ON THE NATURE OF THE PROGENITOR OF THE Type Ia SN2011fe IN M101

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ABSTRACT
The explosion of a Type Ia supernova, SN2011fe, in the nearby Pinwheel galaxy (M101 at 6.4 Mpc) provides an opportunity to study pre-explosion images and search for the progenitor, which should consist of a white dwarf (WD), possibly surrounded by an accretion disk, in orbit with another star. We report on our use of deep Chandra observations and Hubble Space Telescope observations to limit the luminosity and temperature of the pre-explosion WD. It is found that if the spectrum was a blackbody, then pre-SN WDs with steady nuclear burning of the highest possible temperatures and luminosities are excluded assuming moderate $n_H$, values, but values of $kT$ between roughly 10 eV and 60 eV are permitted even if the WD was emitting at the Eddington luminosity. This allows the progenitor to be an accreting nuclear-burning WD with an expanded photosphere 4–100 times the WD itself, or a super-critically accreting WD blowing off an optically thick strong wind, or possibly a recurrent nova with luminosities an order of magnitude lower than Eddington. The observations are also consistent with a double degenerate scenario, or a spinning down WD that has been spun up by accretion from the donor.

Key words: binaries: close – supernovae: general – X-rays: binaries

Online-only material: color figures

1. INTRODUCTION

Type Ia supernovae (SNe Ia) can serve as standardizable candles to large cosmological distances, and have enabled us to discover and study the acceleration of universal expansion (Riess et al. 1998; Perlmutter et al. 1999). While there is a general consensus that an SN Ia results from the thermonuclear explosion of a carbon–oxygen white dwarf (WD) with a mass equal to the Chandrasekhar mass $M_{\text{Ch}}$ (∼1.4 $M_\odot$ for a C–O WD; e.g., Hamda & Salpeter 1961), and that the WD must have a companion that donated mass to it, the exact nature(s) of the companion and the mode(s) of mass transfer are still unknown (see Hillebrandt & Niemeyer 2000 for reviews). In single degenerate (SD) models, the WD accretes matter from its companion. The companion may be a main-sequence star, subgiant, or giant; it may fill its Roche lobe and/or donate mass through winds. In double degenerate (DD) models, matter is donated by another WD, and there may be a merger (e.g., Webbink 1984; Iben & Tutukov 1984; Dan et al. 2011).

The explosion of an SNe Ia (SN2011fe) located at R.A. = 14:03:05.8, decl. = +54:16:25.4; Nugent et al. (2011) in M101, a well-studied galaxy located only 6.4 Mpc away (Shappee &Stanek 2011), allows us to search for the progenitor in pre-explosion images. Of special interest are Chandra observations from the Megasecond survey of M101 in 2003 (PI: Kuntz). SN2011fe was not detected in the Chandra images (Liu 2008, 2011; Li et al. 2011), and our preliminary analysis placed an upper limit on X-ray luminosity of $3–5 \times 10^{35}$ erg s$^{-1}$ (0.3–8 keV; Soderberg et al. 2011). However, this upper limit is expressed in X-ray luminosity in 0.3–8 keV, which is vastly different from the bolometric luminosity more relevant for an exploding WD. In this paper, we use the X-ray data to constrain the bolometric luminosity of the WD that was about to explode. We compute the expectations from each of several possible models to interpret the significance of the lack of a detectable pre-SN X-ray source.

We also predict the level of optical emission that might be expected from an actively accreting WD and the disk that channels mass to it. This allows us to further test the accretion model by comparing the expectations with the results of pre-SN optical observations. Li et al. (2011) have used historical imaging to constrain the optical luminosity of the progenitor to be 10–100 times fainter than previous limits on other SN Ia progenitors. By doing so, they have ruled out luminous red giants and the vast majority of helium stars as the donor, and found that any evolved red companion must have been born with mass $\lesssim 3.5 M_\odot$. These observations favor a model where the pre-explosion WD of SN2011fe accreted matter either from another WD or by Roche lobe overflow from a subgiant or main-sequence companion star. We consider whether the optical observations place additional limits on the accretion model.

