Type Iax Supernovae

17

Saurabh W. Jha

Abstract

Type Iax supernovae (SN Iax), also called SN 2002cx-like supernovae, are the largest class of "peculiar" white dwarf (thermonuclear) supernovae, with over 50 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.

Contents

S.W. Jha (✉)
Department of Physics and Astronomy, Rutgers, The State University of New Jersey, Piscataway, NJ, USA
e-mail: saurabh@physics.rutgers.edu

A.W. Alsabti, P. Murdin (eds.), *Handbook of Supernovae*,
https://doi.org/10.1007/978-3-319-21846-5_42

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."

Here I summarize the properties of SN Iax, describing their observational properties in Sect. 2 and models in Sect. 3. I discuss analogues of SN 2002cx and well-studied examples like SN 2005hk (Chornock et al. 2006; Phillips et al. 2007; Sahu et al. 2008; Stanishev et al. 2007), 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; Cao et al. 2016; Ganeshalingam et al. 2012; White et al. 2015), but I restrict my focus to SN Iax here; other peculiar objects are explored in the ▸ Chap. 16, "The Extremes of Thermonuclear Supernovae" in the Handbook of Supernovae.

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

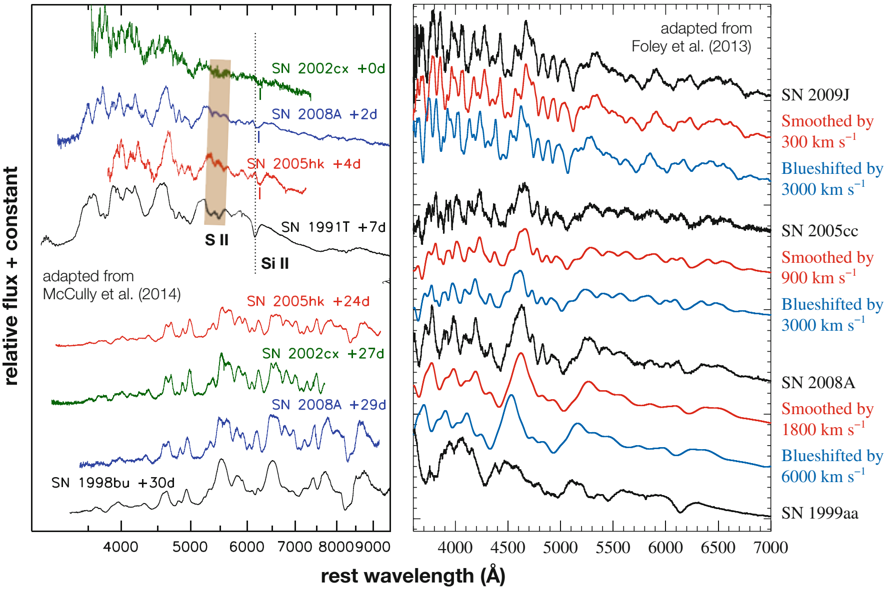


Fig. 1 Near-maximum-light spectra of SN Iax compared to normal and 91T/99aa-like SN Ia. The *left panel* shows the similarity of SN Iax to normal SN Ia (including the weak presence of S II lines sometimes considered hallmarks of thermonuclear SN), but also the lower expansion velocities (e.g., compare the locations of the Si II lines). The *right panel* shows the range of SN Iax expansion velocities, from the lowest-velocity SN 2009J ($v_{\mathrm{exp}} \approx 2200\,\mathrm{km\,s}^{-1}$) at the top, SN 2005cc ($v_{\mathrm{exp}} \approx 5000\,\mathrm{km\,s}^{-1}$) intermediate, and SN 2008A ($v_{\mathrm{exp}} \approx 6400\,\mathrm{km\,s}^{-1}$) 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. 2014b and Foley et al. 2013)

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 (Li et al. 2001; Nugent et al. 1995). The key discriminant for SN Iax is the expansion velocity; unlike typical SN Ia where the line velocity (usually measured with Si II) is $\sim$10,000 km s^{-1}, SN Iax have much lower line velocities anywhere from 6000 to 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 the past observations, like SN 1991bj (Stanishev et al. 2007). (One speculates how the history of supernova cosmology would have changed if the diversity in SN Ia was 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!) Table 1 gives a list of 53 objects that have been classified as SN Iax.

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_{peak}	References
SN 1991bj	IC 344	0.018	−15.3	Stanishev et al. (2007)
SN 1999ax	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 J21736.67+003647.6	0.093	−18.2	Östman et al. (2011)
SN 2007qd	SDSS J20932.72−005959.7	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. (2010b)
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 09ego	SDSS J172625.23+625821.4	0.104	−18.6	White et al. (2015)
PTF 09eiy	⋯	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	Bessell and Schmidt (2010)
PTF 10xk	⋯	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 11hyh	SDSS J014550.57+143501.9	0.057	−18.7	White et al. (2015)
SN 2012Z	NGC 1309	0.007	−18.1	Stritzinger et al. (2015); Yamanaka et al. (2015)
PS1-12bwh	CGCG 205−021	0.023	−16.2	Magee et al. (2017)
LSQ12fhs	⋯	0.033	−18.2	Copin et al. (2012)
SN 2013dh	NGC 5936	0.013	−17.3	Jha et al. (2013)
SN 2013en	UGC 11369	0.015	−17.9	Liu et al. (2015c)
SN 2013gr	ESO 114−G7	0.007	−15.4	Hsiao et al. (2013a,b)

(*continued*)

Table 1 (Continued)

Supernova	Host galaxy	z	M_{peak}	References
OGLE-2013-SN-130	⋯	0.09	−18.0	Bersier 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	Tomasella et al. (2016)
SN 2014cr	NGC 6806	0.019	−17.0	Childress et al. (2014)
LSQ14dtt	⋯	0.05	−18.0	Elias-Rosa et al. (2014)
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. (2017)
SN 2015H	NGC 3464	0.012	−17.7	Magee et al. (2016)
PS15aic	2MASX J13304792+3806450	0.056	−17.9	Pan et al. (2015)
SN 2015ce	UGC 12156	0.017	−17.9	Balam (2017)
PS15csd	⋯	0.044	−17.5	Harmanen et al. (2015)
SN 2016atw	⋯	0.065	−18.0	Pan et al. (2016)
OGLE16erd	⋯	0.035	−17.1	Dimitriadis et al. (2016)
SN 2016ilf	2MASX J02351956+3511426	0.045	−17.6	Zhang et al. (2016)
iPTF 16fnm	UGC 00755	0.022	−15.0	Miller et al. (2017)

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 (∼10–20 days) in all bands, with pre-maximum 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., $\Delta m_{15}(R) \simeq 0.2$–$0.8$ mag, compared to normal SN Ia which have $\Delta m_{15}(R) \simeq 0.6$–$0.8$ 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 (Foley et al. 2013; Lira 1996), 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 300–400 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 Fig. 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$10–15 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$1.5–2 mag in Swift $uvw1 - b$) so that about 10 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 Sect. 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 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 (Foley et al. 2010a, 2016; Jha et al. 2006; Sahu et al. 2008). SN Iax never truly enter a fully "nebular" phase in which broad forbidden lines dominate the optical spectrum (Fig. 3). Rather, in optical spectra taken more than a year past maximum light, SN Iax still show

