

ACCEPTED TO APJ: SEPTEMBER 8, 2008  
Preprint typeset using L<sup>A</sup>T<sub>E</sub>X style emulateapj v. 08/13/06DISCOVERY OF AN UNUSUAL OPTICAL TRANSIENT WITH THE *HUBBLE SPACE TELESCOPE*<sup>1</sup>K. BARBARY<sup>2,3</sup>, K. S. DAWSON<sup>3</sup>, K. TOKITA<sup>4</sup>, G. ALDERING<sup>3</sup>, R. AMANULLAH<sup>5</sup>, N. V. CONNOLLY<sup>6</sup>, M. DOI<sup>4</sup>, L. FACCIOLI<sup>7</sup>,  
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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  $\sim 100$  days, reached a peak magnitude of  $\sim 21.0$  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  $3\sigma$  upper limit of  $i_{775} \geq 26.4$  and  $z_{850} \geq 26.1$ , giving a corresponding lower limit on the flux increase of a factor of  $\sim 120$ . 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 lightcurve is inconsistent with microlensing. The transient's spectrum, in addition to being inconsistent with all known supernova types, is not matched to any spectrum in the Sloan Digital Sky Survey (SDSS) database. We suggest that the transient may be one of a new class.

*Subject headings:* stars: variables: other — stars: individual (SCP 06F6) — supernovae: general

## 1. INTRODUCTION

Supernova (SN) surveys are designed to detect the brightening of supernovae 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) dis-

<sup>1</sup> Based in part on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Institute. STScI is operated by the association of Universities for Research in Astronomy, 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 the National Aeronautics and Space Administration.

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covered an optical transient in the galaxy M85 (Kulkarni et al. 2007; Rau et al. 2007; Ofek et al. 2008) with a lightcurve plateau of  $\sim 80$  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 (PI: Perlmutter; Dawson et al. 2008, in preparation). The discovery was originally reported in a June 2006 IAU circular (Dawson et al. 2006). Its lightcurve rise time of  $\sim 100$  days is inconsistent with all known SN types, and its spectroscopic attributes are not readily matched to any known variable. We present photometry in §2 and spectroscopy in §3. In §4, we discuss constraints and summarize.

## 2. PHOTOMETRY

The optical transient was discovered on 21 February 2006 (UT dates are used throughout this paper) in images taken in the course of the *HST* Cluster SN Survey in a field centered on galaxy cluster CL 1432.5+3332.8 (redshift  $z = 1.112$ ; Elston et al. 2006). As part of the survey this field was imaged repeatedly over nine epochs with the Advanced Camera for Surveys (ACS) Wide Field Camera with a cadence of roughly three weeks. Each epoch consisted of four exposures in the *F850LP* filter (hereafter denoted  $z_{850}$ ; similar to SDSS  $z'$ ) totaling  $\sim 1400$  s and one exposure of  $\sim 400$  s in the *F775W* filter (hereafter denoted  $i_{775}$ ; similar to SDSS  $i'$ ). Table 1 gives a summary of photometric observations. Cosmic ray rejection was performed on the  $z_{850}$  images and each epoch

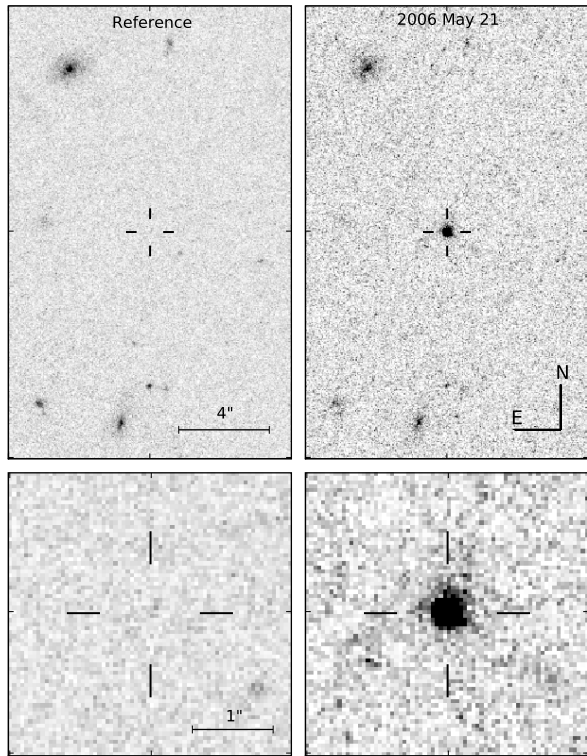


FIG. 1.— Deep stack of the first three epochs in  $z_{850}$  totaling 4400 s where the transient is undetected (*top left* and zoomed in, *bottom left*), and the highest-flux epoch eight  $z_{850}$  exposure of 1400 s (*top right* and zoomed in, *bottom right*). All images have the same greyscale. The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

