Abstract

What makes a supernova truly “peculiar?” In this chapter we attempt to address this question by tracing the history of the use of “peculiar” as a descriptor of non-standard supernovae back to the original binary spectroscopic classification of Type I vs. Type II proposed by [Minkowski (1941)]. A handful of noteworthy examples (including SN 2012au, SN 2014C, iPTF14hls, and iPTF15eqv) are highlighted to illustrate a general theme: classes of supernovae that were once thought to be peculiar are later seen as logical branches of standard events. This is not always the case, however, and we discuss ASASSN-15lh as an example of a transient with an origin that remains contentious. We remark on how late-time observations at all wavelengths (radio-through-X-ray) that probe 1) the kinematic and chemical properties of the supernova ejecta and 2) the progenitor star system’s mass loss in the terminal phases preceding the explosion, have often been critical in understanding the nature of seemingly unusual events.

Keywords

supernovae: general; stars: mass-loss; X-rays: general; supernovae: individual (SN 2012au, SN 2014C, iPTF15eqv, iPTF14hls, ASASSN-15lh)

1 Introduction

Modern transient surveys have uncovered ever-increasing diversity in the observational properties of supernovae (SNe). Well-known surveys include the Palomar Transient Factory (PTF; [Rau et al, 2009]), the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS; [Chambers et al])
La Silla-QUEST (LSQ; Baltay et al. 2013), the Lick Observatory Supernova Search (LOSS; Li et al. 2000), the Catalina Real-Time Transient Survey (CRTS; Djorgovski et al. 2011), the All-Sky Automated Survey for Supernovae (ASAS-SN; Shappee et al. 2014), and the Texas Supernova Search now operating as the ROTSE Supernova Verification Project (RSVP; Quimby 2006). The original classification system of Type I and Type II proposed by Minkowski (1941) has branched considerably from its binary roots and is continually being updated in the face of new objects that bridge subtypes and extend luminosity ranges.

Given the large range of parameter space that a SN progenitor system can occupy, it should not be surprising that a zoo of diverse events will be observed (Beger and Woosley 2002, Woosley et al. 2002, Sukhbold et al. 2016). Mass, metallicity, rotation, single vs. binary evolution (and if binary, the mass ratio between the companion stars and their initial separation) make for a broad range of possibilities (see, e.g., Podsiadlowski et al. 1992, Yoon et al. 2010, Claeys et al. 2011, and Eldridge et al. 2017). And yet, “peculiar” has a tradition of use in the SN community, and each time non-standard SNe are encountered there is often an element of surprise in the reported analysis. In this chapter we seek to understand why this might be and explore patterns of the use of peculiar as a descriptor of SNe.

We include in our investigation the many synonyms of peculiar that can be used to describe unexpected phenomena. This includes, but is not limited to, e.g., “unusual” (Bersten et al. 2016), “unique” (Tominaga et al. 2005, Maeda et al. 2007), or “Perplexing, Troublesome, and Possibly Misleading” (Foley et al. 2010). Peculiar is typically characterized through non-standard bolometric luminosity, either in peak value (e.g., Smith et al. 2007) or longevity (e.g., Arcavi et al. 2017), or it is associated with non-standard spectroscopic emission (e.g., Jha et al. 2006). These outstanding properties may be attributable to explosion dynamics or, more often, characteristics related to mass loss environment sculpted by the progenitor star system. Peculiar is sometimes used interchangeably with rare. Most certainly there are psychological motivations behind use of the word: use of peculiar (or a synonym) evokes mystery, intrigue, and curiosity more than something that is normal and familiar. Fundamentally, use of the word reflects incomplete knowledge.

Here we focus on peculiar supernovae that at the time of discovery did not fit neatly into any single observational classification. We will discuss how time has shown that some events that were once regarded as highly unusual are in hindsight understood as being normal and/or logical extensions of an already well characterized phenomenon. Our chapter is by no means a complete census of “extreme” events and the reader is directed to excellent reviews of core-collapse and thermonuclear supernovae by Gal-Yam (2016), Parrent et al. (2014), and Taubenberger (2017).

