A POPULATION OF INTERGALACTIC SUPERNOVAE IN GALAXY CLUSTERS

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ABSTRACT

We have discovered seven cluster supernovae (SNe) of Type Ia in the course of the Wise Observatory Optical Transients Search in the fields of 0.06 < z < 0.2 galaxy clusters. Two of these events, SN 1998fc in Abell 403 (z = 0.10) and SN 2001al in Abell 2122/4 (z = 0.066), have no obvious hosts. Both events appear projected on the halos of the central cD galaxies but have velocity offsets of 750–2000 km s⁻¹ relative to those galaxies, suggesting they are not bound to them. We use deep Keck imaging of the locations of the two SNe to put upper limits on the luminosities of possible dwarf hosts, \( M_R > -14 \) mag for SN 1998fc and \( M_R > -11.8 \) mag for SN 2001al. The fractions of the cluster luminosities in dwarf galaxies fainter than our limits are less than \( 3 \times 10^{-3} \) and less than \( 3 \times 10^{-4} \), respectively. Thus, 2/7 of the SNe would be associated with \( \leq 3 \times 10^{-3} \) of the luminosity attributed to galaxies. We argue, instead, that the progenitors of both events were probably members of a diffuse population of intergalactic stars recently detected in local clusters via planetary nebulae and red giants. Considering the higher detectability of hostless SNe compared with normal SNe, we estimate that \( 20^{+20}_{-12} (20^{+35}_{-15}) \) percent at the 68% (95%) confidence level of the SN Ia parent stellar population in clusters is intergalactic. This fraction is consistent with other measurements of the intergalactic stellar population and implies that the process that produces intergalactic stars (e.g., tidal disruption of cluster dwarfs) does not disrupt or enhance significantly the SN Ia formation mechanism. Hostless SNe are potentially powerful tracers of the formation of the intergalactic stellar population out to high redshift.

Key words: galaxies: clusters: general — galaxies: clusters: individual (Abell 403, Abell 2122, Abell 2124) — supernovae: general — supernovae: individual (SN 1998fc, SN 2001al)

1. INTRODUCTION

The existence of a diffuse population of intergalactic stars in galaxy clusters was first discussed by Zwicky (1951), who claimed to measure excess starlight between the galaxies in the core of the Coma Cluster. This early result was later debated (e.g., Welch & Sastry 1971; Melnick, Hoessel, & White 1977) and was finally confirmed by recent deep CCD-based surveys (e.g., Feldmeier et al. 2002). The diffuse intergalactic population in the Coma Cluster is also manifest in large, low surface brightness arcs, similar to those observed, are also seen in other nearby clusters (Caldéron-Redón et al. 2000).

Individual intergalactic red giant (RG) stars have been detected with the Hubble Space Telescope (HST) in the Virgo Cluster (Ferguson, Tanvir, & von Hippel 1998; Durrell et al. 2002). Ground-based observations have revealed intergalactic planetary nebulae (PNe) in the Virgo and Fornax Clusters (Arnaboldi et al. 1996; Theuns & Warren 1997; Mendez et al. 1997; Ciardullo et al. 1998; Feldmeier, Ciardullo, & Jacoby 1998). Although some of the initial candidate PNe turned out to be distant background objects (Kudritzki et al. 2000), the majority of the discovered objects are indeed intergalactic PNe (Ciardullo et al. 2002). Typically these studies find that 10%–20% of the stars in galaxy clusters are in the diffuse component. Preliminary results suggest that intergalactic globular clusters may also be used as tracers of the intergalactic stellar population (Hilker 2003; Jordan et al. 2003).

