THE HOST GALAXY OF THE SUPER-LUMINOUS SN 2010gx AND LIMITS ON EXPLOSIVE $^{56}\text{Ni}$ PRODUCTION

TING-WAN CHEN$^1$, STEPHEN J. SMARTT$^1$, FABIO BRESolin$^2$, ANDREA PASTORELLO$^3$, ROLF-PETER KUDRITZKI$^2$, RUBINA KOTAK$^1$, MATT MCCRUM$^1$, MORGAN FRASER$^1$, AND STEFANO VALENTI$^4,5$

$^1$ Astrophysics Research Centre, School of Mathematics and Physics, Queen’s University Belfast, Belfast BT7 1NN, UK
$^2$ Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
$^3$ INAF-Osservatorio Astronomico di Padova, vicolo dell’Osservatorio 5, I-35122 Padova, Italy
$^4$ Las Cumbres Observatory Global Telescope Network, Inc., Santa Barbara, CA 93117, USA
$^5$ Department of Physics, University of California Santa Barbara, Santa Barbara, CA 93106-9530, USA

Received 2012 October 15; accepted 2012 December 27; published 2013 January 11

ABSTRACT

Super-luminous supernovae have a tendency to occur in faint host galaxies which are likely to have low mass and low metallicity. While these extremely luminous explosions have been observed from $z = 0.1$ to 1.55, the closest explosions allow more detailed investigations of their host galaxies. We present a detailed analysis of the host galaxy of SN 2010gx ($z = 0.23$), one of the best studied super-luminous type Ic supernovae. The host is a dwarf galaxy ($M_g = -17.42 \pm 0.17$) with a high specific star formation rate. It has a remarkably low metallicity of $12 + \log (\text{O/H}) = 7.5 \pm 0.1$ dex as determined from the detection of the $\text{[O III]} 4363$ line. This is the first reliable metallicity determination of a super-luminous stripped-envelope supernova host. We collected deep multi-epoch imaging with Gemini + GMOS between 240 and 560 days after explosion to search for any sign of radioactive $^{56}\text{Ni}$, which might provide further insights on the explosion mechanism and the progenitor’s nature. We reach $griz$ magnitudes of $m_{AB} \sim 26$, but do not detect SN 2010gx at these epochs. The limit implies that any $^{56}\text{Ni}$ production was similar to or below that of SN 1998bw (a luminous type Ic SN that produced around 0.4 $M_\odot$ of $^{56}\text{Ni}$). The low volumetric rates of these supernovae ($\sim 10^{-4}$ of the core-collapse population) could be qualitatively matched if the explosion mechanism requires a combination of low-metallicity (below 0.2 $Z_\odot$), high progenitor mass ($> 60 M_\odot$) and high rotation rate (fastest 10% of rotators).

Key words: supernovae: general – supernovae: individual (SN 2010gx)

Online-only material: color figures

1. INTRODUCTION

Novel wide-field survey projects, such as the Panoramic Survey Telescope And Rapid Response System (Pan-STARRS-1; Kaiser et al. 2010) and the Palomar Transient Factory (Rau et al. 2009), have carried out searches for supernovae (SNe) without an inherent galaxy bias. Quimby et al. (2011) identified a class of hydrogen-poor “super-luminous SNe (SLSNe)” with typical g-band absolute magnitudes of around $-21.5$, which is 10–100 times brighter than normal core-collapse SNe. Their intrinsic brightness has allowed them to be discovered at high redshift in the Pan-STARRS-1 survey between $z = 1$ and 1.55 (Chomiuk et al. 2011; Berger et al. 2012). Pastorello et al. (2010) studied one of the closest examples, SN 2010gx ($z = 0.23$), in detail showing it to transition to a normal type Ic SN at 40 days after peak, while multi-color photometry rules out $^{56}\text{Ni}$ as powering the peak magnitude. Two physical mechanisms for SN 2010gx (and the SNe like it from Quimby et al. 2011 and Chomiuk et al. 2011) have been proposed. One is that the type Ic SN is boosted in luminosity by energy deposition from magnetar spin-down (Kasen & Bildsten 2010). The second is the shock breakout through a dense wind (Chevalier & Irwin 2011), or shock interaction of the SN ejecta with massive C–O shells (Blinnikov & Sorokina 2010).Neill et al. (2011) showed that most SLSNe tend to occur in star-forming dwarf galaxies, which have high specific star formation rates (sSFRs). Their intrinsic rate is $10^{-8}$ Mpc$^{-3}$ yr$^{-1}$, or $10^{-4}$ of the normal core-collapse SN rate (Quimby et al. 2011; Gal-Yam 2012). An important question is whether or not the apparent preference they have for dwarf host galaxies is related to requiring low-metallicity progenitor stars. As low metallicity affects stellar structure and evolution through changes in stellar winds, opacity, and rotation, quantitative measurements are required. In this Letter we study the host galaxy of one of the nearest SLSNe, SN 2010gx, and search for evidence of late emission from radioactive $^{56}\text{Ni}$ decay.