was searched for SNe using a modified version of the image subtraction code developed by the Supernova Cosmology Project (Perlmutter et al. 1999) employing earlier epochs as a reference. The transient was discovered in the fourth epoch and is located at  $\alpha = 14^{\text{h}}32^{\text{m}}27^{\text{s}}.395$ ,  $\delta = +33^{\circ}32'24''.83$  (J2000.0), corresponding to galactic coordinates  $l = 55.528943^{\circ}$ ,  $b = 67.345346^{\circ}$  and ecliptic coordinates  $\lambda = 13^{\text{h}}24^{\text{m}}9^{\text{s}}.067$ ,  $\beta = 45^{\circ}21'46''.06$ . This position has a statistical uncertainty of  $0''.01$  relative to the *HST* Guide Star Catalogue 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 (Condon et al. 1998) at 1.4 GHz to the survey  $5\sigma$  detection limit of  $2.5 \text{ mJy beam}^{-1}$ . 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  $7.8 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$  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.

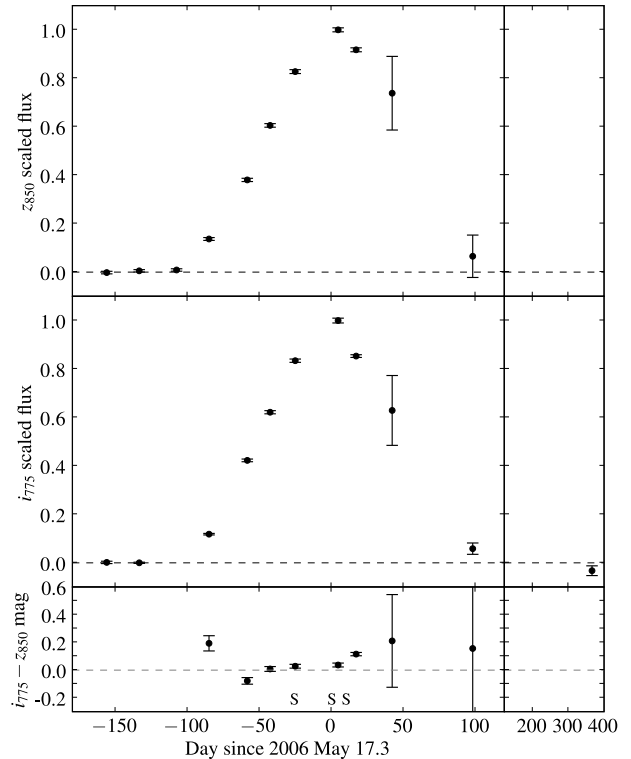


FIG. 2.— Flux lightcurve for  $z_{850}$  (*top panel*) and  $i_{775}$  (*middle panel*) scaled to maximum flux. The last three epochs (starting at +42 days) are Subaru FOCAS observations. *bottom panel*:  $i_{775} - z_{850}$  color for epochs with significant detection in both bands. Though the color only varies  $\sim 0.2$  magnitudes between the five best measured epochs, there is evidence for evolution. The spectral epochs are marked along the abscissa with an “S.”

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 the next year on 2007 May 18. The June observations suffered from poor weather conditions (seeing  $\geq 2''$ ). 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 Subaru image zeropoints 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  $z_{850}$  that there is no significant trend with stellar color.

A deep stack of the first three epochs in  $z_{850}$  totaling 4400 s (Fig. 1) and first two epochs in  $i_{775}$  totaling 550 s provide 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  $< 0.2$  pixels) to a  $3\sigma$  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<sup>2</sup>

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

NOTE. — Flux measurements scaled relative to highest flux epoch; effective zeropoints are 21.077 for  $i_{775}$  and 21.040 for  $z_{850}$ .

surrounding the transient to a surface brightness  $3\sigma$  limit of  $25.0 \text{ mag arcsec}^{-2}$  and  $25.1 \text{ mag arcsec}^{-2}$  in  $z_{850}$  and  $i_{775}$ , respectively. However, there is a  $6\sigma$  detection in a  $3.0$  pixel radius aperture of a  $\sim 25.8 \text{ mag}$  object  $1.''5$  southwest of the transient position in  $z_{850}$  (Fig. 1, *lower left*). If the transient is extragalactic, this might represent a faint host galaxy.

The transient increased in brightness in each of epochs four through eight before finally declining in the ninth epoch, resulting in a rise time of approximately 100 days (Fig. 2). A fit to the brightest five ACS  $z_{850}$  photometry points gives a date of max of 2006 May 17.3 (MJD 53872.3). The declining part of the lightcurve, 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.

