CONFIRMATION OF HOSTLESS TYPE Ia SUPERNOVAE USING HUBBLE SPACE TELESCOPE IMAGING

M. L. GRAHAM, D. J. SAND, D. ZARITSKY, AND C. J. PRITCHET

1 Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA
2 Physics Department, Texas Tech University, Lubbock, TX 79409, USA
3 Steward Observatory, University of Arizona, Tucson, AZ 85721, USA
4 Department of Physics and Astronomy, University of Victoria, P.O. Box 3055, STN CSC, Victoria, BC V8W 3P6, Canada

Received 2015 April 27; accepted 2015 May 13; published 2015 July 2

ABSTRACT

We present deep Hubble Space Telescope imaging at the locations of four, potentially hostless, long-faded Type Ia supernovae (SNe Ia) in low-redshift, rich galaxy clusters that were identified in the Multi-Epoch Nearby Cluster Survey. Assuming a steep faint-end slope for the galaxy cluster luminosity function ($\alpha_d = -1.5$), our data include all but $\lesssim 0.2\%$ of the stellar mass in cluster galaxies (0.005% with $\alpha_d = -1.0$), a factor of 10 better than our ground-based imaging. Two of the four SNe Ia still have no possible host galaxy associated with them ($M_R > -9.2$), confirming that their progenitors belong to the intracluster (IC) stellar population. The third SN Ia appears near a faint disk galaxy ($M_V = -12.2$), which has a relatively high probability of being a chance alignment. A faint, red point source coincident with the fourth SN Ia’s explosion position ($M_V = -8.4$) may be either a globular cluster (GC) or a faint dwarf galaxy. We estimate the local surface densities of GCs and dwarfs to show that a GC is more likely, due to the proximity of an elliptical galaxy, but neither can be ruled out. This faint host implies that the SN Ia rate in dwarfs or GCs may be enhanced, but remains within previous observational constraints. We demonstrate that our results do not preclude the use of SNe Ia as bright tracers of IC light at higher redshifts, but that it will be necessary to first refine the constraints on their rate in dwarfs and GCs with deep imaging for a larger sample of low-redshift, apparently hostless SNe Ia.

Key words: galaxies: clusters: general – galaxies: clusters: intracluster medium – supernovae: general

1. INTRODUCTION

Type Ia supernovae (SNe Ia) are the thermonuclear explosions of carbon–oxygen white dwarf (CO WD) stars, commonly used as cosmological standard candles although their progenitor scenario is not yet well understood (e.g., Howell 2011). Most likely, the WD is in a binary system with either another WD or a red giant or main-sequence star, and the explosion occurs after merger with, or sufficient mass accretion from, the companion. The explosion rate of SNe Ia is correlated with galaxy mass and star formation rate, and most of the discovered SNe Ia reside in large galaxies—but since SNe Ia are very bright, they are also used as “cosmic lighthouses” for faint or diffuse astrophysical structures that are difficult to assess directly. The purpose of this work is threefold: (1) to address the utility of SNe Ia as a bright tracer of baryons in rich galaxy clusters, (2) to confirm that SN Ia progenitors include truly old (>2 Gyr) progenitor systems, and (3) to investigate constraints on the SN Ia rate in faint hosts such as dwarf galaxies and globular clusters (GCs). We motivate each of these science goals in turn.

1.1. Baryon Accounting

Understanding the growth of structure in the universe requires a full accounting of baryonic mass, and this must include the population of intracluster (IC) stars that were stripped from their host galaxy and reside in the cluster potential. Direct measurements of this low surface brightness component are possible (e.g., Gonzalez et al. 2005; Zibetti et al. 2005; Montes & Trujillo 2014; DeMaio et al. 2015), but are difficult beyond the local universe due to cosmological surface brightness dimming. Indirect measurements of the fraction of IC light ($f_{ICL}$) can be made using bright tracers of the underlying stellar population such as planetary nebulae and novae, which has been done for the nearby Virgo and Fornax clusters, respectively (Feldmeier et al. 2004; Neill et al. 2005). At higher redshifts a brighter tracer is required, and $f_{ICL}$ can instead be calculated by comparing the number of SNe Ia hosted by cluster galaxies with the number that appear hostless and belong to the IC stellar population.

This was first done with the Wise Observatory Optical Transients Search (WOOTS) by Gal-Yam et al. (2003), who found that two of their seven SNe Ia in rich, low-redshift galaxy clusters appeared to be hostless, which implied that $f_{ICL} \approx 20\%$. A similar measurement was made with the Sloan Digital Sky Survey (SDSS) by McGee & Balogh (2010), who found that 19 of the 59 SNe Ia in low-redshift galaxy groups appeared to be hostless, which implied that $f_{ICL} \approx 50\%$ for smaller-scale structures (galaxy groups have a total mass ~10% that of rich clusters). Most recently, the Multi-Epoch Nearby Cluster Survey (MENeaCS) from the Canada–France–Hawaii Telescope (CFHT) identified four apparently hostless SNe Ia in low-redshift massive galaxy clusters (Sand et al. 2011), which implied that $f_{ICL} = 0.16^{+0.13}_{-0.09}$.

This usefulness of SNe Ia as tracers of the intracluster light (ICL) depends on their being truly hostless. Stacked imaging from the past surveys left 0.03%–0.3% (WOOTS), 3% (SDSS), and 0.05%–0.1% (MENeaCS) of the stellar mass in cluster galaxies below the detection thresholds. These values are dependent on the logarithmic faint-end slope of the luminosity function, $\alpha_d$ (i.e., the Schechter function). The above results are based on $\alpha_d = -1.0$, which is true for field galaxies (Blanton et al. 2003), but $\alpha_d$ may be higher in rich galaxy clusters (e.g., Milne et al. 2007). Adopting $\alpha_d = -1.5$ as an upper limit, the MENeaCS survey estimated that $\lesssim 2\%$ of the stellar mass in dwarf cluster galaxies is below detection thresholds. If the SNIa occurrence rate per unit mass is
equivalent in all cluster stellar populations—detected galaxies (~82%), undetected dwarf galaxies (≤2%), and IC stars (~16%)—then for MENeACs we expect to find that ≤2% of all the discovered cluster SNe Ia (23) are hosted by faint dwarf galaxies (~0.5 SNe Ia). In this work we use deep \( HST \) imaging at the locations of the four MENeACS IC SNe Ia to further lower the fraction of undetected mass in faint galaxies to 0.2% (0.003%–0.007% with \( \alpha_d = -1.0 \)), analyze previously undetected objects in the vicinity of two SNe Ia, and discuss how our results affect the ability of IC SNe Ia to measure \( f_{\text{ICl}} \) at higher redshifts.

1.2. SN Ia Delay Times

One path toward understanding the progenitor scenario of SNe Ia is to constrain the range of possible ages via the SN Ia delay time distribution (DTD: the time between star formation and explosion). While Type II and Ib/c SNe—core collapse massive stars—are associated with young stellar populations, SNe Ia occur with an explosion rate proportional to both galaxy stellar mass and star formation rate (e.g., Mannucci et al. 2005; Scannapieco & Bildsten 2005; Sullivan et al. 2006). This indicates that SNe Ia are associated with both old and young stellar populations. The current best measurements of the SN Ia DTD indicate that some SN Ia progenitors are quite old, >2 Gyr (e.g., Maoz et al. 2014), which implies long-lived progenitors and/or that the timescales for mass transfer or merger are long.