2. OBSERVATIONS

2.1. Photometry

We used the Gemini South and North observatories with the Gemini Multi-Object Spectrograph (GMOS) to collect $griz$ photometry between 240 and 560 days after the maximum of SN 2010gx (Table 1). To check for the presence of residual SN flux at 240–370 days after peak, we aligned and rescaled all images to the same pixel grid using IRAF/GEOMAP and GEOTRAN packages. We performed imaging subtraction using the High Order Transform of PSF ANd Template Subtraction (HOTPANTS) software to subtract the 2012 January images from the earlier epochs. The host galaxy subtracts off almost perfectly and no SN signal is detected, hence we made the assumption that the final image taken in 2012 January only contains flux from the host galaxy. In addition, the deep spectra of the host do not show any broad features or evidence commonly associated with SNe spectra.

To determine a limiting magnitude for the SN flux in the three epochs, we added six fake stars, one at the SN position and five within a surrounding radius of 0.6 to each of the 240–370 days images. We ran this procedure multiple times with

---

6 http://www.astro.washington.edu/users/becker/hotpants.html
of fake star magnitudes and repeated image subtraction with hotpants. We determined $\sigma$ and $3\sigma$ detection limits by requiring that we could visually detect a fake SN exactly at the position of SN 2010gx and that the measured standard deviation of the set of fake stars added was 0.2 and 0.3 mag, respectively. The resulting upper limits are in Table 1.

The apparent magnitudes (Sloan Digital Sky Survey (SDSS) AB system) of the host galaxy, SDSS J112546.72–084942.0, are $g = 23.71 \pm 0.14$, $r = 22.98 \pm 0.10$, $i = 22.90 \pm 0.13$ and $z = 22.98 \pm 0.16$. These were obtained from aperture photometry (within IRAF/DAOPHOT) on the best seeing images using a zero-point calibration achieved with 10 SDSS reference stars. As deep, pre-explosion images of the host galaxy were not available, we compared our photometry results to both SDSS catalog magnitudes and our own photometry performed on the SDSS images. In the $g$ band, the SDSS catalog Petrosian magnitude for the object is $22.8 \pm 0.5$, while we measure $22.6 \pm 0.6$ mag in the SDSS image. The large uncertainty is due to the marginal detection. Our deep Gemini image shows the host resolved from a fainter neighboring galaxy (which is unresolved from the host in SDSS). If we use a large aperture on our Gemini $g$-band image, to include flux from the neighboring galaxy, then we obtain $g = 23.29 \pm 0.16$ mag. Within the uncertainties, the SDSS and Gemini magnitudes are similar and there is no hint that the +560 days Gemini images are brighter than the SDSS images and contain SN flux. This supports our assumption that the 2012 January images are dominated by galaxy flux and contain no detectable residual SN flux.

### 2.2. Spectroscopy

Spectroscopy of SN 2010gx was taken on 2010 June 5 (Pastorello et al. 2010) with the Gemini South Telescope + GMOS. The B600 grating (ID G5323; $2 \times 1800$ s) provided coverage in the observer frame of 4300–6400 Å (henceforth referred to as the “blue spectrum”). Although this spectrum contains flux from SN 2010gx, we fitted a high-order polynomial (order 15) through the SN continuum and subtracted off this contribution leaving a flat spectrum for which emission lines between 3500 and 5200 Å (rest frame) could be measured. We could not measure the Hα line in this spectrum due to contamination by a strong sky line. A second spectrum was obtained on 2011 December 23 with GMOS at the Gemini North Telescope, using the R400 grating (ID G5305; $3 \times 1800$ s), to cover 5070–8500 Å (henceforth referred to as the “red spectrum”). An order-blocking filter (GG455) and low grating efficiency truncated the wavelength coverage in the blue. Detrending of the data, such as bias subtraction, was established using standard techniques within IRAF. For the red spectra, individual exposures were nodded along the slit, and we used two-dimensional image subtraction to remove the sky background. Wavelength and flux calibrations were achieved using daytime CuAr arcs and the spectrophotometric standard Feige 34.