2 Type Ib – The “first” peculiar supernova

The two main classes of supernovae Type I and II (hereafter SNe I and II) were established by Minkowski (1941). Type II have conspicuous hydrogen
features and Type I do not. Today we further divide Type I into those that show Si and S lines (Type Ia) and those that do not (Type Ib and Ic). Narrow emission lines of SNe IIn are associated with interaction with circumstellar environments.

Generally, SNe Ia are presumed to be from white dwarf progenitor systems and the remaining classes from massive stars (see discussion and references in Milisavljevic 2013). The classifications have remained chiefly spectroscopic, although some information about light curve shape (e.g., IIP and IIL; Barbon et al 1979) and bolometric luminosity (e.g., superluminous supernovae; Gal-Yam 2012) have been incorporated.

It is challenging to accurately pin down the original use of “peculiar” to describe supernovae in the Minkowski (1941) classification scheme. McLaughlin (1963) reported observations of SN 1954A that were conspicuously different from SNe I and II. However, more notable are the observations of SN 1962I in NGC 1073 by Bertola (1964). The spectral evolution of SN 1962I was distinctly different from normal Type I, in particular lacking the Si II 6115 Å absorption feature and having an absolute luminosity lower by 1.4 mag compared with normal Type I.

Two decades later a fusillade of papers published rapidly between 1985-1987 on “peculiar Type I supernovae” zeroed in on what we now refer to as Type Ib (Wheeler and Levreault 1985, Harkness et al 1987, Porter and Filippenko 1987, Wheeler et al 1987). These investigations were spurred on by multiple nearby supernovae (including SN 1984L in NGC 991 and SN 1983N in M83) that also lacked the 6115 Å feature normally associated with Type I maximum-light spectra and exhibited absolute luminosities down by ≈ 1.5 mag compared with normal Type I, despite the shape of the optical light curves being similar. The suggestion that these be called “Type III” supernovae was made (Chevalier 1986), but the term was not adopted.

Perhaps most notable of these reports was on SN 1985F, deemed “A peculiar supernova in the spiral galaxy NGC4618” by Filippenko and Sargent (1985). SN 1985F exhibited an optical spectrum dominated by very strong, broad emission lines of [O I] 6300, 6364, [Ca II] 7291, 7324, the Ca II near-IR triplet, Mg I] 4571, and Na I D (Figure 1). The complete absence of hydrogen led to a formal classification of SN I. However, at that time no known spectra of SNe I, which generally exhibit a complex blend of P-Cyg profiles, resembled that of SN 1985F. Many properties of SN 1985F suggested that the progenitor star was massive and had lost its hydrogen envelope prior to exploding (Filippenko and Sargent 1986, Begelman and Sarazin 1986), which had been anticipated as a plausible SN progenitor system for the supernova remnant Cassiopeia A a decade previously by Chevalier (1976).

The question of whether or not SN 1985F was distinct from SNe Ia and SNe Ib was resolved when Gaskell et al (1986) published a spectrum of the Type Ib SN 1983N obtained eight months past maximum. The two spectra were very similar, and formed a crucial link between SN 1985F and other peculiar SN I (now known as Type Ib). These data demonstrated that SN 1985F was a SN Ib discovered long after maximum and, more generally, made it clear that SNe Ib transition into a nebular phase dominated
Fig. 1 Late-time spectrum of SN 1985F. These “peculiar” emissions were in stark contrast with any previously published supernova spectrum. We now know that these broad [O I], Mg I, and Na I lines are standard emissions observed from metal-rich ejecta of stripped-envelope supernovae observed at nebular epochs. Reproduced with permission from Filippenko and Sargent (1985).

by forbidden transitions that is conspicuously different from SNe Ia. The findings confirmed a previous suggestion by Chugai (1986) that SN 1985F might be a SN Ib discovered long after maximum. The recognition of He I lines in early-time spectra of SNe Ib by Harkness et al (1987), provided additional evidence that SNe Ib are a physically separate subclass of SNe I initiated by the core collapse of a massive star (Wheeler and Levreault 1985). Wolf-Rayet stars were quickly hypothesized as natural progenitor systems (Begelman and Sarazin 1986; Gaskell et al 1986). Late-time observations of Type Ib SN 1984L (Schlegel and Kirshner 1989) and detailed analysis of the nebular spectrum of SN 1985F by Fransson and Chevalier (1989) further supported this notion. For additional discussion the reader is directed to Filippenko (1997) and Branch and Wheeler (2017).