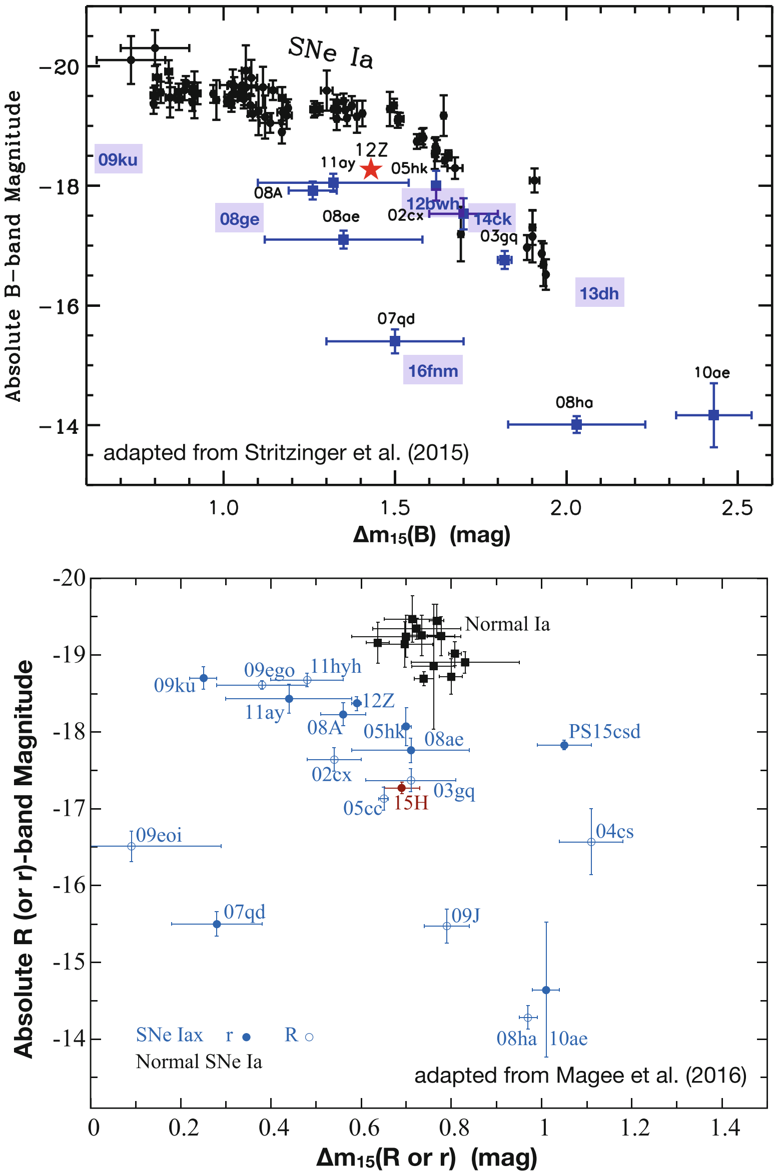


Fig. 2 Absolute magnitude vs. decline rate relation for SN Iax (*colored*) compared to normal SN Ia (*black*) showing the Phillips (1993) relation, in B-band (*above*) and R (or r)-band below (These plots are adapted from Stritzinger et al. 2015 and Magee et al. 2016)

permitted lines of predominantly Fe II, often with low velocities $< 2000\,\mathrm{km\,s^{-1}}$, 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 $< 500\,\mathrm{km\,s^{-1}}$ (McCully et al. 2014b; Stritzinger et al. 2015). The linewidths and

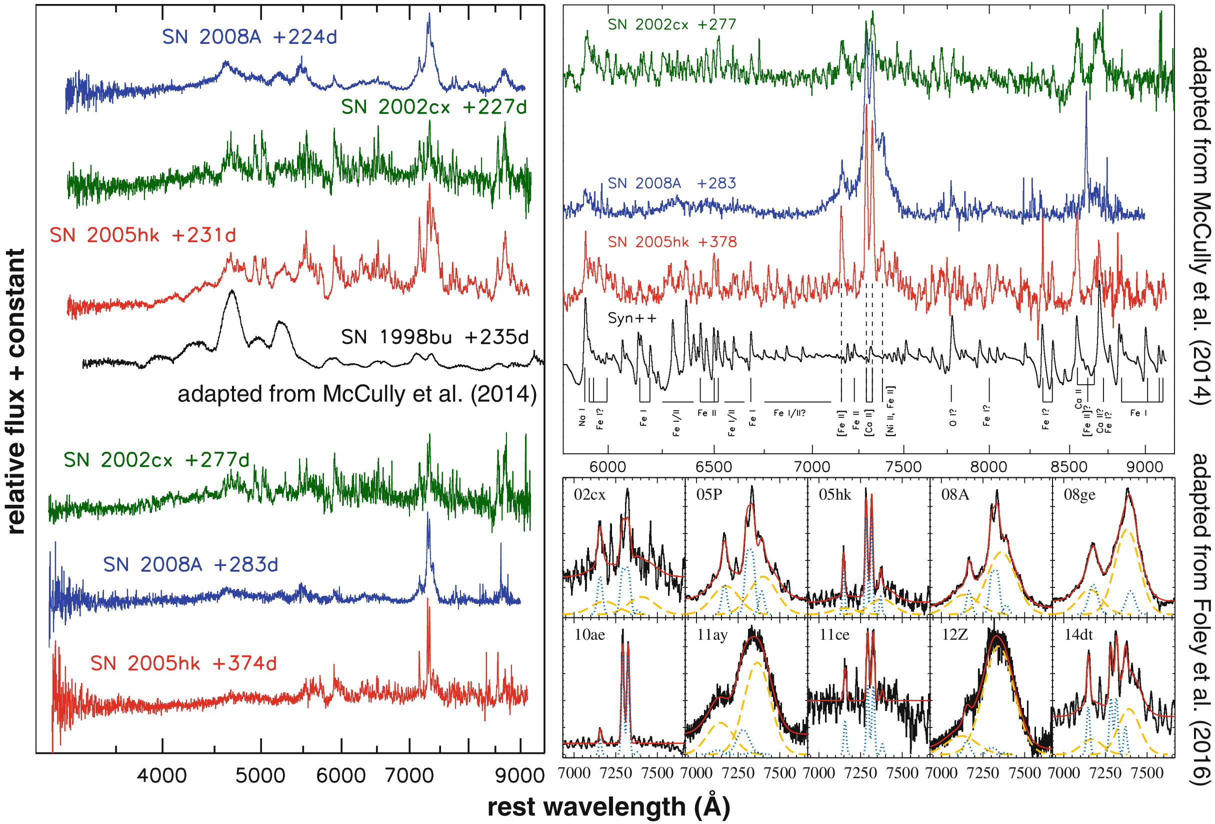


Fig. 3 Late-time spectra of SN Iax (*colored*) compared to a normal SN Ia (*black; left*), showing a clear divergence. Numerous lines that look like "noise" are actually permitted Fe transitions, as seen with the Syn++ (Thomas et al. 2011) spectrum synthesis model (*black*) of SN 2005hk (*upper right*). 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. 2014b and Foley et al. 2016)

relative strengths of the forbidden and permitted lines seem to vary significantly among different SN Iax (Foley et al. 2016; Yamanaka et al. 2015). The late-time linewidth variation, for example, approaches nearly an order of magnitude, from a few hundred to $\sim 3000\,\mathrm{km\,s^{-1}}$. 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; Stritzinger et al. 2014; Valenti et al. 2009). 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 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; Foley et al. 2010b), SN Iax are found in star-forming, late-type host galaxies (Fig. 4). The host-galaxy distribution of SN Iax is closest to those of SN IIP or SN 1991T/1999aa-like SN Ia (Foley et al. 2009; Perets et al. 2010; Valenti et al. 2009). Lyman et al. (2013, 2017) confirm and amplify this result based on Hα imaging and integral-field spectroscopy of

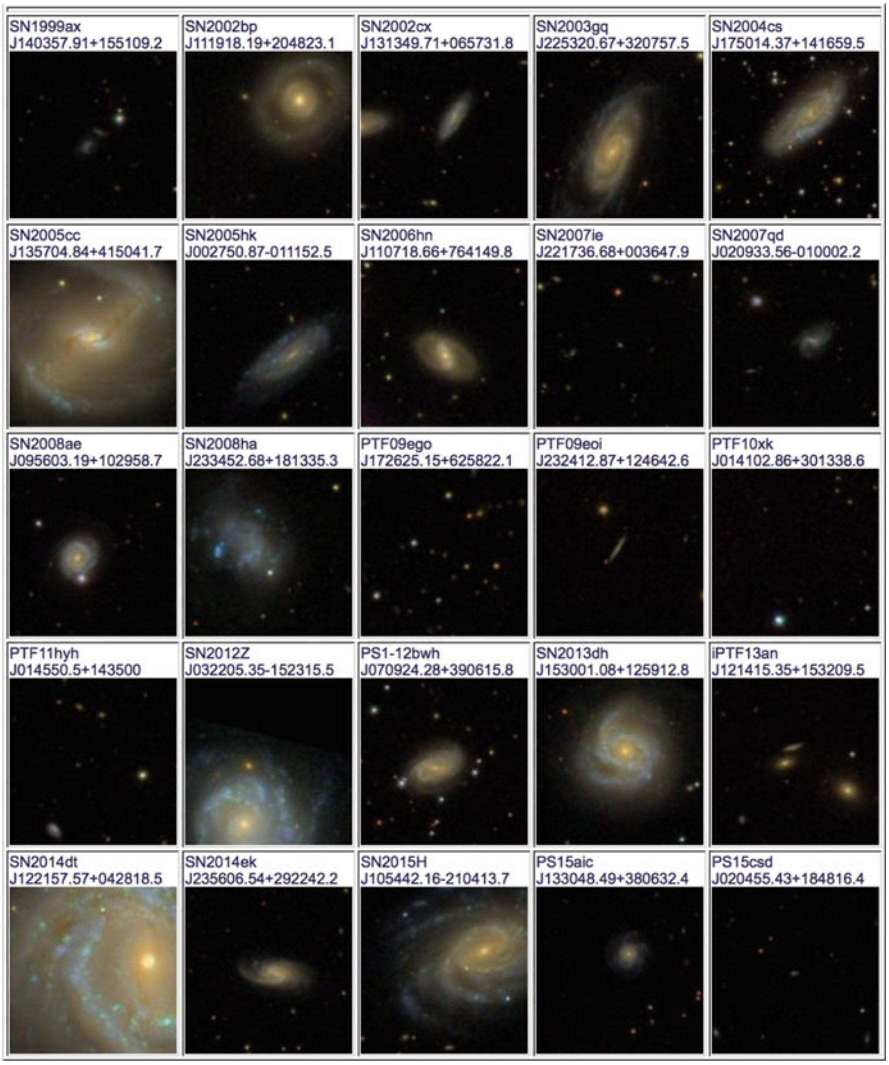


Fig. 4 Sloan Digital Sky Survey images centered at the locations of 25 SN Iax in the SDSS footprint. Note the preponderance of late-type, star-forming host galaxies. Each image is 100 arcsec on a side

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 quantification, 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 (Foley et al. 2013; Graur et al. 2017; Li et al. 2011b). 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 (Fig. 5).

