Discovery of a Transient U-band Dropout in a Lyman-Break Survey: A Tidally-Disrupted Star at z = 3.3?[1,2]

Daniel Stern[3], P. G. van Dokkum[4,5], Peter Nugent[6], D. J. Sand[4], R. S. Ellis[4], Mark Sullivan[9], J. S. Bloom[10], D. A. Frail[4,7], J.-P. Kneib[8], L. V. E. Koopmans[4,11], and Tommaso Treu[4,5,12]

ABSTRACT

We report the discovery of a transient source in the central regions of galaxy cluster Abell 267. The object, which we call "PALS–1", was found in a survey aimed at identifying highly-magnified Lyman-break galaxies in the fields of intervening rich clusters. At discovery, the source had $U_n > 24.7$ (2σ; AB), $g = 21.96 \pm 0.12$, and very blue $g - r$ and $r - i$ colors; i.e., PALS–1 was a "U-band drop-out", characteristic of star-forming galaxies and quasars at $z \sim 3$. However, three months later the source had faded by more than three magnitudes. Further observations showed a continued decline in luminosity, to $R > 26.4$ seven months after discovery. Though the apparent brightness is suggestive of a supernova at roughly the cluster redshift, we show that the photometry and light curve argue against any *known* type of supernova at any redshift. The spectral energy distribution and location near the center of a galaxy cluster are consistent with the hypothesis that PALS–1 is a gravitationally-lensed transient at $z \approx 3.3$. If this interpretation is correct, the source is magnified by a factor of 4–7 and two counter-images are predicted. Our lens model predicts time delays between the three images of 1–10 years and that we have witnessed the final occurrence of the transient. The

---

[1]Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5–26555.

[2]Based on observations obtained at the W. M. Keck Observatory, which is operated jointly by the California Institute of Technology and the University of California.

[3]Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 169-506, Pasadena, CA 91109

[4]California Institute of Technology, MS105-24, Pasadena, CA 91125

[5]Hubble Fellow

[6]Lawrence Berkeley National Laboratory, M.S. 50-F, 1 Cyclotron Road, Berkeley, CA 94720

[7]National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801

[8]Laboratoire d'Astrophysique, Observatoire Midi-Pyrénées, 14 Av. E. Belin, 31400 Toulouse, France

[9]Physics Department, University of Durham, South Road, Durham DH 1 3LE, UK

[10]Harvard-Smithsonian Center for Astrophysics, MS 20, 60 Garden Street, Cambridge, MA 02138

[11]Kapteyn Astronomical Institute, P.O. Box 800, 9700AV Groningen, The Netherlands

[12]Department of Physics and Astronomy, University of California at Los Angeles, Los Angeles, CA 90095

intense luminosity ($M_{\rm AB} \sim -23.5$ after correcting for lensing) and blue UV continuum (implying $T \gtrsim 50{,}000$ K) argue the source may have been a flare resulting from the tidal disruption of a star by a $10^{6-8}\,M_\odot$ black hole. Regardless of its physical nature, PALS–1 highlights the importance of monitoring regions of high magnification in galaxy clusters for distant, time-varying phenomena.

Subject headings: galaxies: clusters: individual (Abell 267) — stars: SNe: general — stars: flare

1. Introduction

The past several years have witnessed dramatic success in our ability to directly observe the high-redshift ($z \gtrsim 3$) Universe. Systematic photometric selection and narrow-band imaging surveys have identified several hundred high-redshift galaxies (e.g., Steidel et al. 1996; Stern & Spinrad 1999; Rhoads et al. 2001; Hu et al. 2002, Dickinson et al. 2004). At $z \sim 3-4$, these studies have allowed us to directly measure ensemble properties of the population, such as its luminosity distribution, color distribution, size distribution, and implied cosmic star formation rate (e.g., Steidel et al. 1999; Shapley et al. 2001; Giavalisco et al. 2004; Ferguson et al. 2004, Hu et al. 2004). At $z \gtrsim 5$, ambitious programs are underway to extend these studies to earlier cosmic epoch (e.g., Kodaira et al. 2003; Rhoads et al. 2004, Kneib et al. 2004). High-redshift studies are now approaching the dark ages, an epoch when the Universe was primarily neutral, prior to the reionization imposed by the first stars and quasars (e.g., Becker et al. 2001; Djorgovski et al. 2001). A critical void in our understanding of the earliest phases of galaxy formation has been the lack of detailed studies of individual sources. However, with $m_R^* = 24.5$ for the $z \sim 3$ Lyman-break galaxies (LBGs; Steidel et al. 1999), detailed astrophysical studies are impractical for the majority of this faint, but important, population.

High-redshift galaxies lensed by rich clusters provide a unique opportunity for studying in detail the processes which govern galaxy formation and star formation in the early Universe. Strong lensing can increase the brightness of a galaxy by a factor of 10–30, making possible observations which would otherwise be impractical (e.g., Yee et al. 1996; Franx et al. 1997; Ellis et al. 2001, Kneib et al. 2004). High-resolution, high signal-to-noise ratio spectroscopy can probe the ages, kinematics, abundances, mass, and initial mass function of young protogalaxies (e.g., Pettini et al. 1999; Teplitz et al. 2000). Observing normal, high-redshift galaxies at unusual wavelengths might also become feasible through gravitational lensing (e.g., Baker et al. 2001). In particular, spectroscopically-confirmed sub-mm galaxies identified by Submillimetre Common-User Bolometer Array (SCUBA; Holland et al. 1999) on the James Clerk Maxwell Telescope (JCMT) have, to date, been largely restricted to extreme starbursts ($\dot{M} \gtrsim 1000\ M_\odot\ {\rm yr}^{-1}$) with some unknown contribution of active galaxies. It is thought that the most actively star-forming, high-redshift Lyman-break systems ($\dot{M} \gtrsim 100\ M_\odot\ {\rm yr}^{-1}$) might comprise the bulk of the sub-mm background (e.g., Adelberger

& Steidel 2000), just below the *unlensed* SCUBA thresholds. This hypothesis could be tested with a sample of gravitationally-magnified, young protogalaxies.

We are undertaking the Palomar Amplified Lyman-break Survey (PALS) with the aim of enlarging the census of luminous, lensed galaxies at $z \gtrsim 3$. PALS is a $U_n gri$ imaging survey of X-ray selected galaxy clusters with the 200″ Hale telescope at Palomar Observatory. The well-established color criteria of Steidel, Pettini, & Hamilton (1995) and Steidel et al. (1999) are used to identify candidate magnified, distant galaxies. Subsequent spectroscopy with the Keck telescopes is used to confirm the redshifts.

As we show in this manuscript, one of the candidate lensed Lyman-break galaxies from our survey has faded by more than four magnitudes since discovery. This object, which we call "PALS–1", cannot be any known type of supernova (SN) at the redshift of the cluster or neighboring spiral galaxy. Instead, we suggest it may be the first optically-selected transient at $z \sim 3$. High-redshift optical transients are of considerable interest because of their links to gamma ray bursts (GRBs; e.g., Rhoads 2001), SNe searches (e.g., Riess et al. 1998; Perlmutter et al. 1999), active galactic nuclei (e.g., Gal-Yam et al. 2002b), and accretion of stars onto black holes (e.g., Rees 1988; Komossa et al. 2004). Unfortunately, the assembled data is insufficient to unambiguously describe the physical nature of PALS–1. We argue that the most likely interpretations are that we have witnessed either a previously-unidentified, peculiar type Ia SN, or we have witnessed the tidal disruption of a star by the dormant, supermassive black hole in the center of a faint, normal galaxy. The latter events reveal themselves by a UV/X-ray flare and were predicted by Lidskii & Ozernoi (1979) and Rees (1988). The *ROSAT* All-Sky Survey identified several plausible soft X-ray candidates (see Li, Narayan, & Menou 2002, and references therein). We are aware of no robust UV/optical candidates published to date. The paper is organized as follows. In § 2 we discuss the observations. In § 3 we explore likely physical interpretations of this unusual flare event, followed by an estimate of their likelihoods in § 4. Our conclusions comprise § 5.

