consistent with symmetry about the maximum. The final photometry point, approximately one year after maximum light, shows no detection. The $i_{775} - z_{850}$ color is approximately constant over the 50 days preceding maximum light, but does show significant signs of evolution at early times and after maximum light.

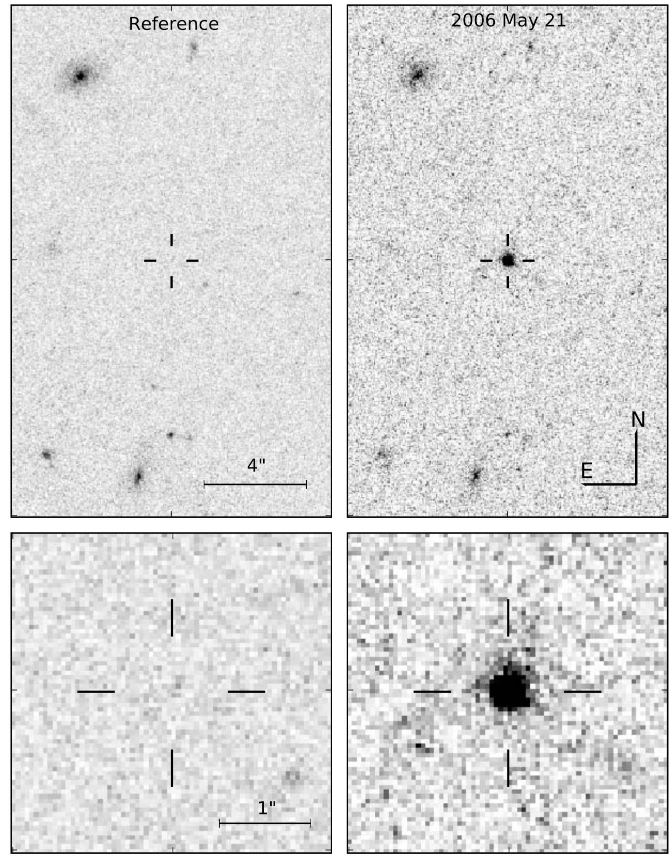

Figure 1. Deep stack of the first three epochs in z_{850} totaling 4400 s where the transient is undetected (top left and zoomed in, bottom left), and the highest-flux epoch 8 z_{850} exposures of 1400 s (top right and zoomed in, bottom right). All images have the same grayscale. The hash marks indicate the transient position and have the same physical scale in all images.

3. SPECTROSCOPY

Spectroscopy was acquired on three dates (Figure 3): 2006 April 22 (−25 days) using Subaru FOCAS, 2006 May 18 (+1 day) using the Focal Reducer and Low Dispersion Spectrograph 2 (FORS2) for the Very Large Telescope (VLT; Appenzeller et al. 1998), and 2006 May 28 (+11 days) with the Keck Low Resolution Imaging Spectrometer (LRIS, Oke et al. 1995).[14] The Subaru spectrum covers wavelengths longward of 5900 Å, while the VLT and Keck spectra cover bluer wavelengths. The VLT spectrum (observed at airmass above 2) is corrected for differential slit loss by applying a linear correction with a slope of 0.25 per 1000 Å, derived from a comparison with the Keck spectrum, which covers the entire wavelength range of the VLT spectrum. The Keck observation was made at the parallactic angle, while Subaru FOCAS is equipped with an atmospheric dispersion corrector, making the Keck and Subaru observations more reliable measures of relative flux.

The spectra show a red continuum and several broad absorption features: a possible absorption feature at 4320 Å (FWHM $\sim$ 180 Å); three strong features at 4870 Å (FWHM $\sim$ 200),

[14] Spectroscopic data are electronically available from http://supernova.lbl.gov/2006Transient/.

