SUPER-CHANDRASEKHAR SNe Ia STRONGLY PREFER METAL-POOR ENVIRONMENTS

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ABSTRACT

We discuss the emerging trend that super-Chandrasekar Type Ia Supernovae (SCSNe) with progenitor mass estimates significantly exceeding \( \sim 1.4 M_\odot \) tend to explode in metal-poor environments. While Taubenberger et al. noted that some of the SCSNe host galaxies are relatively metal-poor, we focus quantitatively on their locations in the hosts to point out that in three out of four cases, the SCSNe explosions occurred in the outer edge of the disks of their hosts. It is therefore very likely that their progenitors had far lower metallicities than those implied by the metallicity of their hosts’ central regions. In two cases (SN 2003fg and SN 2009dc) the explosion sites were outside \( \sim 99\% \) of the host’s light, and in one case (SN 2006gz) the host’s radial metallicity slope indicates that the explosion site is in a metal-poor region. The fourth case (SN 2007if) has the lowest spectroscopically measured SN Ia host metallicity (Childress et al. 2011). It may be possible to explain each of these unusually bright events through some progenitor scenario specific to that case, but a much simpler and straightforward conclusion would be to ascribe the controlling factor to the only physical aspect they have in common—metal-poor environments.

Key words: supernovae: general – supernovae: individual (SNe 2003fg, 2006gz, 2007if, 2009dc) – white dwarfs

Online-only material: color figures

1. INTRODUCTION

Type Ia Supernovae (SNe Ia) are important both as astrophysical probes of cosmology (e.g., Kessler et al. 2009, and references therein) and for their role in the chemical evolution of galaxies (e.g., Kobayashi & Nomoto 2009). At the same time, the nature of SNe Ia progenitors and their explosion mechanism are still uncertain. Two possible explosion scenarios have been proposed. In the single degenerate (SD) scenario (e.g., Whelan & Iben 1973; Piro 2008; Meng et al. 2011a), an accreting carbon/oxygen white dwarf (CO WD) undergoes thermonuclear explosion when its mass approaches the Chandrasekhar limit of \( \sim 1.4 M_\odot \) (Chandrasekhar 1931). In the double degenerate (DD) scenario, two CO WDs merge, possibly with the help of a third star in the system accelerating the merger through the Kozai mechanism (Thompson 2010), to produce a progenitor that potentially is \( > 1.4 M_\odot \) (e.g., Iben & Tutukov 1984; Webbink 1984; Pakmor et al. 2010). The decay of \(^{56}\)Ni produced by SN Ia explosion and the subsequent decay product \(^{56}\)Co power the observed luminosity (Colgate & McKee 1969).

Over the last decade, at least four SNe Ia have been discovered that were too luminous to have resulted from thermonuclear explosions of Chandrasekhar-mass WDs. It has been proposed, first by Howell et al. (2006) for the case of SN 2003fg, that these four SNe Ia exploded through DD mergers. While it requires \( \sim 0.6 M_\odot \) of \(^{56}\)Ni to power a normal SN Ia light curve with a progenitor mass \( \sim 1.4 M_\odot \) (e.g., Nomoto et al. 1984; Branch 1992), the inferred \(^{56}\)Ni masses of the four super-Chandrasekhar SNe Ia range from \( \sim 1.2 M_\odot \) to \( \sim 1.7 M_\odot \) and imply total progenitor masses from \( \sim 2.0 M_\odot \) to \( \sim 2.4 M_\odot \) (see Table 1).

Taubenberger et al. (2011) noted that some of the super-Chandrasekar Type Ia Supernovae (SCSNe) host galaxies are relatively metal-poor. In our discussion of SN 2009nr (Khan et al. 2011), we pointed out that for three of the four confirmed SCSNe events, the SNe were located far from the centers of their host galaxies, and probably were in significantly lower metallicity environments than implied by the metallicity of their hosts’ central regions. The fourth case, SN 2007if, is located in a low-luminosity dwarf galaxy that has the lowest spectroscopically measured metallicity among SN Ia hosts (\( 12 + \log(O/H) = 8.01 \pm 0.09 \) or \( Z \simeq 0.15 Z_\odot \), Childress et al. 2011, using the \( R_{23} \) method of Kobulnicky & Kewley 2004). This motivated us to further examine the currently available evidence that SCSNe show a strong preference for metal-poor environments, quantitatively focusing on their locations in their hosts. Section 2 describes the SNe host galaxy data and Section 3 presents our analysis of the host properties. In Section 4, we consider the implications of our results and their consequences for SNe Ia progenitor theories.