We used 1′′ and 1′′′ slits for red and blue spectra separately, yielding a resolution (as measured from narrow night sky lines) of $\sim$6 Å in the red and $\sim$4.5 Å in the blue. The combined blue and red spectra provide spectral coverage between 4300 and 8500 Å and the overlap region was used to ensure a uniform flux calibration, employing the three strong lines [O III] $\lambda$5007, [O III] $\lambda$4959, and Hβ. We measured the line fluxes in both spectra and applied a linear scaling to bring the blue spectrum into agreement with the red. The line fluxes of these three lines agreed to within 3% after this rescaling.

Line flux measurements were made after fitting a polynomial function to subtract the continuum. Figure 3 shows the final combined spectrum of the host galaxy. We fitted Gaussian line profiles within a custom built idl environment, fixing the FWHM of the mean of the three strong lines; 6.03 Å and 4.45 Å for the red and blue spectra, respectively (Table 2). We also normalized the spectrum and determined the line equivalent widths. These equivalent widths and rms of the continuum provided uncertainty estimates using the expression from Pérez-Montero & Díaz (2003, Table 2).

| Table 1 | Observed Photometry of SN 2010gx and Its Host Galaxy |
|---------|-----------------------------------------------|
| Date    | MJD   | Phase | $g$  | $r$  | $i$  | $z$  | Telescope | Instrument |
|---------|-------|-------|------|------|------|------|-----------|------------|
| 2010 Jun 4 | 55351.97 | 74.4  | 21.13(0.19) |  | | | GS | GMOS-S |
| 2010 Jun 8 | 55354.93 | 76.8  | 23.55(0.28) | 21.52(0.09) | 21.31(0.12) | | WHT | ACAM |
| 2010 Jun 8 | 55355.48 | 77.2  | 21.58(0.13) | 21.31(0.16) | | | FTS | EM03 |
| 2010 Jun 13 | 55360.47 | 81.3  | 23.91(0.30) | 21.81(0.20) | 21.56(0.13) | | FTS | EM03 |
| 2010 Jun 13 | 55360.92 | 81.6  | 23.95(0.49) | 21.83(0.12) | 21.58(0.29) | | LT | RATcam |
| 2010 Jun 16 | 55363.48 | 83.7  | $\geq$23.73 | 21.91(0.16) | | | FTS | EM03 |
| 2010 Jun 29 | 55376.38 | 94.2  | 22.47(0.21) | 22.38(0.33) | | | FTS | EM03 |
| 2010 Dec 30 | 55366.63 | 244.0 | H 22.90(0.13) | H 22.98(0.10) | $>25.94(0.17)$ | $>24.58(0.29)$ | GN | GMOS-N |
| 2011 Jan 14 | 55575.32 | 256.0 | H 23.71(0.14) | H 22.98(0.10) | $>26.42(0.18)$ | $>25.68(0.11)$ | GS | GMOS-S |
| 2011 Feb 28 | 55620.12 | 292.4 | H 23.02(0.13) | H 23.00(0.13) | $>24.78(0.13)$ | $>23.35(0.32)$ | GS | GMOS-S |
| 2011 May 20 | 55701.28 | 358.4 | H 23.72(0.13) | $>26.00(0.15)$ | | | GN | GMOS-N |
| 2011 May 25 | 55706.08 | 362.3 | H 23.08(0.08) | H 23.02(0.11) | H 23.06(0.16) | | GS | GMOS-S |
| 2012 Jan 18 | 55944.22 | 555.7 | H 23.03(0.10) | H 23.02(0.11) | H 23.06(0.16) | | GS | GMOS-S |
| 2012 Jan 20 | 55946.23 | 557.5 | H 23.17(0.11) | | | | GS | GMOS-S |
| 2012 Jan 21 | 55947.21 | 558.3 | H 23.62(0.11) | | | | GS | GMOS-S |