The intergalactic population of stars is thought to be the result of the tidal disruption of cluster galaxies, interacting with other cluster members or with the cluster core potential (Richstone & Malumuth 1983; Merritt 1984, 1985). Tidal disruption of cluster galaxies is reproduced in detailed simulations of galaxy clusters (Dubinski, Miyos, & Hernquist 1996; Moore et al. 1996; Korchagin, Tsuchiya, & Miyama 2001). Recent simulations of both rich and poor clusters produce a diffuse population containing about 10% of the stars in the cluster. The spatial distribution of these stars can be approximated by a continuation of the de Vaucouleurs profile of the central cD galaxy out to a distance of ~1 Mpc from the cluster center (Dubinski 1998). Tidal debris arcs, similar to those observed, are also reproduced (Moore et al. 1996). We collectively refer to all the observed stellar components that are not associated with a particular galaxy,
including diffuse intracluster light, tidal debris, and low surface brightness features, as the intergalactic stellar population. We follow Feldmeier et al. (2002) and include the extended envelopes of the central cD galaxies in this category, as it is observationally unclear whether such envelopes are a feature of cD galaxies or a concentration of intergalactic stars that settle at the bottom of the cluster potential wells. Numerical simulations of rich clusters (Dubinski 1999) seem to confirm the notion that extended cD envelopes and intergalactic tidally stripped stars are one and the same.

Type Ia supernovae (SNe Ia) are known to occur in galaxies of all classes and morphologies. It is therefore plausible that such events also occur among the intergalactic stellar population. Indeed, it is widely accepted that SN Ia progenitors are accreting or merging white dwarfs (WDs; see, e.g., Livio 2001 and references therein). The observation of intergalactic RGs and PNe makes it unavoidable that intergalactic WDs exist also, since they are the end products of the RG-PN-WD evolutionary track. The tidal forces presumably responsible for removing these stars from galaxies are orders of magnitude too weak to separate close binaries, so intergalactic WDs should also be able to accrete from or merge with close companions and then explode as SNe Ia.

Bona fide intergalactic SNe have not been confirmed to date. An interesting candidate, SN 1980I in the Virgo Cluster (Smith 1981), is projected on a stellar "bridge" between two nearby galaxies and may be associated with either of these hosts. Several other candidates have been proposed over the years. In a search for SNe in nearby Abell clusters, Reiss et al. (1998) detected two events with no visible host galaxy, SN 1998bt in Abell 1736 (Germany 1998) and SN 1998dy in Abell 3266 (Reiss 1998). A much deeper search in duplicate HST images of distant galaxy clusters (Gal-Yam, Maoz, & Sharon 2002) revealed a possibly hostless SN in Abell 403 (Gal-Yam, Sharon, & Livio 2001 and references therein). The observation of intergalactic tidal wells. Numerical simulations of rich clusters (Dubinski 2002) seem to confirm the notion that extended cD envelopes and intergalactic tidally stripped stars are one and the same.

In this paper, we report the discovery of two likely intergalactic SNe among a sample of seven confirmed cluster SNe. When applicable, we assume a flat universe with a cosmological constant $\Omega_M = 0.7$ and $h = 0.7$, where $h$ is the Hubble constant in units of 100 km s$^{-1}$ Mpc$^{-1}$.

### 2. OBSERVATIONS

The SNe discussed in this work were discovered by the Wise Observatory Optical Transient Search (WOOTS). Full details about the design and results of this program are given elsewhere (Gal-Yam & Maoz 1999a, 2003). Briefly, WOOTS is an imaging survey of a sample of 163 rich galaxy clusters at redshifts $0.06 \leq z \leq 0.2$. The clusters were observed in the years 1998–2001 with the Wise Observatory 1 m telescope. Using unfiltered ("clear") 600 s CCD images, WOOTS was sensitive to SNe with magnitudes $R \approx 21.5$ mag. Transient or variable objects were detected by comparing each new WOOTS frame with older templates by using point-spread function matching and image subtraction. An effort was made to follow up all transient events photometrically (with the Wise 1 m) and spectroscopically (at various larger telescopes). A total of 14 candidate SNe were discovered in cluster fields, 11 of which were spectroscopically confirmed. Seven of the confirmed events were SNe Ia at the redshifts of their respective galaxy clusters. These cluster SNe are listed in Table 1. No obvious hosts are detected in the Wise images of two of the cluster SNe, 1998fc and 2001al.