2. DATA

We gathered publicly available images of the four SCSNe explosion sites in order to quantitatively characterize their host properties. For SN 2003fg, five Hubble Space Telescope (HST) WFC2 images taken through the F606W filter (HST Prop. ID 8968, PI: J. Mould; Vogt et al. 2005) were obtained from the HST archive, and they were combined to produce Figure 1. For SN 2006gz, a Palomar Schmidt telescope image of the host galaxy IC 1277 taken through the POSS-I blue filter (Figure 2) was obtained from the STScI Digitized Sky Survey archive. For SN 2009dc, a Sloan Digital Sky Survey (SDSS) \( r' \)-band image of the host galaxy UGC 10064 (Figure 4) was obtained from the SDSS Data Release 7 archive. For the SN 2007if host properties, we use the results presented by Childress et al. (2011).

Spectra of the SN 2006gz host galaxy IC 1277 and the large galaxy near the presumed dwarf host of SN 2003fg were

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processed using standard techniques in IRAF,8 including cosmic
filter. The circle marks the location of the SN. The center of the presumed host
filter. The circle marks the location of the SN. The center of the presumed host
Figure 1. HST WFPC2 view of the SN 2003fg explosion site in the F606W
filter. The circle marks the location of the SN. The center of the presumed host
(A color version of this figure is available in the online journal.)

Table 1
Summary of the SCSNe Events and Their Host Properties

| Property                  | SN 2003fg | SN 2006gz | SN 2007if | SN 2009dc |
|---------------------------|-----------|-----------|-----------|-----------|
| R.A.                      | 14h16m18s | 18h10m26s | 1h10m51s  | 15h51m12  |
| Decl.                     | +52°14'55 | +30°59'44 | +15°27'40 | +25°42'28 |
| Redshift                  | 0.2440 ± 0.0003 | 0.0234 ± 0.0004 | 0.07416 ± 0.00082 | 0.022 ± 0.001 |
| $M_V$ (SN)                | −20.0     | −19.2     | −20.4     | −19.8     |
| $\Delta M_V$ (B)         | 0.94      | 0.69 ± 0.04 | 0.71 ± 0.06 | 0.65 ± 0.03 |
| $^{56}$Ni mass            | 1.3 $M_\odot$ | 1.2 $M_\odot$ | 1.6 $M_\odot$ | 1.7 $M_\odot$ |
| $M_{\text{tot}}$         | 2.1 $M_\odot$ | ... | 2.4 $M_\odot$ | $\gtrsim 2 M_\odot$ |
| Host name                 | Unnamed   | IC 1277   | Unnamed   | UGC 10064 |
| Host magnitude            | $M_{\text{F606W}} = −21.3$ | $M_V = −20.3$ | $M_V = −14.1$ | $M_V = −21.9$ |
| Axis ratio (b/a)          | ~0.6      | ~0.7      | ...       | ~0.1      |
| $D_1$                     | 4±8       | 30±5      | ...       | 27        |
| $D_2$                     | 23.5 kpc  | 14.4 kpc  | ...       | 12 kpc    |
| $L(<r)$                  | ~99%      | ~75%      | ...       | ~99%      |

Notes. The SNe properties (coordinates, redshift, peak magnitude, lightcurve decline rate, derived $^{56}$Ni mass and total progenitor mass) are from Howell et al. (2006), Hick et al. (2007), Yamanaka et al. (2009), Scalzo et al. (2010), and Silverman et al. (2011). The host magnitudes are from the RC3 catalog (de Vaucouleurs et al. 1991) for SN 2006gz, Scalzo et al. (2010) for SN 2007if, and the SDSS DR6 catalog (Adelman-McCarthy et al. 2008) for SN 2009dc. As the SN 2003fg host properties, we present those of the morphologically disturbed large neighboring galaxy at the same redshift as the presumed dwarf host, and the absolute magnitude was determined from its GALFIT profile. The exponential disk scale axis ratios are from our GALFIT results, while the presumed dwarf host, and the absolute magnitude was determined from its GALFIT profile. The exponential disk scale axis ratios are from our GALFIT results, while the presumed dwarf host, and the absolute magnitude was determined from its GALFIT profile. The exponential disk scale axis ratios are from our GALFIT results, while