In Section 2, we outline the expectations based on both theoretical work and the results of prior observing programs. In Section 3, we use a blackbody with large ranges of bolometric luminosities and temperatures to represent the pre-SN WD, and check whether the pre-SN Chandra observations would have detected it. Additional constraints from pre-SN Hubble Space Telescope (HST) observations are also employed to constrain the expanded photosphere and the combination of donor and accretion disk. We discuss the implications of our results in Section 4.

2. EXPECTATIONS

An important channel for SNe Ia is WDs accreting at $\dot{M}_{\text{stable}} \simeq 1.32 \times 10^{-7} M_\odot \text{yr}^{-1} < \dot{M} < \dot{M}_{\text{crit}} \simeq 9 \times 10^{-7}(M - 0.5) M_\odot \text{yr}^{-1}$, which can sustain steady or quasi-steady nuclear burning of the accreted materials without ejecting the matter in nova-like events (Nomoto 1982; Iben 1982; Rappaport et al. 1994). For a carbon–oxygen WD about to explode with $M \simeq 1.4 M_\odot$, this accretion rate range corresponds to $4–8 \times 10^{-7} M_\odot \text{yr}^{-1}$, or a bolometric luminosity range of $L_{\text{bol}} \simeq X_H 10^{11} M L_\odot \simeq 1-2 \times 10^{38} \text{erg s}^{-1}$ for $X_H = 0.64$ as adopted
in Iben (1982). Such a WD, with a radius of \( \sim 0.003 R_\odot \), will have a temperature of \( \sim 110–130 \) eV for the above accretion rate range based on Iben (1982; see his Figure 2). Such a system can appear as luminous supersoft X-ray sources (SSSs; van den Heuvel et al. 1992; Rappaport et al. 1994; Kahabka & van den Heuvel 1997). The WD temperature may become cooler based on \( L_{\text{bol}} = 4\pi R^2 \sigma T^4 \) if the WD photosphere expands as observed for some local SSSs (e.g., CAL 83; Greiner & Di Stefano 2002).

When the accretion rate exceeds \( M_{\text{crit}} \), the WD may accrete materials in an optically thick strong wind as suggested by Hachisu et al. (1996, 1999). Such models consist of an accreting WD and a Roche lobe filling low-mass red giant that may suffer from unstable mass transfer. However, the presence of a strong wind from the accreting WD can stabilize the mass transfer when the mass ratio, \( q \), between the mass-losing star and the mass-accreting WD is below 1.15, i.e., \( q < 1.15 \), or even for systems with \( q > 1.15 \) if the wind can strip mass from the red giant very efficiently. A part of the transferred matter can be accumulated on the WD at a rate up to \( M_{\text{crit}} \), and the rest is blown off in the optically thick strong wind. The WD steadily burns the accreted matter, thereby being able to reach \( M_{\text{Ch}} \) and explode as an SN Ia. The photospheric temperature is kept around \( \sim 10–20 \) eV during the strong wind phase. For a pre-SN WD of \( \sim 1.4 M_\odot \), the luminosity from burning the accreted matter can be as high as \( 2 \times 10^{38} \text{ erg s}^{-1} \) for hydrogen nuclear-burning efficiency.

When the accretion rate is slightly below \( M_{\text{stable}} \), the WD appears as a recurrent nova, one possible channel for SNe Ia as recently realized (e.g., Nelson et al. 2008). Unlike classical novae with much lower accretion rates that expel all the accreted materials during the explosive hydrogen burning, recurrent novae undergo weaker shell flashes and may expel only a fraction of the accreted mass (e.g., Prialnik & Kovetz 1995). The rest of the accreted hydrogen materials are burned into helium materials that sink to the WD surface and are thus retained. For example, the detailed nova models of Prialnik & Kovetz (1995) find that the accretion rate of \( M \sim 10^{-7} M_\odot \text{ yr}^{-1} \) onto an \( M \approx M_{\text{Ch}} \) WD leads to a recurrent nova with a nuclear burning, hence a retention rate of \( \sim 30\% \), \( L_{\text{bol}} \approx 10^{37} \text{ erg s}^{-1} \), and \( T \approx 50 \) eV. In addition, recurrent novae may undergo short intervals of steady hydrogen burning with near-Eddington luminosities, as suggested by the supersoft X-ray phase observed for RS Ophi after its 2006 outburst (Osborne et al. 2011). To summarize, the pre-SN WD can have a large range of accretion rates and may appear as a supersoft source with a large range of bolometric luminosities and temperatures, with the highest possible luminosities of \( 1–2 \times 10^{38} \text{ erg s}^{-1} \) and the hottest temperatures of \( 110–130 \) eV for steady nuclear burning on the WD surface.