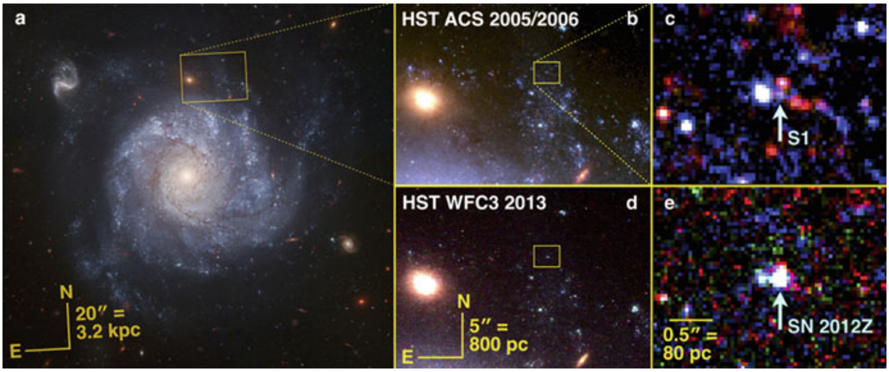


Fig. 5 Discovery of the only known progenitor system for a white dwarf (thermonuclear) supernova. The *left panel* shows the deep Hubble Heritage image of NGC 1309 (made from observations to detect and monitor Cepheids) taken in 2005 and 2006 with HST ACS. *Upper panels* (**b**) and (**c**) zoom in on 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)

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.

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 ("Spectrum is Truth." –R. P. Kirshner), 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 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}Ni $\rightarrow$ ^{56}Co $\rightarrow$ ^{56}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_{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 (Liu et al. 2015a; Meng and Yang 2010; Piersanti et al. 2014; Ruiter et al. 2009, 2011; Wang et al. 2009a,b).

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 $M_\odot$ $+4M_\odot$ close binary that undergoes two phases of mass transfer and common envelope evolution and results in a 1 $M_\odot$ C/OWD + $2M_\odot$ 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 toward a deflagration (subsonic) explosion; pure deflagration models of $M_{\rm Ch}$ 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 $M_{\rm Ch}$ 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 $M_{\rm Ch}$ C/O WD progenitors (e.g., Nonaka et al. 2012; Zingale et al. 2011, 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 (Gamezo et al. 2005; Khokhlov 1991). In SN Iax, one posits that this transition does not occur. Such a model matches many of the observations (Ma et al. 2013; Röpke et al. 2007): 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 $M_{\rm Ch}$; 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 $M_{\rm Ch}$ progenitors because of noncentral, 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 $M_{\rm Ch}$ explosions, the ejecta mass could be significantly less, and the explosions could leave behind a bound remnant.

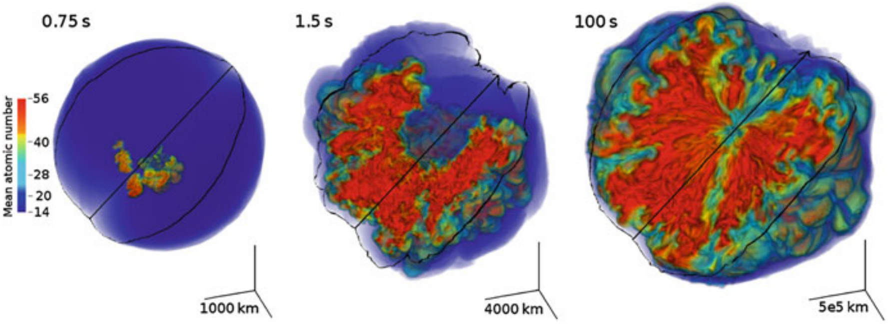
The luminous remnant would be super-Eddington and could be expected to drive an optically thick wind. This scenario might explain the high densities inferred at late times in SN Iax spectra and why they do not become completely nebular ($n \sim 10^9\,\mathrm{cm}^{-3}$; McCully et al. 2014b). Different amounts of ejecta versus wind material could furthermore explain the diversity in linewidths 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 perhaps 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_{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 1D and later in 3D, 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 3D simulations of pure deflagration M_{Ch} C/O WD explosions that did not fully unbind the star (Fig. 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 $0.1M_{\odot}$ to M_{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_{Ch} scenario is based the idea of "hybrid" C/O/Ne white dwarfs (Chen et al. 2014; Denissenkov et al. 2013). 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 (Doherty et al. 2017; Nomoto 1984). Such massive white dwarfs come from more massive progenitors and require less accreted material to reach M_{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; 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



adapted from Kromer et al. (2013)

	Bound remnant ($M_\odot$)	Ejecta ($M_\odot$)
Total	1.028	0.372
C	0.422	0.043
O	0.484	0.060
Ne	0.054	0.005
Mg	0.004	0.013
Si	0.015	0.025
S	0.004	0.009
Ca	0.0003	0.001
Fe	0.004	0.031
Ni	0.025	0.187
^{56}Ni	0.022	0.158

Fig. 6 Snapshots of a partial 3D 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 s 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)

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 (Neunteufel et al. 2016; Wang et al. 2013; Zhou et al. 2014). 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 Conclusions

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 are 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_{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., Liu et al. 2013; Shappee et al. 2013)? What might we expect to observe from bound remnants of SN Iax 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_{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_{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.

5 Cross-References

- ▶ Combustion in Thermonuclear Supernova Explosions
- ▶ Evolution of Accreting White Dwarfs to the Thermonuclear Runaway
- ▶ Explosion Physics of Thermonuclear Supernovae and Their Signatures
- ▶ Light Curves of Type I Supernovae

- ▸ Low- and Intermediate-Mass Stars
- ▸ Nucleosynthesis in Thermonuclear Supernovae
- ▸ Observational and Physical Classification of Supernovae
- ▸ Population Synthesis of Massive Close Binary Evolution
- ▸ Spectra of Supernovae During the Photospheric Phase
- ▸ Supernova Progenitors Observed with *HST*
- ▸ The Extremes of Thermonuclear Supernovae
- ▸ Type Ia Supernovae
- ▸ Unusual Supernovae and Alternative Power Sources

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 the 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.

References

Antilogus P, Garavini G, Gilles S, Pain R, Aldering G, Bailey S, Lee BC, Loken S, Nugent P, Perlmutter S, Scalzo R, Thomas RC, Wang L, Weaver B, Bonnaud C, Pecontal E, Blanc N, Bongard S, Copin Y, Gangler E, Sauge L, Smadja G, Kessler R, Baltay C, Rabinowitz D, Bauer A (2005) Type determination for SN 2005cc. The Astronomer's Telegram 502

Balam D (2017) Transient classification report for 2017-03-31. Transient Name Server Classification Report 381

Bersier D, Dennefeld M, Lyman J, Maund JR, Pastorello A, De Cia A, Benetti S, Inserra C, Smartt S, Smith K, Young D, Sullivan M, Taubenberger S, Valenti S, Fraser M, Yaron O, Gal-Yam A, Manulis I, Scalzo R, Yuan F, Childress M, Tucker B, Schmidt B, Knapic C, Smareglia R, Molinaro M, Baltay C, Ellman N, Hadjiyska E, McKinnon R, Rabinowitz D, Walker ES, Feindt U, Kowalski M, Nugent P, Wyrzykowski L (2013) PESSTO spectroscopic classification of optical transients. The Astronomer's Telegram 5620

Bessell MS, Schmidt BP (2010) Supernova 2010el in NGC 1566. Central Bureau Electronic Telegrams 2337

Blondin S, Calkins M (2008) Supernova 2008ae in IC 577. Central Bureau Electronic Telegrams 1250

Branch D, Baron E, Thomas RC, Kasen D, Li W, Filippenko AV (2004) Reading the spectra of the most peculiar Type Ia supernova 2002cx. Publ Astron Soc Pac 116:903–908. doi:10.1086/425081, http://arXiv.org/abs/astro-ph/0408130

Bravo E, Gil-Pons P, Gutiérrez JL, Doherty CL (2016) Explosion of white dwarfs harboring hybrid CONe cores. Astron Astrophys 589:A38. doi:10.1051/0004-6361/201527861, http://arXiv.org/abs/1603.00641

Brooks J, Schwab J, Bildsten L, Quataert E, Paxton B (2017) Convection destroys the core/mantle structure in hybrid C/O/Ne white dwarfs. Astrophys J Lett 834:L9. doi:10.3847/2041-8213/834/2/L9, http://arXiv.org/abs/1611.03061

Cao Y, Kulkarni SR, Howell DA, Gal-Yam A, Kasliwal MM, Valenti S, Johansson J, Amanullah R, Goobar A, Sollerman J, Taddia F, Horesh A, Sagiv I, Cenko SB, Nugent PE, Arcavi I, Surace J, Woźniak PR, Moody DI, Rebbapragada UD, Bue BD, Gehrels N (2015) A strong ultraviolet pulse from a newborn Type Ia supernova. Nature 521:328–331. doi:10.1038/nature14440, http://arXiv.org/abs/1505.05158

