Multiple images of a highly magnified supernova formed by an early-type cluster galaxy lens

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In 1964,Refsdal hypothesized that a supernova whose light traversed multiple paths around a strong gravitational lens could be used to measure the rate of cosmic expansion. We report the discovery of such a system. In Hubble Space Telescope imaging, we have found four images of a single supernova forming an Einstein cross configuration around a redshift \( z = 0.54 \) elliptical galaxy in the MACS J1149.6+2223 cluster. The cluster's gravitational potential also creates multiple images of the \( z = 1.49 \) spiral supernova host galaxy, and a future appearance of the supernova elsewhere in the cluster field is expected. The magnifications and staggered arrivals of the supernova images probe the cosmic expansion rate, as well as the distribution of matter in the galaxy and cluster lenses. After the discovery of the SBS 0957+561 A/B system 26 years ago (8), a handful of quasi-stellar objects (quasars) multiplied by an intervening galaxy lens have been identified (9). Quasars strongly lensed by clusters are even more rare events, with only several known (10). The use of lensed quasars as robust probes of the distribution of matter in the lenses and of cosmology has only become possible relatively recently, given the long time periods of monitoring needed to match their complex light curves (6, 11–13). In contrast, all SNe have much simpler light curves and evolve comparatively rapidly, which makes the measurement of time delays and magnification among the multiple images substantially more straightforward.

It was recently shown that a different SN, PS1-10afx (14) at redshift \( z = 1.38 \), was strongly magnified (by a factor of \( \sim 30 \)) by an intervening galaxy at \( z = 1.12 \) (15, 16). The available imaging, taken from the ground, had insufficient angular resolution to separate potential multiple images of the SN, so time delays and magnifications could not be measured. In the case presented here, the four images of the SN are clearly resolved (Fig. 1), with an image separation of over 2″, thereby presenting an ideal opportunity to carry out for the first time an experimental similar to that suggested byRefsdal (1), leading us to name the supernova “Refsdal.”

The Grism Lens-Amplified Survey from Space (GLASS) program (GO-10459), principal investiga-
tor (PI) T.T.J. is a 140-orbit Hubble Space Telescope (HST) project that is acquiring near-infrared grism spectra of massive galaxy clusters with the primary goals of studying faint high-redshift \( (z \geq 6) \) galaxies (17) and spatially resolved intermediate-redshift galaxies (18), as well as characterizing the cluster galaxy population. Wide-band near-infrared F105W and F140W exposures are taken using the Wide Field Camera 3 (WFC3) to align and calibrate the grism data, and we have been searching these images for transient sources. In the F140W GLASS images acquired on 10 November 2014, we detected the component images of a quadruple lens system, which we label sources S1 to S4 (Fig. 1). Table 1 gives the coordinates of the variable sources. In Fig. 2, the color-composite image shows the red galaxy lens at \( z = 0.54 \) (19) surrounded by an Einstein ring formed by light from the distorted spiral host galaxy with \( z = 1.49 \) (20), whose nucleus is offset by \(-3.3″\) from the center of the lensing elliptical galaxy. Although sources S1 and S2 do not exhibit a significant change in their fluxes during the imaging taken from 3 to 20 November 2014, the light curve of S3 is consistent with a rise in brightness during this period, which corresponds to approximately a week in the rest frame (Fig. 3; see also fig. S1). The light curve of S4 is difficult to characterize with the currently available data, because it is comparatively faint.

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Several epochs of registered and coadded F140W images of MACS J1149.6+2223, acquired across multiple WFC3 F105W, F110W, F140W, and F160W images of the cluster lens. A search for a source is not an active galactic nucleus (AGN), whose light curves typically vary at the level of a few tenths of a magnitude over several-month time scales (22–24). Finally, the positions of the multiple images also constrain the redshift of the source to 1.1 to 1.7 with 95% confidence, consistent with the $z = 1.49$ redshift of the spiral galaxy lensed into the observed configuration (fig. S2).