Di Stefano & Rappaport (1994) found that nuclear-burning WDs with these properties could be detected in external galaxies, unless there was an extraordinary amount of absorption. The possibility of detecting SNe Ia progenitors prior to explosion inspired searches with Chandra and XMM-Newton for bright, hot SSSs in external galaxies. An algorithm was developed and applied to about half a dozen early-type and late-type galaxies (Di Stefano et al. 2003; Kong & Di Stefano 2003). The results were that the numbers of SSSs in external galaxies of all types were at least one to two orders of magnitude smaller than required to support the hypothesis that the majority of SNe Ia derive from nuclear-burning WDs that are bright at X-ray wavelengths during the time they are accreting and burning matter (Di Stefano et al. 2006, 2009; Di Stefano 2007, 2010a, 2010b). A study of diffuse emission in several early-type environments also found similar results (Gilfanov & Bogdan 2010).

The lack of SSSs is not evidence for a lack of nuclear-burning WDs. A modest change in photospheric radius would shift the spectrum to longer wavelengths, making the sources undetectable in X-ray. In fact, there is evidence that the local population of nuclear-burning WDs can switch "off" and "on" as SSSs when the photosphere expands or contracts, even though their bolometric luminosity remains high (e.g., CAL 83; Greiner & Di Stefano 2002). A second effect, the absorption of the soft radiation by circumbinary material, is also possible, and may be expected even when the donor is a subgiant or main-sequence star that has enough mass to donate to bring the WD to \( M_{\text{Ch}} \). This is especially true if the WD binary has undergone a strong wind phase that generates thick circumbinary medium as suggested by Hachisu et al. (1996, 1999).

A more direct test is to look for pre-SN X-ray emission from the locations of recent SNe Ia in nearby galaxies. There have been no reliable detections of pre-explosion X-rays from the site of an SN Ia. Nielsen et al. (2011) have derived upper limits for the X-ray and bolometric luminosities for ten SNe Ia progenitors. The upper limits for most systems are above a few \( \times 10^{38} \text{ erg s}^{-1} \) and cannot constrain the progenitor models. They derived an upper limit for SN2011fe of about a few times \( 10^{38} \text{ erg s}^{-1} \) at 100 eV, seemingly to exclude a steady nuclear-burning WD model. However, as we will point out in Section 3, their methodology is not appropriate and the resulted upper limits cannot be used to rule out pre-SN emission from a nuclear-burning WD.

3. PRE-SN CHANDRA AND HST OBSERVATIONS

The location of SN2011fe was observed by Chandra ten times during 2003 (PI: Kuntz, Table 1). The data were analyzed using uniform procedures as described in our Chandra/ACIS survey of nearby galaxies (Liu 2008, 2011); SN2011fe was not detected in any of these observations. For this paper we merged the ten observations using standard procedures as implemented in the merge_all script distributed with the CIAO package. The location of SN2011fe has an equivalent total effective exposure time of 226 ks after vignetting corrections for individual observations (Table 1). Since a supersoft source is expected, we use only photons below 1 keV to suppress the background photons. Using CIAO 3.3, we ran wavdetect on the merged observation in the 0.3–1 keV band with scales of 1″, 2″, 4″, and 8″. No point source is detected at the location of SN2011fe, and no apparent feature is found by visual inspection.