Cao Y, Kulkarni SR, Gal-Yam A, Papadogiannakis S, Nugent PE, Masci FJ, Bue BD (2016) SN 2002es-like supernovae from different viewing angles. Astrophys J 832:86. doi:10.3847/0004-637X/832/1/86, http://arXiv.org/abs/1606.05655

Chen MC, Herwig F, Denissenkov PA, Paxton B (2014) The dependence of the evolution of Type Ia SN progenitors on the C-burning rate uncertainty and parameters of convective boundary mixing. Mon Not R Astron Soc 440:1274–1280. doi:10.1093/mnras/stu108, http://arXiv.org/abs/1310.1898

Childress M, Scalzo R, Yuan F, Zhang B, Ruiter A, Seitenzahl I, Schmidt B, Tucker B (2014) Classification of seven supernovae with WiFeS. The Astronomer's Telegram 6302

Chomiuk L, Soderberg AM, Chevalier RA, Bruzewski S, Foley RJ, Parrent J, Strader J, Badenes C, Fransson C, Kamble A, Margutti R, Rupen MP, Simon JD (2016) A deep search for prompt radio emission from thermonuclear supernovae with the very large array. Astrophys J 821:119. doi:10.3847/0004-637X/821/2/119, http://arXiv.org/abs/1510.07662

Chornock R, Filippenko AV, Branch D, Foley RJ, Jha S, Li W (2006) Spectropolarimetry of the peculiar Type Ia supernova 2005hk. Publ Astron Soc Pac 118:722–732. doi:10.1086/504117, arXiv:astro-ph/0603083

Claeys JSW, Pols OR, Izzard RG, Vink J, Verbunt FWM (2014) Theoretical uncertainties of the Type Ia supernova rate. Astron Astrophys 563:A83. doi:10.1051/0004-6361/201322714, http://arXiv.org/abs/1401.2895

Copin Y, Gangler E, Pereira R, Rigault M, Smadja G, Aldering G, Birchall D, Childress M, Fakhouri H, Kim A, Nordin J, Nugent P, Perlmutter S, Runge K, Saunders C, Suzuki N, Thomas RC, Pecontal E, Buton C, Feindt U, Kerschhaggl M, Kowalski M, Benitez S, Hillebrandt W, Kromer M, Sasdelli M, Sternberg A, Taubenberger S, Baugh D, Chen J, Chotard N, Tao CWC, Fouchez D, Tilquin A, Hadjiyska E, Rabinowitz D, Baltay C, Ellman N, McKinnon R, Cellier-Holzem AEF, Canto A, Antilogus P, Bongard S, Pain R (2012) Spectroscopic classification of the peculiar Type Ia SN LSQ12fhs by the nearby supernova factory II. The Astronomer's Telegram 4476

Denissenkov PA, Herwig F, Truran JW, Paxton B (2013) The C-flame quenching by convective boundary mixing in super-AGB stars and the formation of hybrid C/O/Ne white dwarfs and SN progenitors. Astrophys J 772:37. doi:10.1088/0004-637X/772/1/37, http://arXiv.org/abs/1305.2649

Denissenkov PA, Truran JW, Herwig F, Jones S, Paxton B, Nomoto K, Suzuki T, Toki H (2015) Hybrid C-O-Ne white dwarfs as progenitors of Type Ia supernovae: dependence on Urca process and mixing assumptions. Mon Not R Astron Soc 447:2696–2705. doi:10.1093/mnras/stu2589, http://arXiv.org/abs/1407.0248

Dimitriadis G, Pursiainen M, Smith M, Cartier R, Firth R, Prajs S, Chen TW, Fraser M, Inserra C, Kankare E, Maguire K, Smartt SJ, Smith KW, Sullivan M, Valenti S, Yaron O, Young D, Manulis I, Wyrzykowski L, Tonry J, Stalder B, Denneau L, Heinze A, Sherstyuk A, Rest A, Wright D, Chambers K, Flewelling H, Huber M, Magnier E, Waters C, Wainscoat RJ (2016) PESSTO spectroscopic classification of optical transients. The Astronomer's Telegram 9660

Doherty CL, Gil-Pons P, Siess L, Lattanzio JC (2017) Super-AGB stars and their role as electron capture supernova progenitors. ArXiv e-prints http://arXiv.org/abs/1703.06895

Eldridge JJ, Fraser M, Smartt SJ, Maund JR, Crockett RM (2013) The death of massive stars – II. Observational constraints on the progenitors of Type Ibc supernovae. Mon Not R Astron Soc 436:774–795. doi:10.1093/mnras/stt1612, http://arXiv.org/abs/1301.1975

Elias-Rosa N, Tartaglia L, Morales-Garoffolo LTA, Pastorello A, Botticella MT, Inserra C, Maguire K, Smartt S, Smith KW, Sullivan M, Valenti S, Yaron O, Young D, Manulis I, Baltay C, Ellman N, Hadjiyska E, McKinnon R, Rabinowitz D, Walker ES, Feindt U, Kowalski M, Nugent P, Wyrzykowski L (2014) PESSTO spectroscopic classification of optical transients. The Astronomer's Telegram 6398

Fernández R, Metzger BD (2013) Nuclear dominated accretion flows in two dimensions. I. Torus evolution with parametric microphysics. Astrophys J 763:108. doi:10.1088/0004-637X/763/2/108, http://arXiv.org/abs/1209.2712

Filippenko AV, Foley RJ, Silverman JM, Chornock R, Li W, Blondin S, Matheson T (2007) Supernova 2007J in UGC 1778. Central Bureau Electronic Telegrams 926

Fink M, Kromer M, Seitenzahl IR, Ciaraldi-Schoolmann F, Röpke FK, Sim SA, Pakmor R, Ruiter AJ, Hillebrandt W (2014) Three-dimensional pure deflagration models with nucleosynthesis and synthetic observables for Type Ia supernovae. Mon Not R Astron Soc 438:1762–1783. doi:10.1093/mnras/stt2315, http://arXiv.org/abs/1308.3257

Fisher R, Jumper K (2015) Single-degenerate Type Ia supernovae are preferentially overluminous. Astrophys J 805:150. doi:10.1088/0004-637X/805/2/150, http://arXiv.org/abs/1504.00014

Foley RJ, Chornock R, Filippenko AV, Ganeshalingam M, Kirshner RP, Li W, Cenko SB, Challis PJ, Friedman AS, Modjaz M, Silverman JM, Wood-Vasey WM (2009) SN 2008ha: an extremely low luminosity and exceptionally low energy supernova. Astron J 138:376–391. doi:10.1088/0004-6256/138/2/376, http://arXiv.org/abs/0902.2794

Foley RJ, Brown PJ, Rest A, Challis PJ, Kirshner RP, Wood-Vasey WM (2010a) Early- and late-time observations of SN 2008ha: additional constraints for the progenitor and explosion. Astrophys J Lett 708:L61–L65. doi:10.1088/2041-8205/708/1/L61, http://arXiv.org/abs/0912.0732

Foley RJ, Rest A, Stritzinger M, Pignata G, Anderson JP, Hamuy M, Morrell NI, Phillips MM, Salgado F (2010b) On the progenitor and supernova of the SN 2002cx-like supernova 2008ge. Astron J 140:1321–1328. doi:10.1088/0004-6256/140/5/1321, http://arXiv.org/abs/1008.0635

Foley RJ, Challis PJ, Chornock R, Ganeshalingam M, Li W, Marion GH, Morrell NI, Pignata G, Stritzinger MD, Silverman JM, Wang X, Anderson JP, Filippenko AV, Freedman WL, Hamuy M, Jha SW, Kirshner RP, McCully C, Persson SE, Phillips MM, Reichart DE, Soderberg AM (2013) Type Iax Supernovae: a new class of stellar explosion. Astrophys J 767:57. doi:10.1088/0004-637X/767/1/57, http://arXiv.org/abs/1212.2209

Foley RJ, McCully C, Jha SW, Bildsten L, Fong Wf, Narayan G, Rest A, Stritzinger MD (2014) Possible detection of the stellar donor or remnant for the Type Iax Supernova 2008ha. Astrophys J 792:29. doi:10.1088/0004-637X/792/1/29, http://arXiv.org/abs/1408.1091

Foley RJ, Van Dyk SD, Jha SW, Clubb KI, Filippenko AV, Mauerhan JC, Miller AA, Smith N (2015) On the progenitor system of the Type Iax Supernova 2014dt in M61. Astrophys J Lett 798:L37. doi:10.1088/2041-8205/798/2/L37, http://arXiv.org/abs/1412.1088

Foley RJ, Jha SW, Pan YC, Zheng WK, Bildsten L, Filippenko AV, Kasen D (2016) Late-time spectroscopy of Type Iax Supernovae. Mon Not R Astron Soc 461:433–457. doi:10.1093/mnras/stw1320, http://arXiv.org/abs/1601.05955