Table 1
Photometric Observations

Epoch	Date	MJD	Telescope	i_{775}			z_{850}		
				Exp. (s)	Scaled Flux	Magnitude	Exp. (s)	Scaled Flux	Magnitude
1	2005-11-28	53716.1	*HST*	175	0.0018 ± 0.0049	> 26.515	1400	−0.0019 ± 0.0053	> 27.222
2	2006-01-03	53738.7	*HST*	375	0.0002 ± 0.0025	> 27.509	1500	0.0053 ± 0.0049	26.733 ± 0.857
3	2006-01-29	53764.6	*HST*	...	...	...	1500	0.0087 ± 0.0050	26.185 ± 0.524
4	2006-02-21	53787.2	*HST*	515	0.1183 ± 0.0032	23.395 ± 0.025	1360	0.1367 ± 0.0059	23.201 ± 0.040
5	2006-03-19	53813.7	*HST*	440	0.4229 ± 0.0055	22.012 ± 0.012	1360	0.3805 ± 0.0067	22.089 ± 0.016
6	2006-04-04	53829.6	*HST*	515	0.6216 ± 0.0065	21.593 ± 0.010	1360	0.6055 ± 0.0074	21.585 ± 0.011
7	2006-04-22	53847.0	*HST*	515	0.8343 ± 0.0068	21.274 ± 0.008	1360	0.8276 ± 0.0080	21.246 ± 0.009
8	2006-05-21	53876.8	*HST*	295	1.0000 ± 0.0099	21.077 ± 0.009	1400	1.0000 ± 0.0082	21.040 ± 0.008
9	2006-06-03	53889.3	*HST*	800	0.8534 ± 0.0056	21.249 ± 0.006	1200	0.9176 ± 0.0081	21.134 ± 0.008
10	2006-06-28	53914.4	Subaru	960	0.6290 ± 0.1441	21.581 ± 0.211	480	0.7384 ± 0.1520	21.370 ± 0.189
11	2006-08-23	53970.3	Subaru	600	0.0586 ± 0.0234	24.158 ± 0.368	600	0.0654 ± 0.0875	>23.080
12	2007-05-18	54238.5	Subaru	2280	−0.0324 ± 0.0201	...	...	...	...

Note. Flux measurements scaled relative to the highest-flux epoch; effective zero points are 21.077 for i_{775} and 21.040 for z_{850}.

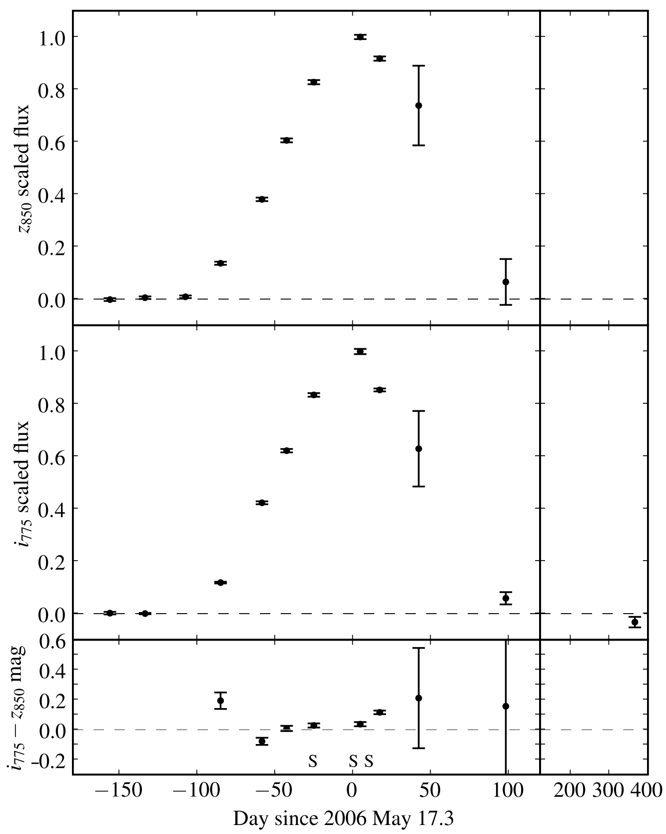

Figure 2. Flux light curve for z_{850} (top panel) and i_{775} (middle panel) scaled to maximum flux. The last three epochs (starting at +42 days) are Subaru FOCAS observations. Bottom panel: $i_{775} - z_{850}$ color for epochs with significant detection in both bands. Though the color only varies ∼ 0.2 mag among the five best measured epochs, there is evidence for evolution. The spectral epochs are marked along the abscissa with an "S."