The upper limit for SN2011fe is estimated by summing up photons from ten observations as listed in Table 1. Photon events are extracted from the SN2011fe location with three different circular apertures, which are the point-source function (PSF) enclosing 95% of the source photons at 0.5 keV, 3′′5 as the exposure-weighted PSF size, and 5′′ as the PSF size for large off-axis angles. The background is carefully estimated from visually inspected surrounding annuli or nearby circular regions if the location is close to the chip edges. After background subtraction as listed in Table 1, we obtain a net count of \( -0.1 \pm 2.9, 0.9 \pm 2.9, \) and \( -0.4 \pm 3.2 \) in the 0.3–1 keV for the three apertures, respectively, or \( <3.8 \) regardless the aperture chosen. Here the errors are computed as Gehrels errors from the number of photon counts \( N \) in the aperture as \( \sigma = 1 + \sqrt{N} + 0.75 \) (Gehrels 1986). Because a progenitor could have a supersoft X-ray spectrum, we
also estimate the photon counts in the 0.1–1 keV band. There are only a few photons below 0.3 keV at the location of SN2011fe, and we obtain a net count rate of −0.9 ± 3.2, 1.3 ± 3.4, and −1.5 ± 3.6 for the three apertures respectively in the 0.1–1 keV band, or <4.7 regardless the aperture chosen.

To be conservative, we place an upper limit of four net counts for SN2011fe in the 0.3–1 keV band. Although the lack of photons below 0.3 keV may place stringent constraints on the supersoft X-ray spectrum of the progenitor, we choose to adopt the 0.3–1 keV band in the following because the instrument response below 0.3 keV is little known. This corresponds to a count rate of \( \lesssim 1.8 \times 10^{-5} \) counts s\(^{-1}\), or a flux of \(<8.6 \times 10^{-17}\) erg s\(^{-1}\) cm\(^{-2}\) (0.3–1 keV) assuming a \(kT = 100\) eV blackbody spectrum and a foreground absorption of \(n_H = 1.2 \times 10^{20}\) cm\(^{-2}\) (Dickey & Lockman 1990), or a luminosity of \(<6.2 \times 10^{35}\) erg s\(^{-1}\) (0.3–1 keV) given the distance of 6.4 Mpc (Shappee & Stanek 2011). In comparison, assuming a power-law spectrum with \(\Gamma = 1.7\) typical for X-ray binaries will lead to a luminosity of \(<1.8 \times 10^{35}\) erg s\(^{-1}\) in the 0.3–1 keV band.

Emission in X-ray wavelengths would represent only a small fraction of the bolometric luminosity as released through accretion and nuclear burning, especially for SSSs. To link the count rate directly to bolometric luminosity and determine accurately whether \(Chandra\) observations can constrain the pre-explosion WD of SN2011fe, we fold a blackbody spectrum through the \Chandra/ACIS-S response matrix to estimate the net counts expected in 226 ks using fakeit under the X-ray fitting package xspec 12.7.0e. Figure 1 shows the expected net counts for different blackbody temperatures and bolometric luminosities of \(L_{bol} = 2 \times 10^{37}, 1 \times 10^{38}, 2 \times 10^{38},\) and \(2 \times 10^{39}\) erg s\(^{-1}\). An \(M = M_{CH}\) WD with steady nuclear burning would have an effective temperature of 110–130 eV and a bolometric luminosity of \(1–2 \times 10^{38}\) erg s\(^{-1}\). For \(L_{bol} = 2 \times 10^{38}\) erg s\(^{-1}\) with a Galactic \(n_H = 1.2 \times 10^{20}\) cm\(^{-2}\), pre-SN \Chandra\ observations would have collected 108–176 net photons in the 0.3–1 keV band. Given the photon count errors of \(\sigma \approx 3\) and upper limit of \(<4\) net counts for SN2011fe, such a hot WD can be excluded at the \(\gtrsim 30\)σ level. For a lower luminosity of \(1 \times 10^{38}\) erg s\(^{-1}\), pre-SN \Chandra\ observations would have collected 55–90 net photons, a possibility that can be excluded at the \(\gtrsim 15\)σ level.

