Type Iax Supernovae

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Author’s version of a review chapter in the *Handbook of Supernovae*, edited by Athem W. Alsabti and Paul Murdin, Springer International Publishing, DOI 10.1007/978-3-319-20794-0

Abstract Type Iax supernovae (SN Iax), also called SN 2002cx-like supernovae, are the largest class of “peculiar” white dwarf (thermonuclear) supernovae, with over fifty members known. SN Iax have lower ejecta velocity and lower luminosities, and these parameters span a much wider range, than normal type Ia supernovae (SN Ia). SN Iax are spectroscopically similar to some SN Ia near maximum light, but are unique among all supernovae in their late-time spectra, which never become fully “nebular”. SN Iax overwhelmingly occur in late-type host galaxies, implying a relatively young population. The SN Iax 2012Z is the only white dwarf supernova for which a pre-explosion progenitor system has been detected. A variety of models have been proposed, but one leading scenario has emerged: a type Iax supernova may be a pure-deflagration explosion of a carbon-oxygen (or hybrid carbon-oxygen-neon) white dwarf, triggered by helium accretion to the Chandrasekhar mass, that does not necessarily fully disrupt the star.

1 Introduction

Type Iax supernovae (SN Iax) are a class of objects similar in some observational properties to normal type-Ia supernovae (SN Ia), but with clear differences in their light-curve and spectroscopic evolution. SN Iax are also called “02cx-like” supernovae, based on the exemplar SN 2002cx, which was described by Li et al. (2003) as “the most peculiar known” SN Ia. Later, Jha et al. (2006) presented other similar objects, making SN 2002cx “the prototype of a new subclass” of SN Ia. Foley et al. (2013) coined the SN Iax classification, arguing these objects should be separated from SN Ia as “a new class of stellar explosion.”

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Here I summarize the properties of SN Iax, describing their observational properties in Section 2 and models in Section 3. I discuss analogues of SN 2002cx and well-studied examples like SN 2005hk (Chornock et al. 2006; Phillips et al. 2007; Stanishev et al. 2007; Sahu et al. 2008), SN 2008A (McCully et al. 2014b), SN 2012Z (Stritzinger et al. 2015; Yamanaka et al. 2015), and SN 2014ck (Tomasella et al. 2016) as well as more extreme members of the class like SN 2008ha (Foley et al. 2009; Valenti et al. 2009) and SN 2010ae (Stritzinger et al. 2014). There may be some connection between SN Iax and other classes of peculiar white-dwarf supernovae (like SN 2002es-like objects; Ganesalingam et al. 2012; White et al. 2015; Cao et al. 2016) but I restrict my focus to SN Iax here; other peculiar objects are explored by Taubenberger (2016).

2 Observations

In this section I discuss the identification and classification of SN Iax, followed by their photometric and spectral properties from early to late time. I also discuss the host environments of SN Iax, their rates, and pre- and post-explosion high-resolution imaging.

2.1 Identification and Classification

Supernovae are traditionally classified by their maximum light optical spectra, and SN Iax are no exception. These objects have spectra very similar to some normal SN Ia, particularly the “hot” SN 1991T-like or SN 1999aa-like objects, with typically weak Si II absorption and prominent Fe III lines (Nugent et al. 1995; Li et al. 2001). The key discriminant for SN Iax is the expansion velocity; unlike typical SN Ia where the line velocity (usually measured with Si II) is around 10,000 km s\(^{-1}\), SN Iax have much lower line velocities anywhere from 6000 – 7000 km s\(^{-1}\) (for objects like SN 2002cx, 2005hk, 2008A, 2012Z, and 2014dt) down to 2000 km s\(^{-1}\) (for objects like SN 2009J). Figure 1 shows maximum-light spectra of SN Iax with a range of expansion velocities, compared to normal SN Ia. Because line velocities are not always measured or reported when SN are classified and host redshifts are sometimes uncertain, on occasion SN Iax have been misclassified as normal SN Ia. Indeed, it is possible to identify unrecognized SN Iax in past observations, like SN 1991bj (Stanishev et al. 2007). Table 1 gives a list of 53 objects that have been classified as SN Iax.

2.2 Photometric properties

The optical light curves of SN Iax show a general similarity to SN Ia, though with more diversity. SN Iax typically have faster rises (∼10 to 20 days) in all bands, with pre-maximum

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1 One speculates how the history of supernova cosmology would have changed if the diversity in SN Ia were not only typified by the extremes SN 1991T and SN 1991bg, but SN 1991bj as well, a SN Iax that would fall off the luminosity/light-curve decline rate relationship!
Type Iax Supernovae

Table 1 Partial list of type Iax supernovae. Host galaxies, redshifts, and estimated peak absolute magnitudes are from the Open Supernova Catalog (Guillochon et al. 2017). The references listed present the classification and/or maximum-light data and are incomplete.