Fox OD, Johansson J, Kasliwal M, Andrews J, Bally J, Bond HE, Boyer ML, Gehrz RD, Helou G, Hsiao EY, Masci FJ, Parthasarathy M, Smith N, Tinyanont S, Van Dyk SD (2016) An excess of mid-infrared emission from the Type Iax SN 2014dt. Astrophys J Lett 816:L13. doi:10.3847/2041-8205/816/1/L13, http://arXiv.org/abs/1510.08070

Gamezo VN, Khokhlov AM, Oran ES, Chtchelkanova AY, Rosenberg RO (2003) Thermonuclear supernovae: simulations of the deflagration stage and their implications. Science 299:77–81. doi:10.1126/science.299.5603.77, arXiv:astro-ph/0212054

Gamezo VN, Khokhlov AM, Oran ES (2004) Deflagrations and detonations in thermonuclear supernovae. Phys Rev Lett 92(21):211102–+. doi:10.1103/PhysRevLett.92.211102, arXiv:astro-ph/0406101

Gamezo VN, Khokhlov AM, Oran ES (2005) Three-dimensional delayed-detonation model of Type Ia Supernovae. Astrophys J 623:337–346. doi:10.1086/428767, arXiv:astro-ph/0409598

Ganeshalingam M, Li W, Filippenko AV, Silverman JM, Chornock R, Foley RJ, Matheson T, Kirshner RP, Milne P, Calkins M, Shen KJ (2012) The low-velocity, rapidly fading Type Ia Supernova 2002es. Astrophys J 751:142. doi:10.1088/0004-637X/751/2/142, http://arXiv.org/abs/1202.3140

González-Gaitán S, Hsiao EY, Pignata G, Förster F, Gutiérrez CP, Bufano F, Galbany L, Folatelli G, Phillips MM, Hamuy M, Anderson JP, de Jaeger T (2014) Defining photometric peculiar Type Ia Supernovae. Astrophys J 795:142. doi:10.1088/0004-637X/795/2/142, http://arXiv.org/abs/1409.4811

Graur O, Bianco FB, Modjaz M, Shivvers I, Filippenko AV, Li W, Smith N (2017) LOSS revisited. II. The relative rates of different types of supernovae vary between low- and high-mass galaxies. Astrophys J 837:121. doi:10.3847/1538-4357/aa5eb7, http://arXiv.org/abs/1609.02923

Groh JH, Meynet G, Georgy C, Ekström S (2013) Fundamental properties of core-collapse supernova and GRB progenitors: predicting the look of massive stars before death. Astron Astrophys 558:A131. doi:10.1051/0004-6361/201321906, http://arXiv.org/abs/1308.4681

Guillochon J, Parrent J, Kelley LZ, Margutti R (2017) An open catalog for supernova data. Astrophys J 835:64. doi:10.3847/1538-4357/835/1/64, http://arXiv.org/abs/1605.01054

Hachisu I, Kato M, Nomoto K, Umeda H (1999) A new evolutionary path to Type IA Supernovae: a helium-rich supersoft X-Ray source channel. Astrophys J 519:314–323. doi:10.1086/307370, http://arXiv.org/abs/astro-ph/9902303

Harmanen J, Dennefeld M, Mattila S, Kangas T, Maguire K, Galbany L, Inserra C, Kankare E, Manulis I, Smartt SJ, Smith KW, Sullivan M, Valenti S, Yaron O, Young D, Wright D, Chambers K, Flewelling H, Huber M, Magnier E, Tonry J, Waters C, Wainscoat RJ (2015) PESSTO spectroscopic classification of optical transients. The Astronomer's Telegram 8264

Höflich P, Khokhlov AM, Wheeler JC (1995) Delayed detonation models for normal and subluminous Type IA Supernovae: absolute brightness, light curves, and molecule formation. Astrophys J 444:831–847. doi:10.1086/175656

Hsiao EY, Marion GH, Marples P, Diamond T, Phillips MM, Morrell N, Stritzinger MD, Contreras C, Kirshner RP (2013a) PSN J01462790-5840238 is a probable SN Iax, classification by FIRE NIR spectrum. The Astronomer's Telegram 5612

Hsiao EY, Morrell N, Phillips MM, Marion GH, Diamond T, Stritzinger MD, Contreras C, Kirshner RP, Dennefeld M, Bersier D, Lyman J, Maund JR, Pastorello A, De Cia A, Benetti S, Inserra C, Smartt S, Smith K, Young D, Sullivan M, Taubenberger S, Valenti S, Fraser M, Yaron O, Gal-Yam A (2013b) Supernova 2013gr in ESO 114-G7 = Psn J01462790-5840238. Central Bureau Electronic Telegrams 3733

Jha S, Branch D, Chornock R, Foley RJ, Li W, Swift BJ, Casebeer D, Filippenko AV (2006) Late-time spectroscopy of SN 2002cx: the prototype of a new subclass of Type Ia Supernovae. Astrono J 132:189–196. doi:10.1086/504599, arXiv:astro-ph/0602250

Jha SW, McCully C, Foley RJ, Cenko SB, Zheng W, Clubb KI, Shivvers I, Filippenko AV, Tucker BE, Garnavich PM (2013) SN 2013dh in NGC 5936 is probably a Type Iax Supernova. The Astronomer's Telegram 5143

Jordan GC IV, Perets HB, Fisher RT, van Rossum DR (2012) Failed-detonation supernovae: subluminous low-velocity Ia supernovae and their kicked remnant white dwarfs with iron-rich cores. Astrophys J Lett 761:L23. doi:10.1088/2041-8205/761/2/L23, http://arXiv.org/abs/1208.5069

Kasen D (2006) Secondary maximum in the near-infrared light curves of Type Ia Supernovae. Astrophys J 649:939–953. doi:10.1086/506588, arXiv:astro-ph/0606449

Kato M, Hachisu I, Kiyota S, Saio H (2008) Helium nova on a very massive white dwarf: a revised light-curve model of V445 Puppis (2000). Astrophys J 684:1366–1373. doi:10.1086/590329, http://arXiv.org/abs/0805.2540

Kelly PL, Fox OD, Filippenko AV, Cenko SB, Prato L, Schaefer G, Shen KJ, Zheng W, Graham ML, Tucker BE (2014) Constraints on the progenitor system of the Type Ia Supernova 2014J from pre-explosion hubble space telescope imaging. Astrophys J 790:3. doi:10.1088/0004-637X/790/1/3, http://arXiv.org/abs/1403.4250

Khokhlov AM (1991) Delayed detonation model for Type IA Supernovae. Astron Astrophys 245:114–128

Kromer M, Fink M, Stanishev V, Taubenberger S, Ciaraldi-Schoolman F, Pakmor R, Röpke FK, Ruiter AJ, Seitenzahl IR, Sim SA, Blanc G, Elias-Rosa N, Hillebrandt W (2013) 3D deflagration simulations leaving bound remnants: a model for 2002cx-like Type Ia Supernovae. Mon Not R Astron Soc 429:2287–2297. doi:10.1093/mnras/sts498, http://arXiv.org/abs/1210.5243

Kromer M, Ohlmann ST, Pakmor R, Ruiter AJ, Hillebrandt W, Marquardt KS, Röpke FK, Seitenzahl IR, Sim SA, Taubenberger S (2015) Deflagrations in hybrid CONe white dwarfs: a route to explain the faint Type Iax Supernova 2008ha. Mon Not R Astron Soc 450:3045–3053. doi:10.1093/mnras/stv886, http://arXiv.org/abs/1503.04292

Le Guillou L, Fleury M, Leget PF, Balland C, Baumont S, Pastorello A, Benetti S, Inserra C, Smartt S, Smith K, Young D, Sullivan M, Taubenberger S, Valenti S, Fraser M, Yaron O, Manulis I, Gal-Yam A, Knapic C, Smareglia R, Molinaro M, Wyrzykowski L (2013) Pessto spectroscopic classification of optical transients. The Astronomer's Telegram 5689

Lecoanet D, Schwab J, Quataert E, Bildsten L, Timmes FX, Burns KJ, Vasil GM, Oishi JS, Brown BP (2016) Turbulent chemical diffusion in convectively bounded carbon flames. Astrophys J 832:71. doi:10.3847/0004-637X/832/1/71, http://arXiv.org/abs/1603.08921

Li W, Filippenko AV, Treffers RR, Riess AG, Hu J, Qiu Y (2001) A high intrinsic peculiarity rate among Type IA Supernovae. Astrophys J 546:734–743. doi:10.1086/318299, arXiv:astro-ph/0006292

Li W, Filippenko AV, Chornock R, Berger E, Berlind P, Calkins ML, Challis P, Fassnacht C, Jha S, Kirshner RP, Matheson T, Sargent WLW, Simcoe RA, Smith GH, Squires G (2003) SN 2002cx: the most peculiar known Type Ia Supernova. Publ Astron Soc Pac 115:453–473. doi:10.1086/374200, arXiv:astro-ph/0301428