2. Observations

2.1. Spectral Energy Distribution on UT 2001 July 20

As part of the PALS survey, the $z = 0.23$ cluster Abell 267 was observed with the Carnegie Observatories Spectoscopic Multislit and Imaging Camera (COSMIC; Kells et al. 1998) on the Palomar 200″ telescope on UT 2001 July 20. Exposure times were 900 s in U_n ($\lambda_c = 3550$ Å; $\Delta\lambda = 600$ Å; Steidel et al. 2003), 600 s in g ($\lambda_c = 5000$ Å; $\Delta\lambda = 800$ Å), 240 s in r ($\lambda_c = 6550$ Å; $\Delta\lambda = 900$ Å), and 240 s in i ($\lambda_c = 8000$ Å; $\Delta\lambda = 1800$ Å). Conditions were photometric, and the seeing was $\approx 1\farcs6$ in all bands. Photometric calibration was performed using the Sloan Digital Sky Survey (SDSS) Early Data Release observations of Abell 267 (York et al. 2000). Throughout, magnitudes are referred to the AB system (Oke & Gunn 1983).

The survey located an object (see Fig. 1) in the envelope of the central cD galaxy with the colors of a young galaxy or quasar at $z \sim 3$. The object, which we call PALS–1, is located at R.A. $= 1^h52^m42.0^s$, Dec. $= 1°00'37''.5$ (J2000). As shown in Fig. 2, at discovery PALS–1 had a very blue continuum redward of ~ 4500 Å, and a strong break between the U_n-band and the g-band. With $U_n > 24.7$ (2σ), $g = 21.96 \pm 0.12$, $g - r = -0.2 \pm 0.2$ and $r - i = -0.4 \pm 0.2$ (see Table 1), the candidate Lyman-break object was situated in a region of color-color space far removed from Galactic and low redshift objects (Steidel et al. 1995; Fan et al. 1999). The colors of PALS–1, in combination with its brightness and its location near the central cD galaxy in Abell 267, made it a promising candidate lensed, high-redshift object. In particular, PALS–1 is approximately 2 magnitudes brighter than m_* of the $z \sim 3$ Lyman-break population (Steidel et al. 1999), comparable to the gravitational magnification provided by our lensing model of the cluster (§3.2.1).

2.2. Light Curve and Host

On UT 2001 October 18 we intended to obtain a spectrum of PALS–1 with the Keck I Low Resolution Imager and Spectrograph (LRIS; Oke et al. 1995), but found that the source was no longer visible on the guider. On UT 2001 October 21 we imaged the field with the Keck II Echelle Spectrograph and Imager (ESI; Sheinis et al. 2002). The ESI images showed a faint red source at the location of PALS–1, with Spinrad $R_s = 25.3 \pm 0.15$ ($\lambda_c = 6890$ Å; $\Delta\lambda = 1370$ Å; Djorgovski 1985) and Johnson $B = 26.7 \pm 0.2$ ($\lambda_c = 4400$ Å; $\Delta\lambda = 980$ Å). We conclude that the object had faded by 3.2 ± 0.2 magnitudes in R over the course of 93 days. The apparent change in color is difficult to interpret because the B filter lies blueward of the g filter. Keck I Near Infrared Camera (NIRC; Matthews & Soifer 1994) observations give an upper limit of $K_{\rm AB} > 24.7$ (3σ) on UT 2002 October 31, and radio observations with the Very Large Array on the same day give a 3σ upper limit of 0.08 mJy at 8.5 GHz[13]. The field was re-observed several times in the optical during November 2001 – February 2002. The source continued to fade over this time interval, to $R > 26.4$ on UT 2002 February 16 (see Table 2).

Archival observations of Abell 267 were obtained from the Digitized Palomar Observatory Sky Survey (DPOSS; Djorgovski et al. 1999), the Near Earth Asteroid Tracking survey (NEAT; Pravdo et al. 1999), the archive of the Isaac Newton Group (ING) of telescopes, the Canadian Astronomy Data Center (CADC; Dahle et al. 2002), and the *Hubble Space Telescope* (*HST*) Archive. A constant f_ν long-ward of ≈ 5000 Å (approximate for PALS–1 around the time of discovery) was assumed in cases where R-band observations were not available.

No further detections were found, except for two cases. Slightly offset from the location of PALS–1 ($0''.2 \pm 0''.1$ in each coordinate), a marginally extended object is detected at 3σ above the

[13]We note that our preferred physical description of PALS–1, a star being tidally disrupted by a supermassive black hole, is clearly related to variability of an AGN, in the limit of a very low accretion rate. Namely, we are witnessing the accretion of a single star.

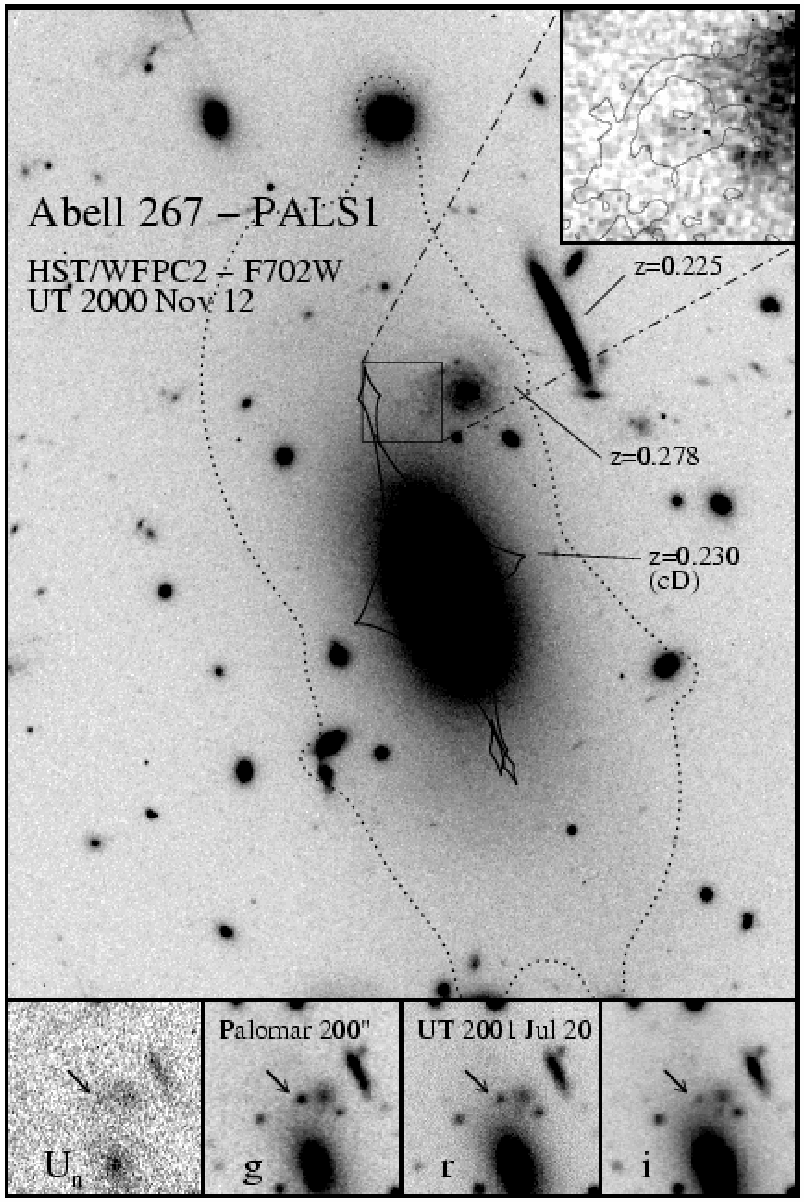

Fig. 1.— **[SEE f1.gif]**. Images of PALS–1 in Abell 267. The bottom panels show the discovery multi-band imaging of PALS–1, obtained on UT 2001 July 20 with the Palomar 200″ telescope. The central panel, subtending 50″ × 62.″5, shows the *HST*/WFPC2 R_{F702W} image taken on UT 2000 November 12. North is up and east is to the left. The dotted contour shows the critical line for a source at $z = 3.3$, and the solid contour shows the caustic. In the lensing hypothesis, PALS–1 would be near a cusp in the source plane and give rise to three images. The top inset, 5″ on a side, shows the *HST* image at the location of PALS–1. The light of the cD galaxy has been subtracted and contours indicate isophotal contours from the discovery r-band image. A faint ($R = 27.7$; 3σ) source is detected, slightly offset from the transient location. This is likely associated with either the galaxy or the star-forming region which hosted the optical transient.