| Supernova     | Host Galaxy | \( z \)   | \( M_{\text{peak}} \) | References                                      |
|---------------|-------------|-----------|------------------------|------------------------------------------------|
| SN 1991bj     | IC 344      | 0.018     | −15.3                  | Stanishev et al. (2007)                          |
| SN 1999az     | A140357+1551| 0.023     | −18.3                  | Foley et al. (2013)                              |
| SN 2002bp     | UGC 6332    | 0.020     | −16.4                  | Silverman et al. (2012)                          |
| SN 2002cx     | CGCG 044-035| 0.023     | −18.8                  | Li et al. (2003)                                 |
| SN 2003gq     | NGC 7407    | 0.021     | −17.2                  | Jha et al. (2006)                                |
| SN 2004cs     | UGC 11001   | 0.014     | −16.1                  | Foley et al. (2013)                              |
| SN 2004gw     | CGCG 283–003| 0.017     | −16.9                  | Foley et al. (2009)                              |
| SN 2005P      | NGC 5468    | 0.009     | −14.8                  | Jha et al. (2006)                                |
| SN 2005cc     | NGC 5383    | 0.007     | −17.6                  | Antilogus et al. (2005)                          |
| SN 2005hk     | UGC 272     | 0.013     | −18.5                  | Chornock et al. (2006); Phillips et al. (2007); |
|               |             |           |                        | Stanishev et al. (2007); Sahu et al. (2008)     |
| SN 2006hn     | UGC 6154    | 0.017     | −18.9                  | Foley et al. (2009)                              |
| SN 2007J      | UGC 1778    | 0.017     | −17.2                  | Filippenko et al. (2007)                         |
| SN 2007ie     | SDSS J1736.67+003647.6| 0.093 | −18.2                  | Ostman et al. (2011)                            |
| SN 2007qd     | SDSS J0932.72–005959.7| 0.043 | −16.2                  | McClelland et al. (2010)                        |
| SN 2008A      | NGC 634     | 0.016     | −19.0                  | McCully et al. (2014b)                          |
| SN 2008ae     | IC 577      | 0.030     | −18.8                  | Blondin and Calkins (2008)                       |
| SN 2008ge     | NGC 1527    | 0.003     | −17.4                  | Foley et al. (2010)                              |
| SN 2008ha     | UGC 12682   | 0.004     | −14.0                  | Foley et al. (2009); Valenti et al. (2009)      |
| SN 2009J      | IC 2160     | 0.015     | −15.9                  | Stritzinger (2009)                               |
| SN 2009ho     | UGC 1941    | 0.048     | −18.2                  | Steele et al. (2009)                             |
| SN 2009ku     | A032953–2805| 0.079     | −17.9                  | Narayan et al. (2011)                            |
| PTF 09egk     | SDSS J172625.23+625821.4| 0.104 | −18.6                  | White et al. (2015)                              |
| PTF 09eyi     | 0.06        |           |                        | White et al. (2015)                              |
| PTF 09eoi     | SDSS J232412.96+124646.6| 0.042 | −16.7                  | White et al. (2015)                              |
| SN 2010ae     | ESO 162-G17 | 0.003     | −14.0                  | Stritzinger et al. (2014)                        |
| SN 2010el     | NGC 1566    | 0.005     | −13.0                  | Bessei and Schmidt (2010)                        |
| PTF 10jk      | ...         | 0.066     | −17.1                  | White et al. (2015)                              |
| SN 2011ay     | NGC 2315    | 0.021     | −18.1                  | Szalai et al. (2015)                             |
| SN 2011ce     | NGC 6708    | 0.008     | −17.1                  | Maza et al. (2011)                               |
| PTF 11hyb     | SDSS J014550.37+143501.9| 0.057 | −18.7                  | White et al. (2015)                              |
| SN 2012ZZ     | NGC 1309    | 0.007     | −18.1                  | White et al. (2015)                              |
| PS1-12bwh     | CGCG 205–021| 0.023     | −16.2                  | Magee et al. (2017)                              |
| LSQ12hs       | ...         | 0.033     | −18.2                  | Copan et al. (2017)                              |
| SN 2013dh     | NGC 5936    | 0.013     | −17.3                  | Jha et al. (2013)                                |
| SN 2013en     | UGC 11369   | 0.015     | −17.9                  | Liu et al. (2013)                                |
| SN 2013gr     | ESO 114-G7  | 0.007     | −15.4                  | Hao et al. (2013b)                               |
| OGLE-2013-SN-130| ...         | 0.09      | −18.0                  | Bessell et al. (2013)                            |
| OGLE-2013-SN-147| ...         | 0.099     | −19.3                  | Le Guillou et al. (2013)                         |
| iPTF 13an     | 2MASX J12141590+1532096| 0.080 | ...                    | White et al. (2015)                              |
| SN 2014ck     | UGC 12182   | 0.005     | −15.5                  | Tomsella et al. (2016)                           |
| SN 2014cr     | NGC 6806    | 0.019     | −17.0                  | Childress et al. (2017)                          |
| LSQ14dtt      | 0.05        |           |                        | Elias-Rosa et al. (2018)                         |
| SN 2014dt     | NGC 4303    | 0.005     | −18.6                  | Foley et al. (2015); Fox et al. (2016)           |
| SN 2014ek     | UGC 12850   | 0.023     | −18.0                  | Zhang and Wang (2014)                            |
| SN 2014ey     | CGCG 048–099| 0.032     | −18.1                  | Lyman et al. (2015)                               |
| SN 2015H      | NGC 3464    | 0.012     | −17.7                  | Magee et al. (2016)                              |
| PS15ac        | 2MASX J13304792+3806450| 0.056 | −17.9                  | Pan et al. (2015)                                |
| SN 2015ce     | UGC 12156   | 0.017     | −17.9                  | Balam (2017)                                     |
| PS15cse       | ...         | 0.044     | −17.5                  | Harmanen et al. (2015)                           |
| SN 2016aw     | ...         | 0.065     | −18.0                  | Pan et al. (2016)                                |
| OGLE16erd     | ...         | 0.035     | −17.1                  | Dimitriadi et al. (2016)                         |
| SN 2016ilf    | 2MASX J02351956+3511426| 0.045 | −17.6                  | Zhang et al. (2016)                              |
| iPTF 16fmm    | UGC 00755   | 0.022     | −15.0                  | Miller et al. (2017)                             |
Fig. 1 Near-maximum light spectra of SN Iax compared to normal and 91T/99aa-like SN Ia. The left panel shows the similarity of SN Iax to normal SN Ia (including the weak presence of S II lines sometimes considered hallmarks of thermonuclear SN), but also the lower expansion velocities (e.g., compare the locations of the Si II lines). The right panel shows the range of SN Iax expansion velocities, from the lowest velocity SN 2009J ($v_{\text{exp}} \approx 2200$ km s$^{-1}$) at the top, SN 2005cc ($v_{\text{exp}} \approx 5000$ km s$^{-1}$) intermediate, and SN 2008A ($v_{\text{exp}} \approx 6400$ km s$^{-1}$) at the bottom, also compared to the normal SN 1999aa below. Note the similarity in the spectra as the lower-velocity objects are smoothed and shifted to resemble the higher-velocity objects. Figure adapted from McCully et al. (2014) and Foley et al. (2013).

