A HIGHLY MAGNIFIED SUPERNOVA AT z = 1.703 BEHIND THE MASSIVE GALAXY CLUSTER A1689

R. Amanullah\(^1,2\), A. Goobar\(^1,2\), B. Clément\(^3\), J.-G. Cuby\(^3\), H. Dahle\(^4,5\), T. Dahlén\(^6\), J. Hjorth\(^7\), S. Fabbro\(^8\), J. Jönsson\(^1,2\), J.-P. Kneib\(^9\), C. Lidman\(^9\), M. Limousin\(^3\), B. Milvang-Jensen\(^7\), E. Mörtsell\(^1,2\), J. Nordin\(^1,2\), K. Paech\(^10\), J. Richard\(^7,11\), T. Riehle\(^2,12\), V. Stanishev\(^3\), and D. Watson\(^7\)

\(^1\) Department of Physics, Stockholm University, Albanova University Centre, SE 106-91 Stockholm, Sweden; rahman@fysik.su.se
\(^2\) The Oskar Klein Centre, Physics Department, Stockholm University, Albanova University Centre, SE 106-91 Stockholm, Sweden
\(^3\) Laboratoire d’Astrophysique de Marseille, UMR 6610, CNRS-Université de Provence, 13388 Marseille Cedex 13, France
\(^4\) Institute of Theoretical Astrophysics, University of Oslo, Blindern, N-0315 Oslo, Norway
\(^5\) Centre of Mathematics for Applications, University of Oslo, Blindern, N-0315 Oslo, Norway
\(^6\) Space Telescope Science Institute, Baltimore, MD 21218, USA
\(^7\) Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark
\(^8\) Department of Physics and Astronomy, University of Victoria, Victoria BC V8T 1M8, Canada
\(^9\) Australian Astronomical Observatory, Epping, NSW 1710, Australia
\(^10\) Physikalisches Institut, Universität Bonn, 53115 Bonn, Germany
\(^11\) CRAL, Observatoire de Lyon, Université Lyon, 69561 Saint Genis Laval Cedex, France
\(^12\) Department of Astronomy, Stockholm University, Albanova University Centre, SE 106-92 Stockholm, Sweden
\(^13\) CENTRA-Centro Multidisciplinar de Astrofísica, IST, 1049-001 Lisboa, Portugal

Received 2011 September 21; accepted 2011 October 6; published 2011 October 31

ABSTRACT

Our ability to study the most remote supernova explosions, crucial for the understanding of the evolution of the high-redshift universe and its expansion rate, is limited by the light collection capabilities of telescopes. However, nature offers unique opportunities to look beyond the range within reach of our unaided instruments thanks to the light-focusing power of massive galaxy clusters. Here we report on the discovery of one of the most distant supernovae ever found, at redshift z = 1.703. Due to a lensing magnification factor of 4.3 ± 0.3, we are able to measure a light curve of the supernova, as well as spectroscopic features of the host galaxy with a precision comparable to what would otherwise only be possible with future generation telescopes.

Key words: galaxies: clusters: individual (A1689) – galaxies: distances and redshifts – gravitational lensing: weak – supernovae: general

Online-only material: color figures

1. INTRODUCTION

Supernovae (SNe), exploding stars at the end of their life cycles, have several astrophysical and cosmological applications. Core-collapse SNe trace the star formation history (Dahlen et al. 2004; Bazin et al. 2009) while the standard candle property of Type Ia SNe (SNe Ia) can be used for probing the expansion history of the universe (see, e.g., Amanullah et al. 2010; Sullivan et al. 2011, and references therein). In particular, it is desirable to study SNe in the distant universe. Our ability to do this is currently limited by the light collecting power of existing telescopes.

Massive galaxy clusters, M \(\geq 10^{14} M_\odot\), act as powerful gravitational telescopes, providing the capability to push observations to higher redshifts (Kneib et al. 2004). For background limited observations, the magnification, \(\mu\), corresponds to a gain factor in exposure length (or mirror area) of \(\mu^2\), which is of particular importance for increasing the depth in the near-IR. For example, in the J-band (Cuby et al. 2000) the atmosphere is \(\sim 3\) mag brighter than in I (Patat 2004), and yet another \(\sim 2.5\) mag brighter in the Ks-band.