As time passed additional heterogeneity in the Type I family beyond the Ia vs. Ib division was recognized. Filippenko et al (1990) reported on a He-poor Type Ib supernova and adopted the nomenclature Type Ic. New Type Ia classifications emerged with SN 1991T (Filippenko et al 1992b), which was more luminous by $\sim 0.5$ mag than regular SNe Ia, and SN 1991bg (Filippenko et al 1992a), which was less luminous by $R \sim 1$ mag compared to normal SNe Ia at peak. Diversity continues to be recognized to this day;
e.g., the class is SN 2002cx-like Type Ia supernovae (also known as SNe Iax) represent one of the most numerous peculiar SN classes (Foley et al. 2013). SNe Iax differ from normal SNe Ia by having a wide range of fainter peak magnitudes, faster decline rates and lower photospheric velocities. We refer the reader to Parrent et al. (2014) for overview of SNe Ia spectra, especially for evolution into the nebular phase. Taubenberger (2017) is another excellent source about extremes of SNe Ia.

The evolving interpretation of the Filippenko and Sargent (1985) observations of SN 1985F is illustrative. In hindsight this event was not so peculiar after all and was no more than spectra of an otherwise normal SN Ib observed several months after explosion. It was, however, perceived as peculiar because observations broke into an unexplored phase space (several months after explosion in this case). In the decades that have followed, larger aperture telescopes along with improvements to detector and instrument efficiencies have made it possible to routinely follow supernovae from explosion to nebular epochs (Figure 2). Dozens of high-quality spectra of supernovae at epochs \( t > 200 \) days post explosion are now available (Matheson et al. 2001, Modjaz et al. 2008, Maeda et al. 2008, Taubenberger et al. 2009, Black et al. 2010, Graham et al. 2017), and in some cases (e.g., SNe 1957D, 1970G, 1979C, 1980K, 1993J) supernovae have even been monitored several years to decades after explosion at optical wavelengths (Fesen and Becker 1988, Long et al. 1989, Turatto et al. 1989, Milisavljevic et al. 2012). These observations show that spectra of SNe Ia and SNe Ib/c evolve in very different manners: SNe Ia consist of many forbidden transitions of Fe and Co, whereas SNe Ib/Ic are dominated by O, Mg, Ca, a mix of Na and He, and other intermediate mass elements. The divergence is a valuable method of spectroscopic fingerprinting supernova progenitor systems in cases when photospheric spectra dominated by P-Cyg absorptions provide ambiguous identifications (see Section 4).

3 Late-time observations: optical, radio, and X-ray

Data outside of optical wavelengths have played crucial roles in constraining the nature of peculiar objects. Ultraviolet, optical, and near-infrared wavelengths trace the bulk of the stellar ejecta, while radio and X-ray wavelengths trace emission from the SN’s interaction with the local circumstellar environment. Considerable insight into the mass loss environment of the original peculiar Type I (i.e., Type Ib) objects came from observations at radio frequencies; e.g., SN 1983N (Sramek et al. 1984) and SN 1984L (Panagia et al. 1986). Asymmetries in the progenitor star’s mass loss can be a major factor contributing to its multi-wavelength emissions and overall degree of “peculiarity” (e.g. Anderson et al. 2017, Bilinski et al. 2017). Notably, many of the aforementioned evolved SNe still detectable at optical wavelengths (e.g., SN 1993J) are also associated with long-lived X-ray and radio emission from interaction between the SN and circumstellar material (CSM) (Weiler et al. 2007). We discuss additional examples of such SN-CSM interaction in Section 3.3.
Fig. 2 Representative evolution of a stripped-envelope supernova from photospheric to nebular epochs. As the supernova expands the P-Cyg profiles originating from the thin expanding photosphere subside to broad emission from forbidden lines originating from the metal-rich ejecta being heated by $^{56}\text{Co}$ decay. Data are for the Type Ib SN 2008ax from Milisavljevic et al (2010).