light curves showing significant variety (Magee et al. 2016, 2017). The $B$ and $V$-band decline rates are similar to normal SN Ia, though generally also on the faster side (Stritzinger et al. 2015), and the optical color evolution in SN Iax (e.g., in $B-V$) has a shape roughly similar to normal SN Ia (Foley et al. 2013). However, SN Iax have significantly slower declines in redder bands, e.g., $\Delta m_{15}(R) \approx 0.2$ to 0.8 mag, compared to normal SN Ia which have $\Delta m_{15}(R) \approx 0.6$ to 0.8 mag (Magee et al. 2016). Faster rising SN Iax are generally faster fading as well, with some exceptions, like SN 2007qd (McClelland et al. 2010). SN Iax do not show the prominent “second-peak” in the redder and near-infrared bands (González-Gaitán et al. 2014) that characterize normal SN Ia. The second-maximum is especially strong in slowly-declining SN 1999aa or 1991T-like SN Ia; thus the SN Ia that are spectroscopically most similar to SN Iax have quite a different photometric behavior. Nonetheless, similar to SN Ia, weeks after maximum light SN Iax show only modest color
evolution. Late-time colors may thus provide a useful diagnostic of host-galaxy reddening (Lira [1996], Foley et al. [2013]), which is otherwise difficult to determine for SN Iax. The very late-time optical light curves of typical SN Iax continue to show a decline slower than SN Ia until about 300 to 400 days past maximum light, after which SN Ia light curves also slow to similar decline rates as SN Iax: 0.01−0.02 mag day$^{-1}$ (McCully et al. [2014b]).

The peak optical luminosity of SN Iax is lower than typical SN Ia and it spans a much wider range, from $M_V \simeq -19$ on the bright end to $M_V \simeq -13$ for the faintest SN Iax known. Compared to the light curve decline rate, SN Iax fall well below the Phillips (1993) relation, by anywhere between 0.5 and several magnitudes (Foley et al. [2013]). Certainly, as seen in Figure 2, SN Iax do not show as tight a relation in this parameter space as normal SN Ia (even including the SN 1991T/1999aa and SN 1991bg extremes of the normal SN Ia distribution). Magee et al. (2016, see their Figure 5) suggest a stronger correlation may exist between peak luminosity and rise time, rather than decline rate.

Near-infrared light curves of SN Iax are limited, with SN 2005hk still providing the best data set (Phillips et al. [2007]). Continuing the trend with wavelength in the optical, the $YJH$ light curves of SN 2005hk show a broad, single peak that is delayed significantly ($\sim 10$ to 15 days) relative to the $B$ peak. The NIR contribution to the quasi-bolometric “UVOIR” flux seems not too dissimilar to normal SN Ia (Stritzinger et al. [2015]), and this fraction seems roughly consistent even for the faintest SN Iax like SN 2008ha and SN 2010ae (Stritzinger et al. [2014]). A major surprise, however, is SN 2014dt, which showed a significant near- and mid-infrared excess beginning $\sim 100$ days past maximum and lasting for a few hundred days at least (Fox et al. [2016]).

The near-UV photometric behavior of SN Iax is also interesting, with objects showing a faster evolution in near-UV minus optical color than SN Ia, and “crossing” the typically parallel tracks made by normal SN Ia in this space. SN Iax start bluer than normal SN Ia in the UV before maximum light but quickly redden (by $\sim 1.5$ to 2 mag in Swift $uvw1−b$) so that about ten days after maximum they are redder than normal SN Ia (Milne et al. [2010]).

As with other thermonuclear supernovae, no SN Iax has been definitively detected in the radio (Chomiuk et al. [2016]) or X-ray (Margutti et al. [2014]).