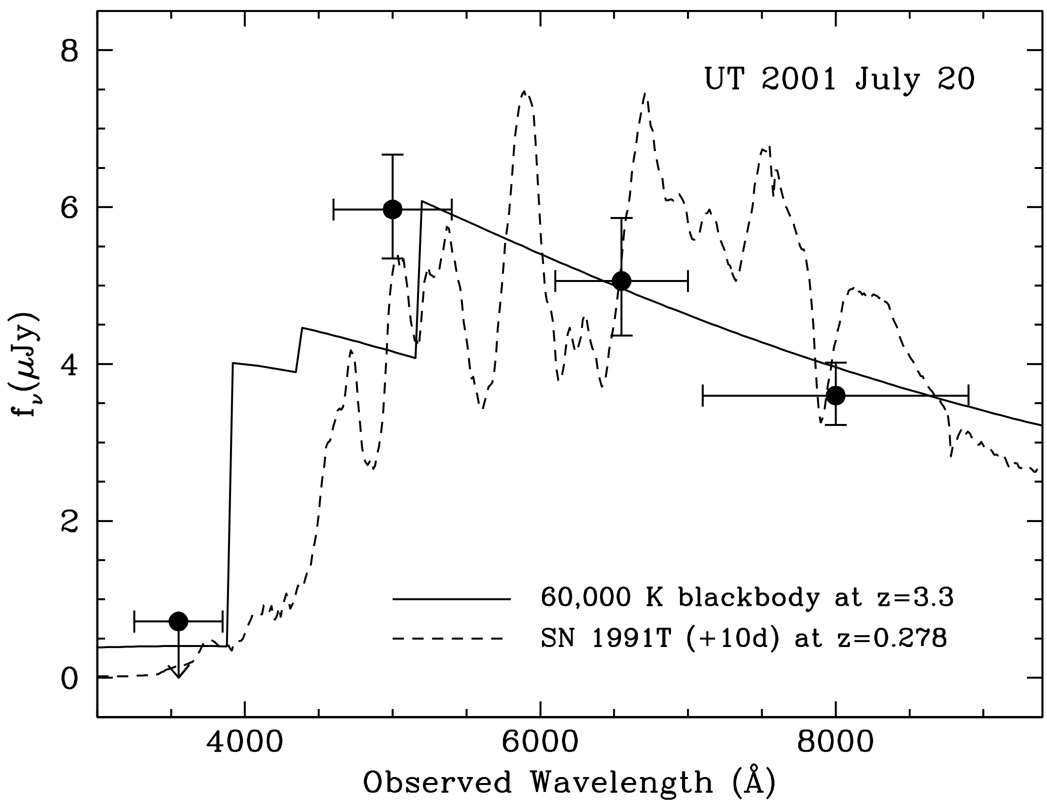

Fig. 2.— Spectral energy distribution of PALS–1 on UT 2001 July 20 (solid circles). The arrow indicates a 3σ upper limit for the U_n-band photometry. Spectra for possible transient object interpretations are overplotted. The solid line shows a 60,000 K black body spectrum redshifted to $z = 3.3$ and subject to hydrogen absorption from interstellar and intergalactic hydrogen. The dashed line shows the scaled spectrum of the type Ia SN 1991T at 10 days after peak brightness, dereddened by $E(B-V) = 0.22$ and redshifted to $z = 0.278$. The spectrum is a combination of *IUE* UV data (Jeffery et al. 1992) and Cerra Tololo optical data (Phillips et al. 1992). For the SN model, our best-fit match to the colors is a $z = 0.278$ 1991T-like type Ia SN 7.25 days after peak brightness (in the observers' frame; §3.1).

local background in an R_{F702W} ($\lambda_c = 6818$ Å; $\Delta\lambda = 1385$ Å) *pre-discovery* image taken on UT 2000 November 12 with the *HST* Wide Field Planetary Camera 2 (WFPC2; Trauger, Ballester, & Burrows 1994). The *HST* image, shown in Fig. 1, was obtained in a survey aimed at measuring the mass distribution of a sample of X-ray clusters at $z \sim 0.2$ (see Smith et al. 2001). The counterpart to PALS–1 is very faint at $R = 27.7^{+0.4}_{-0.3}$ and is likely associated with either the galaxy or star-forming region which hosted the optical transient. The other detection is in data taken on UT 2001 July 25, i.e., 5 days after the Palomar discovery images. During a spectroscopic observation with ESI of an unrelated cluster galaxy, an unfiltered snapshot was taken with the guider camera. An