In addition to the exclusion of a very hot WD, an important message of Figure 1 is the strong temperature dependence of the \Chandra\ count rates. For \(kT \lesssim 60\) eV, the count rate is so small that even a WD emitting at the Eddington luminosity may not have been detected in M101. We therefore compute the blackbody temperature above which the WD would have been detected by pre-SN \Chandra\ observations with bolometric luminosities ranging from \(10^{36}\) to a few \(\times 10^{39}\) erg s\(^{-1}\) over a wide range of temperatures. This is plotted as a red solid curve for a detection threshold of four net counts in the upper part of Figure 2. Systems in the shaded region above this curve would have been detected by \Chandra\ and are thus ruled out by the non-detection. Systems in the unshaded region below this curve would not have been detected and remain viable models. These include WDs burning matter at the Eddington rate but emitting the radiation from an expanded photosphere with

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Expected net counts in 0.3–1.0 keV for a blackbody spectrum with different temperatures under bolometric luminosities of \(L_{bol} = 2 \times 10^{37}, 1 \times 10^{38}, 2 \times 10^{38},\) and \(2 \times 10^{39}\) erg s\(^{-1}\) when observed by the merged pre-SN \Chandra\ observations assuming a Galactic \(n_H = 1.2 \times 10^{20}\) cm\(^{-2}\), and for \(L_{bol} = 2 \times 10^{38}\) with \(n_H = 1 \times 10^{21}\) cm\(^{-2}\). (A color version of this figure is available in the online journal.)}
\end{figure}

\begin{table}
\centering
\begin{tabular}{cccccccccc}
\hline
OBsID & Texp & OAA & PSF & VgF & TST & C100 & C100 & B100 & B100 & BArea \\
\hline
4732.s3 & 70691 & 6.49 & 5.9 & 0.197 & 13926 & 1, 1, 1 & 1, 1, 1 & 9 & 3 & 400 \\
4733.s3 & 25132 & 4.33 & 3.1 & 0.296 & 7459 & 0, 0, 0 & 0, 0, 0 & 8 & 6 & 400 \\
4735.s3 & 29148 & 3.55 & 2.4 & 0.910 & 26525 & 0, 0, 0 & 0, 0, 0 & 11 & 6 & 300 \\
5303.s3 & 52761 & 6.83 & 6.3 & 0.801 & 42262 & 2, 1, 2 & 2, 1, 2 & 12 & 10 & 300 \\
5309.s3 & 71679 & 6.50 & 5.9 & 0.180 & 12902 & 0, 0, 0 & 0, 0, 0 & 16 & 10 & 400 \\
5323.s3 & 43161 & 4.26 & 3.0 & 0.375 & 16185 & 1, 1, 1 & 0, 0, 0 & 4 & 4 & 400 \\
5339.s3 & 14505 & 2.08 & 1.4 & 0.177 & 2567 & 0, 0, 0 & 0, 0, 0 & 5 & 3 & 300 \\
6114.s3 & 67052 & 3.56 & 2.4 & 0.910 & 61017 & 0, 1, 1 & 0, 0, 0 & 26 & 12 & 300 \\
6115.s3 & 36217 & 3.56 & 2.4 & 0.910 & 32957 & 0, 0, 0 & 0, 0, 0 & 5 & 3 & 300 \\
6118.s3 & 11606 & 3.55 & 2.4 & 0.909 & 10550 & 0, 1, 1 & 0, 1, 1 & 3 & 1 & 300 \\
\hline
\end{tabular}
\caption{Pre-SN Chandra Observations for SN2011fe}
\end{table}
temperatures lower than 60 eV, and WDs accreting materials at a rate exceeding \( \dot{M}_{\text{crit}} \) blowing off an optically thick strong wind with photospheric temperatures of 10–20 eV.