8 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.
9 http://www.astronomy.ohio-state.edu/martini/osmos/

obtained on 2011 April 6 with the Ohio State Multi-Object Spectrograph (OSMOS; Stoll et al. 2010; Martini et al. 2011) on the 2.4 m Hiltner telescope. The OSMOS slit was oriented N/S and was centered on the galaxies. The raw data were processed using standard techniques in IRAF,8 including cosmic ray rejection using L. A. Cosmic (van Dokkum 2001). The slit location (the red-sensitive inner slit9) we used provides a wavelength coverage of 3960–6880 Å. The spectra were calibrated in wavelength using Ar arclamp spectra and in flux using coincident observations of a spectrophotometric standard from Oke (1990).

For IC 1277, we extracted spectra of four H ii regions along the slit using apertures of 14 pixels (3.8 arcsec). We determined their oxygen abundances using the N2 diagnostic of Pettini & Pagel (2004), which depends solely on [N ii] λ6584/Hα λ6563. Due to the proximity of the lines, this ratio is very insensitive to reddening. For the galaxy near SN 2003fg, given the wavelength range at this redshift, only R23 methods were available to determine metallicity from the spectrum taken at its center, and estimates from the R23 methods were converted to the N2 scale that we used for IC 1277 using the empirical conversions of Kewley & Ellison (2008). The R23 methods are very sensitive to reddening correction, and we corrected only for Galactic
reducing using $E(B - V) = 0.013$ mag (Schlegel et al. 1998), using the CCM function, and assuming $R = 3.1$.

3. ANALYSIS

We used GALFIT (Peng et al. 2002) to model the host galaxies. We fit simple exponential disk profiles to the large morphologically disturbed galaxy near the presumed dwarf host of SN 2003fg (see Figure 1) and to the host of SN 2006gz (IC 1277). For SN 2009dc, we fit a two-component (exponential plus Sérsic) disk/bulge decomposition profile to the S0 host UGC 10064. We also used the IRAF Ellipse tool to analyze the galaxy profiles produced by GALFIT to approximately determine what fraction of total light is located interior to the location of the SNe in the hosts. Finally, we determined the radial metallicity slope of the host galaxy of SN 2006gz (IC 1277) from the spectroscopic data described in Section 2. A summary of the properties of the SCSNe events and their host galaxies is presented in Table 1. Throughout this section, we assume $H_0 = 72$, $\Omega_M = 0.27$, and a flat universe when translating angular size or separation (arcseconds) to physical distance (kpc).

SN 2003fg is located 4′04E and 2′53S from the center of the morphologically disturbed neighboring galaxy (projected distance $\sim 23.5$ kpc; see Figure 1), which is at the same redshift as the presumed dwarf host, although the dwarf galaxy could also be a tidal feature of the much larger neighbor (Howell et al. 2006). The explosion site is $\sim 0.9$ kpc away from the center of the dwarf host, and thus under any assumption the SN would be located in a metal-poor environment if it is indeed associated with this dwarf galaxy. Alternatively, the parameters derived by GALFIT indicate that the larger neighbor has an exponential disk scale length of $\sim 0.5$ kpc. If this galaxy is the actual host, then the SN exploded $\geq 8$ disk scale lengths away from the center of its host. The GALFIT profile of this galaxy indicates that $\sim 99\%$ of its light is located interior to the location of the SN. An exponential disk profile is likely not the optimal function to model disturbed galaxies such as this, however there does not appear to be any significant flux excess toward the location of the SN except for the dwarf galaxy-like feature, and our estimate for the fraction of light within the SN location appear robust. Metallicity estimates of the center of this galaxy from the spectroscopic data presented in Section 2 using various R23 methods convert to a consistent value of $12 + \log(O/H) \sim 8.57$ ($Z \sim 0.5 Z_\odot$) on the N2 diagnostic scale of Pettini & Pagel (2004). Although the metallicity gradient of morphologically disturbed galaxies is uncertain, our measurement shows that SN 2003fg is likely associated with a low-metallicity environment even if it originated from material ejected from the large galaxy with metallicity as high as that of its central region.

