DÉJÀ VU ALL OVER AGAIN: THE REAPPEARANCE OF SUPERNOVA REFSDAL


ABSTRACT

In Hubble Space Telescope (HST) imaging taken on 10 November 2014, four images of supernova (SN) ‘Refsdal’ ($z = 1.49$) appeared in an Einstein-cross–like configuration (images S1–S4) around an early-type galaxy in the cluster MACS J1149.5+2223 ($z = 0.54$). The gravitational potential of the cluster creates three full images of the star-forming host galaxy of the SN. Almost all lens models of the cluster have predicted that the SN should reappear within approximately one year in a second host-galaxy image, offset by ~8″ from the previous images. In HST observations taken on 11 December 2015, we find a new source that we interpret as a new image of SN Refsdal. This marks the first time the appearance of a SN at a particular time and location in the sky was successfully predicted in advance! We use these data and the light curve from the first four observed images of SN Refsdal to place constraints on the relative time delay and magnification of the new image (SX), compared to images S1–S4. This enables us, for the first time, to test lens model predictions of both magnifications and time delays for a lensed SN. We find that the timing and brightness of the new image are consistent with the blind predictions of a fraction of the models. The reappearance illustrates the discriminatory power of this blind test and its utility to uncover sources of systematic uncertainty in the lens models. From planned HST photometry, we expect to reach a precision of 1–2% on the relative time delay between S1–S4 and SX.

Subject headings: gravitational lensing; strong; supernovae: general, individual: SN Refsdal; galaxies: clusters; general; individual: MACS J1149.5+2223
1. INTRODUCTION

Background sources strongly lensed by galaxies and galaxy clusters that show flux variations in time can be used as powerful probes, because they make it possible to measure the relative time delays between their multiple images. As Refsdal (1964) first suggested, time delays are useful, because they depend sensitively on both the cosmic expansion rate as well as the gravitational potential of the lens. While the positions of the images of lensed galaxies depend on the derivative of the potential, the time delays are directly proportional to differences in the potential.

In addition to the Einstein-Cross–like configuration around an elliptical cluster member, Models of the complex potential of the galaxy cluster and early-type galaxy lenses suggest that three of the four images are magnified by up to a factor of $\sim 10–20$ (Kelly et al. 2015; Oguri 2015). Image SX is also predicted to be significantly fainter than images S1–S3, by a factor of 3-4. Together these predictions indicated that image SX could plausibly have been detected as soon as $HST$ could observe the MACS J1149.5+2223 field beginning on October 30 2015. From late July through late October, it had been too close to the Sun to be observed. Importantly, all of these modeling efforts were completed before the first realistic opportunity to detect image SX on October 30.
2015, making these truly blind predictions.

Here we present a direct test of these lens model predictions, as we revisit the MACS.J1149.5+2223 field and identify the appearance of the anticipated fifth image of SN Refsdal. In this work, Section 2 presents the data processing and photometry on the new HST images. In Section 3 we derive joint constraints on the relative time delay and magnification and compare these to the published predictions from the lens modeling community. We briefly discuss our results in Section 4 and conclude in Section 5. Throughout this paper, magnitudes are given in the AB system (Oke & Gunn 1983), and a concordance cosmology is assumed when necessary ($\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$).

2. METHODS

We processed the WFC3 imaging data using a pipeline constructed from the DrizzlePac software tools26. The images were resampled to a pixel scale of 0.06″/pixel using AstroDrizzle (Fruchter, A. S., et al. 2010) and registered to a common astrometric frame using TweakReg. Template images in each band were constructed by combining all available WFC3 IR imaging collected prior to 30 Oct, 2015, comprising observations from the GLASS program, the Cluster Lensing And Supernova survey with Hubble (CLASH, GO-12068; PI: M. Postman, Postman et al. 2012), the Hubble Frontier Fields (HFF, DD/GO-13504; PI: J. Lotz), the FrontierSN program (GO-13790; PI: S. Rodney), and the SN Refsdal Follow-up program (DD/GO-14041; PI: P. Kelly). We generated difference images by subtracting these template images directly from the search epoch images, without applying any smoothing algorithm (Alard & Lupton 1998), owing to the excellent stability of the HST point spread function (PSF).

To measure the SN flux from the difference images, we used the PythonPhot27 software package (Jones et al. 2015), which employs a PSF-fitting photometry procedure based on the DAOPHOT algorithm (Stetson 1987). We measure photometric uncertainties by planting and recovering 1000 fake stars (copies of the model PSF) in the vicinity of the SN position.

3. RESULTS

In Figure 1 we present the F125W and F160W images taken on 11 December 2015 that show a new image of SN Refsdal in its redshift $z = 1.49$ host galaxy. The location of this image SX in J2000 coordinates is R.A. = 11:49:36.02, Decl. = +22:23:48.102.28 This locates SX at 6.2″ North and 3.9″ East of image S1. Table 1 reports the measured fluxes and uncertainties. The upper limits are measured from the recovery of fake stars. We measure an F125W - F160W color of 0.2±0.3 for image SX, which is consistent with that reported for of S1–S4 at discovery.

Figure 2 shows simultaneous constraints on the time delay and magnification ratio between image S1 discovered in 2014, and the newly discovered image SX, and comparisons with model predictions from several teams reported by Treu et al.2015a,2015b, and independent predictions by Jauzac et al. 2015. In Figure 3, we show a comparison between the coordinates of the new image SX and several published model predictions, which shows a good agreement.