Li W, Bloom JS, Podsiadlowski P, Miller AA, Cenko SB, Jha SW, Sullivan M, Howell DA, Nugent PE, Butler NR, Ofek EO, Kasliwal MM, Richards JW, Stockton A, Shih HY, Bildsten L, Shara MM, Bibby J, Filippenko AV, Ganeshalingam M, Silverman JM, Kulkarni SR, Law NM, Poznanski D, Quimby RM, McCully C, Patel B, Maguire K, Shen KJ (2011a) Exclusion of a luminous red giant as a companion star to the progenitor of supernova SN 2011fe. Nature 480:348–350. doi:10.1038/nature10646, http://arXiv.org/abs/1109.1593

Li W, Leaman J, Chornock R, Filippenko AV, Poznanski D, Ganeshalingam M, Wang X, Modjaz M, Jha S, Foley RJ, Smith N (2011b) Nearby supernova rates from the lick observatory supernova search – II. The observed luminosity functions and fractions of supernovae in a complete sample. Mon Not R Astron Soc 412:1441–1472. doi:10.1111/j.1365-2966.2011.18160.x, http://arXiv.org/abs/1006.4612

Lira P (1996) Light curves of the supernovae 1990N and 1990T. Master's thesis. University of Chile

Liu WM, Chen WC, Wang B, Han ZW (2010) Helium-star evolutionary channel to super-Chandrasekhar mass Type Ia Supernovae. Astron Astrophys 523:A3. doi:10.1051/0004-6361/201014180, http://arXiv.org/abs/1007.4751

Liu ZW, Kromer M, Fink M, Pakmor R, Röpke FK, Chen XF, Wang B, Han ZW (2013) Predicting the amount of hydrogen stripped by the SN explosion for SN 2002cx-like SNe Ia. Astrophys J 778:121. doi:10.1088/0004-637X/778/2/121, http://arXiv.org/abs/1310.3884

Liu ZW, Moriya TJ, Stancliffe RJ, Wang B (2015a) Constraints on single-degenerate Chandrasekhar mass progenitors of Type Iax Supernovae. Astron Astrophys 574:A12. doi:10.1051/0004-6361/201424532, http://arXiv.org/abs/1412.0820

Liu ZW, Stancliffe RJ, Abate C, Wang B (2015b) Pre-explosion companion stars in Type Iax Supernovae. Astrophys J 808:138. doi:10.1088/0004-637X/808/2/138, http://arXiv.org/abs/1506.04903

Liu ZW, Zhang JJ, Ciabattari F, Tomasella L, Wang XF, Zhao XL, Zhang TM, Xin YX, Wang CJ, Chang L (2015c) Optical observations of an SN 2002cx-like peculiar supernova SN 2013en in UGC 11369. Mon Not R Astron Soc 452:838–844. doi:10.1093/mnras/stv1303, http://arXiv.org/abs/1506.02845

Long M, Jordan GC IV, van Rossum DR, Diemer B, Graziani C, Kessler R, Meyer B, Rich P, Lamb DQ (2014) Three-dimensional simulations of pure deflagration models for thermonuclear supernovae. Astrophys J 789:103. doi:10.1088/0004-637X/789/2/103, http://arXiv.org/abs/1307.8221

Lyman JD, James PA, Perets HB, Anderson JP, Gal-Yam A, Mazzali P, Percival SM (2013) Environment-derived constraints on the progenitors of low-luminosity Type I Supernovae. Mon Not R Astron Soc 434:527–541. doi:10.1093/mnras/stt1038, http://arXiv.org/abs/1306.2474

Lyman JD, Taddia F, Stritzinger MD, Galbany L, Leloudas G, Anderson JP, Eldridge JJ, James PA, Krühler T, Levan AJ, Pignata G, Stanway ER (2017) Investigating the diversity of supernovae type Iax: a MUSE and NOT spectroscopic study of their environments. ArXiv e-prints, http://arXiv.org/abs/1707.04270

Ma H, Woosley SE, Malone CM, Almgren A, Bell J (2013) Carbon deflagration in Type Ia Supernova. I. Centrally ignited models. Astrophys J 771:58. doi:10.1088/0004-637X/771/1/58, http://arXiv.org/abs/1305.2433

Maeda K, Terada Y (2016) Progenitors of Type Ia Supernovae. Int J Mod Phys D 25:1630024. doi:10.1142/S021827181630024X, http://arXiv.org/abs/1609.03639

Magee MR, Kotak R, Sim SA, Kromer M, Rabinowitz D, Smartt SJ, Baltay C, Campbell HC, Chen TW, Fink M, Gal-Yam A, Galbany L, Hillebrandt W, Inserra C, Kankare E, Le Guillou L, Lyman JD, Maguire K, Pakmor R, Röpke FK, Ruiter AJ, Seitenzahl IR, Sullivan M, Valenti S, Young DR (2016) The Type Iax Supernova, SN 2015H. A white dwarf deflagration candidate. Astron Astrophys 589:A89. doi:10.1051/0004-6361/201528036, http://arXiv.org/abs/1603.04728

Magee MR, Kotak R, Sim SA, Wright D, Smartt SJ, Berger E, Chornock R, Foley RJ, Howell DA, Kaiser N, Magnier EA, Wainscot R, Waters C (2017) Growing evidence that SNe Iax are not a one-parameter family: the case of PS1-12bwh. ArXiv e-prints http://arXiv.org/abs/1701.05459

Margutti R, Parrent J, Kamble A, Soderberg AM, Foley RJ, Milisavljevic D, Drout MR, Kirshner R (2014) No X-Rays from the very nearby Type Ia SN 2014J: constraints on its environment. Astrophys J 790:52. doi:10.1088/0004-637X/790/1/52, http://arXiv.org/abs/1405.1488

Maund JR, Wheeler JC, Wang L, Baade D, Clocchiatti A, Patat F, Höflich P, Quinn J, Zelaya P (2010) A spectropolarimetric view on the nature of the peculiar Type I SN 2005hk. Astrophys J 722:1162–1174. doi:10.1088/0004-637X/722/2/1162, http://arXiv.org/abs/1008.3985

Maza J, Hamuy M, Antezana R, Gonzalez L, Cartier R, Forster F, Silva S, Carrasco F, Sanchez P, Hervias C, Iturra D, Pignata G, Cifuentes M, Farias C, Conuel B, Folatelli G, Reichart D, Ivarsen K, Haislip J, Crain A, Foster D, Nysewander M, Lacluyze A, Anderson J, Morrell N (2011) Supernova 2011ce in NGC 6708 = Psn J18553580-5343290. Central Bureau Electronic Telegrams 2715

McClelland CM, Garnavich PM, Galbany L, Miquel R, Foley RJ, Filippenko AV, Bassett B, Wheeler JC, Goobar A, Jha SW, Sako M, Frieman JA, Sollerman J, Vinko J, Schneider DP (2010) The subluminous supernova 2007qd: a missing link in a family of low-luminosity Type Ia Supernovae. Astrophys J 720:704–716. doi:10.1088/0004-637X/720/1/704, http://arXiv.org/abs/1007.2850

McCully C, Jha SW, Foley RJ, Bildsten L, Fong WF, Kirshner RP, Marion GH, Riess AG, Stritzinger MD (2014a) A luminous, blue progenitor system for the Type Iax Supernova 2012Z. Nature 512:54–56. doi:10.1038/nature13615, http://arXiv.org/abs/1408.1089

McCully C, Jha SW, Foley RJ, Chornock R, Holtzman JA, Balam DD, Branch D, Filippenko AV, Frieman J, Fynbo J, Galbany L, Ganeshalingam M, Garnavich PM, Graham ML, Hsiao EY, Leloudas G, Leonard DC, Li W, Riess AG, Sako M, Schneider DP, Silverman JM, Sollerman J, Steele TN, Thomas RC, Wheeler JC, Zheng C (2014b) Hubble space telescope and ground-based observations of the Type Iax Supernovae SN 2005hk and SN 2008A. Astrophys J 786:134. doi:10.1088/0004-637X/786/2/134, http://arXiv.org/abs/1309.4457

Meng X, Podsiadlowski P (2014) The birth rate of SNe Ia from hybrid CONe white dwarfs. Astrophys J Lett 789:L45. doi:10.1088/2041-8205/789/2/L45, http://arXiv.org/abs/1406.4208

Meng X, Yang W (2010) A comprehensive progenitor model for SNe Ia. Astrophys J 710:1310–1323. doi:10.1088/0004-637X/710/2/1310, http://arXiv.org/abs/0910.4992

Meng X, Zhang J, Han Z (2017) A polarization sequence for Type Ia supernovae? APJ 841:62 doi:10.3847/1538-4357/aa6f18, arXiv:1704.06386

Metzger BD (2012) Nuclear-dominated accretion and subluminous supernovae from the merger of a white dwarf with a neutron star or black hole. Mon Not R Astron Soc 419:827–840. doi:10.1111/j.1365-2966.2011.19747.x, http://arXiv.org/abs/1105.6096

Miller AA, Kasliwal MM, Cao Y, Goobar A, Knežević S, Laher RR, Lunnan R, Masci FJ, Nugent PE, Perley DA, Petrushevska T, Quimby RM, Rebbapragada UD, Sollerman J, Taddia F, Kulkarni SR (2017) Color me intrigued: the discovery of iPTF 16fnm, a supernova 2002cx-like Object. ArXiv e-prints http://arXiv.org/abs/1703.07449