Notes. Data until 2010 January 29 are from Pastorello et al. (2010). The symbol “H” indicates host galaxy photometry, and the “$>$” expresses the limiting magnitude of the SN ($5\sigma$). Phase has been corrected for time dilation, based on the SN explosion at MJD 55260.5.
2010gx flux at +244 days after the SN explosion, which is $z$.

et al. 2006; Hunter et al. 2009). The fluxes measured in the SN 2002ap and SN 2007gr (Clocchiatti et al. 2011; Tomita et al. 2006; Hunter et al. 2009). Our limits are significantly brighter than these two, hence we can simply say that SN 2010gx did not produce explosive $^{56}$Ni in larger quantities than the brightest known type Ic SNe such as SN 1998bw.

3. Host Galaxy Metallicity and Other Properties

We carried out an abundance analysis of the host galaxy based on the determination of the electron temperature and detection of the [O iii] $\lambda$4363 auroral line (see Bresolin et al. 2009 for further details). First, the emission line fluxes were reddening corrected using the Milky Way law of $A_V = 3.17 \times E(B-V)$. We assumed case B recombination, which requires an intrinsic line ratio of $H_\alpha/H_\beta = 2.86$ and $H_\gamma/H_\beta = 0.47$ at $T_e = 10^4$ K (Osterbrock 1989). The observed ratio of $H_\alpha/H_\beta = 3.88$ yields an extinction coefficient $c(H_\beta) = 0.48$, which we used to calculate reddening-corrected line fluxes. The observed line fluxes and errors are listed in Table 2.

We confidently detected the [O iii] $\lambda$4363 auroral line (signal-to-noise ratio, $S/N \sim 6$) in the GMOS spectrum (Figure 3), allowing us to estimate the electron temperature and calculate the oxygen abundance directly. As in Bresolin et al. (2009), we used a custom-written $\textsc{pyraf}$ script based on the $\textsc{iraf}/\textsc{nebula}$ package. The direct method of estimating oxygen abundances uses the ratio of the intensities of [O iii] $\lambda$4959, 5007/[O ii] $\lambda$4363 lines to determine the electron temperature ($T_e$) in the ionized gas region. We find an oxygen abundance of $12 + \log(O/H) = 7.46 \pm 0.10$ dex, remarkably low even for dwarf galaxies (Figure 3). Assuming a solar value of $8.69 \pm 0.05$ dex (Asplund et al. 2009), this implies that the host galaxy is 1.2 dex below solar abundance or just 0.06 $Z_{\odot}$.

Stoll et al. (2011) estimated a metallicity from the strong lined methods, but it is well documented that the results from this method can vary by up to 0.7 dex depending on which calibration is used (Bresolin et al. 2009). Not surprisingly, they get an estimate of 8.16 dex from the N2 diagnostic, which appears 0.7 dex systematically too high when compared with our direct estimate.

3. ANALYSIS

3.1. $^{56}$Ni Mass Estimation for SN 2010gx

The fact that SN 2010gx was not detected after the host galaxy image subtraction at epochs between +244 and +362 days allows us to determine an upper limit for the mass of $^{56}$Ni ejected. This is somewhat uncertain as it relies on assuming that the gamma-ray trapping in SN 2010gx behaves like in other Ic SNe in the nebular phase, and the late luminosity is directly proportional to the mass of $^{56}$Co present at any epoch.

We estimated the upper limit for any flux coming from SN 2010gx at the effective rest wavelength of the $r$-filters. These were corrected for Milky Way extinction only. We compared the upper limit of the luminosities of SN 2010gx with the late-time luminosities of several type Ic SNe, such as SN 1998bw, SN 2002ap, and SN 2007gr (Clocchiatti et al. 2011; Tomita et al. 2006; Hunter et al. 2009). The fluxes measured in the observed $r$ frames of SN 2010gx were compared with those for the low-redshift SNe in Johnson V and Cousins R as the effective wavelengths roughly match at $z = 0.23$ (see Figure 2).

