A COMPACT DEGENERATE PRIMARY-STAR PROGENITOR OF SN 2011fe

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ABSTRACT

While a white dwarf (WD) is, from a theoretical perspective, the most plausible primary star of a Type Ia supernova (SN Ia), many other candidates have not been formally ruled out. Shock energy deposited in the envelope of any exploding primary contributes to the early SN brightness and, since this radiation energy is degraded by expansion after the explosion, the diffusive luminosity depends on the initial primary radius. We present a new non-detection limit of the nearby SN Ia 2011fe, obtained at a time that appears to be just 4 hr after explosion, allowing us to directly constrain the initial primary radius ($R_p$). Coupled with the non-detection of a quiescent X-ray counterpart and the inferred synthesized 56Ni mass, we show that $R_p \lesssim 0.02 \, R_\odot$ (a factor of five smaller than previously inferred), that the average density of the primary must be $\rho_p > 10^4$ g cm$^{-3}$, and that the effective temperature must be less than a few $\times 10^5$ K. This rules out hydrogen-burning main-sequence stars and giants. Constructing the helium-burning and carbon-burning main sequences, we find that such objects are also excluded. By process of elimination, we find that only degeneracy-supported compact objects—WDs and neutron stars—are viable as the primary star of SN 2011fe. With few caveats, we also restrict the companion (secondary) star radius to $R_c \lesssim 0.1 \, R_\odot$, excluding Roche-lobe overflowing red giant and main-sequence companions to high significance.

Key words: supernovae: individual (2011fe, white dwarfs) – supernovae: general

1. INTRODUCTION

While the nature of the explosion that leads to a Type Ia supernova (SN Ia)—detonation (Woosley et al. 1986; Livne & Arnett 1995), deflagration (Nomoto et al. 1976), or both (Khokhlov 1991)—and the process that leads to the explosion trigger are not well known, it is commonly assumed that an SN Ia is powered by the explosion of a white dwarf (WD) at a pressure and temperature sufficient to ignite carbon (Nomoto 1982; Iben 1984). All viable SN Ia models of the progenitor system include a companion (secondary) star that transfers mass (either steadily or violently) to the WD (Nomoto et al. 1997; Podsiadlowski et al. 2008). Single-degenerate channels involve the transfer of mass from a giant, main sequence, or helium star (Whelan & Iben 1973; Nomoto 1982; Munari & Renzini 1992; Han & Podsiadlowski 2004). Double-degenerate channels involve the merger of two WDs (Webbink 1984; Iben & Tutukov 1984).

There is considerable circumstantial evidence that the primary is a C+O WD (Hoyle & Fowler 1960), but until recently (Nugent et al. 2011; see also Brown et al. 2011 for a similar analysis) there have been very few direct constraints. The evidence is (1) neither hydrogen nor helium are seen in SNe Ia (Leonard 2007), and few astrophysical objects lack these elements, (2) the elements synthesized in SN Ia are consistent with the fusion chain leading from carbon going up to the iron peak,

(3) degenerate objects can result in runaway, explosive burning,

(4) the energy gained from burning a WD matches that seen in an SN Ia, and

(5) simulations of the explosions of C+O WD stars are successful at reproducing SN Ia spectra (e.g., Nomoto 1982). However, the discovery of a class of SNe Ia that require a WD mass above the Chandrasekhar limit (Howell et al. 2006) has caused some to question whether a WD is involved in the explosion after all (Taubenberger et al. 2011).

The SN Ia SN 2011fe was discovered in the Pinwheel Galaxy (M101) more than two weeks before it hit maximum brightness on 2011 September 12 UT (Nugent et al. 2011). To date, SN 2011fe provides some of the best constraints on the progenitor system of an SN Ia: coupled with a well-measured distance modulus to M101 ($DM = 29.05 \pm 0.23$ mag; Shappee & Stanek 2011), the non-detection of a quiescent counterpart at optical, infrared, mid-infrared, and X-ray wavebands were used to place strict limits on the nature of the progenitor system. With optical imaging reaching $\sim 100$ times fainter than previous limits, Li (2011), Nugent et al. (2011), and Horesh et al. (2011) showed that Roche-lobe overflow red giants as the secondary star were excluded; He-star + WD progenitor systems were also largely excluded. Nugent et al. (2011) placed constraints on double-degenerate models based on the non-detection of early-time emission from shock interaction with the disrupted secondary WD material (Shen et al. 2011).