### 2.3 Spectroscopic properties

Beyond the defining spectroscopic features used for classification of these supernovae (Fe III dominated spectra near maximum light and low Si II velocity; see Sec. 2.1), SN Iax show quite homogeneous spectral evolution, which generally matches the evolution of SN Ia over the period of a few months from maximum light, except with lower line velocities (Jha et al. [2006]). Like SN Ia, the early-time spectra show Fe-group and intermediate mass elements (including Si, S, and Ca). This similarity extends to the near-UV (with Fe-group line blanketing). In their near-infrared maximum-light spectra, SN Iax show remarkable similarity to SN Ia, with Fe II and Si III lines, except at lower typical velocities, and most prominently, beautiful and unambiguous detections of Co II in the $H$ and $K$
A.8

Fig. 2 Absolute magnitude vs. decline rate relation for SN Iax (colored) compared to normal SN Ia (black) showing the Phillips (1993) relation, in B-band (above) and R (or r)-band below. These plots are adapted from Stritzinger et al. (2015) and Magee et al. (2016).
bands for SN 2010ae, 2012Z, and 2014ck (Stritzinger et al. 2014, 2015; Tomasella et al. 2016).

It is at late times that the spectra of SN Iax radically diverge from SN Ia, and indeed, almost all other supernovae of any type (Jha et al. 2006; Sahu et al. 2008; Foley et al. 2010a, 2016). SN Iax never truly enter a fully “nebular” phase in which broad forbidden lines dominate the optical spectrum (Figure 3). Rather, in optical spectra taken more than a year past maximum light, SN Iax still show permitted lines of predominantly Fe II, often with low velocities \(< 2000 \text{ km s}^{-1}\), plus Na I D and the Ca II IR triplet. Forbidden lines of [Fe II], [Ni II], and [Ca II] are also usually present, and in some cases with narrow widths down to \(< 500 \text{ km s}^{-1}\) (McCully et al. 2014b; Stritzinger et al. 2015). The linewidths and relative strengths of the forbidden and permitted lines seem to vary significantly among different SN Iax (Yamanaka et al. 2015; Foley et al. 2016). The late-time linewidth variation, for example, approaches nearly an order of magnitude, from a few hundred to \(\sim 3000 \text{ km s}^{-1}\). Spectra of SN Iax seem to show relatively little evolution from 200 to past 400 days after maximum (Foley et al. 2016).

The faintest SN Iax, like SN 2008ha and SN 2010ae, show similar spectra to more luminous counterparts, perhaps with a more rapid spectral evolution to lower velocities in the few weeks after maximum light (Foley et al. 2009; Valenti et al. 2009; Stritzinger et al. 2014). Around 250 days past maximum, the spectra of SN 2002cx (a “bright” SN Iax; Jha et al. 2006) and SN 2010ae (one of the faintest) are nearly identical (see Figure 12 of Stritzinger et al. 2014).

Chornock et al. (2006) and Maund et al. (2010) obtained spectropolarimetric observations of SN 2005hk and report 0.2–0.4% continuum polarization, consistent with spectropolarimetry of normal SN Ia.

Two objects, SN 2004cs and 2007J, have been classified as SN Iax by Foley et al. (2013) and show clear evidence of He I emission in their post-maximum spectra, something never seen in normal SN Ia. White et al. (2015) argue that these objects may be type-IIb supernovae instead, though Foley et al. (2016) counter that claim and call PTF 09ego and PTF 09eiy into question as SN Iax. In the end, there are a handful of objects for which the classification may be ambiguous.

### 2.4 Photometric and spectroscopic correlations

SN Iax span a wide range of peak luminosities and line velocities, and it is natural to ask if these are related. McClelland et al. (2010) suggested a positive correlation between these two, with the lowest-velocity SN Iax also being the lowest luminosity. While such a correlation does seem to hold for the majority of SN Iax, there are clear counterexamples like SN 2009ku (Narayan et al. 2011), which had a low velocity (similar to SN 2008ha or SN 2010ae), but relatively high luminosity (like SN 2002cx or SN 2005hk). Tomasella et al. (2016) show that SN 2014ck is similarly an outlier to the velocity/luminosity correlation. Neither do the lowest-velocity SN Iax necessarily have the fastest optical decline rates: while SN 2008ha and SN 2010ae decline quickly, SN 2014ck has an intermediate
Fig. 3 Late-time spectra of SN Iax (colored) compared to a normal SN Ia (black; left), showing a clear divergence. Numerous lines that look like “noise” are actually permitted Fe transitions, as seen with the Syn++ \cite{thomas2011} spectrum synthesis model (black) of SN 2005hk (upper right). SN Iax show a diversity of line velocities and strengths in the [Fe II] \(\lambda 7155\), [Ca II] \(\lambda\lambda 7291, 7324\), and [Ni II] \(\lambda 7378\) lines at late times. Figure panels adapted from McCully et al. \cite{mccully2014} and Foley et al. \cite{foley2016}.

decline rate similar to other higher-velocity SN Iax, while SN 2009ku in fact has a slower decline rate than higher-velocity SN Iax.