Thermal X-ray emission is one of the clearest indications of circumstellar interaction in supernovae (Chevalier and Fransson 2016). The intensity of the emission depends on the square of the density, and thus is a good estimator of the density of the ambient medium, as long as the emission is not absorbed by the medium. So far, over 60 SNe have been detected in X-rays. All of them until recently had been core-collapse SNe, where the CSM is formed by mass loss from the progenitor star. Deep searches have been conducted for Type Ia explosions with null detections and strong constraints both from radio and X-ray observations (Margutti et al 2012, 2014b, Chomiuk et al 2016), suggesting that these explosions occur in “clean” environments ($n < 3 \text{ cm}^{-3}$ at $R \sim 10^{16}$ cm).

Recently, there has been a successful detection of a special case of Type Ia explosion understood to be interacting with H-rich environments. These are known as SN 2002ic-like or Type Ia-CSM events (Wang et al 2004, Silverman et al 2013). Late-time (500-800 days after discovery) X-ray detections of SN 2012ca in Chandra observations were reported by Bochenek et al (2018), who favor an asymmetric medium with a high-density component ($n > 10^8 \text{ cm}^{-3}$). This finding provides critical insight into the debate as to whether all SNe Ia-CSM are thermonuclear explosions (Fox et al 2015, Inserra et al 2016).

3.1 Supernova metamorphosis: $\text{SN 2014C}$

The remarkable SN 2014C is a closely studied, remarkable example of how late-time SN-CSM interaction can probe fundamental aspects of supernova progenitor systems. SN 2014C was discovered in the nearby spiral galaxy NGC 7331 ($D \sim 15.8$ Mpc) on 5 January 2014 and identified as a compar-
atively normal Type Ib. However, when observations resumed in May 2014 after SN 2014C had emerged from behind the Sun, its multi-wavelength properties had become notably different from those of normal SNe Ib. Optical spectra showed that conspicuous emission centered around the Hα line with an overall full-width-half-maximum (FWHM) velocity dispersion of approximately 1400 km s$^{-1}$ had emerged \cite{Milisavljevic2015a}. This is a feature associated with radiative shocks in dense clumps of CSM normally seen only in Type IIn SNe.

Subsequent observations have demonstrated that this metamorphosis is consistent with a delayed interaction between an H-poor star’s supernova explosion (SN 2014C) and a massive H-rich envelope that had been stripped decades to centuries before core collapse. Coordinated observations with *Swift*, *Chandra*, *NuSTAR*, the *Hubble Space Telescope*, and the Karl G. Jansky Very Large Array (VLA) captured the evolution in detail and revealed the presence of a massive shell of $\sim 1M_\odot$ of hydrogen-rich material at $\sim 6 \times 10^{16}$ cm from the explosion site \cite{Margutti2017a}. The IR luminosity of SN 2014C stayed constant over 800 days, possibly due to strong CSM interaction with the H-rich shell, which is rare among stripped-envelope SNe, and suggests that the CSM shell originated from an LBV-like eruption roughly 100 years pre-explosion \cite{Tinyanont2016}. This reinforces the interpretation that SN 2014C exploded in a low-density region before encountering a dense hydrogen-rich shell of circumstellar material that was likely ejected by the progenitor prior to the explosion.

SN 2014C is a variant of Type IIn and Ibn SNe that exhibit strong shock interaction between their ejecta and pre-existing, slower-moving CSM \cite{Foley2007, Pastorello2007, Smith2016}, and part of larger family of supernovae from H-poor progenitor stars that interact with H-rich CSM months to years after explosion. This includes SN 1986J \cite{Rupen1987, Milisavljevic2008}, the “Wild cousin of SN 1987A” SN 1996cr \cite{Bauer2008}, and SN 2001em \cite{Chugai2006}, which was at first speculated to be a $\gamma$-ray burst seen off-axis \cite{Soderberg2004}. Observations of the majority of these supernovae bridging classifications largely missed the transition from one SN type to another. SN 2014C was unique in the level of details achievable in multi-wavelength follow up across the electromagnetic spectrum.