### 3. SPECTROSCOPY

Spectroscopy was acquired on three dates (Fig. 3): 2006 April 22 ( $-25$  days) using Subaru FOCAS, 2006 May 18 ( $+1$  day) using VLT FORS2 (Appenzeller et al. 1998), and 2006 May 28 ( $+11$  days) with Keck LRIS (Oke et al. 1995).<sup>15</sup> The Subaru spectrum covers wavelengths longward of  $5900 \text{ \AA}$ , while the VLT and Keck spectra cover bluer wavelengths. The VLT spectrum (observed at airmass  $> 2$ ) is corrected for differential slit loss by applying a linear correction with a slope of  $0.25$  per  $1000 \text{ \AA}$ , derived from a comparison to 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  $4320 \text{ \AA}$  (FWHM  $\sim 180 \text{ \AA}$ ), three strong features at  $4870$  (FWHM  $\sim 200$ ),  $5360$  (FWHM  $\sim 230$ ), and  $5890 \text{ \AA}$  (FWHM  $\sim 280 \text{ \AA}$ ), and a weaker absorption feature at  $6330 \text{ \AA}$  (FWHM  $\sim 270 \text{ \AA}$ ). Errors are estimated to be

<sup>15</sup> Spectroscopic data is available electronically from <http://supernova.1bl.gov/2006Transient/>

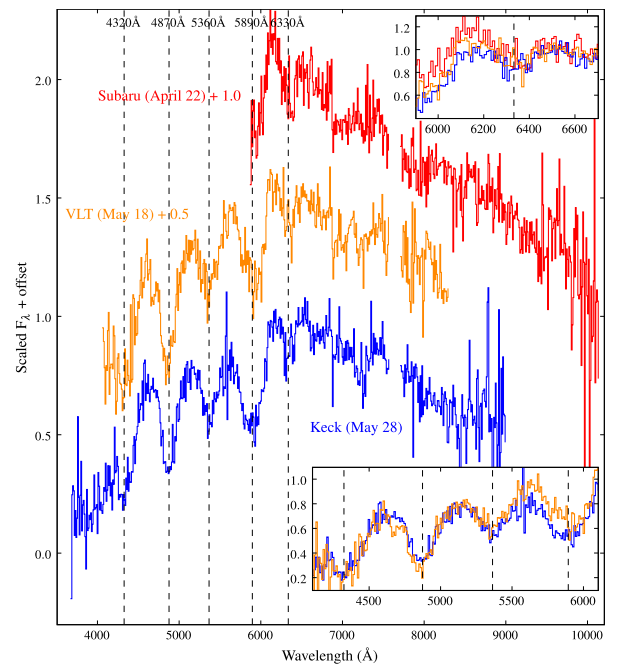


FIG. 3.— Spectra averaged in  $10 \text{ \AA}$  bins. Vertical dotted lines indicate the approximate absorption band centroids. Spectra are normalized to match in the red continuum. Inset figures show regions where spectra differ. *Top Inset*: Overplot of all three spectra (no offset) in the range  $5900 - 6700 \text{ \AA}$ , demonstrating apparent evolution of the flux at  $\sim 6150 \text{ \AA}$  relative to the red continuum. *Bottom Inset*: Overplot of VLT and Keck spectra (no offset) demonstrating apparent evolution at  $4670 \text{ \AA}$  and of the absorption feature at  $5890 \text{ \AA}$ .

$15 \text{ \AA}$ .

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

We compared the spectra to all supernova types using the  $\chi^2$  fitting program described in Howell et al. (2005) as well as 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  $\sim 0.042$  (with the possible exception of the feature at  $6330 \text{ \AA}$ ). If the width of the absorption features is due to a velocity distribution, the FWHM of this distribution would be  $\sim 12,600 \text{ km s}^{-1}$ .

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  $6500 \text{ K}$ . The absorption features at  $4320$  and  $4870 \text{ \AA}$  are consistent with  $\text{H}\gamma$  ( $4341 \text{ \AA}$ ) and  $\text{H}\beta$  ( $4861 \text{ \AA}$ ) respectively, including uncertainty in the shape of the underlying continuum. However, there is no significant  $\text{H}\alpha$  ( $6563 \text{ \AA}$ ) emission or absorption, which would be expected for the presence of strong  $\text{H}\gamma$  and  $\text{H}\beta$  features. (Although there is slight evidence for emission at  $6563 \text{ \AA}$  in the Keck spectrum, this is not seen in the VLT or Subaru spectra.) The absorption feature at  $5890 \text{ \AA}$  is consistent with  $\text{Na I } \lambda\lambda 5890, 5896$ . Although the combination of  $\text{H}\gamma$ ,  $\text{H}\beta$ , and  $\text{Na I}$  consistently fits three of the observed features, the strong feature at  $5360 \text{ \AA}$  and the weaker feature at  $6330 \text{ \AA}$  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  $\alpha$  absorption features shortward of  $4500 \text{ \AA}$  places a hard upper limit of  $z \leq 2.7$  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 a small projected distance from the center of the cluster. At this redshift, the absorption feature at  $5890 \text{ \AA}$  is consistent with  $\text{Mg II } \lambda\lambda 2796, 2803$ . 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  $\sim 2.5 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$ . 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  $\sim 100$  days with a roughly symmetric lightcurve; small but statistically significant color variations across the lightcurve; 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 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 Sloan Digital Sky Survey (SDSS) spectral database, finding no convincing matches.