The conclusion that at least some SNe Ia require progenitors that are >2 Gyr old relies on the SN Ia rate in rich cluster galaxies, where the majority of the stellar population is old (e.g., Sand et al. 2012). However, there is evidence that low levels of star formation are present in elliptical galaxies (e.g., Yi et al. 2005; Suh et al. 2011; Graham et al. 2012). Could it be that all SNe Ia are actually from younger stellar populations? Probably not—for example, Graham et al. (2012) show that the SN Ia DTD result is robust to this small amount of young stars. Even so, direct confirmation of an SN Ia progenitor in a stellar population of purely old stars would strengthen and support the late-time DTD constraints on the progenitor scenario.

A suitable environment for this test is the population of IC stars in rich galaxy clusters: the colors and luminosities of IC stars in Virgo show that the IC stellar population is composed of stars ≥2 Gyr old (Durrell et al. 2002), and theoretical models also suggest that the IC is composed of old stars (e.g., Sommer-Larsen et al. 2005; Purcell et al. 2007). All of the apparently hostless cluster SNe Ia discovered to date are of Type Ia: a lack of IC core-collapse SNe lends credence to the idea that the IC is composed of an older stellar population. In this work, we use deep \( HST \) imaging to show that at least two of the apparently hostless SNe Ia discovered by MENeACs truly belong to the IC stellar population of old stars.

1.3. SN Ia Rates in Faint Hosts

Over the past 10 years, an increasing number of SN surveys have employed an unbiased, wide-field search strategy instead of targeting massive galaxies. This has lead to the discovery that some types of luminous SNe have a higher explosion rate in dwarf hosts (e.g., Lunnan et al. 2014; Neill et al. 2011), attributed to high star formation rates providing more progenitor stars and/or lower metallicity leading to more luminous SNe, or perhaps an elevated rate of binary star formation. As most SNe Ia occur in massive galaxies, it is difficult to assess whether they might also have an enhanced rate in dwarf galaxies because of the large statistical uncertainty on the rate due to the relatively low number of SNe Ia in low-mass hosts (e.g., Quimby et al. 2012). SN surveys of rich galaxy clusters are an efficient way to search many low-mass galaxies at once, owing to both a higher sky density of galaxies and the (putative) upturn in the faint-end slope of the cluster luminosity function (e.g., Milne et al. 2007; Yamanoi et al. 2007). In this work we find that one IC SN Ia may be hosted by a dwarf cluster galaxy, and we discuss the implications of this for SN Ia rates in faint hosts.

GCs are another potential very faint host for IC SNe Ia. No SN has ever been confirmed to be hosted by a GC, although they are theoretically predicted to have an SN Ia occurrence rate 1–10× that of elliptical galaxies owing to dynamical interactions that lead to more WDs in binary systems in GCs (e.g., Ivanova et al. 2006; Shara & Hurley 2006; Pfahl et al. 2009). Non-detections of GCs at the sites of ~45 low-redshift SNe Ia in archival \( HST \) images have constrained the potential rate enhancement to ~42× the rate in elliptical galaxies (Voss & Nelemans 2012; Washabaugh & Bregman 2013). In this work we find that one IC SN Ia may be hosted by a GC, and we discuss the implications of this for SN Ia rates in GCs. Since GCs are also composed mainly of old (5–13 Gyr) stellar populations, confirming a GC-hosted SN Ia would also meet our science goal of confirming SNe Ia with long (>2 Gyr) delay times.

1.4. Paper Overview

In this work, we use the \( Hubble \) Space Telescope (\( HST \)) Advanced Camera for Surveys (ACS) to obtain deep images in filters F606W and F814W at the locations of four apparently hostless SNe Ia from MENeACs (Sand et al. 2011). These are the deepest images, and the largest single survey sample, of IC SN Ia locations in rich clusters ever obtained and analyzed in this way. In Section 2 we present our original CFHT and new \( HST \) observations and discuss our image processing and photometric calibrations. In Section 3 we analyze our deep stacks of \( HST \) ACS imaging: we characterize the faint sources in the vicinity of the SNe Ia, derive our point-source limiting magnitudes, and determine the amount of cluster stellar luminosity remaining below our detection thresholds. In Section 4 we discuss the implications of these results with respect to SN Ia progenitor ages, the rates of SNe Ia in faint cluster objects, and the future use of SNe Ia as tracers of the ICL. We conclude in Section 5. All dates are given in UT, and a standard flat cosmology of \( \Omega_M = 0.3, \Omega_L = 0.7 \) is assumed throughout.

2. OBSERVATIONS

Here we describe our past observations with the MegaCam imager (Boulade et al. 2003) at the CFHT and our new deep imaging taken 4–5 yr later with the \( HST \) ACS (Holland et al. 1998).

2.1. CFHT MENeACS

The MENeACs monitored 57 low-redshift (0.05 < z < 0.15) massive galaxy clusters from 2008 to 2010 with the MegaCam instrument at the CFHT. A total of 23 cluster SNe Ia (Sand et al. 2012) and 7 cluster SNe II (Graham et al. 2012) were discovered. The survey strategy, spectroscopic follow-up,
Table 1

| MENeaCS Identifier | SN Coordinates | BCG Offset (kpc) | Redshift (SNID) | Spectral Type | CFHT Detection Limit | f (L<min) |
|--------------------|----------------|------------------|-----------------|--------------|----------------------|-------------|
| Abell1650_9_13_0   | 12:59:01.33, -01:45:51.68 | 468              | 0.0836          | Ia-norm      | -12.47, -13.04       | 0.0172      |
| Abell2495_5_13_0   | 22:50:26.33, +10:54:41.70 | 148              | 0.0796          | Ia-norm      | -11.72, -12.37       | 0.0127      |
| Abell399_3_14_0    | 02:57:26.41, +12:58:07.63 | 616              | 0.0613          | Ia-norm      | -12.54, -12.56       | 0.0138      |
| Abell85_6_08_0     | 00:42:02.39, -09:26:58.00 | 595              | 0.0617          | Ia-91bg      | -11.15, -11.68       | 0.0091      |

Note.
^ From Table 1 in Sand et al. (2011).

Table 2

| MENeaCS Identifier | Orbits | Observation Date (UT) | Exposure Time (s) | HST Detection Limits (mag) | f (L<min) |
|--------------------|--------|-----------------------|-------------------|-----------------------------|------------|
|                    |        |                       | F606W             | F814W                       |            |
|                    |        |                       |                   |                             |            |
| Abell1650_9_13_0   | 5      | 2013 Jan 25           | 3870              | 28.58, 28.88                | -9.7       | 0.0029      |
| Abell2495_5_13_0   | 4      | 2013 Oct 04           | 2984              | 28.64, 28.90                | -9.8       | 0.0026      |
| Abell399_3_14_0    | 2      | 2013 Dec 04           | 1800              | 28.30, 28.45                | -10.1      | 0.0035      |
| Abell85_6_08_0     | 1      | 2013 Sep 18           | 1800              | …, 28.40                    | …, -9.2    | 0.0020      |
|                   | 1      | 2014 Sep 05           | …                 | …                           | …, 28.49   | …           |

2.2. HST ACS Imaging

To assess whether these four apparently hostless SNe Ia truly belonged to the IC stellar population, we used the HST ACS to obtain deep images at their locations. We waited until >3 yr after peak brightness to obtain these images to avoid contamination from the SN itself (this is discussed in Section 3.5). To either rule out or classify a faint object at the SN position, we required an image that offers both sensitivity and high resolution. Although the Wide Field Camera 3 (WFC3) has slightly better resolution, we chose the ACS for its higher throughput and increased sensitivity beyond 4000 Å because most objects in galaxy clusters are red. At our target position on the CCD we selected aperture “WFC” because amplifier “B” on WFC1 has the lowest read noise. We restricted our telescope orientations to avoid possible stellar diffraction spikes coming near our target coordinates. Because a photometric color is necessary to classify a detected object, we used two wide filters: F606W (V band) and F814W (I band). We divided our integration times into multiple exposures to remove cosmic rays and used small dithers to mitigate the effect of hot pixels, and we were able to obtain all observations of a given cluster in a single visit. We provide a summary of our HST observations in Table 2.