The feasibility of detecting high-z SNe along the line of sight of massive clusters (Gunnarsson & Goobar 2003) was first explored by our team using the Infrared Spectrometer And Array Camera (ISAAC) at European Southern Observatory’s (ESO) Very Large Telescope (VLT), although it has also been discussed in previous work (Kovner & Paczynski 1988; Kolatt & Bartelmann 1998; Sullivan et al. 2000; Gal-Yam et al. 2002). Traditional SN searches are done at optical wavelengths where SNe typically emit most of their light. However, at high redshift the optical region is shifted to the near-IR, which is why we chose to carry out our survey at these wavelengths. In Stanishev et al. (2009) and Goobar et al. (2009) we reported the discovery of a highly magnified SN, although severely dimmed by dust, at z \(\sim 0.6\) behind one of the best studied galaxy clusters, A1689. In this work we report on the discovery of one of the most distant SNe ever found, at redshift z = 1.703, from our \(\sim 10\) hr VLT survey of the same cluster.

2. OBSERVATIONS

We have used the High Acuity Wide field K-band Imager (HAWK-I; Pirard et al. 2004; Casali et al. 2006; Kissler-Patig et al. 2008; Siebenmorgen et al. 2011) camera on VLT to monitor galaxies behind the galaxy cluster A1689 (R.A. = 13:11:30, decl. = +01:20:28 J2000 at redshift, z = 0.187) from 2008 December to 2009 July, with observations separated by approximately one month. Each visit consisted of \(\sim 2\) hr long integrations in the J-band (\(\sim 1170–1340\) nm), with seeing conditions of 0′′60–0′′90 FWHM. At the same time, we carried out a similar programme using The Andalucia Faint Object Spectrograph and Camera (ALFOSC) at the Nordic Optical Telescope (NOT) in the i-band (\(\sim 690–850\) nm). Images from different epochs were aligned, seeing matched, and subtracted in order to find transient objects using the method described in Amanullah et al. (2008). The most distant transient found in the survey was first detected on UT 2009 June 5 in the optical NOT i-band data and was confirmed with a detection in the
HAWK-I J-band data two days later. Follow-up photometry was obtained for the three following months until the target disappeared behind the Sun. All visits are listed in Table 1.

3. THE TRANSIENT AT $z = 1.703$

Figure 1 shows the position of the transient on the sky, while a zoomed view of the host galaxy can be seen in the top right panel of Figure 2. The transient was detected 60° W and 50° S of the cluster center, located 0°:04 ± 0°:03 from the core of the northeastern of the two knots that appear to be part of the same system with a separation of ∼7 kpc. The host galaxy redshift was initially estimated to $z = 1.65 ± 0.10$ from multi-band photometry. One major advantage of searching for SNe in lensed galaxies is that it also allows for accurately studying the host environment. A 1 hr VLT XSHOOTER (D’Odorico et al. 2006) spectrum (D. Watson et al. 2011, in preparation) of the host galaxy, shown in Figure 2, was obtained on 2010 April 23. The redshift could accurately be determined to $z = 1.703$ from the identified Lyα λ1216, Hβ λ4861, [O III] λλ4959, 5007 and Hα λ6563 lines. We also detected a weak Hγ λ4340 line, but no [O II] λλ3726, 3729, or [N II] λλ6583. Using the method from Pettini & Pagel (2004), we derived an upper limit on the metallicity of $12 + \log(O/H) < 8.1$. Furthermore, the line ratios [O III] λλ5007/Hβ and [N II] λ6583/Hα can be used to separate star-forming galaxies from those hosting active galactic nuclei (AGNs; Baldwin et al. 1981 Kauffmann et al. 2003), e.g., no narrow-emission line AGNs have been observed with $\log_{10}([\text{N II}]\lambda6583/\text{Hα}) < -0.7$ (Kewley et al. 2006). Due to the absence of [N II] λ6583 in our spectra, we can put an upper limit on the latter ratio of $\log_{10}([\text{N II}]\lambda6583/\text{Hα}) < -1.3$.

While the transient was active, the galaxy cluster A1689 was observed in $Ks$ (~1960–2400 nm) and the narrowband filter NB1060 (~1055–1070 nm) with HAWK-I in ESO programme 181.A-0485. Combining the observations from all three HAWK-I filters and the NOT observations allowed us to build the four-band light curve shown in Figure 3. The transient is most likely an SN based on the fact that (1) no transient activity has been observed, either in archival data, or in the continuous optical follow-up 1.5 years after the discovery, (2) the observed light curve and the absolute magnitude are consistent with the expectations for an SN at the redshift of the host galaxy, and (3) the host galaxy spectrum is inconsistent with an AGN as described above.

The significant detection in the rest-frame ultraviolet, observed $J$-band, excludes a thermonuclear supernova (SN Ia), and it can be concluded that the observed transient is most likely a core collapse SN. It should be pointed out that the rest-frame optical light curve (the HAWK-I bands) is also consistent with an SN Ia, emphasizing the importance of follow-up over a broad wavelength range when no spectroscopic confirmation is available.