#### 2.1. SN 1998fc in Abell 403

SN 1998fc was discovered in unfiltered Wise 1 m images of Abell 403, obtained on 1998 December 20 (UT dates are used throughout this paper) and confirmed on subsequent frames obtained on 1999 January 7 and 9 (Fig. 1, top left; typical seeing 2.5). No trace of this SN is evident in prior WOOTS images up to 1998 November 14. Assuming the SN was discovered close to maximum light (see also below), we have used the methods of Poznanski et al. (2002) to calculate the colors of this SN at the time of our observations. Using calibrated CCD observations of this field, kindly supplied by R. Gal and the DPOSS team, we selected stars with similar colors and used them to calculate the transformation between unfiltered flux and Cousins $R$. The measured unfiltered flux translates to $R = 20.5$ mag (see Gal-Yam & Maoz 1999b; Table 1). No hint of an underlying host is seen in the deepest WOOTS images of this field, obtained prior to the explosion of SN 1998fc. Figure 1 shows the neighborhood of SN 1998fc.

| SN    | Cluster  | Redshift | Discovery Date | $R$ Magnitude at Discovery | References |
|-------|----------|----------|----------------|---------------------------|------------|
| 1998fc | Abell 403 | 0.10     | 20 1998 Dec 20 | 20.5                      | 1, 2, 3    |
| 2001al | Abell 2122/4 | 0.07     | 26 2001 Mar 21 | 21.4                      | 4, 5       |
| 1998eu | Abell 125 | 0.18     | 14 1998 Nov 20 | 20.7                      | 1, 6       |
| 1999fg | Abell 1607 | 0.14     | 15 1999 Apr 20 | 20.0                      | 7, 8       |
| 1999ch | Abell 2235 | 0.15     | 13 1999 May 19 | 19.8                      | 7, 9       |
| 1999cl | Abell 1894 | 0.12     | 15 1999 May 20 | 20.4                      | 7, 9       |
| 1999ct | Abell 1697 | 0.18     | 13 1999 Jun 21 | 21.2                      | 10, 11     |

* The magnitudes reported here involve improved subtraction of host galaxy light and therefore supersede our previous results, published in IAU Circulars.

** Putative intergalactic SNe.

[References.— (1) Gal-Yam & Maoz 1999b; (2) Filippenko et al. 1999; (3) Gal-Yam & Maoz 1999c; (4) Gal-Yam & Maoz 2001; (5) Filippenko et al. 2001; (6) Gal-Yam & Maoz 1998; (7) Gal-Yam & Maoz 1999d; (8) Gal-Yam, Maoz, & Guhathakurta 1999a; (9) Gal-Yam, Maoz, & Pogge 1999b; (10) Gal-Yam & Maoz 1999c; (11) Gal-Yam, Maoz, & Guhathakurta 2000.**
We determined the effective radii of galaxies by fitting both the Wise images and additional Keck imaging (see § 2.3 below), having ~2″ seeing for Abell 403 and ~0″5 seeing for Abell 2124/2, with a Sersic (1968) profile by using the galaxy-fitting package GALFIT (Peng et al. 2002). We allowed the Sersic index 1/n to vary, including the cases of a de Vaucouleurs (1948) profile (n = 4) and an exponential disk (n = 1). The effective radius values quoted hereafter are for the best-fitting Sersic indices. The galaxy projected closest to the SN is labeled Galaxy 1. However, since the SN is located 14″8 away from the nucleus of this galaxy, more than six times its effective radius, it is unlikely to be related to it. In fact, the only viable host galaxy of SN 1998fc, considering the effective radii of all nearby objects detected in WOOTS images, is the cD galaxy of Abell 403 (PGC 011298; Patuovel et al. 1989), projected 26″8 from the SN (40 h⁻¹ kpc). We will argue below, however, that the SN and the cD have quite different radial velocities.