To make the deepest possible stacks of our HST+ACS data, we use the Astrodizzle software to median-combine images provided by that STScI pipeline (Gonzaga et al. 2012); we use the “FLC” images which have been reduced, drizzled, and corrected for charge transfer efficiency. We use the STScI pipeline’s World Coordinate System (WCS) astrometry. We do this for the F606W and F814W images separately to make a deep stack for each filter that is free of cosmic rays, and then we also create a single sum-combine image for the deepest possible stack.

2.3. HST ACS Photometric Calibrations

To obtain the apparent magnitude of a source, m_p, where f represents filter F606W or F814W, we start with the raw magnitude, m_p, for which we use MAG_AUTO from Source Extractor (Bertin & Arnouts 1996). We add a small point-spread function (PSF) correction for point sources, derived from the simulated sources used for the limiting magnitudes (∼0.1; see Section 3.1). This is not usually necessary with MAG_AUTO, but we find that it is required for the non-Gaussian PSF of the HST ACS (the Tiny Tim PSF: Krist et al. 2011). We also apply the zero point, z_f = -2.5 log P_f - 21.1, where P_f is the PHOTFLAM header keyword, representing the flux of a source with constant F_0 that produces a count rate of 1 electron per second (P_f has units of erg cm^2 s^{-1} Å^{-1}). For our images, z_{F606W} = 26.66 mag and z_{F814W} = 26.78 mag. To transform from the natural system and obtain the apparent magnitude, m_p, where F is the Johnson V or Cousins I filters, we use this equation from Sirianni et al.
Table 3

Photometric Transformations

| Natural Filter | Target Filter | \( C_0 \) | \( C_1 \) | \( C_2 \) | TCOL |
|----------------|---------------|----------|----------|----------|------|
| F606W Johnson V | 26.394 | 0.153 | 0.096 | <0.4 |
| F606W Johnson V | 26.331 | 0.340 | -0.038 | >0.4 |
| F814W Cousins I | 25.489 | 0.041 | -0.093 | <0.1 |
| F814W Cousins I | 25.496 | -0.014 | 0.015 | >0.1 |

\[
m_F = m_{F,raw} + C_{0,F} + (C_{1,F} \times \text{TCOL}) + (C_{2,F} \times \text{TCOL}^2)
\]

(1)

where TCOL is the color in the targeted system; in our case TCOL = \( m_V - m_I \). We use the synthetic coefficient values from Sirianni et al. (2005; see their Table 22), as listed in our Table 3.

3. ANALYSIS

In this section we analyze our deep HST ACS images at the locations of our four IC SNe Ia from MENeaCS. We determine our limiting point-source magnitudes in Section 3.1, and we derive the fraction of cluster luminosity remaining below our detection thresholds in Section 3.2. We present and characterize any objects found near the SN Ia coordinates in each cluster in Section 3.3, quantify the likelihood that detected objects are the result of a chance alignment in Section 3.4, and rule out the possibility of observing the evolved companion star or lingering SN Ia emission in Section 3.5.

3.1. Point-source Limiting Magnitudes

In order to determine the limiting magnitude of our images, we plant 5000 fake stars in each of our stacked F606W and F814W images. These fake stars have apparent magnitudes 26.0 < \( m < 30.0 \), with more stars at fainter magnitudes, and an appropriate PSF from the Tiny Tim model PSF generator (Krist et al. 2011). We ensure that simulated stars are only planted in regions of low surface brightness in order to mimic the locations of our IC SNe Ia. We run Source Extractor on the images with the simulated population of point sources; the relevant detection parameters are given in Table 4. We visually verify that these parameters are returning all and only real sources in the images. In Figure 1 we plot our detection efficiency (i.e., the fraction of objects recovered) as a function of apparent magnitude for the F606W and F814W images of each cluster. The “limiting magnitude” is defined as the magnitude at which the detection efficiency drops to 50%, and it is given for each cluster and filter in the plot legend of Figure 1.

In Section 3.3 below, we visually identify objects below the official limiting point-source magnitude at the locations of our SNe Ia in Abell 2495 and Abell 399. We find that these objects are only detected by Source Extractor if the threshold is lowered to 1\( \sigma \), which also detects many peaks in the background noise and produces a source catalog with large uncertainties in their apparent magnitude. This is why our official limiting magnitude—which needs to be robust because we use it to determine the fraction of cluster stellar luminosity below our detection thresholds in Section 3.2—is slightly brighter than some of the sources discussed in Section 3.3. The caveat here is that brighter, but more extended, objects may fall below our detection threshold also—but most of the faint cluster objects will be point-like (dwarf galaxies and GCs).

3.2. Fraction of Undetected Cluster Light

To determine the fraction of cluster light remaining below our point-source limiting magnitudes, we follow a similar method to that presented by Sand et al. (2011) for our CFHT deep-stack images, the result of which is reproduced in the last column of Table 1.

The absolute R-band luminosity function for the nearby Virgo cluster is modeled by Trentham & Tully (2002) with two components, a Gaussian for the bright end and a Schechter function (see their Equation (2)):

\[
N(M) = N_* e^{-(M-M_s)}/(2\sigma)^2 + N_d \left(10^{0.4(M-M_d)}\right)^{\alpha_d+1} e^{-10^{0.4(M-M_d)}},
\]

(2)

where \( N(M) \) is the number density of galaxies per square Mpc per magnitude bin, \( M \) is the R-band absolute magnitude, and \( N_* = 17.6, M_s = -19.5, \sigma = 1.6, N_d = 3 N_*, M_d = -18.0, \) and \( \alpha_d = -1.03 \). However, the faint-end slope is known to steepen with redshift (e.g., Khochfar et al. 2007), and values down to \( \alpha_d \approx -1.5 \) have been measured for the Coma cluster.

![Figure 1. Detection efficiencies for simulated point sources in our HST ACS images, as described in the text (Section 3.1). Filter and cluster are represented by color and symbol, respectively, as shown in the plot legend. The magnitude at which our detection efficiency falls to 50% is considered our limiting magnitude.](image-url)
The Astrophysical Journal, 807:83 (13pp), 2015 July 1

Graham et al.

Figure 2. Co-registered CFHT (left) and HST (right) images for the SN Ia in Abell 1650.

(Milne et al. 2007) and most recently for Abell 85 ($\alpha_d \approx -1.6$; Agulli et al. 2014). In order to make a robust upper limit on the amount of cluster light below our detection efficiencies, we use $\alpha_d = -1.5$ from here on.