The most interesting measurement is the $i$-band limit for SN 2010gx flux at +244 days after the SN explosion, which is similar to or below what we would expect if SN 1998bw were at this distance. If we take 0.4 $M_\odot$ as the representative $^{56}$Ni mass for SN 1998bw (Maeda et al. 2006), then the flux limit of SN 2010gx suggests an upper limit of about 0.4 $M_\odot$ of $^{56}$Ni ejected by SN 2010gx. For a complete comparison with other type Ic SNe, we also included SN 2002ap and SN 2007gr. Both of these SNe were modeled to indicate that the ejecta contained around 0.08 $M_\odot$ of $^{56}$Ni (Tomita et al. 2006; Hunter et al. 2009). Our limits are significantly brighter than these two, hence we can simply say that SN 2010gx did not produce explosive $^{56}$Ni in larger quantities than the brightest known type Ic SNe such as SN 1998bw.

### Table 2

Main Properties of the Host Galaxy of SN 2010gx

| SDSS name | SDSS J1254.67−084924.0 |
|-----------|-------------------------|
| R.A.      | 11:25:46.72             |
| Decl.     | −08:49:42.0             |
| Redshift  | 0.23                    |
| Apparent g (mag) | 23.71 ± 0.14  |
| Apparent r (mag) | 22.98 ± 0.10  |
| Apparent i (mag) | 22.90 ± 0.13  |
| Apparent z (mag) | 22.98 ± 0.16  |
| Galactic extinction (mag) | 0.13 |
| $k$-correction (mag) | 0.27 ± 0.08  |
| Internal extinction (mag) | ∼0.5 ($R_V = 3.16$)  |
| Luminosity distance (Mpc) | 1114.7  |
| Absolute g (mag) | −17.42 ± 0.17  |
| Physical diameter (kpc) | 2.4 |
| Luminosity (H) (erg s$^{-1}$) | 5.20 × 10$^{40}$ |
| SFR (M$_{\odot}$ yr$^{-1}$) | 0.41 |
| Stellar mass (M$_{\odot}$) | (1.0−2.2) × 10$^{8}$ |
| sSFR (yr$^{-1}$) | (1.9−4.1) × 10$^{-9}$ |
| $12 + \log(O/H)$ ($\Delta T_e$ method) | 7.46 ± 0.1 |

| Line      | Observed Flux ± Error (erg s$^{-1}$ cm$^{-2}$) |
|-----------|-----------------------------------------------|
| [O iii] $\lambda$3727 | (1.30 ± 0.04) × 10$^{-16}$ |
| [Ne ii] $\lambda$3868 | (6.12 ± 0.27) × 10$^{-17}$ |
| H$\alpha$ $\lambda$4102 | (4.25 ± 0.30) × 10$^{-17}$ |
| H$\gamma$ $\lambda$4340 | (5.27 ± 0.36) × 10$^{-17}$ |
| [O iii] $\lambda$4363 | (2.27 ± 0.23) × 10$^{-17}$ |
| H$\beta$ $\lambda$4861 | (1.29 ± 0.03) × 10$^{-16}$ |
| [O iii] $\lambda$4959 | (2.13 ± 0.04) × 10$^{-16}$ |
| [O iii] $\lambda$5007 | (6.57 ± 0.08) × 10$^{-16}$ |
| H$\alpha$ $\lambda$6563 | (5.00 ± 0.05) × 10$^{-15}$ |
| [N ii] $\lambda$6584 | (9.81 ± 0.82) × 10$^{-18}$ |
| [S ii] $\lambda$6717 | (1.92 ± 0.08) × 10$^{-17}$ |
| [S ii] $\lambda$6731 | (1.82 ± 0.09) × 10$^{-17}$ |
| $c(H\beta)$ | 0.48 ±0.04 |
| $-W(H\beta)$ (Å) | 52 |

---

7 Hubble constant of $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, $\Omega_L = 0.7$, gives a luminosity distance 1115 Mpc for $z = 0.23$ (Wright 2006).
respectively, giving a ratio \( W_{2796}/W_{2803} = 0.6 \). The strength of the line \( \lambda 2803 \) component is comparable with that seen toward gamma-ray burst (GRB) lines of sight and somewhat higher than observed for PS1-12bam (Berger et al. 2012). The line ratio is significantly smaller than 2 (the ratio of their oscillator strengths), suggesting that we are not on the linear regime or on the square root regime on the curve of growth. Nevertheless, the absorption line strengths are similar to PS1-12bam and GRB sight lines. The Mg\text{\textsc{ii}} line centroids give identical redshifts (\( z = 0.231 \)) to the [O\text{\textsc{iii}}] emission lines (\( z = 0.230 \)) detected in the same spectrum.