SN 2006gz is located 12 ′W and 28 ′S from the center of the Scd host IC 1277 at a projected distance of 14.4 kpc (Hicken et al. 2007). The parameters derived by GALFIT show that IC 1277 has an exponential disk scale length of $\sim 14′/4$ or 6.7 kpc. This means that the SN exploded $\sim 2.1$ disk scale lengths away from the center of the host at the outer edge of the disk of the galaxy (Figure 2). The SN is located outside of $\sim 75\%$ of the galaxy’s light. Analyzing the spectroscopic data presented in Section 2, we determined the radial oxygen abundance profile of the host. A linear fit to the oxygen abundance measurements has a gradient of $\sim 0.03$ dex kpc$^{-1}$. In Figure 3, the dashed line shows the linear fit to the metallicity measurements and the solid line marks the position of the SN. It is apparent that the location of the SN is metal-poor ($12 + \log(O/H) \sim 8.26$ or $Z \lesssim 0.25 Z_\odot$).

SN 2009dc is located 15′8W and 20′8N of the S0 host galaxy UGC 10064 (Figure 4) at a projected distance of 12 kpc (Silverman et al. 2011). The parameters derived from GALFIT show that the host has an exponential disk scale length of $\sim 13′/8$ ($\sim 6$ kpc) and its bulge (Sérsic index $\sim 3.8$) has an effective radius of $\sim 8′$ ($\sim 3.5$ kpc). This indicates that the SN exploded $\sim 2$ exponential disk scale lengths away from center of UGC 10064. The host is very highly inclined with GALFIT estimates for the axis ratio of $\leq 0.1$ for both the disk and the bulge components. If the SN exploded in an extended disk, the actual distance from the center of the host could be more than 10 times larger, by simple geometric considerations. Although the SN is located...
outside of $\gtrsim 99\%$ of the galaxy’s light, the SDSS $g'$- and $r'$-band images show low surface brightness emission at the position of the SN that is fairly asymmetric around the galaxy, with more light in the side where the SN is (NW) compared to the opposite side (SE). This appears consistent with a fairly inclined disk, perhaps an extended disk. It has also been proposed by Taubenberger et al. (2011) that SN 2009dc might be associated with a faint and narrow tidal stream connecting the host with the $\sim 10$ times less massive neighboring galaxy UGC 10063 and the progenitor system may have formed a few hundred megayears ago during an interaction of these two galaxies. It is impossible to measure the gas phase oxygen abundance or the metallicity gradient of this gas-poor galaxy directly using gas-phase abundances as we did for the host of SN 2003fg, but the central region of UGC 10064 appears to have a relatively undisturbed S0 profile despite being in an interacting system, and it is reasonable to expect a metallicity gradient fairly similar to that of a relatively undisturbed spiral galaxy. Since during a galaxy interaction it is easier to disturb mass that is not deep in the potential well of the significantly more massive galaxy, even if SN 2009dc originated from mass ejected from the host, it is likely associated with low-metallicity material stripped from the outer regions.

4. DISCUSSION

Several papers published recently have discussed low metallicity as an important ingredient for the progenitors of possible SCSNe explosions. Silverman et al. (2011) noted that while the host galaxy types and distances of the SCSNe explosion sites from the centers of their hosts vary, a number of the SCSNe exploded far from the centers of the host galaxies. Childress et al. (2011) pointed out many unusual SNe Ia, including the SCSNe, have been discovered in low-luminosity hosts. Taubenberger et al. (2011) concluded that SCSNe show a tendency to explode in low-mass galaxies, and low-metallicity progenitors may be an important prerequisite for producing superluminous SNe Ia. Khan et al. (2011) observed that three of the four confirmed SCSNe events were located far from the centers of their host galaxies, probably in significantly lower metallicity environments than implied by the metallicity of their hosts’ central regions. In the current work, we have quantitatively focused on their locations in the hosts to show that all of the SCSNe progenitors appear to be associated with regions of their hosts likely to be metal-poor. It is also important to note that the projected distances are only lower limits on the physical separations between the SN explosion sites and the centers of their hosts, and the actual distances will be larger and hence likely will have still lower metallicity. One could argue for a unique explanation for each of these four events, specially given that in two cases (SN 2003fg and SN 2009dc) the SNe are associated with interacting systems, but Occam’s Razor suggests that it is simply due to a characteristic they all share, such as low metallicity.