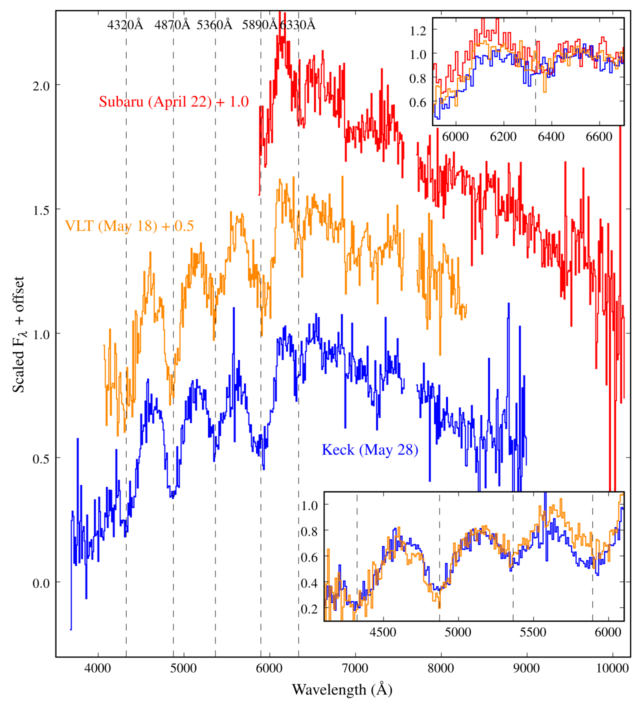

Figure 3. Spectra averaged in 10 Å bins. Vertical dotted lines indicate the approximate absorption-band centroids. Spectra are normalized to match in the red continuum. Inset figures show regions where the spectra differ. Top inset: overplot of all three spectra (no offset) in the range 5900–6700 Å, demonstrating apparent evolution of the flux at ∼ 6150 Å relative to the red continuum. Bottom inset: overplot of the VLT and Keck spectra (no offset) demonstrating apparent evolution at 4670 Å and of the absorption feature at 5890 Å. The spectra are available in tabular form within a tar.gz file from the online journal.

(A color version of this figure is available in the online journal.)

5360 Å (FWHM ∼ 230), and 5890 Å (FWHM ∼ 280 Å); and a weaker absorption feature at 6330 Å (FWHM ∼ 270 Å). Errors are estimated to be 15 Å.

A comparison of the three spectra shows evidence for spectral evolution. The flux at ∼ 6150 Å consistently decreases relative to the red continuum over time (Figure 3, upper inset). Over the 10 day period from the VLT to the Keck spectrum, the absorption feature at 5890 Å appears to move toward shorter wavelengths, while a small absorption feature at 4670 Å in the VLT spectrum seems to disappear in the Keck spectrum (Figure 3, lower inset).

We compared the spectra to all SN types using the χ^2 fitting program, described in Howell et al. (2005), and the program SNID (Blondin & Tonry 2007). No match was found with either program.

Although the cause of the broad absorption features is unclear, we note that $d\lambda/\lambda$ for most of the features is consistent with ∼ 0.042 (with the possible exception of the feature at 6330 Å). If the width of the absorption features is due to a