A spectrum of SN 1998fc was obtained on 1999 January 14, with the EFOSC spectrograph mounted on the ESO 3.6 m telescope (Gal-Yam & Maoz 1999c). Another spectrum was obtained on 1999 January 20, with the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) mounted on the Keck II 10 m telescope (Filippenko, Leonard, & Riess 1999). The LRIS spectrum, which is of superior quality, was obtained near the parallactic angle, but in view of the low air mass (1.10) during the integration we expect very little atmospheric dispersion (Filippenko 1982). Initial inspection of both spectra showed that the SN is of type Ia, was about one month after maximum, and is at approximately the same redshift as the cluster (Fig. 1, bottom). Again, there are no signs of a host galaxy in the SN spectra.

To investigate more carefully the association of the SN with the cluster and with particular galaxies in the cluster, we have attempted to measure accurately the redshift of the SN. However, there are several complicating factors. First, spectra of SNe Ia at this age consist of broad blended features from which it is difficult to determine an accurate redshift. Second, the ejecta of SNe Ia of a given age have a range of velocities, as estimated from the blueshifted centroids of various absorption lines. In general, the lines become less blueshifted with time, as more slowly expanding gas at inner radii becomes optically thin. Thus, reliably estimating a SN velocity relative to a galaxy requires a good knowledge of the age of the SN and of the scatter in measured SN ejecta velocities for that age. Part of that scatter
will also be due to the orbit of the SN in the potential of the host galaxy.

To establish the plausible range of ages for SN 1998fc at the time the LRIS spectrum was obtained, we have compared its spectral features with those of high signal-to-noise ratio (S/N) spectra of nearby SNe Ia at similar ages, drawn from the spectral archive presented by Poznanski et al. (2002). This comparison and the rest of the analysis described below was done after we divided both new and archival spectra by a second-order polynomial fit to the continuum. This procedure assures that our analysis is not affected by low-frequency distortions in the continuum shape, possibly due to atmospheric dispersion or imperfect spectral response calibration. From this comparison we can establish an age of 21 to 42 days past B-band maximum. Younger or older ages are ruled out by the spectra, as visual inspection reveals strong differences in the relative strengths of the major spectral features. Comparison of the Wise photometry of this event with the light curves of SNe Ia (Riess et al. 1999) raises the lower limit on the age to more than 25 days.

Next, we created a composite spectrum of seven spectra of SNe Ia at 28-42 days past maximum light, drawn from the archive of Poznanski et al. (2002). The individual spectra were first deredshifted according to their host-galaxy redshifts. The composite spectrum was created by forming the mean of all spectra, cross-correlating each individual spectrum against the mean, and shifting the spectrum to zero velocity relative to the mean. A new mean spectrum was then calculated and the process repeated iteratively several times. We cross-correlated each of the original seven spectra of SNe Ia mentioned above with the final template. Among this group of spectra, one can see both the trend of velocity rising with time (i.e., decreasing blueshift) and the scatter in this group of spectra, one can see both the trend of velocity times. We cross-correlated each of the original seven spectra of SNe Ia mentioned above with the final template. Among this group of spectra, one can see both the trend of velocity rising with time (i.e., decreasing blueshift) and the scatter in this group of spectra.

Let us consider the measurement by Shectman (1985) of $z = 0.0996$ for the cD galaxy PGC 011298, the only plausible bright galaxy that could host SN 1998fc. The velocity difference between PGC 011292 and SN 1998fc is $\sim 750$ km s$^{-1}$. Given the mean scatter we have measured above and Shectman’s measurement accuracy (50 km s$^{-1}$), this velocity offset is significant. It suggests that SN 1998fc may not be bound to this galaxy. Note that if the measurement by Shectman (1985) is erroneous and that of Kristian et al. (1978) is correct, the velocity difference is even larger ($\sim 1300$ km s$^{-1}$). Assuming the redshift accuracy given by Sandage, Kristian, & Westphal (1976), $Az = 0.001$, the velocity offset between that galaxy and SN 1998fc will still be significant, and the same conclusion will hold. A confirmation of the redshift of PGC 011298 could further illuminate this issue.