There are only very few SNe that have been observed in rest-frame ultraviolet, in particular with coverage in the full wavelength range that was observed here. In order to constrain the nature of the SN further, we carried out template fitting for different SN types. The template that matches our data best is
shown in Figure 3. This corresponds to Peter Nugent’s Type IIn supernova (SN IIn) based on SN 1999el (Di Carlo 2002), where the fitted parameters are the time of maximum light together with the flux normalization. The color of the SN is consistent with the used template. It can be debated whether it is appropriate to fit the narrowband NB1060 data on an equal basis with the other bands, since diversity between individual SNe is certainly expected in narrow wavelength regions. However, refitting the light curve omitting this filter has only a minor impact on the fitted parameters and does not change the SN typing. We have no significant detection of spectroscopic features that can only be associated with the transient. Note, however, that the X-SHOOTER spectrum was obtained ~120 days past maximum light in the rest frame.

The mass distribution model (Limousin et al. 2007) for A1689 is well determined thanks to the large number of constraints based on deep archival multi-band Hubble Space Telescope (HST) observations. It is based on weak and strong lensing analysis of background galaxies and uses 34 multiply imaged systems, of which 24 have spectroscopic redshifts. Using the model, the cluster magnification at the position of the transient for redshift $z = 1.703$ is estimated to be $\Delta m_\mu = 1.58 \pm 0.12$ mag (consistent with the updated model used in Riehm et al. 2011), where $\Delta m_\mu = 2.5 \log_{10} \mu$. Given the lensing magnification, and assuming standard cosmological parameters ($h$, $\Omega_M$, $\Omega_L$) = (0.74, 0.27, 0.73), the absolute $V$-band magnitude is $M_V = -19.56 \pm 0.06$ (phot) $\pm 0.07$ (lens). This places the magnitude of the SN roughly one magnitude brighter than the mean absolute magnitude of SNe IIn in the local universe (Richardson 2002; Kieke 2011). Note, however, that several SNe II much brighter than this have been found in the past (Smith 2008).

4. DISCUSSION

We have demonstrated a relatively inexpensive technique for opening up a high-redshift window for finding SNe, which allows for photometric and, for high magnifications, spectroscopic follow-up, in the rest-frame optical of both SNe and their hosts. In our ~10 h lensing aided survey we found one SN at $z = 1.703$, which is consistent with the expected number of 0.3 SNe Ia and 0.8 core collapse at $z \gtrsim 1.5$. A full rate analysis including discoveries at lower redshifts is the topic for an upcoming paper. A handful of SNe from other surveys have been discovered at redshifts comparable to what is reported here, but they have all been found from much more extensive programs. For example, SN 1997fl at $z \sim 1.7 \pm 0.1$ (Riess et al. 2001) was found by repeated HST observations of the Hubble Deep Field-North, while Cooke et al. (2009) reported the discovery of three $z \sim 2$ Type IIn SNe in seasonal-stacked images from the Supernova Legacy Survey. Furthermore, repeated optical imaging of the Subaru Deep Field from 2002 to 2008 has resulted in 10 single-epoch discovered SNe in the range $1.5 < z < 2.0$ (Poznanski et al. 2007; Graur et al. 2011).

Although wide-field optical surveys may be useful for finding high-$z$ UV-bright SNe, they are less efficient for finding, e.g., SNe Ia with their emission peaking in the rest-frame $B$-band. Carrying out observations in the near-IR is essential for finding these. To illustrate this, the expected magnitude of SNe Ia for different pass bands as a function of redshift is shown in Figure 4 together with the magnitude limits for the deepest SN surveys to date. From this it can be concluded that it is almost impossible to find SNe Ia at $z \gtrsim 2$ in an optical survey. Furthermore, even if such objects are found, using them for probing cosmology requires at the very minimum photometric follow-up in one additional filter, and preferably spectroscopic
Figure 4. SN Ia peak magnitude in different passbands for increasing redshifts assuming an absolute magnitude of $M_B = -19.2$ for $H_0 = 74$ km s$^{-1}$ (Riess et al. 2011). The arrows indicate the redshifts that were reached for a $5\sigma$ detection for the SDF survey as described in Graur et al. (2011), the HST GOODS-South survey (Dahlen et al. 2010), and our own survey with HAWK-I. For the latter we also show the limit that can be reached assuming the same lensing magnification as for the SN discussed in this Letter. (A color version of this figure is available in the online journal.)

confirmation, which is very difficult with existing ground-based telescopes in an unlensed scenario.