The profile of the host galaxy appears slightly broader than the stellar point-spread function (PSF) on the best seeing images, hence we can estimate a physical diameter of the extended source. We measured the FWHMs of both the host galaxy (\( \sim 0.73 '' \)) and the average (\( \sim 0.58 '' \)) of 10 reference stars in the \( r \)-band image taken on 2011 January 14. Assuming the relation (galaxy observed FWHM)\(^2 \approx (\text{PSF FWHM})^2 + (\text{intrinsic galaxy FWHM})^2 \), we estimate a physical diameter of \( \sim 2.4 \) kpc at this redshift. The g-band absolute magnitude of the host galaxy is \( M_g = -17.42 \pm 0.17 \) after applying the Milky Way extinction of 0.13 (Schlafly & Finkbeiner 2011), a k-correction 0.27 \( \pm 0.08 \) (Chilingarian et al. 2010), and a correction for internal dust extinction of \( \sim 0.5 \) mag. The latter comes from the measured intrinsic H\text{\textalpha}/H\text{\beta} ratio and assuming \( R_V = 3.16 \) (applicable for an LMC environment; Pei 1992).\(^8\)

The observed photometric \( g-r, r-i \) color terms were corrected for Milky Way extinction (Schlafly & Finkbeiner 2011) and used to fit the spectral energy distribution (SED) of a stellar population model (Maraston 2005). We used the low-metallicity (\( Z \sim 1/20 Z_{\odot} \)) models, assuming a Salpeter initial mass function (IMF) with red horizontal branch morphology. The measured colors give reasonable agreement with a population model of age between 20 and 30 Myr. We further employed the MAGPHYS galaxy SED models of da Cunha et al. (2008). Figure 1 shows the observed SED and the redshifted MAGPHYS best-fit (\( \chi^2 = 0.58 \)) model spectrum with total stellar mass of \( 1.6 \times 10^8 M_{\odot} \); the fitting also gives a likelihood distribution of parameters, the \( \pm 1\sigma \) values of the likelihood distribution are \( 1.0 \times 10^8 \) and \( 2.2 \times 10^8 M_{\odot} \) separately. Hence an sSFR of \( (1.9-4.1) \times 10^{-9} \) yr\(^{-1} \).

4. DISCUSSION AND CONCLUSION

It has already been demonstrated that the peak luminosity of super-luminous SNe such as SN 2010gx cannot be due to \( 56\text{Ni} \) (Pastorello et al. 2010; Quimby et al. 2011; Chomiuk et al. 2011). Chomiuk et al. illustrated that applying Arnett’s rule (Arnett 1982) results in an unphysical solution, with the mass of \( 56\text{Ni} \) exceeding the total C+O ejecta mass, but see Gal-Yam et al. (2009) and Young et al. (2010). Our search for a luminous tail phase in SN 2010gx was not motivated by what powers the peak luminosity, rather it is to determine if there is any sign of radioactive \( 56\text{Co} \) at this stage and any similarity to \( 56\text{Ni} \)-rich Ic SNe such as SN 1998bw. The only robust conclusion we can draw is that there is unlikely to be any excessive mass of

\(^8\) This would be reduced by 0.05 mag if we used a value suitable for an SMC environment; \( R_V = 2.93 \) (Pei 1992).
Figure 2. Limiting luminosities of SN 2010gx (Pastorello et al. 2010; this work) compared with SN 1998bw (Clocchiatti et al. 2011), SN 2002ap (Tomita et al. 2006), and SN 2007gr (Hunter et al. 2009). At 244 days we have a flux limit similar to that of SN 1998bw. (A color version of this figure is available in the online journal.)

Figure 3. Top: spectrum of the host galaxy of SN 2010gx. The [O\text{III}]-4363 auroral line is shown in the inset. Bottom: luminosity–metallicity relationship for dwarf galaxies in the local Universe, showing the metallicity as measured using the direct (\Te) method, and using data from the literature listed in the figure key. (Skillman et al. 1989; Richer & McCall 1995; Lee et al. 2004; Hoyos et al. 2005; Lee et al. 2006; Kewley et al. 2007; Modjaz et al. 2008; Guseva et al. 2009; Amorín et al. 2012; Berg et al. 2012). Gray lines are the boundary of normal galaxy mass–metallicity relation adapted from Kudritzki et al. (2012), with metallicities calculated using blue supergiants. (A color version of this figure is available in the online journal.)
56\textsuperscript{Co} above and beyond about 0.4 \textit{M}_\odot (Figure 2). This limit on the late luminosity will also allow restrictions on the magnetor models of Kasen & Bildsten (2010) when put in context with other SLSNe of similar types (Inserra et al., in preparation).