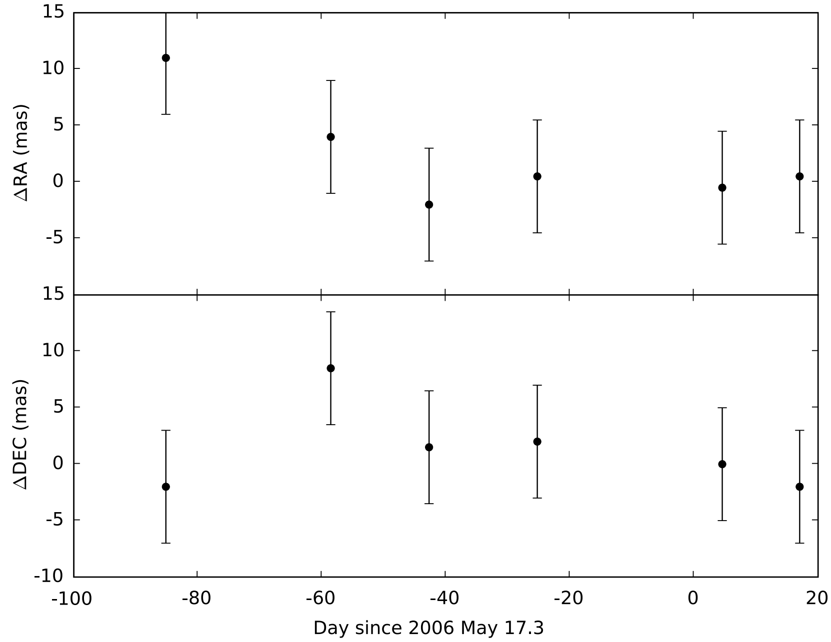

Figure 4. Position of transient in each of the six ACS detection epochs with respect to the overall best fit position, $\alpha = 14^{\rm h}32^{\rm m}27^{\rm s}.395$, $\delta = +33^\circ 32' 24''.83$ (J2000.0). The top and bottom panels are the position in right ascension (α) and declination (δ), respectively. 5 mas = 0.1 pixels.

velocity distribution, the FHWM of this distribution would be $\sim 12{,}600$ km s^{-1}.

One possibility is that the transient is galactic ($z = 0$). For a galactic source, the slope of the red continuum gives a lower-limit blackbody temperature of 6500 K. The absorption features at 4320 Å and 4870 Å are consistent with Hγ (4341 Å) and Hβ (4861 Å), respectively, including uncertainty in the shape of the underlying continuum. However, there is no significant Hα (6563 Å) emission or absorption, which would be expected for the presence of strong Hγ and Hβ features. Although there is slight evidence for emission at 6563 Å in the Keck spectrum, this is not seen in the VLT or Subaru spectra. The absorption feature at 5890 Å is consistent with Na I $\lambda\lambda$5890, 5896. Although the combination of Hγ, Hβ, and Na I consistently fits three of the observed features, the strong feature at 5360 Å and the weaker feature at 6330 Å are left unexplained. No other narrowband emission or absorption lines are detected. The spacing of the five absorption features is inconsistent with periodicity in energy, as might be expected for cyclotron harmonics. Oddly, the features are nearly (but not exactly) periodic in wavelength.

It is also possible that the transient is extragalactic. The absence of Lyman α absorption features shortward of 4500 Å places a hard upper limit of $z \leqslant 2.7$ on its redshift. Among redshifts $0 < z < 2.7$, the cluster redshift of $z = 1.112$ is of specific interest as the transient is located at a small projected distance from the center of the cluster. At this redshift, the absorption feature at 5890 Å is consistent with Mg II $\lambda\lambda$2796, 2803. However, the remaining features are not identified at this redshift. Given the observed spectral energy distribution, a peak apparent magnitude of $i_{775} = 21.077$ implies a total peak observed flux of $\sim 2.5 \times 10^{-14}$ erg s^{-1} cm^{-2}. At $z = 1.112$, this implies a peak absolute bolometric magnitude of approximately -22.1. This is comparable to the peak absolute magnitudes of SN 2005ap (-22.7; Quimby et al. 2007) and SN 2006gy (-22; Smith et al. 2007), the two most luminous SNe observed to date. Finally, we note that the shape of the continuum is inconsistent with $F_\lambda \propto \lambda^{-5/3}$ synchrotron radiation.

4. DISCUSSION AND SUMMARY

We have presented photometric and spectroscopic data of an unusual optical transient discovered during the *HST* Cluster SN Survey. Its key features are as follows: a rise time of ~ 100 days with a roughly symmetric light curve; small but statistically significant color variations across the light curve; no detected host galaxy or progenitor; broad spectral features in the blue, with a red continuum; and some evidence for spectral evolution. Below, we first discuss the constraints on the distance to the source. Next, we consider the possibility that the transient is the result of microlensing, finding this to be unlikely. Lastly, we search for similar objects in the SDSS spectral database, finding no convincing matches.

Any detection of proper motion or parallax would be strong evidence of a galactic source. We tested for this by fitting the position of the transient in each of the six ACS detection epochs using a two-dimensional Gaussian (Figure 4). In all epochs, the position uncertainty is dominated by image coalignment errors caused by residual distortion, rather than statistical error in the fit. Note that this uncertainty in the relative position among epochs is distinct from the uncertainty in the absolute position of the transient discussed in Section 2. For these images and this position, we estimate this error to be 0.1 pixel ($0''.005$) in each coordinate. The most discrepant positions differ by approximately 0.25 pixels ($0''.0125$). As a whole, the positions are consistent with no proper motion or parallax and give little indication of either. The upper limit on proper motion is 62 mas yr^{-1}. The upper limit on parallax is ~ 25 mas, which gives a lower limit on distance of ~ 40 pc. This limit excludes virtually any possible solar system object as the source of the brightening.