Any detection of proper motion or parallax would be

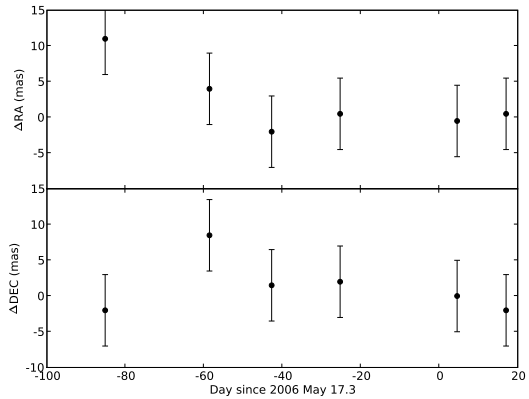


FIG. 4.— Position of transient in each of the six ACS detection epochs with respect to the overall best fit position,  $\alpha = 14^{\text{h}}32^{\text{m}}27^{\text{s}}.395$ ,  $\delta = +33^{\circ}32'24''.83$  (J2000.0). The *top* and *bottom* panels are the position in Right Ascension ( $\alpha$ )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

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 2-d Gaussian (Fig. 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 relative position between epochs is distinct from the uncertainty in the absolute position of the transient discussed in §2. For these images and this position, we estimate this error to be  $0.1 \text{ pixel}$  ( $0.''005$ ) in each coordinate. The most discrepant positions differ by approximately  $0.25 \text{ pixels}$  ( $0.''0125$ ). 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  $62 \text{ mas yr}^{-1}$ . The upper limit on parallax is  $\sim 25 \text{ mas}$ , which gives a lower limit on distance of  $\sim 40 \text{ pc}$ . This limit excludes virtually any possible solar system object as the source of the brightening.

We can derive a more significant constraint on distance from 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  $10 \text{ mag}$  ( $T_{\text{eff}} \sim 25000 \text{ K}$ ) to approximately  $16 \text{ mag}$  ( $T_{\text{eff}} \sim 3000 \text{ K}$ ) and dimmer. If we assume the progenitor is a WD with absolute magnitude  $i_{775} = 16$ , the reference image  $3\sigma$  upper limit of  $i_{775} > 26.4$  gives a distance  $3\sigma$  lower limit of  $\sim 1.2 \text{ kpc}$ . If the progenitor is a source dimmer than  $i_{775} = 16$  (e.g., a cooler WD or a neutron star), the constraints on distance are weaker. Because the source is at high galactic latitude ( $b = 67.3^{\circ}$ ), a limit of  $1.2 \text{ kpc}$  places the WD outside the thin disk of the galaxy, as the thin disk has a WD scale height of approximately  $300 \text{ pc}$  (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 lightcurve (Fig. 2) suggests that the transient is a microlensing event, this interpretation is unlikely. The lightcurve is dramatically broader than the theoretical lightcurve for microlensing of a point source by a single lens (Paczynski 1986). The typical lightcurve FWHM of high-magnification (peak magnification  $\geq 300$ ) microlensing events is on the order of a few hours (e.g., Abe et al. 2004; Dong et al. 2006) whereas the transient’s lightcurve FWHM is  $\sim 100$  days with a peak magnification  $3\sigma$  lower limit of  $\sim 120$ . Also, the color evolves a small but significant amount over the lightcurve, particularly between epochs eight and nine. Some of these difficulties can be overcome if we assume the source is resolved; this can both change the shape of the lightcurve 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 root mean square 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 to 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 don’t 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 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 differ greatly 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 or 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.

We thank James Graham and Patrick Hall for helpful discussion of spectroscopy. We thank Ken’ichi Nomoto and Masaomi Tanaka for comparisons to supernovae. We thank Robert DaSilva for an initial SDSS spectroscopy comparison. Financial support for this work was provided by NASA through program GO-10496 from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555. This work was also supported in part by the Director, Office of Science, Office of High Energy and Nuclear Physics, of the U.S. Department of Energy under Contract No. AC02-05CH11231, as well as a JSPS core-to-core program “International Research Network for Dark Energy” and by a JSPS research grant (20040003). The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. Finally, this work would not have been possible without the dedicated efforts of the daytime and nighttime support staff at the Cerro Paranal Observatory.

*Facilities:* HST (ACS), Subaru (FOCAS), Keck:I (LRIS), VLT:Antu (FOR2)

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