Discovery of a Transient U-band Dropout in a Lyman Break Survey: A Tidally-Disrupted Star at $z = 3.3$?

D. Stern[♠], P.G. van Dokkum[♣], P. Nugent[♢], D.J. Sand[♣], J.S. Bloom[♣], R.S. Ellis[♣], D.A. Frail[♡], J.-P. Kneib[♣], M.Sullivan[♣], & T.Treu[♣]

[♠]Jet Propulsion Laboratory, Caltech

[♣]Dept. of Astrophysics, Caltech

[♢]Lawrence Berkeley National Laboratory

[♡]National Radio Astronomy Observatory

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 $U_{\rm AB} > 24.7$ (2σ), $g_{\rm AB} = 21.96 \pm 0.12$, 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 $R_{\rm AB} > 26.4$ seven months after discovery. We consider two likely interpretations of PALS–1. First, though the photometry argues against a normal supernova at any redshift, they are marginally consistent with a peculiar Type Ia supernova, resembling SN 1991T, at $z \approx 0.28$. Second, 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, 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.

Observations: SED on UT 2001 July 20

As part of the PALS survey, the $z = 0.23$ cluster Abell 267 was observed with COSMIC on the Palomar 200″ telescope on UT 2001 July 20. Exposure times and filter information are provided in Table 1. Conditions were photometric, and the seeing was $\approx 1.6''$ in all bands. Photometric calibration was performed using the Sloan Digital Sky Survey (SDSS) Early Data Release observations of Abell 267. Throughout, magnitudes are referred to the AB system.

The survey located an object in the envelope of the central cD galaxy (shown in Fig. 1) with the colors of a young galaxy or quasar at $z \sim 3$. As shown in Fig. 2, the object, which we call "PALS–1", had a very blue continuum redward of $\sim 4500\,\text{Å}$, and a strong break between the U-band and the g-band. With $U > 24.7$ (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.

PALS–1: A Supernova at $z = 0.28$?

PALS–1 is located 4.5″ from a bright spiral galaxy (see Fig. 1) and we first consider the hypothesis that the transient is a supernova 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.

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 (Filippenko 1997). However, the colors of PALS–1 at the time of discovery are incompatible with most types of supernovae at $z \sim 0.28$. Fig. 4 shows the $U - g$ and $g - r$ color evolution of supernovae for $z = 0.28$: any form of Type II or Type Ib/c supernova can be ruled out as an explanation of PALS–1.

However, one peculiar form of Type Ia supernova, resembling SN 1991T (Filippenko *et al.* 1992), does have an acceptable fit to the $g - r$ color of PALS–1. Such supernovae represent 5–20% of the Type Ia population (Branch *et al.* 1993; Li *et al.* 2001). They are characterized by dusty environments and are typically $\sim$ 0.4 mag overluminous in V (Nugent *et al.* 1995). A χ^2

PALS–1: A Lensed Transient at $z \approx 3.3$?

Another natural explanation for the U-band "dropout" signature seen in PALS–1 on UT 2001 July 20 is absorption by the 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 $z = 3.3$. 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.S̃mith *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 (C3) is a factor 4–7, and two counterimages C1 and C2 are predicted, magnified by factors of 3.5–5 (see Fig. 5).

PALS–1: A Tidally-Disrupted Star?

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 powerlaw with exponent $-5/3$. As shown by the dashed line in Fig. 3, the observed decay of PALS–1 is consistent with this powerlaw index, provided that the flare was observed ≈ 15 days (≈ 3 days in the rest frame) after the initial tidal disruption.

Detection of such 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, and we may expect to find unlensed examples of this type of transient. The photometric properties of the flare are thought to depend on the mass of the black hole (Ulmer 1999).

of $M_V = -18.64 \pm 0.2$ is 0.7-1.3 mag underluminous. Potentially this offset can be attributed to dust, which is commonly associated with SN 1991T-like Type Ia supernovae.

We note that finding gravitationally-lensed Type Ia supernovae 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 (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. Type Ia supernovae are likely the best candidate such source, though PALS–1 is poorly-suited to this task without a precise measure of its dust extinction.

Next, we consider the scenario that the U-band dropout signature of PALS–1 is indeed associated with 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) shows the remnants of such a star star forms a stream of stellar matter in far-ranging orbits. Assuming equal fractions of mass in equal binding energy intervals, the inferred accretion rate declines as $t^{-5/3}$,

REFERENCES

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

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

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

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

Filippenko, A.V. *et al.* 1993, ApJ, 384, 15

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

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

Kneib, J. *et al.* 1996, ApJ, 471, 643

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

Li, W. *et al.* 2001, ApJ, 546, 743

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

Nugent, P. *et al.* 1995, ApJ, 455, L147

Perlmutter, S. *et al.* 1997, ApJ, 483, 565

Rees, M.J. 1998, Nature, 333, 523

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

Saha, A. *et al.* 2001, ApJ, 551, 973

Steidel, C.C. *et al.* 1995, AJ, 110, 2519

Steidel, C.C. *et al.* 1999, ApJ, 519, 1

Ulmer, A. 1999, ApJ, 514, 180

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

Yee, H.K.C. *et al.* 1996, AJ, 111, 1783