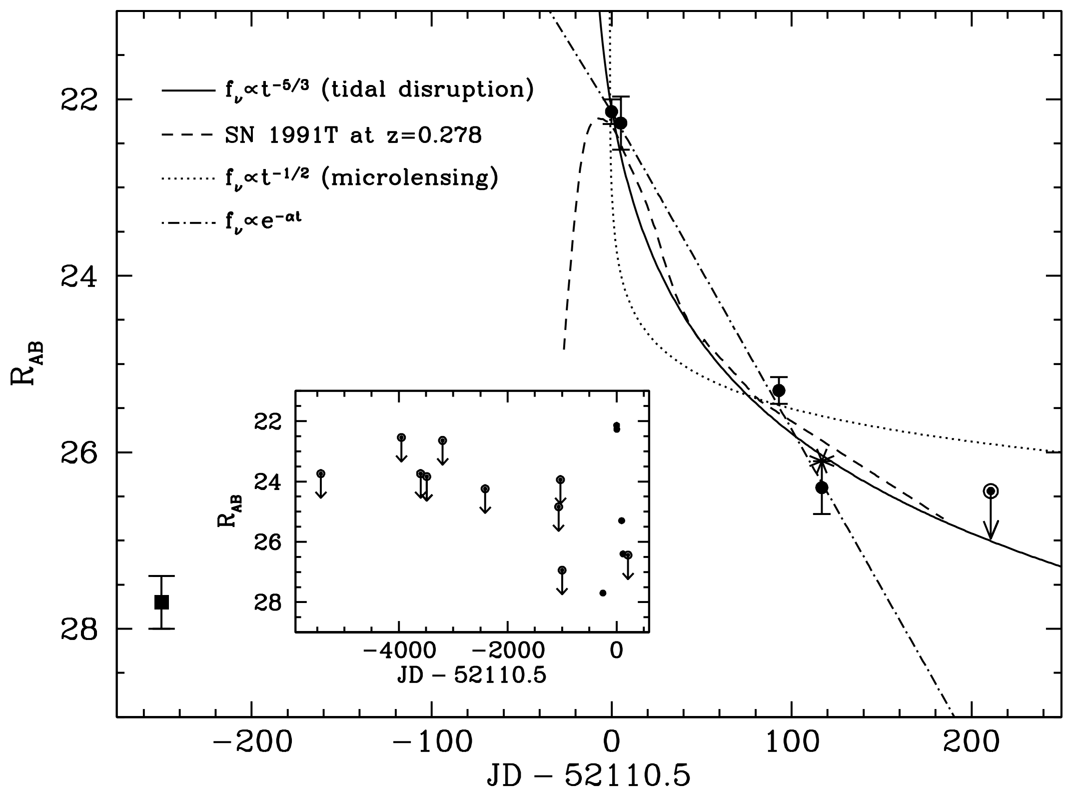

Fig. 3.— Light curve in the R band; arrows indicate 2σ upper limits. The data point at ΔJD = −250 comes from the *HST* image and is assumed associated with the host galaxy. The data point at ΔJD = 117 was corrected for the luminosity of the underlying host (see Fig. 1); the asterisk shows the uncorrected measurement. Lines show temporal evolution of various models, all fitted to the data after JD 52110.5. The solid line shows a power-law with index −5/3, as expected for the flare generated by a tidally-disrupted star (§ 3.2). The dashed line shows our best-fit SN model (§ 3.1), an underluminous 1991T-like type Ia SN at z = 0.278 with maximum brightness occurring 7.25 days prior to the discovery images. The dotted line shows a power-law with index −1/2 (dotted), as expected for a microlensing event. The dot-dashed line shows an exponential fit.

approximate photometric calibration was obtained from blue stars in the guider field.

The light curve of PALS–1 constructed from these various observations is shown in Fig. 3. Shallow (19–20 mag) limits from NEAT are not shown. The decay after JD 52110.5 can be approximated by an exponential of the form $f_\nu \propto e^{\alpha t}$, with $\alpha = -0.033 \pm 0.001$ and t measured in days. We note that since the Palomar observations were not taken concurrently, the apparent U_n-band drop could be due to rapid variability. However, given the long-timescale secular fading seen in the R-band, we consider short-term variability an unlikely explanation for the ultraviolet drop.

3. The Redshift of PALS–1

3.1. A Supernova at $z \approx 0.25$?

PALS–1 is located 4$''\!.$5 east of a bright spiral galaxy (see Fig. 1) and we first consider the hypothesis that the transient is a SN in the outskirts of this galaxy. In this interpretation the object detected in the *HST* image is a star forming region at the same redshift as the spiral galaxy. A 2400 s long slit spectrum containing both PALS–1 and the spiral galaxy was obtained on UT 2001 October 22 with ESI on Keck II. The redshift of the spiral galaxy is $z = 0.278$, as determined from Hα, [N II], and [S II] emission lines. We now demonstrate that no *known* SNe are able to simultaneously match the colors and brightness of PALS–1.

The rest-frame rate of decay for $z = 0.28$ would be approximately 0.046 mag day^{-1}, and the brightness at discovery would be $M_g \sim -18$ after a 0.5 mag correction for lensing. These values are in the range expected for type I and type IIL SNe (e.g., Filippenko 1997). However, the colors of PALS–1 at the time of discovery are incompatible with most types of SNe at this redshift range. Type II SNe at $z \sim 0.25$ only become red in $U_n - g$ at late stages ($\gtrsim$ 100 days), while PALS–1 is red in $U_n - g$ near maximum brightness. Furthermore, when $z \sim 0.25$ type II SNe exhibit red $U_n - g$ colors, they are red across the optical window, which does not match the discovery spectral energy distribution (SED) of PALS–1. Finally, type II SNe do not fade fast enough to match our 4 magnitudes of dimming in 100 days. We conclude that PALS–1 is unlikely to be a type II SN.

Similarly, type Ib/c SNe can be ruled out since the 4 magnitudes of fading in $\sim$ 100 days would require that our discovery imaging occurred right at maximum, at which time the SED is problematic. Poznanski et al. (2002) predict that any normal type I SN at $z \sim 0.28$ has $g - r > 0.4$ at all epochs, compared to the observed $g - r = -0.2 \pm 0.2$ for PALS–1 at discovery (Fig. 4). Similar considerations lead us to conclude that any normal form of type I or type II SN at $z < 1$ can be ruled out as an explanation of PALS–1.

One peculiar form of type Ia SN, resembling SN 1991T (Filippenko et al. 1992), does, however, have a marginally acceptable fit to the colors of PALS–1 (Fig. 4). Such SNe represent 5–20% of the type Ia population (Branch, Fisher, & Nugent 1993; Li et al. 2001a). They are characterized by dusty environments and are typically $\sim$ 0.4 mag overluminous in V (Nugent et al. 1995). A χ^2 fit to the SED and light curve of PALS–1, assuming $z = 0.278$, finds a peak brightness occurring at JD 52103.25 (e.g., 7.25 days prior to our discovery imaging) with no extinction and a peak, corrected magnitude $R = 22.22$. Fig. 2 illustrates our discovery photometry with the observed spectrum of SN 1991T at 10 days after peak brightness (Jeffery et al. 1992; Phillips et al. 1992). Adopting $z = 0.23$, the cluster redshift, degrades the fit. For these analyses, we applied a 0.23 mag color term correction to the U_n magnitude limit to account for the differences between the U_n and SDSS u' filter convolutions with blue stars (which were used to calibrate the Palomar images; § 2.1) and early-time 1991T-like SNe at $z = 0.278$. The correction is adopted in Fig. 4 and implies that, at discovery, PALS–1 had $U_n > 24.47$ for the SN interpretation.

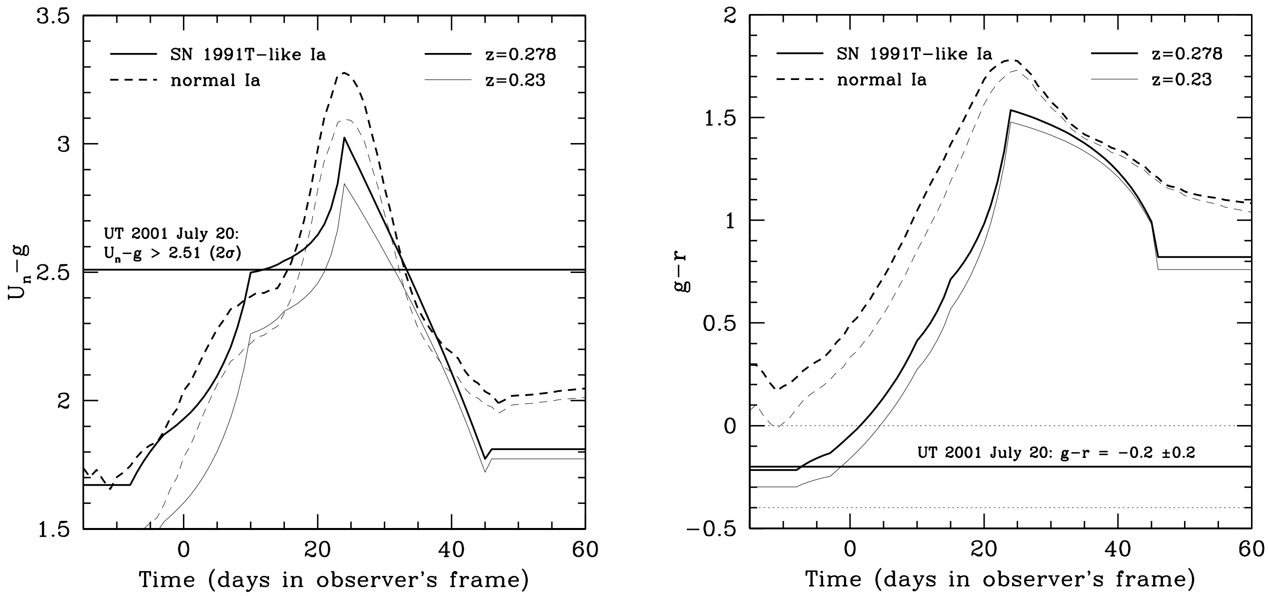

Fig. 4.— Color evolution of type Ia SNe at $z = 0.278$ (darker lines; the redshift of the nearby spiral galaxy) and $z = 0.230$ (thinner lines; the redshift of galaxy cluster Abell 267). Dashed lines illustrate the color evolution for normal type Ia SNe, while solid lines show color evolution for 1991T-like type Ia SNe. The red $U_n - g$ color of PALS-1 at discovery is matched by type Ia SNe at $z \sim 0.25$ for observed times approximately $10 - 30$ days after maximum. However, the blue $g - r$ color of PALS-1 at discovery is difficult to self-consistently match. A normal type Ia SN should have been a least one magnitude redder in $g - r$ at this epoch. A 1991T-like type Ia SNe is consistent with the observed colors at ~ 10 days after peak brightness, but has significant problems matching the observed brightness.