In Sand et al. (2012) the total $r'$-band luminosity is calculated for all MENeACS clusters. We convert this to $R$ band using the conversion factors from Blanton & Roweis (2007), $R = r - 0.0576 - 0.3718[(r - i) - 0.2589]$. Because most of the cluster light is from old stellar populations, we use the typical SDSS color of elliptical galaxies, $r - i \sim 0.4$, from Eisenstein et al. (2001). We integrate the galaxy luminosity function down to the CFHT point-source limiting magnitudes listed in Table 1 from Sand et al. (2011) and then normalize to the total $R$-band luminosity for each cluster.

We convert the absolute $R$-band luminosity function for each cluster into apparent $V$ and $I$ band using the cluster’s redshift, the elliptical galaxy template spectrum from Kinney et al. (1996), and the line-of-sight Galactic extinction for each cluster: $A_V, A_{I,1650} = 0.047, A_{V, A399} = 0.211, A_{V, A399} = 0.467, A_{V, A85} = 0.103, A_{I, 1650} = 0.026, A_{I, A2495} = 0.116, A_{I, A399} = 0.256$, and $A_{I, A85} = 0.057$ (Schlafly & Finkbeiner 2011; Schlegel et al. 1998). We convert the $V$- and $I$-band luminosity function into the HST ACS natural system filters using the transformations of Sirianni et al. (2005), as described in Section 2.3. In Table 1, we report the point-source detection limit in absolute $M_R$ magnitudes and the fraction of the cluster’s $R$-band stellar luminosity remaining below this limit. For all clusters we find that $<0.2\%$ of the stellar mass in cluster galaxies remains below our official point-source limiting magnitude. This result is discussed further in Section 4.

3.3. Potential Hosts in the Deep HST ACS Images

We use the IRAF tasks GEOMAP and GEOTRAN to co-register our CFHT images to the new, deeper HST ACS images. In Figures 2–5 we show the results, side by side, for comparison. The CFHT images are composed of two 120 s $r'$ exposures and contain the SN Ia—we do not use our SN-free deep stacks here, because we need the SN’s coordinates in the co-registered frames. The HST images are our deepest stacks, the sum-combined F606W and F814W filtered images. Green circles mark the position of the SN in each image, with a radius equal to $3\times$ the positional uncertainty of the SN Ia. These positional uncertainties, listed in Table 5, are a combination of Source Extractor’s uncertainty in the PSF centroid for the SN in the co-registered CFHT image (using windowed output parameters) and the error in GEOMAP’s transformation between images. The dashed cyan lines enclose nearby objects (sizes chosen to guide the eye). Image information such as the cluster name, UT date of acquisition, filters, scale bar, and compass is shown in yellow along the bottom. These images all have a $30'' \times 30''$ field of view.

As in Sand et al. (2011), we use the dimensionless parameter $R$ to identify whether nearby objects could be considered as potential hosts of the SNe Ia. This parameter is defined in the Source Extractor manual as

$$R^2 = C_{xx} x_r^2 + C_{yy} y_r^2 + C_{xy} x_r y_r$$

(3)

where $C_{xx}$, $C_{yy}$, and $C_{xy}$ are object ellipse parameters, $x_r = x_{SN} - x_{gal}$ and $y_r = y_{SN} - y_{gal}$, and $R > 3$ describes the isophotal limit of the galaxy (see also Sullivan et al. 2006). An SN is typically only classified as “hostless” if $R > 5$, but depending on the surface brightness profile of the galaxy, a significant amount of the stellar mass may reside beyond this radius (e.g., $\geq 10\%$ for the potential host of the SN in Abell 399, as determined in Sand et al. 2011).

3.3.1. Abell 1650

In Figure 2, we see that the location of the SN Ia is truly devoid of objects. We ran Source Extractor with very relaxed parameters and still recovered no sources in this area. Of the three nearby objects enclosed by dashed circles in Figure 2, the
SN location is $R \gtrsim 15$ away. Our IC SN Ia in Abell 1650 therefore appears to be truly hostless.

### 3.3.2. Abell 2495

In Figure 3 we see several sources near the location of the SN Ia that were not apparent in the CFHT deep stacks presented in Sand et al. (2011), but none are within the positional uncertainty of the SN Ia. We ran Source Extractor with very relaxed parameters and still recovered no sources within the positional uncertainty. In Figure 6 we show this region in detail and identify nearby sources A, B, C, and D. Sources A and B are unlikely to be physically associated, as the SN Ia is $R \sim 17$ away from them. We discuss objects C and D in turn.

Object C is likely a part of object D, which is clumpy and extended, as shown by the contour plot in the right panel of Figure 6. However, object C is identified by Source Extractor as an independent source at the 1σ level in the F814W image, with $m_{F814W} = 29.0 \pm 0.2$ mag. In the F606W image it is not officially detected by Source Extractor, but it is just visible to the eye, and with aperture photometry we estimate it to be $m_{F606W} = 29.8 \pm 0.2$ mag. In both filters, object C falls below our 50% detection efficiency for Abell 2495 (see Figure 1 in
that object D is \( m_V \approx 25.6 \) mag and \( m_I \approx 24.5 \) mag. We apply the distance modulus of Abell 2495 (\( \mu \approx 37.8 \) mag) and find that intrinsically object D is \( M_V \approx -12.2 \) mag and \( M_I \approx -13.3 \) mag. This is brighter than the limiting magnitudes quoted for the CFHT deep stack of Abell 2495, but those limits are for point-like sources and object D is extended—in fact, it is just barely visible as an extended source in Figure 3 of Sand et al. (2011).

Object D is clumpy and has an ellipticity of 0.7, which is higher than the ellipticity of the bright red sequence galaxies we identify in Abell 2495. Morphologically, object D resembles an inclined disk galaxy—can we use the disk scale length to assess whether it may be a blue spiral galaxy at higher redshift? Disk galaxies are generally well fit by an exponential function for the flux intensity as a function of radius, \( I(R) = \phi_0 e^{-R/R_d} \), where \( R_d \) is the characteristic disk scale length. We estimate \( R_d \lesssim 0.4 \) kpc, with no attempt to de-project or account for inclination. If object D is a cluster member, this corresponds to \( R_d \approx 0.6 \) kpc, which is roughly appropriate for a disk galaxy. In Section 3.4 we also discuss the relatively large probability that this is a chance alignment, but formally we cannot exclude the possibility that object D is a cluster member and the host of the SN in Abell 2495.

### 3.3.3. Abell 399

In Figure 4 we see a large elliptical galaxy near the location of the SN Ia. Sand et al. (2011) describe how the SN is \( \sim 7R \) from the large elliptical, and how the SN’s and galaxy’s line-of-sight velocities differ by \( 3\sigma \), indicating that they are not associated. We use these \( HST \) images to re-evaluate the parameter \( R \) from Equation (3), which describes the SN’s offset in terms of the galaxy’s isophotes. We find that \( R \sim 6 \) in both F606W and F814W, re-establishing the SN as independent of the stellar population of this large neighbor galaxy.

In Figure 4 we see a small, faint source at the center of the green circle marking the SN Ia’s position, labeled object F in Figure 8. Object F is detected with low significance, but with
coincidence in both the F606W and F814W images. It is a point-like source, with an FWHM of \( \sim 3 \) pixels, and is offset by \(<1\) pixel from the SN Ia location. Object F is therefore very likely to be physically associated with the SN Ia in Abell 399—the small probability of a chance alignment with a foreground star or background host is discussed in Section 3.4. In Figure 8 we also label the next-nearest object E; it is a clumpy extended source, but we find it far less likely to be physically associated with the SN, and so we focus our attention on object F.

