CHANDRA DETECTION OF SN 2010da FOUR MONTHS AFTER OUTBURST: EVIDENCE FOR A HIGH-MASS X-RAY BINARY IN NGC 300

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ABSTRACT

We present the results of a 63 ks Chandra observation of the “supernova impostor” SN 2010da four months after it was first observed on 2010 May 24. We detect an X-ray source at ∼7σ confidence coincident with the optical location of the outburst. Our imaging analysis has revealed a hard central point source, surrounded by soft diffuse emission extending ∼8′ north of the central source. The diffuse emission has a hardness ratio (−0.4), 0.35–2 keV luminosity (∼6 × 1035 erg s−1), and size (∼70 pc) consistent with that of a supernova remnant, although the low number of counts prohibits detailed spectral modeling. The 0.5–6 keV spectrum of the central point source is well described by both a power law with Γ ∼ 0 and a blackbody with kT ∼ 1.8 keV, with no evidence for intrinsic absorption beyond the Galactic column. We estimate the 0.3–10 keV luminosity to be ∼2 × 1037 erg s−1, a factor of ∼25 decrease since the initial outburst. The high X-ray luminosity and slow fading rate is not consistent with this object being a single massive star undergoing an outburst. When combined with the optical and infrared properties of the outburst and progenitor systems, our X-ray observations suggest the SN 2010da system may be a Be X-ray binary system which experienced an extremely bright optical outburst near simultaneously with a bright, Type II X-ray outburst.

Key words: stars: massive – supernovae: individual (SN 2010da) – X-rays: binaries

1. INTRODUCTION

Supernova (SN) 2010da was first detected as an optical transient on 2010 May 24 in NGC 300 (Monard 2010). Within hours of the initial optical detection, SN 2010da was observed by the Swift X-ray Telescope (XRT; Immler et al. 2010), and an X-ray point source with a 0.2–10 keV luminosity of (4.5+0.5−0.4) × 1038 erg s−1 was found to be coincident with the optical outburst. Such optical transients are commonly assigned an official SN designation only to be later recognized as “impostors,” and frequently result from the outbursts of massive stars. However, the brightest stellar X-ray emitters have outburst luminosities on the order of 1035 erg s−1 (Guerrero & Chu 2008), three orders of magnitude lower than what was observed by Swift.

Such high X-ray luminosities are observed in high-mass X-ray binaries (HMXBs), consisting of a compact object primary with a secondary massive star, typically either a Be (non-supergiant, fast rotating B-type stars with spectral lines in emission) or an OB supergiant. Known Be/X-ray binaries (BeXBs) contain a neutron star in a wide, moderately eccentric orbit and undergo X-ray outbursts during periastron passage of the compact object. The majority of known HMXBs are BeXBs (∼60%; see Liu et al. 2006 and references therein), although the true fraction of BeXBs may be higher owing to the transient nature of the sources. Somewhat less numerous are supergiant X-ray binaries (SGXBs), consisting of a compact object orbiting within the wind of a supergiant OB star. These systems show persistent X-ray emission (with X-ray luminosities of 1035–1036 erg s−1) either from direct accretion of the stellar wind or from Roche lobe overflow via an accretion disk. Only a few dozen confirmed or suspected SGXBs are known in the Milky Way (Liu et al. 2006; Walter et al. 2006), although this number is increasing with higher energy surveys (i.e., Chaty et al. 2010). The relatively low number of SGXB systems is naturally explained by the short lifetimes of the supergiant companion stars.

In this Letter, we report an X-ray detection of SN 2010da taken by the Chandra X-Ray Observatory four months after the initial outburst, and argue that SN 2010da is consistent with being an extragalactic HMXB. We describe our observations and data reduction procedures in Section 2. The results of our imaging, hardness ratio analysis, spectral fitting, and time evolution since the outburst are presented in Section 3. In Section 4 we argue that SN 2010da is consistent with being a BeXB and summarize our results in Section 5. Throughout this work, we assume a distance to NGC 300 of 2.0 Mpc (Dalcanton et al. 2009) and all spectral models include a column of neutral absorption fixed at the Galactic column N_H,Gal of 4.09 × 1020 cm−2 (Kalberla et al. 2005).