The metamorphosis emphasizes how SN-CSM interaction can dramatically change SN emission features. Despite originally being an H-poor Type Ib, after only one year SN 2014C rapidly evolved to resemble the H-rich Type II SN 1980K (Figure 5) at three decades of age. The overall phenomenon poses significant challenges to current theories of massive star evolution, as it requires a physical mechanism responsible for the ejection of the deepest hydrogen layer of H-poor SN progenitors to be synchronized with the onset of stellar collapse. Although the brief timescales between eruption and supernova explosion have been anticipated in special cases of very massive stars \cite{Quataert2012}, a growing number
Fig. 3 Real-time monitoring of the delayed interaction between an H-poor star’s supernova explosion (SN 2014C) and its previously stripped H-rich envelope. (A) A spectrum of SN 2014C obtained around the time of maximum light compared to the H-poor type Ib SN 2008D. (B) Months later, SN 2014C exhibits typical type Ib emissions originating from O- and Ca-rich inner ejecta, but also unexpected new and extended (FWHM ≈ 1400 km/s) Hα emission normally only seen in strongly interacting SNe. (C) One year after explosion, Hα emission dominates the spectrum. Also seen are low and high ionization emissions of narrow to broad widths originating from many regions (see Fig. 3 for enlargement). SN 2014C represents the first time a type Ib SN has been seen to slowly evolve into a strongly interacting Type IIn. Adapted from Milisavljevic et al (2015a).

4 Peculiar supernovae of debated origin

4.1 The SN Ib,c–GRB–SLSN Connection: SN 2012au

Twentieth century samples of well-studied SNe were gathered primarily through surveys that targeted known, bright, nearby galaxies. Most of the SNe discovered this way had absolute peak magnitudes fainter than about ≈ −20 (see e.g., results in Jha et al 2006, Richardson et al 2006). The latest generation of searches, however, have begun gathering SNe via untargeted surveys that are not biased in this way. One surprising result is that a significant percentage of SNe found in dwarf galaxies peak at −21 magnitude or brighter. These superluminous supernovae (SLSNe) are a factor of 10−100 times brighter than normal core-collapse supernovae. The energy emitted in optical light alone rivals the total explosion energy available to typical core-collapse supernovae (> 10⁵¹ erg). SLSNe are broadly differentiated as...
SN2014C is the first young extragalactic SN for which soft X-rays (Chandra - CXO) and hard X-rays (with NuSTAR) emission were detected and monitored. These observations reveal a thermal spectrum (left panels) with evolving temperature (T, right upper panel) and absorption (NH, lower right panel). Updated from Margutti et al. (2017a), with the most recent Chandra-NuSTAR observations obtained \(\sim 1000 \) days since explosion.

hydrogen-rich SLSN-II (e.g., Smith et al. 2007), and hydrogen-poor SLSN-I (e.g., Quimby et al. 2011). A further classification for radioactively powered events SLSN-R has also been suggested (Gal-Yam 2012).

Though some SLSNe may be powered mainly by the radioactive decay of \(^{56}\)Ni, many reach peak luminosities far too great to be reasonably explained this way. Interactions between SN ejecta with pre-SN winds is a natural explanation for some systems (Smith et al. 2007), but others show no obvious signs of such ongoing interactions or are unclear (Inserra et al. 2013, Nicholl et al. 2013, Lunnan et al. 2016). Fundamentally different engines may be powering these observationally distinct events. A leading candidate is energy injection from a rapidly rotating neutron star (i.e., magnetar) that gets transferred to the kinetic energy of the SN (Kasen and Bildsten 2010, Woosley 2010).

Numerous connections have been established between SLSNe and other classifications. The similarity between the spectra of SN 2010gx (SLSN-I) and those of broad-lined Type Ic SNe first hinted that the two classes potentially had similar progenitor star systems (Pastorello et al. 2010). This connection was further strengthened and extended to lower-luminosity counterparts with discovery of SN 2012au, an energetic explosion having a rarely observed combination of late-time properties linking subsets of en-
Fig. 5 Optical spectra of SN 2014C [Milisavljevic et al. 2015a] compared to SN 1980K [Milisavljevic et al. 2012]. Interaction with a dense H-rich CSM shell accelerated the SN-to-SNR evolution (c.f. Milisavljevic & Fesen 2017) of SN 2014C such that at one year its reverse shock had developed strong enough to excite metal-rich material. Shown here is a comparison to the Type II SN 1980K at 31 yr.