Object F is \( m_{F606W} = 28.7 \pm 0.3 \) mag and \( m_{F814W} = 28.7 \pm 0.2 \) mag, below our limiting magnitudes as shown in Figure 1. Its photometry is consistent with a red sequence galaxy in Abell 399, which is very similar to the red sequence shown for Abell 2495 in Figure 7. We use Sirianni et al. (2005) to convert this photometry into the Landolt filter system and find that object F is \( m_V \approx 28.8 \) mag and \( m_I \approx 27.4 \) mag. We apply the distance modulus of Abell 399 (\( m \approx 37.2 \) mag) and find that intrinsically object F is \( M_V \approx -8.4 \) mag and \( M_I \approx -9.8 \) mag and has a color of \( V - I \approx 1.4 \). This is also well matched to the expected magnitude and color of a bright GC: the luminosity function for GCs is a Gaussian that peaks at \( M_I \approx -7.4 \) and has \( \sigma \approx 1.2 \),
and GC colors span the range $M_V - M_I \approx 0.7 - 1.5$ (e.g., West et al. 2011). Although GCs have been found distributed between galaxies in rich clusters (e.g., Peng et al. 2011; West et al. 2011), their density drops with clustercentric radius, and we would not expect a significant number of IC GCs at the location of this SN Ia, 616 kpc from the BCG. However, the presence of the nearby elliptical galaxy (Figure 4) makes the GC hypothesis more likely.

In Section 4.1, we show that the SN Ia rate enhancements in dwarf galaxies or GCs implied by the nature of object F are within all existing theoretical and observational limits. If we assume that the rate per unit mass of SNe Ia is not much larger in dwarf galaxies versus GCs (or vice versa)—which would put a strong prior on the nature of object F—we can estimate the expected surface densities of dwarf red sequence galaxies and red GCs at this location in order to assess which is more probable. Based on our extrapolation of the cluster luminosity function for Abell 399 (Section 3.2), we estimate there to be $\sim 1.5 \times 10^9 L_\odot$ in dwarf cluster galaxies at $M_V > -10$ mag. That is about 100–500 dwarf galaxies of $(5-10) \times 10^8 L_\odot$ within a clustercentric radius of $\sim 1$ Mpc, or $(1-5) \times 10^{-4}$ dwarfs kpc$^{-2}$. This would apply at any location in the cluster, and so it applies for the location of object F. To assess whether satellites of the nearby elliptical galaxy might raise the predicted surface density at this location, we use the radial distribution of low-redshift, low-mass satellite galaxies presented by Prescott et al. (2011; see their Figure 5). The location of the SN in Abell 399 is $R \approx 10$ kpc from the center of the nearby elliptical; at this radius Prescott et al. (2011) find that the surface density of satellites is $\sim 7 \times 10^{-6}$ kpc$^{-2}$. The caveat here is that they consider only isolated primary galaxies, and so their results represent an upper limit on the radial distribution we could expect in rich clusters. However, as this is much lower than what we expect from the cluster luminosity function, we conclude that object F is unlikely to be a satellite galaxy of the nearby elliptical.

We can estimate the surface density of GC from the nearby elliptical galaxy (Figure 4), which has absolute magnitudes of $M_V \approx -19.5$ mag and $M_I \approx -20.7$ mag and a stellar mass of $\sim 7.6 \times 10^9 M_\odot$ (Bell et al. 2003). A galaxy of this stellar mass has between 10 and 100 GCs within $R < 50$ kpc, and the surface density radial distribution for GCs is $N(r) = N_0 r^{-2.4}$ GC kpc$^{-2}$ (Zaritsky et al. 2015); $\sim 75\%$ of the GCs are internal to 10 kpc (the distance of the SN in Abell 399 from the nearby elliptical). Normalizing the radial distribution to a total of 10–100 GCs gives $N \approx 0.3 - 3 \times 10^{-2}$ GC kpc$^{-2}$. Based on the GC luminosity function of West et al. (2011), $\sim 84\%$ of all GCs are below our limiting magnitudes, and so the observable surface density at 10 kpc is lowered to $0.5 - 5 \times 10^{-3}$ GC kpc$^{-2}$. This is higher than our estimated surface density for cluster dwarf galaxies, suggesting that it is more likely to see a GC at the location of object F than a cluster dwarf. However, as our lower limit for the GC surface density is equal to our upper limit on the dwarf galaxy surface density, the estimates are not significantly different enough to make a robust claim regarding the nature of object F. The caveat here is that we have used a radial distribution for all GCs, but the population of red GCs has a significantly shorter radial extent than blue GCs—in fact, for cluster ellipticals the radial distribution of red GCs appears to be truncated near the effective radius of the parent galaxy (e.g., Brodie & Strader 2006).

In summary, we find that the SN Ia in Abell 399 is likely physically associated with object F. Without any constraints from expected SN Ia rates, we find that object F is less likely to be a dwarf galaxy than a GC from the nearby elliptical. We discuss the probability of chance alignments in Section 3.4 and the possibility that object F is lingering emission from the SN Ia in Section 3.5. We discuss the implications of object F for SN Ia rates in dwarf galaxies and GCs, and whether these implications provide a prior on the nature of object F, in Section 4.1 and the impact of object F on using SNe Ia as tracers of the ICL at high redshift in Section 4.2.

### 3.3.4. Abell 85

In Figure 5, we see that the location of the SN Ia appears devoid of objects. For the nearest source, labeled object G in Figure 5, the SN is $R \sim 13$ away. We ran Source Extractor with very relaxed parameters, but found that the few sources detected are consistent with noise peaks (i.e., they were detected at very low significance in F814W only and were not visually confirmed in the F606W+F814W stack). We conclude that the SN Ia in Abell 85 is truly hostless.

### 3.4. Probabilities of Random Line-of-sight Alignments

In our discussion of the nature of object F in Abell 399 we estimated the surface densities of faint cluster objects such as dwarf red sequence galaxies and GCs to be $\sim 5 \times 10^{-4}$ objects per kpc$^2$. The probability of a faint cluster object appearing randomly within the positional uncertainty of our IC SNe Ia is negligible, $\lesssim 0.0003\%$. The presence of object F is not a chance alignment with a cluster object.

We used TRILEGAL (Girardi et al. 2005) to simulate a foreground star population in the directions of our four fields to a limiting magnitude of $m_V = 29$. The probability of a star appearing randomly within $0.5\%$ of our IC SN Ia coordinates is $\lesssim 0.02\%$. We judge that it is extremely unlikely that object F at the location of the SN in Abell 399 is a foreground red star.

We used the Hubble Deep Field catalogs (Williams et al. 1996) to simulate a population of faint objects between $25.0 < m_{F814W} < 29.5$. This is the magnitude range in which we detect sources in our HST images but not our CFHT images. The new sources detected near the SN Ia locations in Abell 2495 and Abell 399 fall in this magnitude range. We find that the probabilities of a faint field object randomly being within $0.5\%$ and $2.5\%$, respectively. In our original work $\sim 2\%$ of the cluster stellar mass in faint dwarf galaxies was below our detection limit (Sand et al. 2011). Assuming that the SN Ia occurrence rate per unit mass is equivalent in all populations (high- and low-mass galaxies, and IC stars), this means that $\sim 2\%$ of all MENeaCS SNe Ia should be hosted by undetected, faint dwarf galaxies ($\sim 0.5$ out of 23 SNe Ia). We now see that this is approximately the same chance as finding a background galaxy within the positional uncertainty. However, object F in Abell 399 is not just within the positional uncertainty, but appears within $0.05\%$ (1 ACS pixel) of the SN location. The probability of random alignment with a background object within $0.05\%$ is just $0.3\%$. On the other hand, if we increase the radius to $1\%$ (i.e., the distance encompassing nearby objects for Abell 2495), the probability of chance alignment increases to $\sim 18\%$.