2.5 Environments and Rates

SN Iax have a dramatically different distribution of host galaxies than normal SN Ia. In all but a couple of cases (like SN 2008ge; \cite{foley2010}), SN Iax are found in star-forming, late-type host galaxies (Figure 4). The host galaxy distribution of SN Iax is closest to those of SN IIP or SN 1991T/1999aa-like SN Ia \cite{foley2009, valenti2009, perets2010}. Lyman et al. \cite{lyman2013, lyman2017} confirm and amplify this result based on H\(\alpha\) imaging and integral-field spectroscopy of Iax locations and hosts: SN Iax must arise from a relatively young population. Qualitatively, based on SN Iax with high-resolution Hubble Space Telescope like SN 2008A, SN 2012Z, and SN 2014dt, it seems as if SN Iax prefer the “outskirts” of their star-forming hosts, but this needs further quan-
Type Iax Supernovae

tification, given the selection bias against finding these fainter SN on a bright galaxy background. SN Iax show no strong preference for high- or low-metallicity galaxies (Magee et al. 2017), though their explosion locations are more metal-poor than normal SN Ia (Lyman et al. 2017).

The host reddening distribution of SN Iax is uncertain because of the difficulty in disentangling extinction from the intrinsic photometric diversity in the class, but most known SN Iax have low reddening, up to $E(B-V) \simeq 0.5$ mag for SN 2013en (Liu et al. 2015c). Again, selection biases work against finding heavily extinguished members of this already intrinsically faint class of supernovae.

Because the luminosity function of SN Iax extends down to quite faint magnitudes, precisely estimating the rate of SN Iax is challenging. Foley et al. (2013) calculate the Iax rate to be $31^{+17}_{-13}$% of the SN Ia rate in a volume-limited sample. Consistent with this, Miller et al. (2017) found one SN Iax (iPTF16fnm; $M \simeq -15$ mag) and 4 SN Ia in a volume-limited survey. The overall SN Iax rate is dominated by the lower luminosity objects; the rate of brighter SN Iax (comparable in luminosity to SN 2002cx or SN 2005hk) is likely to be between 2 and 10% of the SN Ia rate (Li et al. 2011b; Foley et al. 2013; Graur et al. 2017). SN Iax are the most numerous “peculiar” cousins to normal SN Ia.

2.6 Progenitors and Remnants

A major breakthrough in understanding SN Iax came with the discovery of the progenitor system of SN 2012Z (McCully et al. 2014a). Nature was kind: SN 2012Z exploded in the nearby galaxy NGC 1309, which was also the host of the normal type-Ia SN 2002fk, a calibrator for the SN distance scale to measure $H_0$ (Riess et al. 2011). As such, extremely deep, multi-epoch HST imaging of NGC 1309 (to observe Cepheids) covered the location of SN 2012Z before its explosion (Figure 5). This deep, high-resolution pre-explosion imaging revealed a source coincident with SN 2012Z, the first time a progenitor system has been discovered for a thermonuclear supernova. The detected source is luminous and blue ($M_V \simeq -5.3$ mag; $B-V \simeq -0.1$ mag), and McCully et al. (2014a) argue that it is a helium-star companion (donor) to an exploding white dwarf. Further images taken after the supernova faded reveal the source has not disappeared, consistent with the companion scenario (McCully et al., in preparation). This discovery marks a critical contrast for SN Iax compared to normal SN Ia: no such progenitor system has ever been seen for a SN Ia! Note, however, there are only two normal SN Ia, SN 2011fe (Li et al. 2011a) and SN 2014J (Kelly et al. 2014), with pre-explosion limits that are as deep as the data for SN 2012Z.

Foley et al. (2014) detect a luminous ($M_I \simeq -5.4$ mag), red ($R-I \simeq 1.6 \pm 0.6$ mag) source consistent with the location of SN 2008ha in HST imaging taken about 4 years after the supernova explosion. At these epochs the SN ejecta flux should have faded well below this level, so Foley et al. (2014) suggest they may be observing a companion star to the supernova, or else a luminous “remnant” of the explosion.
Fig. 4  Sloan Digital Sky Survey images centered at the locations of 25 SN Iax in the SDSS footprint. Note the preponderance of late-type, star-forming host galaxies. Each image is 100 arcsec on a side.
Fig. 5 Discovery of the only known progenitor system for a white-dwarf (thermonuclear) supernova. The left panel shows the deep Hubble Heritage image of NGC 1309 (made from observations to detect and monitor Cepheids) taken in 2005 and 2006 with HST ACS. Upper panels (b) and (c) zoom in on the region where the type Iax SN 2012Z was to explode, revealing the luminous, blue progenitor system S1, believed to be a helium star donor to an exploding white dwarf. Lower panels (d) and (e) show the region after the SN explosion, allowing for a precise measurement of its position with HST/WFC3, coincident with the progenitor. This figure is adapted from McCully et al. (2014a).

3 Models

In this section I discuss potential models for SN Iax, starting from general considerations and observational constraints, and then moving to specific scenarios that have been proposed in the literature.

3.1 SN Iax are likely thermonuclear, white dwarf supernovae

SN Iax show undeniable spectroscopic similarities to normal SN Ia, particularly near and in the few months after maximum light, with lower velocities being the primary distinguishing factor. Given that spectroscopic observations probe different layers of supernova ejecta over time, a natural starting point would be to suggest that SN Iax and SN Ia share commonalities in their progenitors and explosions.