Milne PA, Brown PJ, Roming PWA, Holland ST, Immler S, Filippenko AV, Ganeshalingam M, Li W, Stritzinger M, Phillips MM, Hicken M, Kirshner RP, Challis PJ, Mazzali P, Schmidt BP, Bufano F, Gehrels N, Vanden Berk D (2010) Near-ultraviolet properties of a large sample of Type Ia Supernovae as observed with the Swift UVOT. Astrophys J 721:1627–1655. doi:10.1088/0004-637X/721/2/1627, http://arXiv.org/abs/1007.5279

Moriya T, Tominaga N, Tanaka M, Nomoto K, Sauer DN, Mazzali PA, Maeda K, Suzuki T (2010) Fallback supernovae: a possible origin of peculiar supernovae with extremely low explosion energies. Astrophys J 719:1445–1453. doi:10.1088/0004-637X/719/2/1445, http://arXiv.org/abs/1006.5336

Narayan G, Foley RJ, Berger E, Botticella MT, Chornock R, Huber ME, Rest A, Scolnic D, Smartt S, Valenti S, Soderberg AM, Burgett WS, Chambers KC, Flewelling HA, Gates G, Grav T, Kaiser N, Kirshner RP, Magnier EA, Morgan JS, Price PA, Riess AG, Stubbs CW, Sweeney WE, Tonry JL, Wainscoat RJ, Waters C, Wood-Vasey WM (2011) Displaying the heterogeneity of the SN 2002cx-like subclass of Type Ia Supernovae with observations of the Pan-STARRS-1 discovered SN 2009ku. Astrophys J Lett 731:L11. doi:10.1088/2041-8205/731/1/L11, http://arXiv.org/abs/1008.4353

Neunteufel P, Yoon SC, Langer N (2016) Models for the evolution of close binaries with He-star and white dwarf components towards Type Ia Supernova explosions. Astron Astrophys 589:A43. doi:10.1051/0004-6361/201527845, http://arXiv.org/abs/1603.00768

Nomoto K (1984) Evolution of 8–10 solar mass stars toward electron capture supernovae. I – formation of electron-degenerate O + Ne + Mg cores. Astrophys J 277:791–805. doi:10.1086/161749

Nonaka A, Aspden AJ, Zingale M, Almgren AS, Bell JB, Woosley SE (2012) High-resolution simulations of convection preceding ignition in Type Ia Supernovae using adaptive mesh refinement. Astrophys J 745:73. doi:10.1088/0004-637X/745/1/73, http://arXiv.org/abs/1111.3086

Nugent P, Phillips M, Baron E, Branch D, Hauschildt P (1995) Evidence for a spectroscopic sequence among Type 1a Supernovae. Astrophys J Lett 455:L147+. doi:10.1086/309846, arXiv:astro-ph/9510004

Östman L, Nordin J, Goobar A, Amanullah R, Smith M, Sollerman J, Stanishev V, Stritzinger MD, Bassett BA, Davis TM, Edmondson E, Frieman JA, Garnavich PM, Lampeitl H, Leloudas G, Marriner J, Nichol RC, Romer K, Sako M, Schneider DP, Zheng C (2011) NTT and NOT spectroscopy of SDSS-II supernovae. Astron Astrophys 526:A28. doi:10.1051/0004-6361/201015704, http://arXiv.org/abs/1011.5869

Pan YC, Foley RJ, Downing S, Jha SW, Rest A, Scolnic D, Smith KW, Wright D, Smartt SJ, Huber M, Chambers KC, Flewelling H, Willman M, Primak N, Schultz A, Gibson B, Magnier E, Waters C, Tonry J, Wainscoat RJ (2015) ATel 7534: spectroscopic classifications of optical transients with Mayall/KOSMOS. The Astronomer's Telegram 7534

Pan YC, Miller JA, Hounsell RA, Foley RJ, Jha SW, Rest A, Scolnic D, Smith KW, Wright D, Smartt SJ, Huber M, Chambers KC, Flewelling H, Willman M, Primak N, Schultz A, Gibson B, Magnier E, Waters C, Tonry J, Wainscoat RJ (2016) Spectroscopic classifications of optical transients with SOAR. The Astronomer's Telegram 8810

Perets HB, Gal-Yam A, Mazzali PA, Arnett D, Kagan D, Filippenko AV, Li W, Arcavi I, Cenko SB, Fox DB, Leonard DC, Moon DS, Sand DJ, Soderberg AM, Anderson JP, James PA, Foley RJ, Ganeshalingam M, Ofek EO, Bildsten L, Nelemans G, Shen KJ, Weinberg NN, Metzger BD, Piro AL, Quataert E, Kiewe M, Poznanski D (2010) A faint type of supernova from a white dwarf with a helium-rich companion. Nature 465:322–325. doi:10.1038/nature09056, http://arXiv.org/abs/0906.2003

Phillips MM (1993) The absolute magnitudes of Type IA Supernovae. Astrophys J Lett 413:L105–L108. doi:10.1086/186970

Phillips MM, Li W, Frieman JA, Blinnikov SI, DePoy D, Prieto JL, Milne P, Contreras C, Folatelli G, Morrell N, Hamuy M, Suntzeff NB, Roth M, González S, Krzeminski W, Filippenko AV, Freedman WL, Chornock R, Jha S, Madore BF, Persson SE, Burns CR, Wyatt P, Murphy D, Foley RJ, Ganeshalingam M, Serduke FJD, Krisciunas K, Bassett B, Becker A, Dilday B, Eastman J, Garnavich PM, Holtzman J, Kessler R, Lampeitl H, Marriner J, Frank S, Marshall JL, Miknaitis G, Sako M, Schneider DP, van der Heyden K, Yasuda N (2007) The peculiar SN 2005hk: do some Type Ia Supernovae explode as deflagrations? Publ Astron Soc Pac 119:360–387. doi:10.1086/518372, arXiv:astro-ph/0611295

Piersanti L, Tornambé A, Yungelson LR (2014) He-accreting white dwarfs: accretion regimes and final outcomes. Mon Not R Astron Soc 445:3239–3262. doi:10.1093/mnras/stu1885, http://arXiv.org/abs/1409.3589

Postnov KA, Yungelson LR (2014) The evolution of compact binary star systems. Living Rev Relativ 17:3. doi:10.12942/lrr-2014-3, http://arXiv.org/abs/1403.4754

Pumo ML, Turatto M, Botticella MT, Pastorello A, Valenti S, Zampieri L, Benetti S, Cappellaro E, Patat F (2009) EC-SNe from super-asymptotic giant branch progenitors: theoretical models versus observations. Astrophys J Lett 705:L138–L142. doi:10.1088/0004-637X/705/2/L138, http://arXiv.org/abs/0910.0640

Riess AG, Macri L, Casertano S, Lampeitl H, Ferguson HC, Filippenko AV, Jha SW, Li W, Chornock R, Silverman JM (2011) A 3 % solution: determination of the hubble constant with the hubble space telescope and wide field camera 3. Astrophys J 730:119. doi:10.1088/0004-637X/730/2/119, http://arXiv.org/abs/1103.2976

Röpke FK, Hillebrandt W, Schmidt W, Niemeyer JC, Blinnikov SI, Mazzali PA (2007) A three-dimensional deflagration model for Type Ia Supernovae compared with observations. Astrophys J 668:1132–1139. doi:10.1086/521347, http://arXiv.org/abs/0707.1024

Ruiter AJ, Belczynski K, Fryer C (2009) Rates and delay times of Type Ia Supernovae. Astrophys J 699:2026–2036. doi:10.1088/0004-637X/699/2/2026, http://arXiv.org/abs/0904.3108

Ruiter AJ, Belczynski K, Sim SA, Hillebrandt W, Fryer CL, Fink M, Kromer M (2011) Delay times and rates for Type Ia Supernovae and thermonuclear explosions from double-detonation sub-Chandrasekhar mass models. Mon Not R Astron Soc 417:408–419. doi:10.1111/j.1365-2966.2011.19276.x, http://arXiv.org/abs/1011.1407

Sahu DK, Tanaka M, Anupama GC, Kawabata KS, Maeda K, Tominaga N, Nomoto K, Mazzali PA, Prabhu TP (2008) The evolution of the peculiar Type Ia Supernova SN 2005hk over 400 days. Astrophys J 680:580–592. doi:10.1086/587772, http://arXiv.org/abs/0710.3636

Shappee BJ, Kochanek CS, Stanek KZ (2013) Type Ia single degenerate survivors must be overluminous. Astrophys J 765:150. doi:10.1088/0004-637X/765/2/150, http://arXiv.org/abs/1205.5028

Shen KJ, Schwab J (2017) Wait for it: post-supernova winds driven by delayed radioactive decays. Astrophys J 834:180. doi:10.3847/1538-4357/834/2/180, http://arXiv.org/abs/1610.06573