As a final, alternative estimate we use our own source catalogs for all four HST ACS fields and find that the fraction of our imaged area within $R < 5$ of an object is $\sim 3\%$. While it
remains very unlikely that object F is a chance alignment with the SN Ia in Abell 399 (Figure 8), we cannot say the same for the objects near the SN Ia location in Abell 2495 (Figure 6).

3.5. Limits on the SN Ia and/or Its Companion

A normal SN Ia has faded \(-4\) mag by \(-100\) days after peak brightness. After this time, the decline is set by the decay rate of Co\(^{56}\), and the SN Ia continues to fade at \(-1\) mag per 100 days in \(I\) band and \(-1.3\)–\(-1.5\) mag per 100 days in \(BVR\) (e.g., as seen for normal twin SNe Ia SN 2011fe and SN 2011by; Graham et al. 2015a). For a normal SN Ia such as SN 2011fe, the intrinsic brightness at \(-1000\) days is \(V \approx -5\) mag (e.g., Kerzendorf et al. 2014; Graham et al. 2015b). Most of the flux comes from blue emission features of [Fe II] at <6000 Å (e.g., Taubenberger et al. 2015; Graham et al. 2015b), and the late-time \(V - I\) color of a normal SN Ia is expected to be \(-8\). After \(-1000\) days, the predicted rate of decline for normal SNe Ia is even slower (Seitenzahl et al. 2009), and so \(V \approx -5\) mag is a conservative upper limit on SN Ia brightness after 1000 days.

Overluminous SNe Ia that resemble SN 1991 T have been observed to decline more slowly. For example, SN 1991 T itself was \(V \approx -10\) at \(-600\) days (Cappellaro et al. 1997), and SN 2000cx had a \(V\)-band slope of \(-0.65\) mag per 100 days at \(-700\) days after peak brightness (Sollerman et al. 2004), so an SN 1991 T-like event could be \(V \lesssim -7\) at 1000 days. However, none of the MENEaCS SNe Ia were spectroscopically similar to SN 1991 T, and they are furthermore unlikely to belong to this subclass because 91 T-like SNe Ia are associated with younger stellar populations (Howell et al. 2009). Although less is known about the late-time decline of subluminous SNe Ia, SN 1991bg itself was already \(V \approx -6\) by \(-600\) days after peak brightness (Turatto et al. 1996). Our IC SN Ia in Abell 85 was classified as SN 1991bg-like, but no object is detected at its location in the \(HST\) ACS imaging.

Could we detect the emission from a shocked companion star? For normal SNe Ia, theoretical predictions for a non-degenerate companion shocked by the SN Ia ejecta include an increase in temperature and luminosity, up to \(10^3\)–\(10^4\) \(L_\odot\) by 1–10 yr after explosion (Pan et al. 2013; Shappee et al. 2013). Such a companion would be blue and have \(V > -4\) mag, which is well below our limiting magnitudes. A light echo is also likely to be blue, similar to the color of an SN Ia at peak light, and even fainter. In order to formally rule out the possibility that the objects identified near the SN locations in Abell 2495 and Abell 399 are lingering emission from the SN Ia or its binary companion, we discuss each in turn.

**Abell 2495**—In Figure 6 we identify object C as a possible point source near the location of the SN Ia in Abell 2495. The spectrum of this SN Ia was obtained on 2009 June 18.58 UT at Gemini Observatory as part of the MENEaCS follow-up campaign, and we classified it as a normal SN Ia at \(\sim +3\) months after peak brightness. At the time of our \(HST\) ACS images obtained on 2013 October 04, the SN Ia would be \(+1569\) days old (4.3 yr). At this time, object C is \(m_{F606W} = 29.8 \pm 0.2\) mag and \(m_{F814W} = 29.0 \pm 0.2\) mag, or \(m_V \approx 30.0\) mag and \(m_I \approx 27.8\) mag, in our \(HST\) ACS imaging. We apply the distance modulus of Abell 2495 (\(\mu \approx 37.8\) mag) and find that intrinsically object C is \(M_V \approx -7.8\) mag and \(M_I \approx -10.0\) mag. This is both significantly brighter and redder than a normal SN Ia is predicted to be at \(-4\) yr. We conclude that object C is unlikely to be the SN Ia or an evolved companion star.

**Abell 399**—In Figure 8 we identify object F as a point source at the location of the SN Ia in Abell 399. The classification spectrum of this SN Ia, obtained on 2008 November 28.49 UT at Gemini Observatory as part of the MENEaCS follow-up campaign, showed it to be a normal SN Ia at \(\sim +2\) weeks after peak brightness. In our \(HST\) ACS images obtained on 2013 December 04, the SN Ia would be \(+1832\) days old (5 years). This object is \(M_V \approx -8.4\) mag and \(M_I \approx -9.8\) mag and has a color of \(V - I \approx 1.4\), both significantly brighter and redder than a normal SN Ia is predicted to be at extremely late times. We conclude that object F is unlikely to be the SN Ia or an evolved companion star.

4. DISCUSSION

Our analysis of the \(HST\) ACS images at the locations of our four IC MENEaCS SNe Ia has shown that one is hosted by either a dwarf red sequence galaxy or red GC (Abell 399), one is potentially associated with a nearby spiral or irregular galaxy consistent with the red sequence but also has a relatively high probability of being a chance alignment (Abell 2495), and two appear to be truly hostless (Abell 1650 and Abell 85). We discuss the implications of our results for the rates of SNe Ia in faint cluster hosts in Section 4.1 and for the use of SNe Ia as tracers of the ICL in Section 4.2.

4.1. Implications for SN Ia Rates in Clusters

In Section 3 we found that the SN Ia in Abell 399 was likely hosted by the faint object F, and that this source is consistent with being either a cluster dwarf galaxy or a GC. Here we consider the implications of both scenarios on the rate of SNe Ia in dwarf galaxies and GCs, and whether established SN Ia rates (or limits) in these populations can constrain the physical nature of object F.