Rather than focus on the progenitor system as a whole, in this Letter we investigate what can be gleaned about the primary

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star, the body directly responsible for powering the SN. Nugent et al. (2011) have previously noted that the primary size was small ($R_p \lesssim 0.1 R_\odot$) based on considerations of the early-time light curve. They concluded, based also on carbon and oxygen observed in the early-time spectra, that a C+O WD was the likely primary. Here, coupling a new, more stringent radius measurement and explicitly discussing mass constraints (based on explosive yield) and temperature constraints (from quiescent non-detection) we narrow the parameter space for the primary even further. Whereas the Nugent et al. (2011) radius constraint was insufficient to rule out carbon-burning main-sequence stars, our results appear to exclude such bodies. By process of elimination, we find that a WD (or a neutron star, NS) are the only allowable primary candidates.

2. PRIMARY CONSTRAINTS

2.1. Mass

As a manifestly “normal” SN Ia (spectroscopically and in peak brightness), SN 2011fe is expected to show the characteristic decline of the half-life of the radioactive process $^{56}$Co $\rightarrow$ $^{56}$Fe, which in turn suggests at least $\sim 0.5 M_\odot$ of synthesized $^{56}$Ni powered the early light curve (e.g., Hoeflich & Khokhlov 1996). We thus consider $M_{p,\mathrm{lim}} = 0.5 M_\odot$ as a conservative lower limit to the mass of the primary; this value is below the lower-mass limit ($M_{p,\mathrm{lim}} = 0.7$) for sub-luminous SN Ia models (Sim et al. 2010; Woosley & Kasen 2011). While a Chandrasekhar mass, $M_{\mathrm{ch}} = 1.4 M_\odot$, is typically invoked for the primary, there are no stringent upper limits on the primary mass. To accommodate so-called super-Chandrasekhar events, we thus consider a conservative mass range for the primary to be $M_p = 0.5$ to $3 M_\odot$.

2.2. Radius

Observations for several days after discovery of SN 2011fe showed a remarkable $r^2$ behavior of the optical light curve, attributed to radioactive heating of the SN ejecta (Nugent et al. 2011). Extrapolating the light curve back in time to zero flux gave an explosion date of $t_0 = 55796.687 \pm 0.014$ MJD (UT 2011 August 23, 16:29 $\pm$ 20 minutes; Nugent et al. 2011). Importantly, the lack of a significant flux excess above the $r^2$ behavior at the $t_0 + 11$ hr discovery image suggested little-to-no contribution from shock heating (see below), allowing Nugent et al. (2011) to place a constraint on the primary to be $R_p \lesssim 0.1 R_\odot$.

Starting about 7.5 hr before the Palomar Transient Factory (PTF) discovery image, we had fortuitously acquired a series of images of M101, covering the position of SN 2011fe for one hour; the data were obtained on PIRATE (Physics Innovations Robotic Astronomical Telescope Explorer) on the The Open University’s 0.4 m telescope in Mallorca (Holmes et al. 2011). We analyzed these images and found no significant excess flux at the SN location (Figure 1). Since the filter system was clear we translated the non-detection to a $g$-band magnitude equivalent under the assumption of a range of blackbody temperatures of the shock. For blackbody temperatures in the range 3000–150,000 K, we find a robust upper limit of $g = 19.0$ AB mag at 5σ (at a mean time of 3.92 hr post-explosion). We use this new non-detection to constrain the primary radius under several different shock models.