2.2. SN 2001al in Abell 2122/4

SN 2001al was discovered in unfiltered Wise 1 m images of Abell 2122/4 obtained on 2001 March 26 and confirmed on unfiltered and R-band frames obtained on March 28 (Fig. 2, top left; typical seeing $\sim 2''$). From these we measure $R = 21.4$ mag. No trace of this SN is evident in prior WOOTS images, obtained on 2000 August 20 (see Gal-Yam & Maoz 2001; Table 1). A search for possible underlying host galaxies in prior WOOTS images of this field reveals no likely candidates. Figure 2 shows the location of SN 2001al and nearby galaxies. The closest galaxies detected near SN 2001al are marked as Galaxies 1 and 2. The SN is located 8.4 and 8.5 away from the nuclei of these galaxies, which is 40 and 6 times their effective radii, respectively. The cD galaxy of Abell 2122/4, UGC 10012, is projected 112 h$^{-1}$ kpc away from SN 2001al.

Prompt follow-up spectroscopy obtained on 2001 March 29 with LRIS mounted on the Keck 1 10 m telescope (Filippenko, Barth, & Leonard 2001) shows that the SN is of type Ia, several weeks after maximum (Fig. 2, bottom). The spectrum was obtained at low air mass (1.1) near the parallactic angle. Using the same methods as for SN 1998fc, we estimate, based on comparison with our spectral database, that the spectrum was obtained 21 to 33 days after maximum light. Cross-correlation against a template composed of nearby SN Ia spectra that are similar to SN 2001al and are in this age bracket gives a redshift of 0.0723 $\pm 0.0011$. We note, however, that the agreement between the spectrum of SN 2001al and the SN Ia template spectrum is not as good as for SN 1998fc. This may be the result of some problem in the SN 2001al data or a real spectral peculiarity in this SN. This disagreement may affect the accuracy of the redshift determined by cross-correlation. A visual comparison of the LRIS spectrum with redshifted versions of the template allows us to set limits on the allowed range of redshifts for this event, 0.070 $\leq z \leq 0.076$, which is $\sim$ within 1100-2800 km s$^{-1}$ of the redshift of Abell 2122/4 ($z = 0.0661$; Strubble & Rood 1999). As in the case of SN 1998fc, there appears to be a large velocity difference between SN 2001al and the cD galaxy UGC 10012 ($\sim 1700$ km s$^{-1}$). This suggests the SN is not bound to the

$^4$ Abell, Corwin, & Olowin 1989 list two clusters, Abell 2122 and Abell 2124, less than 5' away from the location of SN 2001al. Strubble & Rood 1999 give the same redshift for both clusters ($z = 0.0661$, based on seven and 63 measurements for Abell 2122 and A2124, respectively), which is also the redshift of the cD galaxy UGC 10012. Thus it appears that all available data are best explained by one cluster, at $z = 0.0661$, which we denote by Abell 2122/4, with the cD galaxy UGC 10012 at its center.
2.3. Deep Imaging of the SN Locations

The lack of visible host galaxies in WOOTS imaging suggests that SNe 1998fc and 2001al may be the first examples of intergalactic SNe. However, one must consider the possibility that these SNe reside in faint dwarf galaxies, invisible in our WOOTS images. An illustration is the SN Ia 1999aw, whose faint host has absolute magnitudes $M_B = -12.2$, $M_V = -12.5$, and $M_I = -12.2$ mag (Strolger et al. 2002).

To test for the possible existence of such faint dwarf host galaxies, we undertook deep imaging of the locations of SNe 1998fc and 2001al.

We observed the location of SN 1998fc on 2002 January 18 with LRIS mounted on the Keck I 10 m telescope. Sixteen 60 s frames were obtained in direct imaging mode, with no filter. Observing conditions were poor, with $\lambda 2''$ seeing and imminent fog. Nevertheless, tying the combined 960 s unfiltered image with our calibrated WOOTS frames, we estimate that the limiting magnitude for point sources of the unfiltered LRIS image is equivalent to $R = 24.5$ mag (with $\lambda 2''$ seeing, typical dwarf galaxies at the cluster redshift would be practically unresolved). No object is seen at or near the location of SN 1998fc down to the limiting magnitude of the LRIS image (Fig. 1, top right). This translates to a limit of $M_R > -14$ mag for any possible dwarf hosts.