The above results can be modified when different \( n_H \) values are used. In the above calculations, a Galactic value of \( n_H = 1.2 \times 10^{20} \text{ cm}^{-2} \) is adopted assuming \( \text{SN}2011fe \) is in front of M101. Inspection of the H i map of M101 (Walter et al. 2008) shows that \( \text{SN}2011fe \) is in an H i hole in the spiral arm, with an H i column density of \( \sim 6 \times 10^{19} \text{ cm}^{-2} \) intrinsic to M101. Assuming \( \text{SN}2011fe \) is in front of M101 will change \( n_H \) to about \( 2 \times 10^{20} \text{ cm}^{-2} \); however, this change only affects the results slightly at the low luminosities as shown in Figure 2. Greater \( n_H \) values are possible, e.g., due to the presence of circumbinary medium from the common envelope phase, and the predicted X-ray photons may be reduced significantly. To illustrate this effect, we have computed the cases for higher values of \( n_H = 10^{21}, 3 \times 10^{21}, 10^{22} \text{ cm}^{-2} \), for which the computed curves move up gradually as plotted in Figure 2. Unless in the most extreme case of \( n_H = 10^{22} \text{ cm}^{-2} \), an \( M = \dot{M}_{\text{Ch}} \) WD with steady nuclear burning can be excluded as shown in Figure 2.

An expanded photosphere pushes the radiation to longer wavelengths and can therefore be constrained in the optical with pre-SN HST observations. As reported by Li et al. (2011), only upper limits can be derived for the progenitor. To obtain these limits, we photometer the HST observations, taken with ACS/WFC in three filters (F435W, F555W, F814W; Pf; Kuntz), using the PSF-fitting package dolphot (Dolphin 2000). Based on the detected 2\( \sigma \) point-like objects on the same images, we derive the 2\( \sigma \) detection limits in STMAG as 28.3 mag, 28.0 mag, and 27.5 mag in the F435W, F555W, and F814W filters, respectively. Note that these limits are roughly 0.5 mag deeper than those derived by Li et al. (2011) because we use the PSF-fitting photometry in this dense stellar field, while Li et al. make very conservative estimates with the local background light.

To check whether the expanded photosphere would have been detected by pre-SN HST observations, its expected optical light is compared to the 2\( \sigma \) detection limits for HST observations as shown on the \( vF_v \) plot in Figure 3. Based on this comparison, we compute the blackbody temperature below which the expanded photosphere would have been detected by HST observations for bolometric luminosities ranging from \( 10^{36} \) to a few \( 10^{39} \text{ erg s}^{-1} \). This is plotted as the blue dashed curve above the shaded region in the lower part of Figure 2. Clearly, the pre-SN HST observations would have detected an expanded photosphere with \( L_{\text{bol}} = 2 \times 10^{38} \text{ erg s}^{-1} \) and \( kT \lesssim 10 \text{ eV} \), or an expanded photosphere with \( L_{\text{bol}} = 3 \times 10^{37} \text{ erg s}^{-1} \) and \( kT \lesssim 5 \text{ eV} \) in the shaded region, thus ruling them out. Models in the unshaded region above the dashed curve and below the solid curve could not be detected by either pre-SN HST or Chandra observations, and thus cannot be ruled out.
The accretion model can be further constrained when the optical light from the accretion disk and the donor is considered. Li et al. (2011) have shown that the donor could have been born with a mass no larger than 3.5 \( M_\odot \). We consider a 2.5 \( M_\odot \) subgiant, which by itself provides flux not too much below the \( HST \) limit. To compute the radiation from the disk, we consider a standard multi-color disk model but include the effects of irradiation (for a detailed discussion, see Popham & Di Stefano 1996). Figure 3 shows an example of a realistic system, including radiation from the WD, the donor, and the disk, which cannot be ruled out. As shown in Figure 2, the addition of the accretion disk and the donor further excludes some expanded photosphere models that are allowed if only the photosphere is considered.

Nature has provided some realistic systems with all of the above components, with some resembling the allowed models considered here. As shown in Table 2 and Figure 2, the deep pre-SN \( HST \) observations would have detected the M101 analog of the recurrent nova RS Ophi in its supersoft phase during the outburst (e.g., Osborne et al. 2011) unless \( n_H \) exceeds the Galactic plus M101 value greatly. The supersoft X-ray source CAL 87 in LMC (Greiner et al. 1991), if placed in M101, could have been detected by \( CHANDRA \), but could also have been missed by \( CHANDRA \) given the large uncertainties in its temperature, especially when \( n_H \) is greatly enhanced by the presence of circumstellar medium. The M101 analog of RX J0513.9–6951 could not be detected by \( CHANDRA \), but would have been detected by \( HST \).