The four images of SN Refsdal form an Einstein cross configuration around the massive elliptical galaxy at $z = 0.54$, which adds onto and locally perturbs the cluster potential. Because the elliptical galaxy is located close to the critical lines of the cluster lens (25), the contribution of the galaxy cluster to the gravitational potential needs to be taken into account. As a first, simple approximation of the lensing system, we construct a single isothermal ellipsoid embedded in a strong external shear (26). This yields times delays on the order of several to tens of days. S1 is generally the leading image, typically followed by S2, S3, and then S4. Magnifications are $\sim 2$ for the least magnified image S4 and $\sim 10$ for the other images. These magnifications, however, do not include the additional contribution from the cluster, which is expected to be very substantial, especially because earlier modeling has found a relatively flat, nearly convergent central mass distribution, which is evident from the relatively undistorted shape of the magnified spiral images (25).

To account more completely for the effects of the cluster potential, we have constructed a detailed set of lens models of the entire cluster potential, including the elliptical galaxy, for several different prior probability distributions and sets of constraints. These models, which are also constrained by the positions of the SN images, generally yield magnifications of $\sim 10$ to $30$ at the positions of the four images, and times delays on the order of days to months, in agreement with independent models (27, 28). The typical arrival sequence is consistent with the predictions of the simpler galaxy-lens model (S1, S2, and then either S3 or S4), although some models also predict different arrival orders. These time delays are also in accord with our identification of the four newly detected sources as a multiply imaged SN, because the luminosity of a SN is not expected to vary dramatically over the time scale of less than a week in the rest frame. The spiral host galaxy itself is multiply imaged by the galaxy cluster (20, 25). Consequently, our models predict both that the SN could be detected at future
epochs in a different image of the spiral host galaxy and that it has already appeared elsewhere in yet another image of the spiral. A search of archival HST imaging in both the optical (F606W, F814W, and F850LP) and infrared (F105W, F125W, F140W, and F160W) at the locations of the multiple images of the presumed host galaxy has revealed no evidence for SN Refsdal when these data were taken. Our set of cluster lens models predicts that the SN will appear in the central image of the spiral host galaxy, at an approximate position of \(a = 11^\text{h}49^\text{m}36.01^\text{s}, \delta = +22^\circ23'48.13''\) (J2000.0) at a future time, within a year to a decade from now (2015 to 2025). This is in broad agreement with independent model predictions (27, 28). The uncertainties highlight the power of a time-delay measurement to constrain lens models.

The archival HST imaging and the configuration show that this is a multiply imaged SN. This discovery demonstrates in principle the feasibility of the experiment suggested five decades ago by Refsdal (1), consisting of using the time delays between the multiple images of the SN to constrain the foreground mass distribution and eventually the geometry and content of the universe.
The fastest unbound star in our Galaxy ejected by a thermonuclear supernova

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Hypervelocity stars (HVSs) travel with velocities so high that they exceed the escape velocity of the Galaxy. Several acceleration mechanisms have been discussed. Only one HVS (US 708, HVS 2) is a compact helium star. Here we present a spectroscopic imaging through the FrontierSN program supported by NASA through Hubble Fellowship grant HST–GF–53120.1 awarded by STScI, which is operated by the Association of Universities for Research in Astronomy for NASA under contract NAS 5–26555. Follow-up imaging through the FrontierSN program is supported by NASA through HST grant GO–13386. A.F.V.’s group at the University of California Berkeley has received generous financial assistance from the Christopher R. Redlich Fund, the TABASGO Foundation, Gary and Cynthia Bender, and NSF grant AST–221356. The Dark Cosmology Centre is funded by the Danish National Research Foundation. Support for A.Z. was provided by NASA through Hubble Fellowship grant HST–GF–53120.1 awarded by STScI. SN research at Rutgers University is supported in part by NSF CAREER award AST–0847517 to S.W.I. J.C.M. is supported by NSF grant AST–1313448 and by NASA HST grants GO–13343 and GO–13386; this research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. R.G. acknowledges the Centre National d’Etudes Spatiales for financial support on the GLASS project. Some of the data presented here 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 NASA; the observatory was made possible by the generous financial support of the W. M. Keck Foundation. The HST imaging data used in this paper can be obtained from the Barbara A. Mikulski Archive for Space Telescopes at https://archive.stsci.edu, and the Keck–I IRIS spectra can be obtained at http://hercules.berkeley.edu/database.