4. DISCUSSION

Lensed SN provide a powerful means to test the accuracy of the lens models of the foreground deflector, or to provide additional input constraints (e.g. Riess et al. 2011). Previous tests have been based on SN that are magnified but not multiply imaged (Patel et al. 2014b; Nordin et al. 2014). Recently, Rodney et al. 2015 discovered a Type Ia SN magnified by a factor of $\sim 2\times$ by a galaxy-cluster potential, and found that its calibrated luminosity was in tension with some – but not all – models of the cluster potential.

With SN Refsdal we have for the first time been able to test predictions for both the lensing time delay as well as the magnification. This is important because the time delay depends on the difference in gravitational potential, while magnification depends on a combination of second derivatives, and therefore the two observables test different aspects of the potential. In principle, time delays are much less sensitive than magnification ratios to milli and microlensing and should therefore be more robustly predicted.

It is important to keep in mind that all of these tests are local, and thus a larger sample is needed to assess the global goodness-of-fit of every model. Nevertheless, these tests are an extremely valuable probe of systematics. In fact, as discussed by Treu et al. 2015a, the uncertainties reported by modelers do not include all sources of systematic errors. For example, systematic uncertainties arising from unmodeled milli-lensing, residual mass-sheet degeneracy, and multiplane lensing, are very difficult to calculate and are thus not included. The lensed-supernova tests provide estimates of the amplitude of the unknown uncertainties. Other known sources of errors are not included either. For example, a 3% uncertainty on the Hubble constant (Riess et al. 2011) implies a 3% uncertainty on time delays, i.e. approximately 10 days for a year-long delay. Furthermore the uncertainties are typically highly non-Gaussian so that the 95% confidence interval is not simply twice as wide as the 68% one.

5. CONCLUSIONS

We have detected the reappearance of SN Refsdal in a different multiple image of its host galaxy from the one where the event was originally discovered in 2014. Keeping in mind the caveats given in the previous section, we can reach two major conclusions. First, SN Refsdal

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### Table 1

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</table>

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26 http://drizzlepac.stsci.edu
27 https://github.com/djones1040/PythonPhot
28 The coordinates are registered to the astrometric system used for the CLASH, GLASS, and HFF images and catalogs http://www.stsci.edu/hst/campaigns/frontier-fields/
Figure 1. Coadded WFC3-IR $F125W$ and $F160W$ exposures of the MACS J1149.5+2223 galaxy-cluster field taken with HST. Top panel shows images taken on 11 December 2015 which reveal the new image SX of SN Refsdal. The middle panel shows images taken on 20 April 2015 where the four images forming the Einstein cross are close to maximum brightness, but no flux is evident at the position of SX. Bottom panel shows images acquired in 2011 without images of the SN.
Figure 2. Simultaneous constraints on the relative time delay between S1 and SX from the measured magnitude of SX. The two-dimensional contours show the 68% and 95% confidence levels, while the model predictions plot 68% confidence levels. The $F160W$ (approximately rest-frame $R$) light curve of SN Refsdal is reasonably well-matched by that of a slowly evolving SN similar to 1987A (Kelly et al., in prep.). We use separate second-order polynomial fits to the $F125W$ and $F160W$ light curves of image S1 of SN Refsdal as models for the light curves of SX to compute joint constraints on the time delay and the magnification ratio between S1 and SX, for comparison with model predictions. Except for the Jauzac et al. (2015) prediction, labels refer to models presented in Treu et al. (2015a). While all other plotted predictions were made in advance of the HST Cycle 23 observations in Fall 2015, ‘Zitrin-c’ is a post-blind prediction that supercedes the ‘Zitrin-g’ model; in this model the lens galaxy was left to be freely weighted to reassure its critical curves pass between the four Einstein-cross images. We note that many of the lensing predictions are not Gaussian distributed, and 68% limits do not imply that are necessarily inconsistent with the measurements. The greater the S1-SX delay, the earlier we currently are in the light curve of SX. The black dashed line marks the delay beyond which we lack data on the light curve of SN Refsdal. Our model for the light curve at earlier epochs is an extension of the second-order polynomial.
Figure 3. Comparison between the position of image SX and published predictions. Coordinates are overplotted on the combined F125W and F160W difference image from the 11 December 2015 and template imaging acquired in 2011. The Jauzac et al. (2015) and Grillo et al. (2015) positions both agree within the rms scatter reported between input and best-fit positions in each paper. An uncertainty was not available for the Diego et al. (2015) prediction and we show an annulus with a 0.6′′ radius.

Indeed reappeared approximately as predicted, implying that the unknown systematic uncertainties are not substantially larger than the random uncertainties, at least for some models. This is a remarkable and powerful validation of the model predictions specifically and of general relativity indirectly. The second conclusion is that already this first detection provides some discriminatory power: not all models fare equally well. Grillo-g, Oguri-g, Oguri-a, and Sharon-a appear to be the ones that match the observations most closely. In general most models seem to predict a slightly higher magnification ratio than observed, or shorter delays. A detailed statistical analysis of the agreement between the model predictions and the observations will have to wait for the actual measurement of the magnification and time delays, which will require analysis of the full light curve past its peak during 2016.

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