Some less luminous SSSs, if placed in M101, could not be detected by either \( CHANDRA \) or \( HST \) observations. These include CAL 83 with a high WD mass of 1.3\( \pm 0.3 \ M_\odot \) (Lanz et al. 2005), RX J0537.7–7034 (Orio et al. 1997), and RX0019.8+2156 (Greiner & Wenzel 1995). Both CAL 83 and RX J0537.7–7034 exhibited X-ray on and off states, suggestive of photosphere expansion and contraction, on timescales of months to years. During the X-ray off state, SSSs can brighten by up to a magnitude in the optical, making the already optically bright CAL 83 possibly detectable with pre-SN \( HST \) observations.

Nielsen et al. (2011) found much lower luminosity limits for the same temperatures, which would have detected even CAL 83. However, the X-ray to bolometric luminosity conversion factors they apparently used for spectral peak temperatures \( T_{\text{peak}} \) = 30/50/100/150 eV were actually the factors for the blackbody temperatures \( T_{\text{BB}} \) = 30/50/100/150 eV that correspond to \( T_{\text{peak}} = 2.7 \times T_{\text{BB}} \). This will lead to bolometric luminosity upper limits 10\(^0\)/2000/16/4 times lower. In addition, they used exposure maps for 30/50/100/150 eV, even though the \( CHANDRA \)/ACIS-S response matrix is not to be trusted or used below 0.3 keV. The approach we use here does not require use of the low-energy response matrix.

### 4. DISCUSSION

As new optical surveys discover large numbers of SNe Ia, they are becoming ever more important resources for measuring...
cosmological parameters. Rather than being dominated by statistics, the uncertainties are now dominated by systematic effects. The most important of these is likely to be related to the progenitor model, since environmental circumstances such as the amount of gas and dust in the vicinity of the explosion, and the presence of a donor can affect observable explosion and post-explosion characteristics.

Given its relative proximity and the extensive pre-SN observations, SN2011fe in M101 provides a unique opportunity to constrain the SNe Ia progenitor models. Unfortunately, though, in all SNe Ia progenitor models the pre-SN system is much dimmer than is typical for core collapse supernovae, making detection difficult. Even in SD models, which are relatively bright, the top bolometric luminosity of the WD is likely to be comparable to the Eddington luminosity, \(\sim 2 \times 10^{38} \text{erg s}^{-1}\). The disk will be dimmer, typically by one or two orders of magnitude. Unless the donor is a giant, a possibility ruled out by Li et al. (2011), it is expected to be much dimmer than the disk. Therefore, the existing data so far neither select a unique model nor rule out most models.

Nevertheless, important information has been derived that places limits on the progenitor system of SN2011fe. Li et al. (2011) rule out bright optical emission that would be associated with a giant or supergiant donor. In this paper we rule out the 110–130 eV blackbody emission with \(L_{\text{bol}} = 1 - 2 \times 10^{38} \text{erg s}^{-1}\) at the \(\geq 15\sigma - 30\sigma\) level assuming a Galactic \(n_{\text{HI}} = 1.2 \times 10^{20} \text{cm}^{-2}\). This rules out that the progenitor WD was a Chandrasekhar mass WD accreting and burning matter steadily, with a photosphere comparable in size to the WD itself. If there is local enhancement of neutral hydrogen in the circumbinary medium, the non-detection in \(\text{Chandra}\) observations is less constraining. For moderate \(n_{\text{HI}}\) values of up to a few times \(10^{21} \text{cm}^{-2}\), the Chandrasekhar mass WD with such temperature and luminosities can still have been detected by \(\text{Chandra}\). For extremely high \(n_{\text{HI}}\) values of \(\geq 10^{22} \text{cm}^{-2}\), however, such a pre-SN WD could not have been detected by \(\text{Chandra}\) observations as shown in Figure 2.