\[ L(t) = 1.2 \times 10^{40} \frac{R_{10} E_{51}^{0.85}}{M_{30}^{0.69} \kappa_{0.2} f_p^{0.16} I_d^{0.31}} \text{ erg s}^{-1} \]

\[ T_{\text{eff}}(t) = 4105 \frac{R_{10}^{1/4} E_{51}^{0.016} M_{30}^{0.03} \kappa_{0.2}^{0.27} I_d^{0.47}}{f_p^{0.022}} \text{ K}, \]

where $R_{10}$ is the progenitor radius $R_p/10^{10}$ cm, $E_{51}$ is the explosion energy $E/10^{51}$ erg, $M_{30}$ is the progenitor mass in units of $M_\odot$, and $\kappa_{0.2}$ is the opacity $\kappa/0.2$ cm$^2$ g$^{-1}$. These expressions assume a constant opacity, which is appropriate when electron scattering dominates in fully ionized C/O ejecta. The factor $f_p$ depends on the density profile of the primary star, and has estimated values in the range 0.031 and 0.13 (Calzavara & Matzner 2004; Rabinak et al. 2011).

We constructed theoretical light curves of the early optical luminosity assuming the spectrum was given by a blackbody with $T_{\text{eff}}$, and the flux at the effective wavelength of the filter.
Figure 2. Absolute $g$-band magnitude vs. time since explosion in three theoretical models for the early-time shock-heated evolution of Type Ia SNe. Shown is 4 hr, 5σ non-detection discussed in Section 2.2 and the first two detections from PTF (Nugent et al. 2011). The black line shows the $L \propto t^2$ radioactive-heating behavior seen in later-time PTF data, consistent with the non-detection. For the Kasen (2010) companion interaction model, Fig. 2. the separation distance between the two stars, and the light curve is shown for an observer aligned with the collision axis, which produces the brightest observed luminosity.

(given the temperature) was consistent with the non-detection. Figure 2 shows the results for a selection of different analytical models, assuming $E_{51}/M_c = 1$ (constant explosive yield per unit mass), $f_p = 0.05$, $k_{0.2} = 1$, and a variety of values of $R_p$. The PIRATE observation at 4 hr is the most constraining data point, which limits $R_p \lesssim 0.02\, R_\odot$. Table 1 summarizes the detailed radius constraints under different assumptions of progenitor mass and under the different models.

The expressions we have used for the early luminosity hold only under the assumption that radiation energy dominates in the post-shock ejecta. In fact, the diffusion wave will eventually recede into higher density regions of ejecta where gas pressure dominates. The luminosity is then expected to drop suddenly; Rabinak et al. (2011) show that, for constant opacity, the time $t_{\text{drop}}$ determined in Table 1, suggesting that the breakdown of radiation energy domination is not likely to undermine our results.

The early photometry of SN 2011fe also tightly constrains the nature of a possible companion star. The interaction of the SN ejecta with a companion star produces emission which depends linearly on the separation distance (Kasen 2010). This emission will be anisotropic and vary by a factor of $\sim 10$ depending on the orientation. Assuming the companion star in Roche-lobe overflow, such that its radius is $\lesssim 1/2$ of the separation distance, and that the observer’s viewing angle is unfavorable (such that the light curve is fainter by a factor of 10 from its maximum) our data restrict the companion star radius to $R_c \lesssim 0.1\, R_\odot$. Unless the time since explosion for the PIRATE data is vastly underestimated (by $\gtrsim$ day), this apparently excludes Roche-lobe overflowing red giant and main-sequence companions to high significance.