A normal type Ia SN at $z = 0.278$ would have a peak apparent magnitude of $R = 21.25$. SN 1991T-like type Ia SN are typically a few tenths of a magnitude overluminous, implying an expected apparent magnitude of $R = 21.0$ at peak, or $R = 21.1$ at $+7.25$ days. For $z = 0.278$, our lens model (see §3.2.1) implies PALS–1 has been magnified by ≈ 0.5 mag, implying that the *expected* apparent magnitude of PALS–1 in our discovery images would have been $R = 20.6$. This is 1.5 magnitudes brighter than what was actually seen. This brightness offset is quite worrisome. Though 1991T-like SNe are always associated with some extinction, attributing the brightness offset to dust extinction will redden the expected SED and aggravate the color fit to the discovery photometry. Additionally, 1991T-like SNe typically occur in strong star-forming regions, closer to the host galaxy nuclei than PALS–1 is observed relative to the presumed $z = 0.278$ host spiral galaxy. We conclude that PALS–1 can not be a 1991T-like type Ia SN event.

Finally, since a SN interpretation for PALS–1 requires an underluminous type Ia event, we consider known underluminous type Ia SNe. The best studied of this class are 1991bg-like type Ia SNe. However, since Ti absorption causes such SNe to be red in $g - r$ at all epochs, we conclude that PALS–1 can not be such an event. Li et al. (2003b) recently reported on SN 2002cx, a peculiar type Ia SN, unlike any known prior SNe. SN 2002cx exhibits a SN 1991T-like premaximum spectrum, but a SN 1991bg-like luminosity, suggesting it could be a good match to PALS–1. However, SN 2002cx reddens very rapidly after maximum, making a poor fit to the discovery photometry of PALS–1, which is expected to coincide with approximately a week after peak brightness. We conclude that all *known* forms of SNe can be ruled out as an explanation of PALS–1, though the possibility exists that a new form of SN could be identified which would match the colors, lightcurve, and brightness of PALS–1.

3.2. A Gravitationally-Lensed Transient at $z \approx 3.3$?

3.2.1. Lens Model

Another natural explanation for the U-band "dropout" signature seen in PALS–1 on UT 2001 July 20 is absorption by the interstellar medium (ISM) and intergalactic medium (IGM) of a UV bright source at $z \sim 3$. The SED can then be fit equally well by a power law with index $\beta_\nu = 1.0 \pm 0.4$ or a thermal spectrum. As an example, the dashed line in Fig. 2 shows a 60,000 K thermal spectrum at the best-fit redshift $z = 3.3$, including the effects of the ISM and IGM. Temperatures $\gtrsim$ 50,000 K and redshifts $3.1 \lesssim z \lesssim 3.5$ provide good fits to the photometric data.

If the Lyman-break interpretation is correct, the source is strongly lensed by Abell 267. The mass distribution of the cluster was modeled following the techniques described in Kneib et al. (1996) and is discussed in full in G. Smith et al. (in preparation). The absolute mass distribution is somewhat uncertain because no arc redshifts have yet been measured in this cluster. Accordingly, we consider two mass models spanning the likely range. Assuming PALS–1 is in the redshift range $3.1 < z < 3.5$, consistent with the Palomar photometry, the amplification at the location of PALS–1 is a factor 4–7, and two counterimages are predicted, magnified by factors of 3.5–5. Although several candidate counterimages can be identified in the *HST* image, deeper multi-color data are required to unambiguously identify the counterimages.

The correspondence between the $z \sim 3$ Lyman-break colors of PALS–1 and its location near the $z \sim 3$ critical line of our Abell 267 lens model argues strongly that the object may indeed be at this high redshift. Although highly-magnified images of distant objects can be found out to $\sim 30''$ from the cD galaxy, they should lie in restricted regions typically close to the critical line. Considering the area within $30''$ of the cD, the probability that PALS–1 would by chance be located at a position where highly-magnified $z \sim 3$ objects can be expected is only ~ 0.02.

The lens model predicts differing light travel times for the lens images, and implies that PALS–1 represents the the final occurrence of the transient. The absolute time delays between the images are not well constrained, but are in the range 1–10 years. We carefully examined the archival data discussed in § 2.2 to look for a previous occurrence of the transient in a counterimage. As might have been expected from the sparse sampling in the time domain, no convincing cases of previous occurrences were found.

3.2.2. A Tidally-Disrupted Star?

The potential description of PALS–1 as a SN at the redshift of nearby galaxies is thoroughly discussed in §3.1. We now speculate on the physical nature of PALS–1, assuming it is a lensed transient at $z \sim 3$. The luminosity in the far UV at the time of discovery ($M_{\rm AB} \sim -23.5$ after correcting for lensing) is orders of magnitude larger than expected from any SN. GRBs have typical spectral indices $-1.5 \lesssim \beta_\nu \lesssim -0.5$ in the optical (Rhoads 2001), much redder than the observed index $\beta_\nu = 1.0 \pm 0.4$. Variability of an Active Galactic Nucleus (AGN) is possible but not likely, given the lack of detections in numerous archival observations, the large amplitude of the observed variation as compared to typical "violently variable" AGN (e.g., Pollock et al. 1979; Gal-Yam et al. 2002b; Geha et al. 2003), and the non-detection at 8.5 GHz. Micro-lensing of a radio-quiet, optically-faint AGN by a compact object in the cD halo (Walker & Ireland 1995) is highly unlikely, because the luminosity does not decay as $L \propto t^{-1/2}$ at late times and it would require that the event was observed within hours of maximum brightness (see Fig. 3).

An intriguing possibility, consistent with all observations to date, is that PALS–1 was a flare resulting from the tidal disruption of a star by a $10^{6-8}\,M_\odot$ black hole (Rees 1988). Such events are predicted to be very luminous and to give rise to extremely blue spectra, corresponding to effective temperatures $> 10^4$ K (e.g., Ulmer 1999). Both the UV luminosity and the blackbody temperature of PALS–1 are within the range expected for these events. The time scale can vary significantly, ranging from weeks to years. In the "fallback stage" (Rees 1988) the luminosity is expected to decay as a power-law with exponent $-5/3$. As shown by the dashed line in Fig. 3, the observed decay of PALS–1 is consistent with this power-law index, provided that the flare was observed ≈ 15 days (≈ 3 days in the rest frame) after the initial tidal disruption.

The slight offset between the observed flare and the presumed faint host identified in the *HST* images is slightly worrisome for the stellar disruption scenario. However, for $z \sim 3.3$, the *HST* image would trace rest frame UV (≈ 1650 Å) light, which generally does not trace the mass of a star-forming galaxy, and thus would not necessarily coincide with the galaxy nucleus.