2. OBSERVATIONS AND DATA REDUCTION

We have obtained a 63 ks observation of NGC 300 using the Chandra Advanced CCD Imaging Spectrometer (ACIS-I) on 2010 September 24. The X-ray observation was reduced using CIAO version 4.3 and CALDB version 4.4.2, using standard extraction procedures. We created exposure maps for the images using the CIAO script merge_all.4 Point sources were found using the CIAO task wavdetect,5 and positions, positional errors, and 0.5–8 keV fluxes were measured for each point source, and spectra were extracted for all sources using ACIS-Extract (AE; Broos et al. 2010) version 2011-03-15. AE is a multi-purpose source extraction and characterization tool which determines source and background count rates, fluxes, and significances. AE uses the MARX6 raytrace program to generate a source extraction region by finding the contour level

4 See http://cxc.harvard.edu/ciao/ahelp/merge_all.html.
5 See http://cxc.harvard.edu/ciao/ahelp/wavdetect.html.
6 See http://space.mit.edu/CXC/MARX/index.html.
Figure 1. Top left panel shows a raw RGB image of our observation; the extraction region determined by AE is shown in yellow. The white 18″ × 18″ box shows the same region as the adaptively smoothed RGB image in the top right panel. The same extraction region is shown in blue in our smoothed image. In both cases, red = 0.5–1 keV, green = 1–2 keV, and blue = 2–8 keV. The bottom panel shows a radial profile of the counts in our SN 2010da detection (black) and the Chandra point-spread function (red). A clear excess is seen past ∼6 pixels, corresponding to the diffuse emission in the top left and right panels.

which encloses 90% of the Chandra ACIS point-spread function (PSF) at the source location.

SN 2010da was detected at ∼7σ significance R.A. (J2000) = 00h55m04.s85 and decl. (J2000) = −37.4143.43, in excellent agreement (within 0.′2) with the position of the optical outburst (Monard 2010). The source is 3.8 off-axis from the Chandra aim point. We detect a net 71 source counts in the 0.5–8 keV band. The background was estimated using an annular region, centered on the source position, extending from a radius of 25″ to 30″ away from the source. The 0.5–8 keV background count rate was found to be ∼2 × 10^{-6} counts s^{-1} arcsec^{-2}.

All spectral fitting was performed in XSPEC (Arnaud 1996) v.12.6.0q. We use C-statistics in lieu of χ^2 statistics due to the low number of source counts. Errors correspond to the 90% confidence level. We report the C-statistic per degrees of freedom (C/dof) for each spectral model, and used the XSPEC command goodness to perform 10^4 Monte Carlo realizations of the SN 2010da spectrum using our best-fit model. The command returns the percentage of simulated spectra that had a fit statistic less than that obtained from the fit to the real data—a value of ∼50% indicates the best-fit model is a good representation of the data. Percentages much smaller than 50% indicate the data is overparameterized by the model, and percentages much higher than 50% indicate the model is a poor fit to the data. We denote the Monte Carlo goodness-of-fit percentage as MC.

We supplement our Chandra observation with archival X-ray data. The mid-outburst Swift XRT observations for SN 2010da are publicly available from the UK Swift Science Data Centre7 (Evans et al. 2009), where data products (i.e., spectra and light curves) are automatically generated. SN 2010da was detected by XRT at R.A. (J2000) = 00h55m05.02 and decl. (J2000) = −37.4144.5 with ∼270 counts. We use archival XMM-Newton images containing the SN 2010da progenitor within the field of view to estimate the 3σ upper limit on the precursor X-ray luminosity using the FLIX^8 web interface. The upper limits determined by FLIX are found using the algorithm described in Carrera et al. (2007).

3. RESULTS

3.1. Imaging and Hardness Ratios

Our Chandra observation was divided into three images consisting of different energy bands: “soft” (0.5–1 keV), “medium” (1–2 keV), and “hard” (2–8 keV). Each image was adaptively smoothed using the CIAO task csmooth.9 Figure 1 shows a raw red giant branch (RGB) image, a smoothed RGB rendering.
and the radial count distributions for both our detection and the Chandra PSF. The AE extraction region is shown in both images, and the surface brightness profile shows emission in excess of the PSF out to a radius \(\sim 8''\) (\(\sim 70\) pc) at \(\sim 4\sigma\) significance. The largest possible sphere of influence of the outburst would have a radius of only \(\sim 0.1\) pc, indicating the diffuse emission, if associated with the SN 2010da system, is the result of earlier activity in the system’s history.