Conversely, the primarily star-forming environments of SN Iax may point to a core-collapse, massive-star supernova origin. Indeed Valenti et al. (2009) argue that SN 2008ha has similarities to some faint core-collapse SN, and suggest a “fallback” massive-star supernova (Moriya et al. 2010) or an electron-capture supernovae (Pumo et al. 2009) could explain SN 2008ha, though not without some difficulties (Eldridge et al. 2013). This core-collapse model does not seem to be able to account for higher luminosity SN Iax.

2 “Spectrum is truth.” –R. P. Kirshner
and so would require objects like SN 2008ha, 2010ae, and 2010el to be distinct from other SN Iax.

The preponderance of evidence suggests that SN Iax are thermonuclear explosions of white dwarfs. Spectra near maximum light show carbon, intermediate mass elements like sulfur and silicon (weakly), and strong features of iron group elements. The Co II infrared lines (Stritzinger et al. 2015; Tomasella et al. 2016) clearly point to a fraternity with normal SN Ia. Iron lines are seen at a wide range of velocities, implying efficient mixing of fusion products rather than a highly layered structure. The lack of star formation or luminous massive stars in pre-explosion imaging of SN 2008ge (Foley et al. 2010b) and SN 2014dt (Foley et al. 2015), and the non-disappearance of the progenitor system flux in SN 2012Z (McCully et al. 2014a) argue against the explosion of massive luminous stars. The peak luminosities of SN Iax compared to their late-time photometry and modeling suggest a $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ radioactively powered light curve (McCully et al. 2014b).

Moreover, even fainter, lower velocity objects like SN 2008ha and 2010ae seem to connect to brighter SN Iax. Foley et al. (2010a) show an early spectrum of SN 2008ha that features sulfur lines similar to those seen in normal SN Ia. Stritzinger et al. (2014) show that SN 2010ae has strong Co II lines like other SN Iax and normal SN Ia, and its late-time spectrum is very similar to the SN Iax prototype, SN 2002cx.

### 3.2 General observational constraints

The environments of SN Iax do indeed suggest they come from a young population, but this does not require a core-collapse origin. SN 1991T-like SN Ia have a quite similar host galaxy preference (Foley et al. 2009; Perets et al. 2010) to SN Iax, and those SN Ia are still nearly-universally construed as white dwarf explosions. In fact, the problem can be turned around: the requirement for a young population favors certain binary systems that can produce and explode white dwarfs quickly. HST observations of nearby stars in the field of SN 2012Z yield ages of 10–50 Myr (McCully et al. 2014a), while for SN 2008ha the nearby population is $\lesssim 100$ Myr (Foley et al. 2014). Though young, these are still significantly older than the expected lifetimes of, for example, Wolf-Rayet stars that might yield hydrogen-poor core-collapse supernovae (Groh et al. 2013).

Short evolutionary times in a binary system suggest that SN Iax arise from more massive white dwarfs. If the explosions are occurring at the Chandrasekhar mass ($M_{\text{Ch}}$), as supported by other evidence (see below), then the quickest binary channel for a carbon/oxygen white dwarf (C/O WD) is to accrete helium from a He star companion (Hachisu et al. 1999; Postnov and Yungelson 2014). The stable mass transfer rate can be high for helium accretion, and Claeys et al. (2014) show that this channel dominates the thermonuclear SN rate between 40 Myr (with no younger systems) and 200 Myr (above which double-degenerate and hydrogen-accreting single degenerate systems dominate). This has been seen in several binary population synthesis studies; these generally find no problem for the He star + C/O WD channel to produce the required fraction of SN Iax relative to normal SN Ia, but the total rates may not quite reach the observed values (Ruiter...
Of course the WD+He star channel is in good accord with observations of SN 2012Z, for which the putative companion is consistent with a helium star. This scenario may also explain the helium observed in SN 2004cs and SN 2007J. In fact, Foley et al. (2013) predicted this type of system for SN Iax before the SN 2012Z progenitor discovery. Liu et al. (2010) present a model (though intended to explain a different kind of system) that starts with a 7 $M_{\odot}$ + 4 $M_{\odot}$ close binary that undergoes two phases of mass transfer and common envelope evolution and results in a 1 $M_{\odot}$ C/O WD + 2 $M_{\odot}$ He star. As the He star evolves, it can again fill its Roche lobe and begin stable mass transfer onto the white dwarf (at a high accretion rate, $\sim 10^{-5} M_{\odot}$ yr$^{-1}$, for instance) that could lead to the SN Iax.

The low ejecta velocities of SN Iax imply lower kinetic energy compared to SN Ia (under the reasonable assumption that SN Iax do not have significantly higher ejecta mass). Their lower luminosity also points in this direction (though that depends specifically on how much $^{56}$Ni is synthesized). Moreover, there is a much larger variation in the kinetic energy in SN Iax. All of this points towards a deflagration (subsonic) explosion; pure deflagration models of $M_{\text{Ch}}$ C/O WDs show convoluted structure from the turbulent flame propagation (e.g., Gamezo et al. 2003, Townsley et al. 2007) that can produce a wide range of explosion energies. This contrasts with $M_{\text{Ch}}$ detonation scenarios that lead to more uniform energy release and a layered structure (Gamezo et al. 2004, 2005).