Exploiting this technique for several comparable clusters and over an extended period of time would have important implications for the study of high-redshift star formation, which is closely linked to the rate of core collapse SNe, the progenitor scenario of SNe Ia, and of course cosmology with SN Ia, most specifically the nature of dark energy. Although these are key goals for future instruments such as the James Webb Space Telescope, the successor of the HST, or ground-based extremely large telescopes (>25 m), we can start addressing them already today thanks to Nature’s own gravitational telescopes. Long-term monitoring of massive clusters will also yield strongly lensed, multiply imaged SN images, expected at a rate of about once every five years per cluster, for which a time delay will provide independent information about the cosmological distance scale to a precision of a few percent.

The authors thank Claes Fransson for many useful discussions. The work is based, in part, on observations obtained at the ESO Paranal Observatory (ESO programmes 082.A-0431;0.83.A-0398, PI: A. Goobar, 085.A-0909, PI: D. Watson 181.A-0485; PI: J. G. Cuby). It is also based, in part, on observations obtained at the Nordic Optical Telescope (NOT programme P39-011, PI: A. Goobar) with ALFOSC, which is provided by the Instituto de Astrofisica de Andalucia (IAA) under a joint agreement with the University of Copenhagen and NOTSA. The Dark Cosmology Centre is supported by the Danish National Research Foundation.

REFERENCES

Amanullah, R., Lidman, C., Rubin, D., et al. 2010, ApJ, 716, 712
Amanullah, R., Stanishev, V., Goobar, A., et al. 2008, A&A, 486, 375

Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Bazin, G., Palanque-Delabrouille, N., Rich, J., et al. 2009, A&A, 499, 653
Casali, M., Pirard, J.-F., Kissler-Patig, M., et al. 2006, Proc. SPIE, 6269, 29
Cooke, J., Sullivan, M., Barton, E. J., et al. 2009, Nature, 460, 237
Cuby, J., Lidman, C., & Moutou, C. 2000, ESO Messenger, 101, 3
Dahlen, T., Mobasher, B., Dickinson, M., et al. 2010, ApJ, 724, 425
Dahlen, T., Strolger, L.-G., Riess, A. G., et al. 2004, ApJ, 613, 189
Di Carlo, E. 2002, ApJ, 573, 144
D’Odorico, S., Dekker, H., Mazzoleni, R., et al. 2006, Proc. SPIE, 6269, 98
Gal-Yam, A., Maoz, D., & Sharon, K. 2002, MNRAS, 332, 37
Goobar, A., Paech, K., Stanishev, V., et al. 2009, A&A, 507, 71
Graur, O., Poznanski, D., Maoz, D., et al. 2011, MNRAS, 417, 916
Gunnarsson, C., & Goobar, A. 2003, A&A, 405, 859
Kaufmann, G., Heckman, T. M., Tremonti, C., et al. 2003, MNRAS, 346, 1055
Kewley, L. J., Groves, B., Kauffmann, G., & Heckman, T. 2006, MNRAS, 372, 961
Kneib, J.-P., Ellis, R. S., Santos, M. R., et al. 2004, ApJ, 607, 697
Kolatt, T. S., & Bartelmann, M. 1998, MNRAS, 296, 763
Kovner, I., & Paczynski, B. 1988, ApJ, 335, L19
Limousin, M., Richard, J., Jullo, E., et al. 2007, ApJ, 668, 643
Patat, F. 2004, ESO Messenger, 115, 18
Pettini, M., & Pagel, B. E. J. 2004, MNRAS, 348, L59
Pirard, J.-F., Kissler-Patig, M., Moorwood, A., et al. 2004, Proc. SPIE, 5492, 1763
Poznanski, D., Maoz, D., Yasuda, N., et al. 2007, MNRAS, 382, 1169
Richardson, D. 2002, AJ, 123, 745
Riehm, T., Mörtsell, E., Goobar, A., et al. 2011, A&A, in press, arXiv:1109.6351
Riess, A., Nugent, P. E., Gilliland, R. L., et al. 2001, ApJ, 560, 49
Riess, A. G., Macri, L., Casertano, S., et al. 2011, ApJ, 730, 119
Siebenmorgen, R., Carraro, G., Valenti, E., et al. 2011, The Messenger, 144, 9
Smith, N. 2008, ApJ, 686, 467
Stanishev, V., Goobar, A., Paech, K., et al. 2009, A&A, 507, 61
Sullivan, M., Ellis, R., Nugent, P., Smail, I., & Madau, P. 2000, MNRAS, 319, 549
Sullivan, M., Guy, J., Conley, A., et al. 2011, ApJ, 737, 102