The size and structure of the extended emission is reminiscent of a supernova remnant (SNR). We therefore calculate the hardness ratio of the diffuse emission, using the definition from Prestwich et al. (2003) and the Plucinsky et al. (2008) catalog of SNRs in M33: HR = \((M - S)/(S + M + H)\), where \(S\) is the soft 0.35–1.1 keV band, \(M\) is the medium 1.1–2.6 keV band, and \(H\) is the hard 2.6–8.0 keV band. The diffuse emission has a HR = −0.4; using the best-fit temperature of SNRs in M33 (\(kT \sim 0.6\) keV), we estimate a 0.35–2 keV luminosity of \(\sim 6 \times 10^{35}\) erg s\(^{-1}\). All these quantities are consistent with being an SNR; however, with only \(\sim 10\) net counts, we are unable to perform detailed spectral fitting to confirm this interpretation. We examined public H\(\alpha\) imaging of NGC 300\(^{10}\) and find a low-significance H\(\alpha\) knot coincident with the northern tip of the shell. We find no obvious, bright H\(\alpha\) emission coincident with the soft X-ray shell, making the source of the X-ray emission difficult to reliably classify.

We estimate the probability of an SNR falling within \(\sim 8''\) of the X-ray and optical outburst location. Due to its similarities in stellar mass, morphology, and star formation histories to NGC 300, we use the M33 catalog of 137 SNRs (Long et al. 2010) in our estimate. NGC 300 covers an area of \(\sim 270\) arcmin\(^2\) (from the optical \(D_{25}\) isophote), implying a density of \(\sim 0.5\) SNRs arcmin\(^{-2}\) or \(1.4 \times 10^{-4}\) SNRs arcmin\(^{-2}\). Within a search area of 200 arcsec\(^2\) (the size of the SN 2010da region considered in this work), this produces a probability of \(\sim 3\%\). This probability is likely a lower limit, since HMXBs and SNRs are preferentially found in star-forming regions.

The detection of diffuse emission surrounding the central X-ray point source has potentially interesting implications. If the emission is indeed an SNR, it may be the remains of the SN that produced the compact companion and would provide useful constraints on HMXB evolution models. Alternatively, ejecta from an earlier outburst event may interact with the surrounding ISM, producing shock-heated gas that radiates as soft X-rays. Assuming an outflow velocity of \(\sim 1000\) km s\(^{-1}\), we can roughly estimate the time since the last outburst to be \(\sim 20,000\) yr.

### 3.2. Spectral Fitting

Soft, thermal X-ray emission (such as from a stellar origin) does not provide an acceptable fit to our 0.5–6 keV spectrum. Allowing the temperature, abundances, or both to vary does not improve the goodness of the fit, and all two-temperature thermal plasma models overparameterize the data. Similarly, all models that included an absorption component beyond the Galactic column overparameterize the data.

The best-fit Swift spectral model is a power law with \(\Gamma = -0.03^{+0.11}_{-0.08}\), an unabsorbed 0.3–10 keV flux of \(8.6^{+1.6}_{-4.0} \times 10^{-13}\) erg s\(^{-1}\) cm\(^{-2}\), and a corresponding unabsorbed 0.3–10 keV luminosity of \(4.5^{+1.9}_{-2.1} \times 10^{38}\) erg s\(^{-1}\). This luminosity implies a super-Eddington outburst, assuming a 1.4 \(M_\odot\) neutron star. To directly compare our observation with the Swift spectrum, we model the 0.5–6 keV spectrum with a power law. We find a statistically acceptable fit for \(\Gamma = 0.15 \pm 0.42\), with \(C/dof = 276/511\) and \(MC = 58\%\). We next use the \(bbody\) model in XSPEC, which yields a temperature of \(kT = 1.75^{+0.04}_{-0.03}\) keV with \(C/dof = 242/373\) and \(MC = 67.29\%\). Both cases yield a 0.3–10 keV luminosity of \(1.6^{+2.4}_{-2.4} \times 10^{37}\) erg s\(^{-1}\); details of our spectral fitting are summarized in Table 1. Our best-fit blackbody spectral model and residuals are shown in Figure 2. In both cases, adding an additional absorbing column does not improve the quality of the fit; we therefore find no evidence for absorption beyond the Galactic column.