Deflagrations are thought to naturally occur in the onset of runaway carbon burning for $M_{\text{Ch}}$ C/O WD progenitors (e.g., Zingale et al. 2011, Nonaka et al. 2012, and references therein). Indeed for years, a leading model to match observations of normal SN Ia has been the delayed detonation scenario, in which an initial deflagration transitions to a detonation after the WD has expanded to lower density (Khokhlov 1991, Gamezo et al. 2005). In SN Iax, one posits that this transition does not occur. Such a model matches many of the observations (Röpke et al. 2007, Ma et al. 2013): lower yet varied energy release, well-mixed composition (this inhibits the secondary near-infrared maximum; Kasen 2006), unusual velocity structure (e.g., Ca interior of Fe, something not seen in normal SN Ia; Foley et al. 2013), and the strength of [Ni II] in late-time spectra implying stable nickel, preferentially produced at high density (near $M_{\text{Ch}}$; Maeda and Terada 2016).

Early on, Branch et al. (2004) suggested a pure deflagration model to match spectra of SN 2002cx. In these models, there is a prediction of significant unburned material (C/O), which may be confirmed: carbon features are nearly ubiquitous in SN Iax, more so than SN Ia (Foley et al. 2013), and there are hints of low-velocity oxygen in some late-time spectra of SN Iax (Jha et al. 2006). There remain challenges to a pure-deflagration model of SN Iax; for example, Fisher and Jumper (2015) find generically too-weak deflagrations for $M_{\text{Ch}}$ progenitors because of non-central, buoyancy driven ignition. Furthermore, asymmetry in pure deflagrations may lead to polarization signatures in excess of what is observed for SN 2005hk (Chornock et al. 2006, Maund et al. 2010, Meng et al. 2017).

The low-velocity late-time features, which have final velocities that can be much less than the typical escape velocity from the surface of a white dwarf, suggest that perhaps
not all of the material was unbound. Similarly, the range of energies that deflagrations produce could include outcomes less than the binding energy. Thus, in this model, though SN Iax would be $M_{\text{Ch}}$ explosions, the ejecta mass could be significantly less, and the explosions could leave behind a bound remnant. The luminous remnant would be super-Eddington, and could be expected to drive an optically thick wind. This scenario might explain the high densities inferred at late times in SN Iax spectra and why they do not become completely nebular ($n \sim 10^9$ cm$^{-3}$; McCully et al. 2014b). Different amounts of ejecta versus wind material could furthermore explain the diversity in line widths and strengths between permitted and forbidden lines at late times (Foley et al. 2016). A wind “photosphere” may also explain the luminous, red source seen in post-explosion observations of SN 2008ha (Foley et al. 2014) and is involved in producing the infrared excess in SN 2014dt (Fox et al. 2016). Shen and Schwab (2017) present an intriguing model for these radioactively powered winds and show good agreement with SN Iax observations.

### 3.3 Specific models for SN Iax

In some sense, the pure-deflagration $M_{\text{Ch}}$ model is a “failed” SN Ia; indeed the primary reason these models were first explored was to explain normal SN Ia. However, first in 1-d and later in 3-d, it was shown these were unlikely to match observations of SN Ia (see references listed above). After the identification and rapid observational growth in the SN Iax class, it became clear that these “failures” might be successfully applied to SN Iax.

Jordan et al. (2012) and Kromer et al. (2013) presented 3-d simulations of pure-deflagration $M_{\text{Ch}}$ C/O WD explosions that did not fully unbind the star (Figure 6), and connected these to observed properties of SN Iax, as described above. Fink et al. (2014) explore a range of initial conditions in this scenario varying the number and location of ignition spots and find that they can yield a wide range of total energy and ejecta masses from 0.1 $M_{\odot}$ to $M_{\text{Ch}}$ (i.e., complete disruption). This provides a natural way to explain the diversity observed in SN Iax, and Magee et al. (2016) show some success in matching a particular realization of this explosion model to observations of SN 2015H. Long et al. (2014) also show qualitatively similar results in being able to reproduce SN Iax properties, but find the opposite sense in the relation between energy yield and the number of ignition spots, with high luminosity objects resulting from fewer ignition points.

A new wrinkle on the pure-deflagration $M_{\text{Ch}}$ scenario is based the idea of “hybrid” C/O/Ne white dwarfs (Denissenkov et al. 2013; Chen et al. 2014). Uncertainties in convective mixing and carbon-flame quenching may allow for central carbon to exist in WDs as massive as 1.3 $M_{\odot}$, rather than the traditional $\sim 1.05 M_{\odot}$ boundary between C/O and O/Ne white dwarfs (Nomoto 1984; Doherty et al. 2017). Such massive white dwarfs come from more massive progenitors and require less accreted material to reach $M_{\text{Ch}}$; both of these lead to shorter delay time between formation and explosion (perhaps as low as 30 Myr), and thus could be particularly relevant to SN Iax (Meng and Podsiadlowski 2014).
**Fig. 6** Snapshots of a partial 3-d deflagration of a Chandrasekhar-mass carbon-oxygen white dwarf that leaves a bound remnant. Note the lack of burned material in the white dwarf core in the middle panel (1.5 sec into the explosion). While the thermonuclear runaway in the outer parts of the white dwarf surrounds and engulfs the core at later times, the explosion energy is not sufficient to unbind the star. The model predicts the composition of the ejecta and remnant in the table shown. This figure is adapted from [Kromer et al. (2013)].