Detection of UV flares is of great interest because it may be the only way to detect massive black holes in non-active galaxies at $z \gtrsim 3$. The time domain is just starting to be explored at faint levels (e.g., Dell'Antonio et al. 2001), and we may expect to find unlensed examples of this type of transient. Indeed, Genzel et al. (2003) and Ghez et al. (2003) recently reported near-infrared flares from the supermassive black hole at the center of the Milky Way, possibly associated with the accretion of comet- or small asteroid-sized bodies. The photometric properties of flares are thought to depend on the mass of the black hole (Ulmer 1999), and with sufficiently large samples it may be possible to extend studies of the relation between massive black holes and their host galaxies (e.g., Ferrarese & Merrit 2000) to very high redshift.

4. Event Rates

Though we have shown that PALS–1 is unlike any *known* type of SN, the possibility exists that we have discovered a new, rare type of SN, similar to a 1.5 magnitude underluminous 1991T-like type Ia SN. In the past four years alone, three "unique", never-seen-before, nearby type-Ia SNe have been discovered: SN 2000cx (Li et al. 2001b), SN 2002cx (Li et al. 2003b), and SN 2002ic (Deng et al. 2004). Underluminous SNe would likely be under-represented in flux-limited surveys. Alternatively, PALS–1 may be associated with the optical flare caused by a tidally-disrupted star, also a never-seen-before phenomenon. Subject to the uncertainties inherent in estimating the rates of such singular events, we next compare the relative likelihoods of a peculiar SN at $z \approx 0.25$ and a gravitationally-lensed, tidally-disrupted star at $z \approx 3.3$. Again, we emphasize that neither phenomena have been observed previously, so the following estimates are subject to substantial uncertainties.

4.1. Peculiar Type Ia Supernovae at $z \approx 0.25$

Based on the color and apparent brightness of PALS–1 at discovery, a SN identification would likely be near the cluster redshift. Since the light curve of PALS–1 argues against it being associated with a type II SN (§ 3.1), we begin our estimate with the type Ia SN rate in galaxy clusters; field galaxies at similar redshifts are unlikely to increase this number by more than a small factor. Gal-Yam, Maoz, & Sharon (2002a) recently measured the type Ia SN event rate for galaxy clusters, finding $0.20^{+0.84}_{-0.19}\ h_{50}^{2}$ type Ia SNe century^{-1} per $10^{10}\ L_{B\odot}$ for $0.18 \leq z \leq 0.37$ galaxy clusters. Typical galaxy clusters have $2.5 \times 10^{12}\ h_{50}^{-2}\ L_{B\odot}$. As argued in § 3.1, for this scenario PALS–1 is likely related to a 1991T-like type Ia SN. Such SNe represent 5−20% of the type Ia population (Branch et al. 1993; Li et al. 2001a). Perhaps as much as 5% of the 1991T population could match our underluminosity requirement, *i.e.,* $\lesssim 0.5\%$ of the type Ia SN population are potentially peculiar and could match PALS–1. This is the largest uncertainty in our estimate; current and future ambitious SNe surveys will refine, and possibly measure, this number. A SN at $z \approx 0.25$ would have been visible to our survey for approximately two months, though the red $U - g$ and blue $g - r$ colors which would have caused us to notice such a SN are only present for ≈ 12 days. Folding these factors together, we estimate a $\lesssim (4 - 400) \times 10^{-6}$ probability that PALS–1 is an as-yet-unknown, peculiar type Ia SN in Abell 267 at $z = 0.23$. We emphasize that the photometry analysis found a better match for a SN in the background $z = 0.278$ spiral galaxy (e.g., Fig. 4) rather than in the cluster, implying that this estimate is potentially several orders of magnitude optimistic.

4.2. Gravitationally-Lensed, Tidally-Disrupted Stars at $z \approx 3.3$

According to the hypothesis that PALS–1 is a $z \approx 3.3$ tidally-disrupted star gravitationally-lensed by Abell 267, the $R = 27.7$ source identified in our *HST* image is the host galaxy. Our lens model (§ 3.2.1) implies $1.5 - 2.1$ magnitudes of gravitational magnification. We first calculate the likelihood that an intrinsically $R \approx 29.5$ LBG at $z \sim 3$ has been highly magnified by the cluster, and we then use the theoretical stellar disruption rate calculated by Magorrian & Tremaine (1999) to estimate the probability of the tidal disruption scenario.

The $z \sim 3$ LBG luminosity function from Steidel et al. (1999) implies a surface density of 30.4 LBGs arcmin^{-1} for $29 < R < 30$. Lensing magnification by a factor of five dilutes the surface density by the same factor. Since only 2% of the area with $30''$ of the cluster cD galaxy is highly magnified, we estimate ≈ 0.1 faint ($R \approx 29.5$), $z \sim 3$ LBGs are highly magnified by Abell 267.

Based on dynamical models of real galaxies with supermassive, central black holes, Magorrian & Tremaine (1999) calculate approximately one star is tidally disrupted per 10^4 yr for faint ($L \lesssim 10^{10} L_\odot$) galaxies. The event rate is approximately flat for $10^{8.5} < L/L_\odot < 10^{10}$. More massive galaxies have more massive black holes which swallow dwarf stars whole and hence do not emit flares. This, combined with the flatter central density profiles in such galaxies, causes the tidal disruption rate to decrease for more massive galaxies.

For the Steidel et al. (1999) rest frame UV $z \sim 3$ LBG luminosity function, $m_R^* = 24.48 \pm 0.15$. Shapley et al. (2001), based on near-infrared imaging of $z \sim 3$ LBGs, finds the corresponding $m_K^* = 20.70 \pm 0.25$, or $M_V^* = -22.21 \pm 0.25 + 5 \log h$ (for $\Omega_m = 0.3, \Omega_\Lambda = 0.7$). An $R \approx 29.5$ LBG at $z \sim 3$ is thus $\approx 10^{8.8} L_\odot$ and has a $\approx 10^{7.3} M_\odot$ central black hole according to the Magorrian et al. (1998) black hole mass – galaxy luminosity relation. Modulo uncertainties in black hole mass evolution, galaxy density profile evolution, and evolution in the mass-to-light ratio, these numbers imply a central blackhole well within the $10^{6-8} M_\odot$ black hole mass range required to produce tidal disruption events (Rees 1988), as well as a galaxy luminosity well within the plateau range in the Magorrian & Tremaine (1999) tidal disruption rate.

Correcting the Magorrian & Tremaine (1999) tidal disruption rate for the $1 + z$ time dilation, assuming that the resultant flares would only be visible for ≈ 2 months, and using the number of highly-lensed $z \sim 3$ LBGs determined above, we estimate an $\approx 4 \times 10^{-7}$ probability that PALS–1 is associated with the gravitationally-lensed optical flare caused by a tidal disruption event at $z \approx 3.3$.

5. Conclusions

We report the discovery of a transient source, "PALS–1", in the field of Abell 267. At discovery, the source was undetected in the UV, $U_n > 24.7$ (2σ), but had blue colors from 5000 Å to 9000 Å, with $m_{\rm AB} \approx 22.2$ at 6500 Å and a blue spectral index, $\beta_\nu = 1.0 \pm 0.4$. The spectral energy distribution suggested PALS–1 to be an ideal candidate lensed Lyman-break galaxy at $z \sim 3$;

indeed, our lensing model for Abell 267 places PALS–1 near a cusp in the source plane for this redshift. However, unlike Lyman-break galaxies, subsequent observations showed "PALS–1" to fade by over four magnitudes in seven months. We discuss potential interpretations of PALS–1. Similar sources likely contaminate Lyman-break surveys (e.g., Steidel et al. 1999) at some level.