Our detection of the [O \textsc{iii}] \lambda 4363 auroral line gives confidence to our measurement of the remarkably low metallicity of 12 + log(O/H) = 7.46 \pm 0.10 dex (0.06 \textit{Z}_\odot). In Figure 3 we show a compilation of other dwarf galaxies with the [O \textsc{iii}] \lambda 4363 direct method measurements, including four GRB hosts from Modjaz et al. (2008). The host of SN 2010gx is on the lower end and is amongst the lowest metallicity dwarf galaxies known. It has been clear from the early discoveries of these SNe at $z < 1$ (Pastorello et al. 2010; Quimby et al. 2011; Chomiuk et al. 2011) that the hosts are faint dwarf galaxies and Neill et al. (2011) showed that they have high SFRs. If the extremely low value we determine is a common factor amongst these SNe then it will be a major constraint on the progenitor channel.

The magnetar scenario suggested by Kasen & Bildsten (2010) to explain these SNe may benefit from low metallicity progenitors. Massive stars rotate more rapidly at Small Magellanic Cloud (SMC) metallicity (0.2 \textit{Z}_\odot) than solar (Martayan et al. 2007), although 0.06 \textit{Z}_\odot is unexplored territory. Evolutionary models of rotating stars have focused attention on low-metallicity environments as mass loss is reduced (Mokiem et al. 2007), hence angular momentum loss is lower (Maeder & Meynet 2000). The energy input required from a magnetar requires the neutron star to be both highly magnetic ($B \sim 10^{14}$ G) and rotating rapidly at formation ($P_r \sim 2–20$ ms). It must also occur in a Wolf–Rayet or carbon–oxygen star, since there is no sign of hydrogen in the spectra of SN 2010gx or any similar SNe. Gal-Yam (2012) gives an estimated relative rate of the number of 2010gx-like SNe compared to the total core-collapse SN rate of $10^{-4}$. This is probably uncertain by a factor of a few, and is more likely to increase due to previous events not being recognized as highly luminous. If the progenitor channel requires low metallicity (as we measure), high mass (to produce a WC star), and fast rotation (to produce a rapidly rotating magnetar), then this very low rate may not be unexpected. Young et al. (2008) estimate that \sim 1\% of the star formation in the Local Universe ($z < 0.4$) is in galaxies with $Z < 0.2 \textit{Z}_\odot$; around 13\% of massive stars above the SN threshold of 8 \textit{M}_\odot are \textgreater 60 \textit{M}_\odot (assuming a Salpeter IMF); and about 10\% of O-stars in the SMC rotate faster than \sim 300 km s$^{-1}$ (Mokiem et al. 2007). One can speculate that all of these three conditions are required to produce the rate of the 2010gx-like SNe and the estimated rate (which is itself uncertain) would be qualitatively reproduced. The high-mass requirement could also be substituted for an interacting binary system which causes spin-up in the CO core that collapses, similar to the proposed GRB systems (Cantiello et al. 2007). The Chevalier & Irwin (2011) scenario of interaction with a dense wind would probably require extreme progenitor mass and pulsational mass loss. The fact that we see Wolf–Rayet stars at very low metallicity (e.g., in IZw13 at 0.02 \textit{Z}_\odot; Brown et al. 2002) could suggest that pulsational mass loss is more prevalent at low metallicity. This one measurement is intriguing new information on these extreme SNe but further measurements of the metallicity, SFR, and volumetric rates of these SNe are required to constrain their explosion channels further.

S.J.S. acknowledges support from an European Research Council Advanced Grant. T.-W. Chen thanks Meng-Chun Tsai, Zheng Zheng, Kai-Lung Sun, Christy Tremonti, Elisabete da Cunha, Stephane Charlot, and Maryam Modjaz for useful advice.

**Facilities:** Gemini:South (GMOS), Gemini:Gillett (GMOS)

**REFERENCES**