| Model                      | Parameter    | Best-fit Value               | Units          |
|----------------------------|--------------|------------------------------|----------------|
| Swift power law, during outburst | \(\Gamma\)    | \(\sim 0.03^{+0.11}_{-0.08}\) | \(10^{-13}\) erg s\(^{-1}\) cm\(^{-2}\) |
|                            | Unabs. flux  | \(8.6^{+1.6}_{-4.0}\)       | \(10^{-13}\) erg s\(^{-1}\) cm\(^{-2}\) |
|                            | Unabs. luminosity | \(4.5^{+1.9}_{-2.1}\)       | \(10^{38}\) erg s\(^{-1}\) |
|                            | \(C/dof\)   | 255/237                      |                |
| Chandra power law, post-outburst | \(N_H\)    | \(4.09 \times 10^{20}\) (fixed) | \(cm^{-2}\) |
|                            | \(\Gamma\)    | \(0.15 \pm 0.15\)           |                |
|                            | Unabs. flux  | \(4.5 \pm 2.5\)             | \(10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\) |
|                            | Unabs. luminosity | \(2.4 \pm 1.3\)            | \(10^{37}\) erg s\(^{-1}\) |
|                            | \(C/dof\)   | 276/511                      |                |
|                            | MC           | 58.14\%                      |                |
| Chandra blackbody, post-outburst | \(N_H\)    | \(4.09 \times 10^{20}\) (fixed) | \(cm^{-2}\) |
|                            | \(kT\)      | \(1.75^{+0.04}_{-0.03}\)    | \(keV\) |
|                            | Unabs. flux  | \(3.1^{+0.4}_{-1.1}\)       | \(10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\) |
|                            | Unabs. luminosity | \(1.6^{+0.2}_{-0.6}\)       | \(10^{37}\) erg s\(^{-1}\) |
|                            | \(C/dof\)   | 242/373                      |                |
|                            | MC           | 67.29\%                      |                |

Note. All reported fluxes and luminosities are unabsorbed, and correspond to a 0.3–10 keV energy range.

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\(^{10}\) Images obtained via NED, http://nedwww.ipac.caltech.edu/.
cases (Vela X-1 and GX 301-2) show continuum $\Gamma$-consistent spectra. The dashed line shows the expected distribution for a constant count rate. A two-sided K-S test against a constant count rate source yields a probability of 0.85, indicating our observation is consistent with a constant count rate. We attempt to further constrain the nature of the SN 2010da X-ray source using its time evolution. Figure 3 shows the cumulative photon arrival time distribution. While short-term variability is a common feature of HMXB systems, a two-sided Kolmogorov–Smirnov (K–S) test against a constant count rate source yields a probability of 0.85. While we do not detect rapid X-ray variability in our observation, we note that the low number of source counts makes our observation relatively insensitive to strong, rapid variability.

The long-term X-ray emission from SN 2010da can be constrained using four archival XMM-Newton observations (taken on 2000 December 26, 2001 January 1, 2005 May 22, and 2005 November 25) which contain the position of the SN 2010da progenitor within the field of view. During all four observations, the $3\sigma$ upper limit of the unabsorbed 0.3–10 keV luminosity is estimated to be $\sim(3–9) \times 10^{36}$ erg s$^{-1}$, two orders of magnitude lower than the observed outburst X-ray luminosity and $\sim3$ times lower than its current luminosity. These estimates are relatively insensitive to our choice of spectral model, and including heavy absorption as observed in the progenitor system changes our luminosity estimates by less than 20%. Figure 4 shows luminosity estimates from all available X-ray data for SN 2010da and the progenitor system.

We additionally compare the decay rate of the SN 2010da X-ray emission to decay of optical brightness. Multicolor optical photometry of SN 2010da in $B$, $V$, $R$, and $I$ bands was obtained during the outburst (Bond 2010) and nine days later (Prieto et al. 2010) on the SMARTS 1.3 m telescope at Cerro Tololo using the ANDICAM camera. We calculate the $\tau$-fold time for each optical filter and the X-ray emission. We use the X-ray luminosity derived from the unabsorbed $\Gamma \sim 0$ spectral model for both the Swift and Chandra observations to ensure the luminosity change is not due to a change in assumed spectral model between observations. We find $\tau$-fold times for X-ray, $B$, $V$, $R$, and $I$ bands to be 41, 13, 18, 20, and 11 days, respectively. Compared to the decay rates of the optical magnitudes, the X-ray emission decay rate is $\sim2$–4 times slower.

4. SN 2010da: A HIGH-MASS X-RAY BINARY?

The 0.5–6 keV spectrum of SN 2010da is well described by either a $\Gamma \sim 0$ power law or a blackbody with $kT \sim 1.8$ keV, both of which are used in the literature to describe known HMXB systems. The X-ray hardness and peak luminosity are consistent with the system possessing a neutron star primary. The X-ray luminosity of the progenitor ($\sim8 \times 10^{36}$ erg s$^{-1}$) and sharp increase in X-ray emission coincident with an increased mass-loss rate of the secondary further supports the HMXB scenario. Both the Chandra and Swift X-ray detections suggest that the X-ray outburst may have been fueled by a mass-loss event from the secondary, or that the optical outburst originated from an accretion event onto the primary.