First we consider the possibility that PALS–1 is a SN, either at the cluster redshift ($z = 0.23$) or in a slightly background ($z = 0.278$) spiral galaxy $4\farcs5$ WNW of PALS–1. We briefly note that finding gravitationally-lensed type Ia SNe behind galaxy clusters is potentially quite interesting as a technique to remove the mass-sheet degeneracy that arises when weak lensing studies of gravitational shear are used to infer the cluster mass (e.g., Kolatt & Bartelmann 1998; Holz 2001). In short, because the shear field is insensitive to magnification, a uniform sheet of matter anywhere between the source and the observer will remain undetected in weak lensing analyses. Detection of a strongly-lensed standard candle provides direct measurement of the magnification, thus lifting the mass-sheet degeneracy. We show that normal type I and type II SNe at all epochs have colors inconsistent with PALS–1. A somewhat rare SN 1991T-like type Ia SN has similar colors to PALS–1 near peak brightness for $z = 0.278$, but would be 1.5 magnitudes more luminous than PALS–1. Known, underluminous type Ia SNe have inconsistent spectral energy distributions. We conclude that PALS–1 is unlikely to be associated with any known SN, though the possibility exists that PALS–1 marks the first discovery of a new type of rare SN.

Next, we consider the scenario that the U-band dropout signature of PALS–1 is indeed associated with interstellar and intergalactic hydrogen absorption for a source at $z \sim 3$. We argue that the most likely explanation for both the SED and light curve is tidal disruption of a star by a massive black hole in the core of a galaxy. Rees (1988) show the remnants of such a star forms a stream of stellar matter in far-ranging orbits (see also Cannizzo, Lee, & Goodman 1990). Assuming equal fractions of mass in equal binding energy intervals, the inferred accretion rate declines as $t^{-5/3}$, consistent with the light curve of PALS–1. Such events are predicted to be very luminous and to give rise to extremely blue spectra, corresponding to effective temperatures $>$ 10,000 K (e.g., Ulmer 1999). Loeb & Ulmer (1997) note that such events potentially provide a crude measure of the central black hole mass. In particular, for black holes more massive than $\approx 10^8 M_\odot$, the tidal radius lies inside the innermost stable orbit ($6GM_{\rm bh}/c^2$) and stars are swallowed whole, without much emission (Hills 1974). Flares produced by tidally-disrupted stars have the potential to extend studies of the accretion history of the universe and the relation between black holes and their host galaxies to quiescent galaxies and to very high redshift.

It is somewhat dissatisfying that since PALS–1 was a transient phenomenon, we may never know what it truly was. A crude estimate of the relative event rates for $z = 0.23$ peculiar, type Ia cluster SNe and $z \sim 3.3$ stellar disruption flares argue that the former is perhaps a few orders of magnitude more likely, depending upon the existence and frequency of cluster SNe which would exactly match the colors and brightness of PALS–1. What observations could help unwrap this mystery? Foremost would be archival observations of Abell 267 obtained in Summer/Fall 2001. Though the R-band light curves for both post-maximum $z \sim 0.25$ SNe and tidal disruption events are similar (Fig. 3), the expected color evolutions are quite different and would likely provide conclusive information (e.g., Fig. 4). Moderately-deep R-band imaging from the few weeks prior to the discovery images would also unambiguously distinguish a pre-maximum SN from a tidally-disrupted stellar flare. Further study of Abell 267 would also be useful. Though challenging, color information for the $R \approx 28$ presumed host could distinguish a $z \approx 0.25$ star-forming region from a $z \approx 3.3$ LBG. Deep imaging could also help improve the mass modeling of Abell 267 and identify potential counter images. Finally, improved knowledge about type Ia SNe, particularly at ultraviolet wavelengths, will also be useful. The growing census of well-studied type Ia SNe will improve our estimate of the fraction that are peculiar, as well as elucidate the breadth of this variety. If indeed an underluminous 1991T-like SN were identified, it would strengthen the case the PALS–1 is a similar event.

We note that PALS–1 was found with a rather shallow survey of ≈ 100 galaxy clusters and, assuming it is a tidal disruption flare at $z \approx 3.3$, the amplification was at most a factor of 10. This implies that deeper surveys (not restricted to clusters) could commonly find more disruption events. Distant field (e.g., the Deep Lens Survey; Wittman et al. 2002) and nearby galaxy (e.g., the robotic KAIT program; Li et al. 2003a) surveys should be routinely searched for such events at galaxy centers. Future variability surveys (e.g., PanSTARRS and LSST, expecting to reach more than 2.5 magnitudes deeper than PALS) might also be optimized to discover disruption events. Finally, we note that transients like PALS–1 are relevant for future SN search programs, such as the *Supernova Acceleration Probe* (*SNAP*). If PALS–1 had indeed been a disruption event, its existence (well-above the *SNAP* threshold), with a light curve similar to a type Ia SN, strengthens the case for well-sampled multi-color light curves with spectra taken near peak. If PALS–1 had been a peculiar type Ia SN, such sources, otherwise assumed to be normal type Ia SNe, would act as contaminants for cosmology programs.

We gratefully acknowledge Avishay Gal-Yam, Avi Loeb, and Peter Wannier for useful comments. We thank Chuck Steidel for use of his U_n-band filter, Graham Smith for the *HST* image of Abell 267, and David Kaplan for NIRC observations. Haakon Dahle and Ashish Mahabal assisted in obtaining archival data. The work of DS was carried out at Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. PGvD is supported by NASA through Hubble Fellowship HF-01126.01-99A awarded by the Space Telescope Science Institute. DJS would like to acknowledge financial support from NASA's Graduate Student Research Program, NASA grant No. NAGT-50449. JSB acknowledges support by the Fannie and John Hertz Foundation. MS acknowledges support from a PPARC fellowship. TT acknowledges support from NASA through Hubble Fellowship grant HF-01167.01. We also extend our thanks to Martin Kirby, under whose influence this project commenced.

REFERENCES

Adelberger, K. L. & Steidel, C. C. 2000, ApJ, 544

Baker, A. J., Lutz, D., Genzel, R., Tacconi, L. J., & Lehnert, M. D. 2001, A&AS, 372, 37

Becker, R. H. et al. 2001, AJ, 122, 2850

Branch, D., Fisher, A., & Nugent, P. 1993, AJ, 106, 2383

Cannizzo, J. K., Lee, H. M., & Goodman, J. 1990, ApJ, 351, 38

Dahle, H., Kaiser, N., Irgens, R. J., Lilje, P. B., & Maddox, S. J. 2002, ApJS, 139, 313

Dell'Antonio, I., Tyson, J. A., Wittman, D., Becker, A., Margoniner, V., Wilson, G., & DLS Team. 2001, BAAS, #101.12

Deng, J., Kawabata, K., Ohyama, Y., Nomoto, K., Mazzali, P., Wang, L., Jeffery, D., & Iye, M. 2004, ApJ, submitted, astro-ph/0311590

Dickinson, M. E. et al. 2004, ApJ, 600, L99

Djorgovski, S. G. 1985, PASP, 97, 1119

Djorgovski, S. G., Castro, S. M., Stern, D., & Mahabal, A. A. 2001, ApJ, 122, 598

Djorgovski, S. G., Gal, R. R., Odewahn, S. C., de Calvalho, R. R., Brunner, R., Longo, G., & Scaramella, R. 1999, in *Wide Field Surveys in Cosmology*, ed. Y. Mellier & S. Colombi (Gif sur Yvette: Editions Frontières), 89

Ellis, R. et al. 2001, ApJ, 560, L75

Fan, X. et al. 1999, AJ, 118, 1

Ferguson, H. C. et al. 2004, ApJ, 600, L107

Ferrarese, L. & Merrit, D. 2000, ApJ, 539, L9

Filippenko, A. V. 1997, ARA&A, 35, 309

Filippenko, A. V. et al. 1992, ApJ, 384, 15

Franx, M., Illingworth, G. D., Kelson, D. D., van Dokkum, P. G., & Tran, K.-V. 1997, ApJ, 486, L75