We can derive a more significant constraint on the distance from the reference image magnitude limits, assuming that the transient is an outburst and a progenitor star exists. The dimmest stars (aside from neutron stars) known to undergo outbursts are white dwarfs (WDs). WDs range in absolute magnitude from approximately 10 mag ($T_{\rm eff} \sim 25000$ K) to approximately

16 mag ($T_{\rm eff} \sim 3000$ K) and dimmer. If we assume that the progenitor is a WD with absolute magnitude $i_{775} = 16$, the reference image 3σ upper limit of $i_{775} > 26.4$ gives a distance 3σ lower limit of ~ 1.2 kpc. If the progenitor is a source dimmer than $i_{775} = 16$ (e.g., a cooler WD or a neutron star), the constraints on the distance are weaker. Because the source is at high galactic latitude ($b = 67.^\circ3$), a limit of 1.2 kpc places the WD outside the thin disk of the galaxy, as the thin disk has a WD scale height of approximately 300 pc (Boyle 1989). However, there is a significant population of relatively cool WDs residing in the thick disk and stellar halo. Galaxy models predict between tens (Castellani et al. 2002) and hundreds (Robin et al. 2003) of WDs, far dimmer than our reference image detection limit in a single ACS field at this galactic latitude. Despite the large range (which reflects the uncertainty in the density of ancient WDs in the stellar halo), it is clear that the density is high enough to make a galactic WD a possible progenitor.

Although the symmetry of the light curve (Figure 2) suggests that the transient is a microlensing event, this interpretation is unlikely. The light curve is dramatically broader than the theoretical light curve for microlensing of a point source by a single lens (Paczynski 1986). The typical light-curve FWHM of high-magnification (peak magnification $\geqslant 300$) microlensing events is on the order of a few hours (e.g., Abe et al. 2004; Dong et al. 2006) whereas the transient's light-curve FWHM is ~ 100 days with a peak magnification 3σ lower limit of ~ 120. Also, the color evolves by a small but significant amount over the light curve, particularly between epochs 8 and 9. Some of these difficulties can be overcome if we assume that the source is resolved; this can both change the shape of the light curve and allow for color variation as different source regions are differentially magnified. However, this typically results in a lower peak magnification. Finally, microlensing would still not explain the mysterious spectrum.

In an effort to identify objects with similar spectra, we cross-correlated the broad features of the spectrum with the SDSS spectral database. Each SDSS spectrum was warped with a polynomial function to best fit the Keck spectrum, based on a least-squares fit. The value of the rms of the difference between the spectra was used to determine the correlation. An allowance for relative redshift was made, with the requirement that the spectra overlapped in the range of the strongest features (3500–6200 Å)—no convincing matches were found. Changing the warping function between linear and quadratic and varying the wavelength range used in the fit altered which SDSS objects had the highest correlation, but did not result in a more convincing match. The SDSS objects with the highest correlation were broad absorption line quasars (BAL QSOs) at various redshifts and carbon (DQ) WDs. Although BAL QSOs do have similarly broad features, they do not exhibit the spacing or rounded profiles of those of the transient. Also, BAL QSOs typically include emission features. The DQ WDs most similar to the transient are known as DQp WDs. Like the transient, DQp WDs have broad, rounded absorption features between 4000 Å and 6000 Å with a red continuum (see, e.g., Hall & Maxwell 2008). However, the positions and spacing of the absorption features shortward of 5000 Å greatly differ from those of the transient spectrum. In addition, DQp WDs show increased emission toward the UV, which is not seen in the transient.

The absence of similar spectra in the SDSS database implies that such variables are either very rare, typically fainter than the SDSS detection threshold, or both. If they are typically faint, this would seem to argue for an extragalactic origin, though a galactic origin is, of course, still possible. If this transient does indeed represent a new class of either galactic or extragalactic transients, such objects will be of great interest for future extensive surveys of the time-variable sky.

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Facilities: HST (ACS), Subaru (FOCAS), Keck:I (LRIS), VLT:Antu (FORS2)

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