SUPPLEMENTARY MATERIALS

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Materials and Methods

Figs. S1 to S4

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References (S–Z)

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STELLAR DYNAMICS

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Hypervelocity stars (HVSs) travel with velocities so high that they exceed the escape velocity of the Galaxy. Several acceleration mechanisms have been discussed. Only one HVS (US 708, HVS 2) is a compact helium star. Here we present a spectroscopic and kinematic analysis of US 708. Traveling with a velocity of ~1200 kilometers per second, it is the fastest unbound star in our Galaxy. In reconstructing its trajectory, the Galactic center becomes very unlikely an origin, which is hardly consistent with the most favored ejection mechanism for the other HVSs. Furthermore, we detected that US 708 is a fast rotator. According to our binary evolution model, it was spun-up by tidal interaction in a close binary and is likely to be the ejected donor remnant of a thermonuclear supernova.

According to the widely accepted theory for the acceleration of hypervelocity stars (HVSs) (1–3), a close binary is disrupted by the supermassive black hole (SMBH) in the center of our Galaxy, and one component is ejected as a HVS (4). In an alternative scenario, US 708 was proposed to be ejected from an ultracompact binary star by a thermonuclear supernova type Ia (SN Ia) (5). However, previous observational evidence was insufficient to put firm constraints on its past evolution. Here we show that US 708 is the fastest unbound star in our Galaxy, provide evidence for the SN ejecta scenario, and identify a progenitor population of SN Ia.

In contrast to all other known HVSs, US 708 has been classified as a hot subdwarf star [subdwarf O- or B-type (sdO/B) star]. Those stars are evolutionarily advanced, core helium-burning objects with low masses around 0.5 times the mass of the Sun (M⊙). About half of the sdB stars reside in close binaries with periods ranging from ~0.1 to ~30 days (6, 7). The hot subdwarf is regarded as the core of a former red giant star that has been stripped of almost all of its hydrogen envelope through interaction with a close companion star (8, 9). However, single hot subdwarf stars like US 708 are known as well. Even in this case, binary evolution has been proposed, as the merger of two helium white dwarfs (He-WDs) is a possible formation channel for those objects (10).

The hot subdwarf nature of US708 poses a particular challenge for theories that aim to explain the acceleration of HVSs. Within the slingshot scenario proposed by Hills, a binary consisting of two main-sequence stars is disrupted by the close encounter with the SMBH in the center of our Galaxy. While one of the components remains in a bound orbit around the black hole, the other one is ejected with high velocity (4). This scenario explains the existence of the so-called S-stars orbiting the SMBH in the Galactic center and provides the most convincing evidence for the existence of this black hole (11). It is also consistent with the main properties of the known HVS population consisting of young main-sequence stars (2, 11). However, more detailed analyses of some young HVSs challenge the Galactic center origin (4), and most recently, a new population of old main-sequence stars likely to be HVSs has been discovered. Most of those objects are also unlikely to originate from the Galactic center, but the acceleration mechanism remains unclear (12).

In the case of the helium-rich sdO (He-sdO) US 708, the situation is even more complicated. In contrast to all other known HVSs, which are main-sequence stars of different ages, this star is in the phase of shell helium burning, which lasts for only a few tens of millions of years. More importantly, it has been formed by close binary interaction. To accelerate a close binary star to such high velocity, the slingshot mechanism requires either a binary black hole (13) or the close encounter of a hierarchical triple system, where the distant component becomes bound to the black hole and the two close components are ejected (17). Similar constraints apply to the dynamical ejection out of a dense cluster, which is the second main scenario discussed to explain the HVSs.

Close binary requires specific modifications of the canonical HVS scenarios. However, it is a necessary ingredient for an alternative scenario, in which US 708 is explained as the ejected donor

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