4.1.1. Dwarf Galaxies

If object F in Abell 399 is a dwarf galaxy, does this imply a significantly enhanced SN Ia rate in faint cluster galaxies? The rate per unit mass in a population, \(R_\star\), is expressed by \(R_\star = C \times N(M)/M\), where \(C\) is a detection efficiency, \(N\) is the number of SNe Ia, and \(M\) is the mass in the population. As described in Sand et al. (2011), our original CFHT deep stacks left \(\lesssim 2\%\) of the mass in faint cluster galaxies undetected, but we now believe that that population has hosted one SN Ia. We can estimate the implied relative rate per unit mass in the faintest 2% of cluster galaxies with the following equation:

\[
R_{\%} = \frac{C_{\%} \times N_{\%}/M_{\%}}{C \times N/M}.
\]

Sand et al. (2011) describes how a small difference in MENEaCS detection efficiencies between hosted and hostless SNe Ia is introduced by two effects: (1) it is more difficult to detect transients on top of a host galaxy (even with difference imaging techniques), and (2) the spectroscopic follow-up coverage for the hostless population was slightly more extensive than for the hosted SNe (they were run under separate proposals). Together, this difference works out to be \(C_{\%} = 1.2C\). Sand et al. (2012) present that the number of
SNe Ia hosted by all cluster galaxies within 1 Mpc is $N = 11$, and so with $N_{25} = 1$ we find that $R_{25}/R \approx 5.5$. Repeating this calculation using only red sequence cluster galaxies yields a similar rate enhancement because the number of SNe Ia in red sequence members within 1 Mpc is $N_{RS} = 6$ (i.e., 0.5$N$), the stellar mass in red sequence galaxies is $M_{RS} \sim 0.5M_\odot$, and $C_{RS} = C$.

Ultimately this potential rate enhancement by a factor of $\sim 5$ is quite uncertain, as it is based on just one SN Ia and an indirect estimate of the amount of mass in faint cluster galaxies. As introduced in Sections 1.1 and 3.4, by assuming that the SN Ia rate per stellar mass is equal in all cluster populations, we estimated that the expectation value for the number of MENeaCS SNe Ia in dwarf hosts is $\sim 0.5$. For a more restrictive estimate of the expectation value, we limit to red sequence galaxies within the clustercentric radius of 1 Mpc used above. Assuming that the rate in bright cluster red sequence galaxies ($\sim 50\%$ of the stellar mass hosting $N_{RS} = 6$ SNe Ia) is the same as in dwarf red sequence galaxies ($\sim 2\%$ of the stellar mass), the expectation value is $\sim 0.24$ SNe Ia in dwarf hosts. With Poisson statistics the probability of observing $\geq 1$ SN Ia given this expectation value is 0.16, and the $1\sigma$ uncertainties of our estimated rate enhancement are $5.5_{-4.5}^{+2.7}$ (Gehrels 1986)—consistent with no rate enhancement. Furthermore, if the luminosity function is steeper than expected, there could be more than $2\%$ of the stellar mass residing in such faint red galaxies. We plan to use our deep HST images to constrain the faint-end slope of the cluster luminosity function in later work, but consider it beyond the scope of this paper.

The potential SN Ia rate enhancement by a factor of $\sim 5$ in the faintest dwarf galaxies is not too large to be unphysical, as the SN Ia rate is known to vary by factors of that size (and more) with host galaxy properties such as the specific star formation rate (e.g., Mannucci et al. 2005; Scannapieco & Bildsten 2005; Sullivan et al. 2006; Smith et al. 2012). This potential rate enhancement is also not so large that we expect to have already observed it in wide-field sky surveys such as SDSS. For example, Smith et al. (2012) find that the SN Ia rate per unit mass decreases as a function of host stellar mass, but their lowest stellar mass bin is $\sim 5 \times 10^8 M_\odot$ and the uncertainty on its rate is a factor of $\sim 2$–3. Furthermore, they mention that $\sim 2\%$ of the SNe Ia in their sample have undetected host galaxies. Current and future wide-field surveys such as the Palomar Transient Factory and the Large Synoptic Survey Telescope (LSST) should be able to improve the SN Ia rate in faint dwarf galaxies (e.g., Conroy & Bullock 2015).

4.1.2. Globular Clusters

If object F in Abell 399 is a GC, it would be the first confirmed GC to host an SN Ia. As GCs are purely old stellar populations ($> 2$ Gyr), such an association would also be direct confirmation that SN Ia progenitors include truly old star systems. The fraction of galaxy stellar mass in GC systems is $\sim 2 \times 10^{-3}$ for elliptical galaxies (Peng et al. 2008; Harris et al. 2009; Zaritsky et al. 2015). Based on this and the total stellar mass in red sequence galaxies in MENeaCS clusters, we estimate that $\geq 10^{12} M_\odot$ in GCs has been surveyed by MENeaCS. If object F is a GC and has produced an SN Ia, it implies a rate $\sim 25$ times higher than the rate in our cluster red sequence galaxies from Sand et al. (2012). This is on a similar scale to theoretically predicted enhancements due to dynamical interactions in the dense stellar environments of GCs (Pfahl et al. 2009) and below the current limits placed by non-detections of GCs at the locations of SNe Ia in archival HST images ($\lesssim 42 \times$; Voss & Nelemans 2012; Washabaugh & Bregman 2013).

Would such an enhanced rate in GCs have already been noticed? Potentially not. It would imply that $\lesssim 5\%$ of the SNe Ia in ellipticals are hosted by their GCs, but as we discussed in Section 3.3.3, the radial distribution of GCs follows the galaxy light profile and drops off at $\sim 5R$. It is entirely conceivable that GC-hosted SNe have simply been assigned as belonging to the parent galaxy. This might lead to a relative rate enhancement in the outer regions of ellipticals, which could be measured and attributed to GCs. However, such an effect would be difficult to confidently measure for two reasons. First, there is a detection bias of SNe being easier to find when they are not embedded deep in the host galaxy. Second, a stellar population originating in GCs—able to produce an enhanced rate of SN Ia—may have previously released into the halos (or bulges) of galaxies from GCs owing to collisions with clouds or other GCs, winds from SNe in the GCs, tidal forces for GCs on elliptical orbits about their host, evaporation of stars during internal GC relaxation, and/or dynamical friction (Fall & Rees 1985). It is conceivable that these issues combined could conspire to blur the signal of an SN Ia rate enhancement in GCs in the radial distribution of SNe Ia.

4.1.3. Rate Summary

We find that the implied SN Ia rate enhancements in either dwarf galaxies or GCs do not conflict with existing observations or theoretical predictions, but they also do not provide a means to constrain the nature of object F. Additionally, if either of the two SNe Ia in Abell 1650 and Abell 85—which appear hostless in our deep HST images—were in fact hosted by the $\sim 0.2\%$ of the stellar mass in small galaxies that remains below our limiting magnitudes, then by Equation (4) this indicates a rate enhancement by a factor of $\sim 55$ in the faintest dwarf galaxies. This is conspicuously high and would have been noticed in wide-field surveys. We therefore conclude that these two SNe Ia were truly hosted by the population of IC stars stripped from their host galaxy and residing in the cluster’s gravitational potential.

4.2. Implications for IC SNe Ia as Tracers of the ICL

Sand et al. (2011) reported that of the 23 cluster SNe Ia discovered by MENeaCS, 4 had no apparent host galaxy in deep CFHT images that left just $\sim 2\%$ of the total cluster stellar mass in undetected faint galaxies. With our deep HST imaging we find that 1 out of the 23 cluster SNe Ia, $\sim 4\%$, is hosted by a faint point source (object F in Abell 399). Finding $\sim 4\%$ of the SNe Ia hosted by $\sim 2\%$ of the stellar mass is not surprising, but here we take a closer look at how $f_{ICL}$ is derived in order to confirm the utility of SNe Ia as tracers of the ICL at higher redshift.