[Wang et al. (2014)]. Furthermore, a range of masses for the C/O core could play a role in SN Iax diversity ([Denissenkov et al. 2015] [Kromer et al. 2015]. Bravo et al. (2016) suggest that even delayed detonations of hybrid white dwarfs could explain SN Iax, though [Willcox et al. (2016)] find the detonation phase makes these explosions more similar to normal SN Ia. Liu et al. (2015b) argue that from a binary evolution point of view the companion star to SN 2012Z is best explained in a system with a C/O/Ne white dwarf primary. Doherty et al. (2017) note some concerns about the viability of the hybrid white dwarf scenario, including whether the carbon flame can be successfully quenched ([Lecoanet et al. 2016]) or if the central C/O region can survive without being mixed into the O/Ne layer above ([Brooks et al. 2017]).

Another class of SN Iax models explores the recent resurgence in sub-$M_{Ch}$ double-detonation scenarios for normal SN Ia. In this case varying WD mass at explosion can lead to diversity, and perhaps explain both prompt SN Ia and the full range of SN Iax ([Wang et al. 2013] [Zhou et al. 2014] [Neunteufel et al. 2016]). Stritzinger et al. (2015) argue that the ejecta mass for SN 2012Z is consistent with $M_{Ch}$ and advocate a pulsational delayed detonation model ([Höflich et al. 1995]) for bright SN Iax. Metzger (2012) and Fernández and Metzger (2013) explore the potential of SN Iax to result from white dwarf plus neutron star mergers.

**4 Conclusion**

Taken together, observations and theory point to a leading model that needs to be tested: a type Iax supernova results from a C/O or (hybrid C/O/Ne) white dwarf that accretes helium from a He-star companion, approaches the Chandrasekhar mass, and explodes as a deflagration that does not necessarily completely disrupt the star. It is quite possible,
even likely, that one or more aspects of this model is wrong, but it nonetheless gives observers something to directly test and modelers a general framework to explore and pick apart. Even within this model, there are important questions: is $M_{\text{Ch}}$ always required? Is it always a deflagration? Does varying the ejecta/remnant mass explain the diversity? Does the WD + He-star channel always lead to a SN Iax?

In addition to testing this and other models with a broad range of observations, we can look forward to some novel possibilities. For example, what should happen to the He-star companion of SN 2012Z (e.g., Shappee et al. 2013, Liu et al. 2013)? What might we expect to observe from SN Iax bound remnants and what happens to them? Will future extremely-large-telescopes be able to spectroscopically confirm that the companion to SN 2012Z ($m \approx 27.5$) was actually a helium star?

What are the broader impacts of our understanding of SN Iax? Is there a connection to systems like the Galactic “helium nova” V445 Pup, a near $M_{\text{Ch}}$ white dwarf accreting from a helium star (Kato et al. 2008, Woudt et al. 2009)? Is it a SN Iax precursor, or is some parameter different (e.g., the accretion rate) that leads to the nova outcome? Is there a connection between SN Iax and 2002es-like SN (Ganeshalingam et al. 2012)? Those are found in older environments, but also have a detection of a likely single-degenerate progenitor (Cao et al. 2015). What is the relation of SN Iax the population of Ca-rich transients (Perets et al. 2010)? Are those C/O + He WD mergers?

Of course, one of the key reasons why understanding SN Iax is important is the insight that gives us about normal SN Ia. But what is that insight telling us? Does it point to sub-$M_{\text{Ch}}$ or double degenerate progenitors for SN Ia? Is some form of detonation required in SN Ia? Does the single degenerate channel always lead to peculiar supernovae? One factor in explaining why the SN Ia progenitor/explosion problem has been with us for decades is the vast array of possibilities to explode white dwarfs. Given the enormous effort that has gone into explaining normal SN Ia, it is astounding to think that we may have a better understanding of their peculiar cousins, SN Iax.

**Cross-References**

Combustion in Thermonuclear Supernova Explosions (Röpke 2017)
Evolution of Accreting White Dwarfs to the Thermonuclear Runaway (Starrfield 2016)
Explosion Physics of Thermonuclear Supernovae and Their Signatures (Hoeflich 2017)
Light Curves of Type I Supernovae (Bersten and Mazzali 2017)
Low- and Intermediate-Mass Stars (Karakas 2017)
Nucleosynthesis in Thermonuclear Supernovae (Seitenzahl and Townsley 2017)
Observational and Physical Classification of Supernovae (Gal-Yam 2017)
Population Synthesis of Massive Close Binary Evolution (Eldridge 2017)
Spectra of Supernovae During the Photospheric Phase (Sim 2017)
Supernova Progenitors Observed with HST (Van Dyk 2016)
The Extremes of Thermonuclear Supernovae (Taubenberger 2016)
Type Ia Supernovae (Maguire 2016)
Acknowledgements I thank Ryan Foley and Curtis McCully for our close collaboration working on SN Iax and their assistance with this manuscript. I am also grateful to Mark Sullivan, Daniela Graf, and Kerstin Beckert, for their seemingly inexhaustible patience. This work was supported in part by US National Science Foundation award 161545 and benefited greatly from discussions at the Munich Institute for Astro- and Particle Physics Scientific Program “The Physics of Supernovae” and associated Topical Workshop “Supernovae: The Outliers.” I dedicate this review to the memory of my friend and colleague, Weidong Li, who started it all.

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