### Table 1

| $M_p$ | $R_{p,\text{max}}$ | $\rho_p$ | $L_{\text{shock}}$ | $T_{\text{shock}}$ |
|------|------------------|---------|------------------|------------------|
| $M_\odot$ | $(R_\odot)$ | (g cm$^{-3}$) | (erg s$^{-1}$) | (K) |
| Shock breakout—Rabinak et al. (2011)$^b$ |
| 0.5... | 0.022 | $6.29 \times 10^4$ | 4.50 $\times 10^{39}$ | 6024 |
| 1.0... | 0.020 | $1.77 \times 10^5$ | 4.48 $\times 10^{39}$ | 6043 |
| 1.4... | 0.019 | $2.93 \times 10^5$ | 4.47 $\times 10^{39}$ | 6053 |
| 3.0... | 0.017 | $9.16 \times 10^5$ | 4.46 $\times 10^{39}$ | 6075 |
| Ejecta heating secondary—Kasen (2010)$^c$ |
| 0.5... | 0.038 | $1.26 \times 10^4$ | 3.94 $\times 10^{39}$ | 8043 |
| 1.0... | 0.027 | $7.05 \times 10^4$ | 3.96 $\times 10^{39}$ | 7388 |
| 1.4... | 0.023 | $1.58 \times 10^5$ | 4.00 $\times 10^{39}$ | 7103 |
| 3.0... | 0.017 | $9.29 \times 10^5$ | 4.18 $\times 10^{39}$ | 6531 |
| Shock breakout—Piro et al. (2010)$^d$ |
| 0.5... | 0.016 | $1.73 \times 10^4$ | 5.27 $\times 10^{39}$ | 12110 |
| 1.0... | 0.019 | $2.07 \times 10^5$ | 5.26 $\times 10^{39}$ | 12091 |
| 1.4... | 0.021 | $2.26 \times 10^5$ | 5.26 $\times 10^{39}$ | 12082 |
| 3.0... | 0.025 | $2.75 \times 10^5$ | 5.25 $\times 10^{39}$ | 12062 |

Notes.

$^a$ 5σ limit assuming the 4 hr non-detection (see the text) and shock opacity $\kappa = 0.2$ cm$^2$ g$^{-1}$.

$^b$ Assumes $f_p = 0.05$ and $E_{51}/M_c = 1$. Extremum values of $f_p (0.03-0.13)$ change $R_{p,\text{max}}$ by no more than 20% from that given. Fixing $E_{51} = 1$ yields an $R_{p,\text{max}}$ about 50% smaller at $M = 0.5\, M_\odot$ and about two times larger at $M = 3.0\, M_\odot$.

$^c$ The radius derived is the separation distance and the limit derived is assuming the brightest possible viewing angle. The radius limit comes from the requirement that primary size must be smaller than the semimajor axis of the binary.

$^d$ Using their Equations (35) and (36) but corrected by a factor of $\approx 7^{-1/3}(L)$ and $7^{-1/3}(T_{\text{eff}})$ to fit the improper scalings.

Temperature–radius. Non-detections of a quiescent counterpart in Hubble Space Telescope (HST) imaging yield a specific luminosity ($L_\nu$) constraint at certain optical frequencies. With the assumption of a spectrum of the primary, these limits can be turned into a limit on the bolometric luminosity ($L$). Li (2011) considered mostly spectra of an unseen secondary, using model input spectra of red giants to derive $L$ constraints. For a high effective temperature primary, here we consider a blackbody as the input spectrum and solve for the bolometric luminosity and effective radius using the Stefan–Boltzmann law (see also Liu et al. 2011 for a similar analysis). We perform a similar analysis with the Chandra X-ray non-detection, convolving different input blackbody spectra to find a radius limit. At $10^6$ K, for example, the limits (1σ, 2σ, and 3σ) are $1.2 \times 10^{-3}\, R_\odot$, $1.5 \times 10^{-3}\, R_\odot$, and $1.8 \times 10^{-3}\, R_\odot$.

In Figure 3, we show these primary-star constraints as a function of effective temperature and average density. Primary stars with average density less than $\rho_p = 10^4$ g cm$^{-3}$ and effective temperatures larger than $10^6$ K ($\rho_p = 10^{12}$ g cm$^{-3}$) are excluded.

3. COMPARISONS TO PRIMARY CANDIDATES

Accepting $0.5\, M_\odot$ as a conservative lower limit for the primary mass, low-mass main-sequence stars, brown dwarfs, and planets are not viable. In Figure 3, we show the main sequence of stably H-burning stars with mass 0.5, 1, 1.4, and $3\, M_\odot$. The hydrogen main sequence, shown using solar-metallicity isochrones from Marigo et al. (2008), is excluded as...
the SN 2011fe primary. Accepting the radius constraints, giants (not plotted) are also excluded for the primary of SN 2011fe.