Still allowed, regardless of the \(n_{\text{HI}}\) values, would be a nuclear-burning WD emitting at near Eddington luminosity with \(kT\) less than 60 eV but higher than 10 eV when both \(\text{Chandra}\) and \(\text{HST}\) observations are considered. These include a WD with an expanded photosphere 4–100 times the WD itself, or a WD accreting at \(M > M_{\text{crit}}\) but burning accreted matter at a rate of \(M = M_{\text{crit}}\) with the rest blown away from the WD in an optically thick strong wind (Hachisu et al. 1996, 1999). The non-detections are also consistent with WD models with lower luminosities and slightly larger range of temperatures as shown by the unshaded region in Figure 2. These include sub-Chandrasekhar WDs with quasi-steady nuclear burning on their surface (as shown in Figure 2 of Iben 1982), and recurrent novae such as RS Ophi in the quiescent state (\(L_{\text{bol}} \sim 10^{35} \text{erg s}^{-1}\), \(kT \sim 1 \text{eV}\); Zamanov et al. 2010). Also allowed are some local candidates for nuclear burning WDs as listed in Table 2. A recurrent nova outburst like the 2006 outburst of RS Ophi would certainly have been detected by pre-explosion \(\text{Chandra}\) observations. The non-detection, however, is not necessarily evidence against the recurrent nova scenario because the 10 pre-explosion \(\text{Chandra}\) observations in 2003 covered less than one year and may have missed the outburst completely. Li et al. (2011) investigated the stacked images of 12 years before explosion from different monitoring programs and conclude that a typical nova would have been detected with a probability of 63%. It is still possible for the monitoring programs to miss the outbursts in 12 years, especially in the first seven years with sparse sampling and shallow detection thresholds, given that the recurrent rate for an exploding WD can be as long as a few years (e.g., Shen & Bildsten 2009) and the outbursts fade by 3 mag in a few days (Prialnik & Kovetz 1995).

The expanded photosphere models and the recurrent nova scenario can be tested further with the presence or the absence of H \(\text{II}\) regions. Despite the difference in accretion rates and hydrogen-burning efficiencies, both can be modeled as a black-body with temperatures mostly above 15 eV. Like Wolf–Rayet stars, these models will photoionize the surrounding materials from the common envelope stage, if exist, and make SN2011fe progenitor appear as H \(\text{II}\) regions. We searched the Hodge et al. (1990) and the Snowden et al. (1992) catalogs of H \(\text{II}\) regions in M101, and found no known H \(\text{II}\) regions within 20′ of SN2011fe location. An upper limit of \(1.6 \times 10^{-14} \text{erg s}^{-1} \text{cm}^{-2}\) for \(H_{\alpha}\) flux is placed using the faintest H \(\text{II}\) region in Snowden et al. (1992), or \(8 \times 10^{-15} \text{erg s}^{-1}\) given the distance of M101, or \(5 \times 10^{10} \text{H}_{\alpha}\) photons s\(^{-1}\). A blackbody emitter with bolometric luminosity of \(2 \times 10^{38} \text{erg s}^{-1}\) can produce at most \(4.1 \times 10^{38}\) photons above 13.6 eV s\(^{-1}\) when the blackbody temperature is 6.3 eV. Even assuming the highest photoionizing efficiency, this blackbody emitter will produce \(H_{\alpha}\) photons ten times lower than the Snowden upper limit. Thus, the non-detection of H \(\text{II}\) regions cannot exclude the expanded photosphere models or the recurrent nova scenario.

The non-detection of SN2011fe in pre-explosion \(\text{Chandra}\) and \(\text{HST}\) observations can also be explained if there indeed is no hydrogen burning on the exploding WD. This is possible if the accretion has spun up the WD so that it remains stable with mass exceeding \(M_{\text{Ch}}\). Such a fast rotating WD needs to spin down for it to explode as type Ia SN (e.g., Di Stefano et al. 2011). The spin-down phase can take a long time, without accretion from the donor thus no X-ray emission from hydrogen burning. The exploding WD in the DD scenario also lacks hydrogen burning or an accretion disk that can radiate in the X-ray, thus consistent with the non-detections. This is because the two WD are detached for as long as Hubble time without any mass transfer before gravitational radiation drives them into contact and merge in a few tens of orbits (e.g., Dan et al. 2011). Such a double WD system in M101 cannot be detected directly with optical or X-ray observations and can be confirmed only by gravitational wave experiments or by excluding the SD scenario.

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