On 2002 March 11 we observed the location of SN 2001al with ESI (Sheinis et al. 2002) mounted on the Keck II 10 m telescope. Exposures totaling 600 s in $B$, 600 s in $I$, and 200 s in $R$ were obtained under good conditions, with $\lambda 0''7$ seeing. A possible faint source was marginally detected in the $I$-band and $B$-band images. To further check the reality of this source we inspected a deep 8400 s $R$-band image of this field obtained with LRIS in 1997, kindly made available by J. Blakeslee (see Blakeslee & Metzger 1999 for details). This image has a limiting surface brightness of $\lambda 26$ mag arcsec$^{-2}$, and the seeing was $\lambda 0''5$. The possible source detected in our ESI images is resolved in the deeper LRIS $R$-band image into three faint sources, located near the position of SN 2001al (Fig. 2, top right). Tying the LRIS $R$-band photometry with our calibrated WOOTS photometry, we measure $R = 26.0 \pm 0.2$ mag for the brightest of these sources (labeled “Source 1”). At the redshift of SN 2001al...
(\(z = 0.0723\)), we find an absolute magnitude of \(M_R = -11.8\) for this possible host galaxy. Source 1 is \(\sim 1''\) from the location of SN 2001al.

However, at such faint magnitudes, the probability of finding unrelated background sources near any given location is significant. From the deep R-band image, we measure a surface density of 0.02 sources per square arcsecond that are as bright as or brighter than Source 1, in this area. The probability of finding such a source within 1'' of any location is significant, \(P = 0.06\). Nevertheless, in what follows we will explore the consequences of assuming that one of the faint sources is the SN host.

3. DISCUSSION AND CONCLUSIONS

Using deep images of the locations of SNe 1998fc and 2001al we have set upper limits on the luminosity of possible dwarf host galaxies. We now address the question of whether or not these SNe are part of the intergalactic stellar population by considering the galaxy luminosity function in clusters. It is well documented that SN rates are roughly proportional to host-galaxy luminosity (e.g., Tammann 1970; van den Bergh & Tammann 1991). Given the galaxy luminosity function in clusters, one can calculate the fraction of a cluster’s luminosity contained in dwarfs that are fainter than a certain limit and thus estimate the probability that a SN is associated with such faint hosts.

Recently, Trentham & Tully (2002) measured the luminosity function in the Virgo Cluster down to very low absolute magnitudes (\(M_R = -10\) mag). They find that their measurements in the R band are well fitted by a modified Schechter function,

\[
N(M)dM = N_0g e^{-(M-M_d)/\sigma_g}/(2\sigma_g^2) + N_d\left[10^{-0.4(M-M_d)/(\alpha_d+1)}\right]
\times e^{-10^{-0.4(M-M_d)}}dM,
\]

where the contribution of giant galaxies is parameterized by a Gaussian with normalization \(N_g = 17.6\), a characteristic peak magnitude \(M_g = -19.5\) mag, and a dispersion \(\sigma_g = 1.6\) mag. Dwarf galaxies are parameterized by a Schechter function with an exponential cutoff magnitude \(M_d = -18\), normalization \(N_d = 66.88\), and a faint-end slope \(\alpha_d = -1.03\). Integrating this function, we derive the fraction \(f\) of the luminosity contained within dwarf galaxies that are fainter than some minimum luminosity, \(L_{\text{min}}\),

\[
f(< L_{\text{min}}) = \frac{\int_{L_{\text{min}}}^{L_{\text{tot}}} N(L)L\,dL}{L_{\text{tot}}}.
\]

After converting the absolute magnitudes given by Trentham & Tully from \(h = 0.77\), implied by their use of the distances to Virgo galaxies taken from Tonry et al. (2001), to \(h = 0.7\), we find \(f(< L_{\text{min}}) = 0.0024\) and 0.0003 for luminosity values corresponding to limiting absolute magnitudes \(M_R = -14\) and \(M_R = -11.8\) mag, respectively.