We also constructed idealized He- and C-burning main-sequence stars with the stellar evolution code MESA (Paxton et al. 2011). Uniform composition stars (with the stellar evolution code MESA (Paxton et al. 2011)). Uniform composition stars (e.g., Timmes & Swesty 2000), and nuclear reactions (Caughlan & Fowler 1988) were employed, including recently updated triple-$\alpha$, $\alpha+^{12}$C, and $^{12}$C+^{12}C rates. These results are plotted in Figure 3 for He star masses of 0.5, 1.0, 1.4, and 3.0 $M_\odot$, and C star masses of 1.0, 1.4, and 3.0 $M_\odot$: stable configurations of C stars supported by nuclear burning do not exist below 1.0 $M_\odot$ (Boozer et al. 1973). Comparisons to previous He star calculations (e.g., Divine 1965) and C star calculations (e.g., Sugimoto et al. 1968) match to ~10% in the radius and effective temperature. Evidently, He-main-sequence stars and C-burning main-sequence stars are also excluded as the SN 2011fe primary.

Several WDs in eclipsing binary systems, with measured temperature, radii, and mass, are shown in Figure 3 (SDSS1210: Pyrazas et al. 2012; V471 Tau: Pyrazas et al. 2009; Sirius B: Barstow et al. 2005). We also depict the isolated NS RX J185635–3754 ($M \approx M_\odot$), which has strong observed constraints on temperature and density (Pons et al. 2002). These systems are all allowed by our constraints. Note that SDSS1210 ($M = 0.415 \pm 0.1 M_\odot$; $R = 0.0159 \pm 0.002 R_\odot$; $\rho \approx 1.3–1.6 \times 10^5$ g cm$^{-3}$) is a He WD and has a mass less than our suggested $M_p > 0.5$ constraint. It is also marginally excluded by the Piro et al. (2010) model.

4. SUMMARY AND DISCUSSION

We have placed limits on the average density, effective temperature, and radius of the primary (exploding) star of the Type Ia SN SN 2011fe. We consider the $g = 19.0$ AB mag non-detection as conservative and assuming that the $i^2$ behavior accounted for some of the flux at 4 hr, the flux from the shock inferred from this non-detection would necessarily have been even smaller than that derived from $g = 19.0$ AB mag. In this respect, we take the radius constraint of the primary to be very conservative with the important proviso: if the explosion time was significantly earlier than the time inferred from the $i^2$ fit, the radius constraints are less stringent. In particular, if the PIRATE observations occurred at $t_0 + 28$ hr instead of $t_0 + 4$ hr, then $R_p \lesssim 0.2 R_\odot$ (still sufficient to rule out H and He main sequences but not the C MS). Another important caveat is the radius constraint requires shock heating, naturally expected with a deflagration–detonation transition (Khokhlov 1991). A pure deflagration of a WD that does not produce a strong shock would not exhibit the early-time behavior of the models presented in Table 1; however, pure deflagration is disfavored on nucleosynthetic grounds (e.g., Nomoto et al. 1984). With these caveats aside, these are the most stringent limits on the primary radius and temperature of an SN Ia reported to date.

Clearly, the density and temperature in the core of a primary are higher than the reported constrained quantities; and since at high density and high central temperature a star may be supported by pressure other than that associated with fermionic degeneracy pressure, we cannot formally exclude all non-degenerate stars. However, by process of elimination we find that only compact degenerate objects (WD, NS) are allowed as the explosive primary. That is, we suggest that the progenitor could not have been a non-degenerate star that followed a reasonable evolutionary path. This statement comes from considerations almost orthogonal to the traditional spectral modeling in SNe Ia that are invoked to claim WDs as the exploding primary. Since the explosive nucleosynthetic yield from the phase transition of an NS to a quark star is expected to be very small (~0.1 $M_\odot$ in $r$-process elements) and is unlikely to produce light elements (Jaikumar et al. 2007), an NS primary is likewise disfavored.

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15 “Double-detonation” scenarios (Woosley & Weaver 1994) could also lead to heating, but with (slightly) different heating than considered by the models in Section 3.

16 As noted in Nugent et al. (2011), the early observations of C and O in the spectrum are highly suggestive that the primary was a C+O WD.