Silverman JM, Foley RJ, Filippenko AV, Ganeshalingam M, Barth AJ, Chornock R, Griffith CV, Kong JJ, Lee N, Leonard DC, Matheson T, Miller EG, Steele TN, Barris BJ, Bloom JS, Cobb BE, Coil AL, Desroches LB, Gates EL, Ho LC, Jha SW, Kandrashoff MT, Li W, Mandel KS, Modjaz M, Moore MR, Mostardi RE, Papenkova MS, Park S, Perley DA, Poznanski D, Reuter CA, Scala J, Serduke FJD, Shields JC, Swift BJ, Tonry JL, Van Dyk SD, Wang X, Wong DS (2012) Berkeley supernova Ia program – I. Observations, data reduction and spectroscopic sample of 582 low-redshift Type Ia Supernovae. Mon Not R Astron Soc 425:1789–1818. doi:10.1111/j.1365-2966.2012.21270.x, http://arXiv.org/abs/1202.2128

Stanishev V, Taubenberger S, Blanc G, Anupama GC, Benetti S, Cappellaro E, Elias-Rosa N, Féron C, Goobar A, Krisciunas K, Pastorello A, Sahu DK, Salvo ME, Schmidt BP, Sollerman J, Thöne CC, Turatto M, Hillebrandt W (2007) The peculiar Type Ia Supernova 2005hk. In: di Salvo T, Israel GL, Piersant L, Burderi L, Matt G, Tornambe A, Menna MT (eds) The multicolored landscape of compact objects and their explosive origins. American institute of physics conference series, vol 924. pp 336–341, doi:10.1063/1.2774878, arXiv:astro-ph/0611354

Steele TN, Cobb BE, Li W, Silverman JM, Chornock R, Filippenko AV (2009) Supernovae 2009hn, 2009ho, and 2009hp. Central Bureau Electronic Telegrams 1889

Stritzinger M (2009) Supernovae 2009I, 2009J, and 2009K. Central Bureau Electronic Telegrams 1665

Stritzinger MD, Hsiao E, Valenti S, Taddia F, Rivera-Thorsen TJ, Leloudas G, Maeda K, Pastorello A, Phillips MM, Pignata G, Baron E, Burns CR, Contreras C, Folatelli G, Hamuy M, Höflich P, Morrell N, Prieto JL, Benetti S, Campillay A, Haislip JB, LaClutze AP, Moore JP, Reichart DE (2014) Optical and near-IR observations of the faint and fast 2008ha-like supernova 2010ae. Astron Astrophys 561:A146. doi:10.1051/0004-6361/201322889, http://arXiv.org/abs/1311.4525

Stritzinger MD, Valenti S, Hoeflich P, Baron E, Phillips MM, Taddia F, Foley RJ, Hsiao EY, Jha SW, McCully C, Pandya V, Simon JD, Benetti S, Brown PJ, Burns CR, Campillay A, Contreras C, Förster F, Holmbo S, Marion GH, Morrell N, Pignata G (2015) Comprehensive observations of the bright and energetic Type Iax SN 2012Z: interpretation as a Chandrasekhar mass white dwarf explosion. Astron Astrophys 573:A2. doi:10.1051/0004-6361/201424168, http://arXiv.org/abs/1408.1093

Szalai T, Vinkó J, Sárneczky K, Takáts K, Benkő JM, Kelemen J, Kuli Z, Silverman JM, Marion GH, Wheeler JC (2015) The early phases of the Type Iax Supernova SN 2011ay. Mon Not R Astron Soc 453:2103–2114. doi:10.1093/mnras/stv1776, http://arXiv.org/abs/1508.00602

Thomas RC, Nugent PE, Meza JC (2011) SYNAPPS: data-driven analysis for supernova spectroscopy. Publ Astron Soc Pac 123:237–248. doi:10.1086/658673

Tomasella L, Cappellaro E, Benetti S, Pastorello A, Hsiao EY, Sand DJ, Stritzinger M, Valenti S, McCully C, Arcavi I, Elias-Rosa N, Harmanen J, Harutyunyan A, Hosseinzadeh G, Howell DA, Kankare E, Morales-Garoffolo A, Taddia F, Tartaglia L, Terreran G, Turatto M (2016) Optical and near-infrared observations of SN 2014ck: an outlier among the Type Iax Supernovae. Mon Not R Astron Soc 459:1018–1038. doi:10.1093/mnras/stw696, http://arXiv.org/abs/1603.07084

Townsley DM, Calder AC, Asida SM, Seitenzahl IR, Peng F, Vladimirova N, Lamb DQ, Truran JW (2007) Flame evolution during Type Ia Supernovae and the deflagration phase in the gravitationally confined detonation scenario. Astrophys J 668:1118–1131. doi:10.1086/521013, http://arXiv.org/abs/0706.1094

Valenti S, Pastorello A, Cappellaro E, Benetti S, Mazzali PA, Manteca J, Taubenberger S, Elias-Rosa N, Ferrando R, Harutyunyan A, Hentunen VP, Nissinen M, Pian E, Turatto M, Zampieri L, Smartt SJ (2009) A low-energy core-collapse supernova without a hydrogen envelope. Nature 459:674–677. doi:10.1038/nature08023, http://arXiv.org/abs/0901.2074

Wang B, Chen X, Meng X, Han Z (2009a) Evolving to Type Ia Supernovae with short delay times. Astrophys J 701:1540–1546. doi:10.1088/0004-637X/701/2/1540, http://arXiv.org/abs/0906.4148

Wang B, Meng X, Chen X, Han Z (2009b) The helium star donor channel for the progenitors of Type Ia Supernovae. Mon Not R Astron Soc 395:847–854. doi:10.1111/j.1365-2966.2009.14545.x, http://arXiv.org/abs/0901.3496

Wang B, Justham S, Han Z (2013) Producing Type Iax Supernovae from a specific class of helium-ignited WD explosions. Astron Astrophys 559:A94. doi:10.1051/0004-6361/201322298, http://arXiv.org/abs/1310.2297

Wang B, Meng X, Liu DD, Liu ZW, Han Z (2014) The hybrid CONe WD + He star scenario for the progenitors of Type Ia Supernovae. Astrophys J Lett 794:L28. doi:10.1088/2041-8205/794/2/L28, http://arXiv.org/abs/1409.7759

White CJ, Kasliwal MM, Nugent PE, Gal-Yam A, Howell DA, Sullivan M, Goobar A, Piro AL, Bloom JS, Kulkarni SR, Laher RR, Masci F, Ofek EO, Surace J, Ben-Ami S, Cao Y, Cenko SB, Hook IM, Jönsson J, Matheson T, Sternberg A, Quimby RM, Yaron O (2015) Slow-speed supernovae from the palomar transient factory: two channels. Astrophys J 799:52. doi:10.1088/0004-637X/799/1/52, http://arXiv.org/abs/1405.7409

Willcox DE, Townsley DM, Calder AC, Denissenkov PA, Herwig F (2016) Type Ia Supernova explosions from hybrid carbon-oxygen-neon white dwarf progenitors. Astrophys J 832:13. doi:10.3847/0004-637X/832/1/13, http://arXiv.org/abs/1602.06356

Woudt PA, Steeghs D, Karovska M, Warner B, Groot PJ, Nelemans G, Roelofs GHA, Marsh TR, Nagayama T, Smits DP, O'Brien T (2009) The expanding bipolar shell of the helium nova V445 puppis. Astrophys J 706:738–746. doi:10.1088/0004-637X/706/1/738, http://arXiv.org/abs/0910.1069

Yamanaka M, Maeda K, Kawabata KS, Tanaka M, Tominaga N, Akitaya H, Nagayama T, Kuroda D, Takahashi J, Saito Y, Yanagisawa K, Fukui A, Miyanoshita R, Watanabe M, Arai A, Isogai

M, Hattori T, Hanayama H, Itoh R, Ui T, Takaki K, Ueno I, Yoshida M, Ali GB, Essam A, Ozaki A, Nakao H, Hamamoto K, Nogami D, Morokuma T, Oasa Y, Izumiura H, Sekiguchi K (2015) OISTER optical and near-infrared observations of Type Iax Supernova 2012Z. Astrophys J 806:191. doi:10.1088/0004-637X/806/2/191, http://arXiv.org/abs/1505.01593

Zhang J, Wang X (2014) Spectroscopic classification of PSN J23560655+2922423 as a peculiar Type Ia Supernova. The Astronomer's Telegram 6611

Zhang J, Chang L, Wang X, Li W, Rui L, Xiang D, Zhang T, Xu Z, Tan H (2016) Spectroscopic classification of SN 2016ilf as a peculiar SN 2002cx-like Type Ia Supernova. The Astronomer's Telegram 9795

Zhou WH, Wang B, Zhao G (2014) Double-detonation model of Type Ia Supernovae with a variable helium layer ignition mass. Res Astron Astrophys 14:1146-1156. doi:10.1088/1674-4527/14/9/005

Zingale M, Nonaka A, Almgren AS, Bell JB, Malone CM, Woosley SE (2011) The convective phase preceding Type Ia Supernovae. Astrophys J 740:8. doi:10.1088/0004-637X/740/1/8