Gal-Yam, A., Maoz, D., & Sharon, K. 2002a, MNRAS, 332, 37

Gal-Yam, A., Ofek, E. O., Filippenko, A. V., Chornock, R., & Li, W. 2002b, PASP, 114, 587

Geha, M. et al. 2003, AJ, 125, 1

Genzel, R., Schödel, R., Ott, T., Eckart, A., Alexander, T., Lacombe, F., Rouan, D., & Aschenbach, B. 2003, Nature, 425, 934

Ghez, A. M. et al. 2003, ApJ, in press, astro-ph/0309076

Giavalisco, M. et al. 2004, ApJ, 600

Hills, J. G. 1974, Nature, 254, 295

Holland, W.S. et al. 1999, MNRAS, 303, 659

Holz, D. E. 2001, ApJ, 556, L71

Hu, E. M., Cowie, L. L., McMahon, R. G., Capak, P., Iwamuro, F., Kneib, J.-P., Maihara, T., & Motohara, K. 2002, ApJ, 568, L75

Hu, E. M., Cowie, L. L., Capak, P., McMahon, R. G., Hayashino, T., & Komiyama, Y. 2004, AJ, 127, 563

Jeffery, D. J., Leibundgut, B., Kirshner, R. P., Benetti, S., Branch, D., & Sonneborn, G. 1992, ApJ, 397, 304

Kells, W., Dressler, A., Sivaramakrishnan, A., Carr, D., Koch, E., Epps, H., Hilyard, D., & Pardeilhan, G. 1998, PASP, 110, 1487

Kneib, J., Ellis, R. S., Smail, I., Couch, W. J., & Sharples, R. M. 1996, ApJ, 471, 643

Kneib, J.-P., Ellis, R. S., Santos, M. R., & Ricard, J. 2004, AJ, accepted, astro-ph/0402319

Kodaira, K. et al. 2003, PASJ, 55, 17

Kolatt, T. S. & Bartelmann, M. 1998, MNRAS, 296, 763

Komossa, S., Halpern, J., Schartel, N., Hasinger, G., Santos-Lleo, M., & Predahl, P. 2004, ApJ, 603, L17

Li, L.-X., Narayan, R., & Menou, K. 2002, ApJ, 576, 753

Li, W., Filippenko, A. V., Chornock, R., & Jha, S. 2003a, BAAS, 202, #38.05

Li, W., Filippenko, A. V., Treffers, R. R., Riess, A. G., Hu, J., & Qiu, Y. 2001a, ApJ, 546, 734

Li, W. et al. 2001b, PASP, 113, 1178

—. 2003b, PASP, 115, 453

Lidskii, V. V. & Ozernoi, L. M. 1979, AZh Pis'ma, 5, L28

Loeb, A. & Ulmer, A. 1997, ApJ, 489, 573

Magorrian, J. & Tremaine, S. 1999, MNRAS, 309, 447

Magorrian, J. et al. 1998, AJ, 115, 2285

Matthews, K. & Soifer, B. T. 1994, in *Infrared Astronomy with Arrays: The Next Generation*, ed. I. McClean (Dordrecht: Kluwer), 239

Nugent, P., Phillips, M., Baron, E., Branch, D., & Hauschildt, P. 1995, ApJ, 455, L147

Oke, J. B., Cohen, J. G., Carr, M., Cromer, J., Dingizian, A., Harris, F. H., Labrecque, S., Lucinio, R., et al., 1995, PASP, 107, 375

Oke, J. B. & Gunn, J. E. 1983, ApJ, 266, 713

Perlmutter, S. et al. 1999, ApJ, 517, 565

Pettini, M., Steidel, C. C., Adelberger, K. L., Dickinson, M., & Giavalisco, M. 1999, ApJ, 528, 96

Phillips, M. M., Wells, L. A., Suntzeff, N. B., Hamuy, M., Leibundgut, B., Kirshner, R. P., & Foltz, C. B. 1992, AJ, 103, 1632

Pollock, J. T., Pica, A. J., Smith, A. G., Leacock, R. J., Edwards, P. L., & Scott, R. L. 1979, AJ, 84, 1658

Poznanski, D., Gal-Yam, A., Maoz, D., Filippenko, A. V., Leonard, D. C., & Matheson, T. 2002, PASP, 114, 833

Pravdo, S. H. et al. 1999, ApJ, 117, 1616

Rees, M. J. 1988, Nature, 333, 523

Rhoads, J. E. 2001, ApJ, 557, 943

Rhoads, J. E., Malhotra, S., Dey, A., Stern, D., Spinrad, H., & Jannuzi, B. T. 2001, ApJ, 545, L85

Rhoads, J. E., Malhotra, S., Xu, C., Dawson, S., Dey, A., Wang, J., Jannuzi, B., Spinrad, H., et al., 2004, ApJ, in preparation

Riess, A. G. et al. 1998, AJ, 116, 1009

Schlegel, D., Finkbeiner, D., & Davis, M. 1998, ApJ, 500, 525

Shapley, A. E., Steidel, C. C., Adelberger, K. L., Dickinson, M., Giavalisco, M., & Pettini, M. 2001, ApJ, 562, 95

Sheinis, A. I. et al. 2002, PASP, 114, 851

Smith, G. P., Kneib, J., Ebeling, H., Czoske, O., & Smail, I. 2001, ApJ, 552, 493

Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1

Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Giavalisco, M. 2003, ApJ, 592, 728

Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, L17

Steidel, C. C., Pettini, M., & Hamilton, D. 1995, AJ, 110, 2519

Stern, D. & Spinrad, H. 1999, PASP, 111, 1475

Teplitz, H. I. et al. 2000, ApJ, 533, 65

Trauger, J. T., Ballester, G. E., & Burrows, C. J. 1994, ApJ, 435, L3

Ulmer, A. 1999, ApJ, 514, 180

Walker, M. A. & Ireland, P. M. 1995, MNRAS, 275, L41

Wittman, D. M. et al. 2002, SPIE, 4836, 73

Yee, H. K. C., Ellingson, E., Bechtold, J., Carlberg, R. G., & Cuillandre, J. 1996, AJ, 111, 1783

York, D. G. et al. 2000, AJ, 120, 1579

Table 1. UT 2001 July 20 photometry of PALS–1

$U_{\rm AB}$	$g_{\rm AB}$	$r_{\rm AB}$	$i_{\rm AB}$
> 24.7	21.96 ± 0.12	22.16 ± 0.16	22.56 ± 0.12

Note. — U-band photometry is a 2σ upper limit. Photometry has been corrected for Galactic extinction of $E(B-V) = 0.025$ towards Abell 267, determined from the dust maps of Schlegel, Finkbeiner, & Davis (1998).

Table 2. R-band photometry of PALS–1

Julian Date	$R_{\rm AB}$	Telescope/Instrument
46679.3	> 23.7	DPOSS
48159.6	> 22.5	DPOSS
48511.3	> 23.7	DPOSS
48624.3	> 23.8	JKT
48915.8	> 22.6	DPOSS
49698.3	> 24.2	WHT
51045.3	> 24.8	JKT
51081.3	> 23.9	SDSS
51109.8	> 26.9	UH 2.2m
51860.4	$27.7^{+0.4}_{-0.3}$ †	*HST*
52110.5	22.14 ± 0.14	Palomar 200″
52115.6	22.3 ± 0.3	Keck guider
52203.4	25.30 ± 0.15	Keck/ESI
52227.3	26.1 ± 0.3	Keck/ESI
52321.2	> 26.4	Keck

Note. — Limits are 2σ upper limits. †*HST* detection is presumed associated with the host star-forming region or galaxy.