To derive a self-consistent model constraining the physical properties of the secondary is beyond the scope of this Letter. However, if we estimate the mass of the progenitor star using a luminosity of $1.3 \times 10^6 L_\odot$ as estimated from the spectral energy distribution of the progenitor...
system (Prieto et al. 2010) and the mass–luminosity relation of main-sequence stars (above ~1 $M_\odot$; Demircan & Kahraman 1991), we estimate the mass of the SN 2010da progenitor to be ~11 $M_\odot$. Although many ATels have referred to this source as an “LBV outburst,” our low-mass estimate combined with the low luminosity (assuming all optical luminosity originated from the secondary) suggest a different class of star; for example, a Be-type star.

Be-type stars show line emission and excess infrared emission attributed to a circumstellar envelope (see Wilson et al. 2008 and references therein), both of which were observed in SN 2010da (Khan et al. 2010; Chornock & Berger 2010). Mass loss from the Be star changes the density of the surrounding disk, and drives the disk to become optically thick at optical/IR wavelengths (e.g., Negueruela et al. 2001; Miroshnichenko et al. 2001); BeXBs are therefore observed to brighten in the IR prior to outburst events, as was observed in the SN 2010da progenitor (Laskar et al. 2010). Additionally, the optical outburst spectrum of SN 2010da showed a He II λ4686 emission feature, often used as a signature of accretion around neutron stars in both low-mass and high-mass XRB systems (i.e., where streams impact the accretion disk or from disk winds; Still et al. 1997; Val Baker et al. 2005; Pearson et al. 2006).

X-ray variability in BeXBs can occur on timescales of seconds to years. Two types of outbursting activity are observed in these systems: the lower-luminosity, (quasi)periodic Type I outbursts, and the more luminous, longer-lived Type II outbursts, which show a 3–4 order of magnitude increase in X-ray luminosity (reaching the Eddington limit of a neutron star) and remaining luminous for months or longer (see Reig 2008 and references therein) as in SN 2010da. While BeXB outbursts are characterized by their X-ray properties, optical spectroscopic surveys of the Be companions have been undertaken in both the Milky Way (i.e., Reig 2011 and references therein) and the Small Magellanic Cloud (Coe et al. 2005; Antoniou et al. 2009). The optical absolute magnitudes of the Be companions reported in these catalogs are ~4 mag fainter than the observed SN 2010da outburst (Bond 2010). Such an extreme optical outburst that coincides with an X-ray outburst has not been observed in nearby BeXBs, and may be indicative of a giant stellar eruption of the secondary, a flaring event originating in the accretion disk around the neutron star, or some other related phenomenon.

We favor a BeXB interpretation of the outburst and progenitor observations of SN 2010da. The low luminosity of the progenitor star, the optical emission lines, and excess infrared emission are consistent with a Be star origin, with the hard X-ray emission observed by both Swift and Chandra originating from a neutron star companion. Additional optical and infrared photometric and spectroscopic monitoring of this system is required to confirm the theory of a Be companion star, and to better constrain the origin of the unusually luminous optical outburst that SN 2010da exhibited.

5. SUMMARY

We have obtained a 63 ks Chandra observation of SN 2010da, four months after it was initially detected on 2010 May 24. We detect an X-ray source at ~7σ confidence coincident with the optical location of the SN 2010da outburst. Our imaging analysis reveals a hard central point source, surrounded by soft diffuse emission extending as far as ~8" north of the central source. The hardness ratio (HR = −0.4), luminosity (~6 × 10$^{35}$ erg s$^{-1}$), and size (~70 pc) of the diffuse emission are consistent with typical SNRs in M33 (Plucinsky et al. 2008). However, with only ~10 net counts, detailed spectral modeling to confirm an SNR origin of the X-ray emission is impossible.

The central point source exhibits significantly harder X-ray emission, consistent with neutron star X-ray emission. The 0.5–6 keV spectrum is well described by either a Γ = ~0 power law or a blackbody with $kT \sim 1.8$ keV (with no evidence for intrinsic absorption beyond the Galactic column), consistent with well-known HMXB systems. We estimate the 0.3–10 keV luminosity to be 1.6$^{+0.2}_{-0.6}$ × 10$^{37}$ erg s$^{-1}$, a factor of ~25 decrease since the initial outburst four months previously. We use archival XMM-Newton images to constrain the 3σ upper limit X-ray luminosity of the progenitor to be (3–9) × 10$^{36}$ erg s$^{-1}$.

Deep follow-up X-ray observations, sensitive to a limiting luminosity of a few 10$^{35}$ erg s$^{-1}$, would be capable of verifying the quiescent X-ray luminosity of this system and would monitor the SN 2010da system for future outburst events that may strengthen the case for a BeXB origin. Additional sensitive observations may provide further evidence for an SNR origin of the diffuse emission. Time-resolved optical spectroscopy of the massive star may confirm the presence of a compact object primary and provide constraints on the masses and orbital parameters of this system.

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