Assuming that the Trentham & Tully luminosity function is representative of rich clusters in general (such as the clusters in the WOOTS sample) and that the SN rate per galaxy is proportional to its luminosity, we have performed a Monte Carlo simulation to estimate the probability that two out of seven cluster SNe would be associated with dwarf host galaxies fainter than the limits obtained above. This was done by drawing \(10^4\) ensembles of seven host galaxies with luminosities drawn from the luminosity-weighted distribution function (the integrand in eq. [2]) and counting how many times two or more of the host galaxies were as faint as or fainter than our limits. We find this probability is small, \(\leq 6 \times 10^{-5}\), indicating it is unlikely that the two SNe we have found belong to the stellar population bound to galaxies.

A possible caveat is that it is more difficult to discover SNe within bright host galaxies than SNe in fainter or undetected hosts. The five WOOTS SNe with detected hosts could constitute only a fraction of the true number of SNe associated with bright hosts, while the majority of such events had remained undetected. The true fraction of SNe with very faint hosts would then be smaller and perhaps consistent with the luminosity function analysis above. We have carried out detection efficiency experiments by adding artificial SNe to real WOOTS images, with the SNe distributed in position as the starlight (see Gal-Yam et al. 2002 for more details). We then processed the data like real data and noted the detection efficiency for such normal SNe, relative to hostless SNe that are placed far from any galaxy. Typical values are 0.7 (0.4) for SNe with \(R = 20.5\) (21.5) mag. By taking these values into account, our efficiency-corrected sample contains 10 events, eight in bright hosts and two hostless. We find that the probability for 2/10 of the SNe to reside in undetected dwarfs, calculated as above, is still small, \(\leq 8 \times 10^{-5}\).

The most plausible conclusion is that SNe 1998fc and 2001al are indeed related to the intergalactic stellar population. The two intergalactic SNe imply that 20–25 (20–35) percent at the 68% (95%) confidence level of the stellar population in clusters is intergalactic, after accounting for the relative detection efficiencies between normal and hostless SNe, and binomial statistics.

We are aware of no bias that would favor successful spectroscopic follow-up of either normal or hostless SNe among the 14 SN candidates found by WOOTS in cluster fields. The 2/7 ratio should therefore be representative of the true fraction we would have found with full spectroscopic confirmation. Among the three candidates lacking spectroscopy, all appear to be associated with hosts. Even if there was a bias and all three are cluster SNe Ia, the probability that SNe 1998fc and 2001al have dwarf hosts is still \(\leq 1 \times 10^{-4}\).

The fraction of intergalactic SNe in our sample would then be 20% (2/10), implying that 15+17−9 (15+30−13) percent at the 68% (95%) confidence level of the stellar population in clusters is intergalactic, after accounting for our detection efficiency as above.

A final point we consider is the possible connection between SNe 1998fc and 2001al and the cD galaxies of their host clusters. The main argument suggesting that the progenitors of these events were not associated with the cD galaxies in each case is the large difference in velocity between the measured velocities of the SNe and the value listed for the galaxy in the literature. We note, however, that the discrepant redshifts of PGC 011298 (possibly hosting SN 1998fc) and the slight peculiarities in the spectrum of SN 2001al preclude a definite statement in both cases. It is conceivable that errors in the published redshifts of the cD galaxies have conspired with exceptionally large deviations of the intrinsic velocities of these events (relative to the mean for SNe Ia of similar age) to produce large apparent differences in redshift, when in fact these SNe occurred in bound members of the galaxies.
Even if this is the case, both events reside in the sparse outer halos of these giant galaxies, with SN 2001al projected 160 kpc (for $h = 0.7$) from the galaxy center. As discussed in § 1, the extended envelopes of cD galaxies are frequently considered a component of the intergalactic stellar population. In other words, the distinction between the remote envelope of the central galaxies in rich clusters and the intracluster stellar population may simply be a matter of semantics. High-quality spectroscopy of a few more examples of hostless SNe in galaxy clusters could resolve this question by testing whether the redshift offsets between the SNe and the cD galaxies in their host clusters are consistently larger than the expected intrinsic scatter in SN Ia velocities. If the model predictions of Dubinski (1998) are correct and the intergalactic stellar population is distributed with a de Vaucouleurs-like profile with an effective radius of order 1 Mpc, then some intergalactic SNe will be discovered at very large projected distances from the central galaxies. Their intergalactic nature would then be unquestionable, regardless of the subtleties of SN redshift determination.