Although a detailed study of the stellar populations at the outer edges of the SCSNe host galaxies is not possible, studies of Local Group galaxies demonstrate that the outer regions of galaxies primarily contain metal-poor stars. The halo of the Milky Way is dominated by metal-poor stellar populations (Brown et al. 2010). In case of the M31 spheroid, the metallicity is known to decrease monotonically with increasing radius—it has mean [Fe/H] values of $\sim -0.65$ at 11 kpc, $\sim -0.87$ at 21 kpc, and $\sim -0.98$ at 35 kpc from the nucleus (Brown et al. 2007). For M33, the stellar halo is significantly more metal-poor ([Fe/H] $\approx -1.5$) than would be inferred from the metallicity of the disk stars ([Fe/H] $\approx -0.9$; McConnachie et al. 2006). These results provide strong circumstantial evidence supporting our conclusion that the SCSNe explosions far from the center of their hosts imply that their progenitors were located in metal-poor environments, likely linked to low-metallicity star formation not associated with central regions of their hosts.

Beyond the Local Group, discovery of extended UV disks around nearby galaxies M83 (Thilker et al. 2005) and NGC 4625 (Gil de Paz et al. 2005) have shown that while there is evidence for ongoing star formation in the outer edges of these galaxies, both the star formation rate and total stellar mass in these regions are very small. Dwarf galaxies and extended disks contain only a few percent of the total stellar mass or star formation (e.g., Benson et al. 2007), and in the local universe about half of the stellar mass is contained in elliptical galaxies or the bulges of large spirals (e.g., Tasca & White 2011). Yet, all four of the confirmed SCSNe exploded in these environments. Even including the additional candidate SCSNe considered by Taubenberger et al. (2011), for which the evidence of their SCSN nature is less conclusive, none has exploded in an early-type galaxy. In other words, what is most striking about the SCSNe explosion sites is not where they are located, but rather where they are not: they avoid both spiral galaxy disks and elliptical galaxies, even though these are the regions that contain almost all the stellar mass and star formation. This is highly unlikely to be a selection effect, given that the SCSNe are some of the brightest SNe Ia ever detected, and thus are easier to discover in SN surveys than ordinary SNe Ia.

The four confirmed SCSNe events are the high-luminosity tail of the observed SNe Ia luminosity distribution, and thus by inference, total WD mass. This raises the possibility that other slightly less luminous SNe Ia may also have resulted from double-degenerate mergers resulting in progenitor masses exceeding the Chandrasekhar limit by a narrower margin. As we discussed in Khan et al. (2011), these bright SNe Ia also tend to lie far from the centers of their hosts or in dwarf galaxies, suggesting more generally that their higher luminosities are likely related to the lower metallicities of their environments, although whether this is driven by age or metallicity is hotly debated (e.g., Hamuy et al. 2000; Gallagher et al. 2005, 2008; Prieto et al. 2008; Howell et al. 2009). For example, Figure 21 of Hicken et al. (2009) shows that roughly a third of all SNe Ia have a projected distance of $\gtrsim 10$ kpc from the centers of hosts. Some specific examples include SN 2007bk, where the over-luminous SN was found $\sim 9$ kpc away from its metal-poor ($Z \approx 0.25 Z_\odot$) dwarf host (Prieto et al. 2008), and the 1991T-like SN 2009nr which is located 4.3 disk scale lengths away from its host (Khan et al. 2011).

It is possible that in metal-poor systems the WD initial–final mass relation is highly unconventional and the low metallicity systems produce an unexpected abundance of SCSNe (e.g., Umeda et al. 1999b). Metallicity may also significantly contribute to the SN Ia delay time distribution (e.g., Meng et al. 2011b). Alternatively, the mapping of total WD mass to the expected $^{56}$Ni yield in the DD scenario (e.g., Howell et al. 2009) may be especially problematic in the very metal poor tail of WD populations, and comparable WD masses may lead to a wide range of luminosities (e.g., Umeda et al. 1999a; Chen & Li 2009; Pakmor et al. 2010). In the SD scenario, differential rotation of the WD has been proposed as a means of exceeding the Chandrasekhar-mass limit (Piro 2008) and low-metallicity may be required for SD progenitors to highly surpass this threshold (Hachisu et al. 2011). The small sample size of
four confirmed SCSNe limits our ability to verify any of these hypotheses, but the discovery of more SCSNe and re-analysis of previously discovered very luminous SNe Ia should lead to a deeper understanding of the underlying systematics affecting SNe Ia luminosities, rates, and the nature of their progenitors.

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