The fraction of IC light, $f_{ICL}$, is calculated by dividing the number of hostless SNe Ia by the total number of cluster SNe Ia (hosted+hostless) discovered by MENeaCS (Sand et al. 2011). To do this, the detection efficiencies must be equal for hosted and hostless SNe Ia; in other words, a survey must apply the same discovery and spectroscopic classification constraints to both populations, or be able to account for any bias in the
pipeline. This was true for all MENeCS SNe Ia except the IC SN in Abell 2495, which was preferentially observed with Gemini spectroscopy despite being fainter than the magnitude limit applied to follow-up of MENeCS SNe. For this reason, the hostless SN in Abell 2495 was not included in the calculation of the fraction of IC stellar mass in Sand et al. (2011). In order to combine only the same physical regions of each cluster, they limit to a radius \( < R_{200} \) (i.e., the virial radius); all four apparently hostless SNe Ia are within \( R_{200} \). Using the remaining three apparently hostless SNe Ia as IC, and the 13 host SNe Ia within \( R_{200} \), Sand et al. (2011) measure \( f_{\text{ICL}} = 0.16_{-0.09}^{+0.13} \).

Given the proximity of the SN Ia in Abell 399 to a large nearby galaxy (see Section 3.3.3), they also repeat this calculation assuming that this SN Ia was hosted, and find \( f_{\text{ICL}} = 0.11_{-0.07}^{+0.12} \). In light of the faint object F at the location of the SN Ia in Abell 399, we can now say that the latter is the more accurate measurement of \( f_{\text{ICL}} \). Although this distinction may not seem significant because the difference between these two \( f_{\text{ICL}} \) measurements is within their relatively large statistical errors, future facilities such as the LSST will generate bigger sample sizes and have smaller uncertainties, and a better understanding of the fraction of apparently hostless SNe Ia will be needed in this regime. LSST itself will be able to provide this because its deep stack images have a projected detection limit of \( r \sim 27.5 \) mag.5

Until then, we can only caution that future surveys will have to consider that 25%–30% of apparently hostless SNe Ia might not belong to the IC stellar population. Is that too large for hostless SNe Ia to be scientifically useful tracers of \( f_{\text{ICL}} \) at higher redshifts? Some numerical simulations indicate that \( f_{\text{ICL}} \) grows with cosmological time and by \( z \sim 0 \) is \( \sim 2 \times \) larger than at \( z \sim 0.4 \) (e.g., Murante et al. 2007); others find that most IC stars are stripped at \( z > 1 \), in which case \( f_{\text{ICL}} \) would remain constant since then (Puchwein et al. 2010). Direct measurements of this low surface brightness component have shown that \( f_{\text{ICL}} \lesssim 25% \) at \( z \lesssim 0.1 \) and \( \sim 10% \) at \( z \sim 0.2 \) (e.g., Zibetti et al. 2005; Gonzalez et al. 2007), but \( HST \) imaging of \( 0.4 < z < 0.8 \) clusters has found no evolution in \( f_{\text{ICL}} \) since \( z < 0.8 \) (Guennou et al. 2012). We therefore surmise that assessments of \( f_{\text{ICL}} \) from SNe Ia will require uncertainties of \( <30% \) in order to compare with some theoretical models and the direct surface brightness measurements. This sounds discouraging, but there is hope: below, we suggest that the best way to improve this uncertainty and use hostless SNe Ia as high-redshift ICL tracers is to constrain the SN Ia occurrence rate in faint hosts.

Dwarf galaxies represent a small fraction of the total cluster stellar mass, which is constrained by measurements of the galaxy luminosity function. If their SN Ia occurrence rate is equal to that in elliptical galaxies, then measurements of \( f_{\text{ICL}} \) can account for the contamination from apparently hostless SNe Ia in dwarf hosts. However, in the preceding section we show that if object F is a cluster dwarf, the SN Ia occurrence rate in the faintest \( \sim 2% \) of cluster galaxies could be up to \( \sim 5 \times \) higher than in elliptical galaxies. If confirmed, the number of SNe Ia in faint dwarfs could be up to half of all apparently hostless SNe Ia.

Compared to dwarf galaxies, GCs represent an even smaller fraction \( (\lesssim 0.002) \) of the total stellar mass in clusters—much less than the fraction of IC stars \( (\sim 0.16) \). If their SN Ia occurrence rate is equal to that in elliptical galaxies, accidentally including the very few SNe Ia in GCs at large radial offsets from their host as part of the ICL will have a negligible effect on measurements of \( f_{\text{ICL}} \). (Most SNe Ia in GCs will be associated with elliptical galaxies, because GCs have a radial distribution similar to that of stars.) On the other hand, if the SN Ia occurrence rate in GCs is \( 25 \times \) that in elliptical galaxies—as implied if object F is a GC—then up to \( \sim 5% \) of all cluster SNe Ia, and up to \( \sim 30% \) of the apparently hostless cluster SNe Ia, may actually be associated with GCs.

In this work we have shown that \( \sim 75% \) of all apparently hostless SNe Ia are truly IC, and that contamination is only a significant problem if the SN Ia occurrence rate in low-mass galaxies or GCs is enhanced. This issue can be resolved by SN Ia rate analyses from low-redshift, wide-field surveys such as the Palomar Transient Factory, SDSS, or LSST, combined with deep imaging for a larger sample of low-redshift apparently hostless SNe Ia. Such an effort should sufficiently constrain the SN Ia rate in dwarfs and GCs such that extremely deep imaging will not be required to confirm all apparently hostless cluster SNe Ia, and facilitate their use as tracers of the ICL to higher redshifts.

5. CONCLUSION

We have presented deep \( HST+\text{ACS} \) images at the locations of four IC SNe Ia in rich galaxy clusters, obtained \( >3 \) yr after explosion. This is the largest single-survey sample of IC SNe Ia in rich clusters, and these data are the deepest images ever obtained at the locations of IC SNe Ia, lowering the amount of stellar mass left undetected in cluster galaxies from \( \sim 2% \) to just \( \sim 0.2% \) \( (\lesssim 0.005% \) if we assume a shallow faint-end slope for the galaxy luminosity function, \( \alpha_d = -1.0 \)). We have confirmed that the two SNe Ia in Abell 1650 and Abell 85 are hostless and truly belong to the IC stellar population of stars stripped from their host galaxy and residing in the cluster potential. This indicates that at least some SN Ia progenitors have truly old progenitor stars \( (>2 \) Gyr). We could not rule out that the SN Ia in Abell 2495 was hosted by a nearby disk galaxy that has a magnitude, color, and size consistent with cluster membership, but we also found a relatively high probability that this is a random association. We have shown that the SN Ia in Abell 399 was very likely hosted by a faint, red point-like source that has a magnitude and color consistent with both dwarf red sequence galaxies and red GCs. Our statistical analysis of the expected surface densities has shown that a dwarf galaxy is less likely at that location than a GC, due to the presence of a nearby elliptical galaxy. We have demonstrated that the rate enhancements in dwarfs or GCs implied by this new faint host are plausible under current observational constraints, and we do not reject either hypothesis. We have also explicitly ruled out the possibility that we could observe extremely late-time emission from the SNe Ia themselves or a possible shocked companion.

Our discovery of a faint host galaxy for one of the four SNe Ia that appeared to be hostless is a potential problem for measuring the evolution in the fraction of IC light across cosmic time, because \( f_{\text{ICL}} \) will need to have uncertainties \( <25% \) in order to distinguish between models or compare with independent measurements. For this reason we argue that hostless SNe Ia in rich clusters should be used to measure \( f_{\text{ICL}} \) with caution, and that it would be best if deep imaging for a

http://lsst.org/lsst/science/science_portfolio