Key questions in galaxy-cluster evolution include the evolution of the early-to-late and blue-to-red galaxy fractions, cluster-induced onset and turnover of star formation in galaxies, and the possible transformation ofspirals into S0 galaxies (e.g., Butcher & Oemler 1984; Dressler et al. 1997; Couch et al. 1998; Neistein et al. 1999; Poggianti et al. 1999; Hinz, Rix & Bernstein 2001). These questions are potentially connected with the evolution of the intergalactic stellar population, since the same processes that affect cluster galaxies may also be responsible for the creation of the intergalactic component. However, existing methods that probe this intergalactic population are severely limited beyond the local universe. Measuring low surface brightness diffuse light is hindered by cosmological $(1+z)^4$ surface brightness dimming, and searches for individual PNe or RGs are limited by the faintness of these objects. Intergalactic SNe Ia, being bright point sources, are visible to great distances and could be used as tracers of the intergalactic stellar component out to high $z$. Admittedly, limits on dwarf hosts would be increasingly difficult to obtain at higher $z$. Still, possible hosts with absolute magnitudes as faint as $M_R \leq -14$ mag would have $R \leq 28.3$ ($R \leq 30.1$) mag at $z = 0.5$ ($z = 1$), so useful limits could be set by observations with 8–10 m class ground-based telescopes or with HST. Numerical simulations (e.g., Dubinski 1998) show that the accessible redshift range ($z \leq 1$) covers the period of intense tidal stripping of galaxies in rich clusters, suggesting the possibility of following the growth of the intergalactic stellar population by measuring the intergalactic SN fraction as a function of $z$.

To summarize, we have presented a sample of seven cluster SNe discovered by WOOTS. Of these events, two have no obvious hosts other than the cluster cD galaxies in whose halos the SNe appear. We have estimated the intrinsic redshifts of the hostless SNe, compared them with published redshifts of the cDs, and argued that the SNe are unlikely to be bound to the cDs. Using deep Keck images, we have set upper limits on the luminosity of possible dwarf host galaxies. Applying the recently measured luminosity function of the Virgo Cluster to Abell 403 and Abell 2122/4, we have argued that the fraction of the luminosity of these clusters contained in faint dwarfs is extremely small, so that such galaxies are highly unlikely to host two out of the seven WOOTS cluster SNe. This statement holds even when considering that we have missed some of the SNe that occurred in bright hosts. We conclude that, most likely, the progenitors of both hostless SNe were members of the intergalactic stellar population, which we have detected by means of SNe for the first time. The intergalactic stellar fraction that we find, $20^{+20}_{-12}$ $(20^{+35}_{-12})$ percent at the 68% (95%) confidence level, is consistent with the fraction found by other means in nearby clusters. This is in line with the expectation that the process that produces intergalactic stars (e.g., tidal disruption of cluster dwarfs) does not disrupt or enhance significantly the SN Ia formation mechanism. The existence of intergalactic SNe needs to be confirmed by means of additional examples of the phenomenon. Such SNe can serve as tracers of intergalactic stars in galaxy clusters out to high $z$. The effects that a population of intergalactic SNe may have on the properties of the intracluster medium (e.g., Sasaki 2001) remains a topic for further study.

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