SN 2014C had energetic and H-poor SNe with SLSNe. Initial spectroscopic observations of SN 2012au showed prominent helium absorption features of an otherwise ordinary Type Ib supernovae. However, continued monitoring through to nebular stages ($t > 250$ days) revealed extraordinary emission properties in its optical and near-infrared spectra not unlike those observed in SLSNe (Milisavljevic et al. 2013b).

SN 2012au had a large explosion kinetic energy of $\sim 10^{52}$ erg and $^{56}$Ni mass of $\approx 0.3 M_\odot$ on par with SN 1998bw (Takaki et al. 2013). Its intriguing late-time properties included persistent P-Cyg absorptions attributable to Fe II at $< 2000$ km s$^{-1}$, and unusually strong emissions from Ca II H&K, Na I D, and O I 7774 Å (see Figure 6). Persistent P-Cyg absorptions and asymmetries between elements and their ions in the emission line profiles are consistent with expectations of a moderately aspherical and potentially jetted explosion that was most likely initiated by the core collapse of a massive progenitor star. Aside from some differences in the strength and velocity widths of the Fe and Mg emissions, above $\approx 5600$ Å emissions from SN 2012au are almost indistinguishable from those of hypernovae SN 1997dq and SN 1997ef, and the superluminous SN 2007bi. Like SN 2012au, these objects exhibited slow spectroscopic evolution and slowly declining light curves.
Fig. 6 Spectral fingerprinting SN 2012au. The top panels show the SN Ib SN 2008D [Tanaka et al 2009] and the hypernova SN 1998bw [Patat et al 2001], where spectroscopic evolution is normal and O I $\lambda$7774 is not detected. These SNe are representative of late-time emissions from the majority of SNe Ib/c. The bottom panels show the hypernova SN 1997dq [Matheson et al 2001] and the SLSN SN 2007bi [Gal-Yam et al 2009], where spectroscopic evolution is slow, strong O I $\lambda$7774 emission is detected, and emission from Fe lines forms an emission plateau between 4000 and 5600 Å. This connection between SNe Ib/c and SLSNe initially made in Milisavljevic et al (2013b) was strengthened with late-time observations of the SLSN SN 2015bn (Nicholl et al 2016). Adapted from Milisavljevic et al (2013b).

Extensive radio and X-ray observations of SN 2012au closely follow models of synchrotron emission from a CSM with wind density profile $\rho \propto r^{-2}$ and mass-loss rate of the progenitor of $\dot{M} = 3.6 \times 10^{-6} M_\odot yr^{-1}$ [Kamble et al 2014]. Together with the large explosion energy and the large $^{56}$Ni mass, the progenitor of SN 2012au likely had a main-sequence mass $> 20 M_\odot$, for which the outer hydrogen envelope had been stripped away but the helium layer still remained. Milisavljevic et al (2013b) concluded that a single framework involving the core collapse of a massive progenitor and a subsequent asymmetric explosion could unify subsets of SNe and SLSNe that span $-21 < M_B < -17$ mag.

Observations of other extraordinary events have corroborated the notion that connections between some seemingly ordinary Type Ib,c, SLSNe, and SNe associated with long duration gamma-ray bursts (GRBs) may exist. SN 2011kl was associated with the ultra-long-duration gamma-ray burst, GRB 111209A, at a redshift $z$ of 0.677 [Greiner et al 2015]. Its light curve was significantly overluminous compared to other GRB-associated SNe and suggested a link between SN-GRB and SLSNe. Also significant in this regard
is nebular-phase spectroscopy of the SLSN-I SN 2015bn spanning +250–400 days after maximum light. These spectra (among the latest ever obtained for a SLSN) are virtually identical to SN 2012au and other energetic SNe Ic (Nicholl et al 2016), and supported the Milisavljevic et al (2013b) interpretation that relatively narrow O I λ7774 line may be the signature of a central engine.

4.2 Calcium-rich transients: \textit{iPTF15eqv}

The class of “Ca-rich transients” defined by unusually strong calcium line emissions that develop in optical spectra months after explosion has garnered considerable attention in the last decade. They were first reported by Filippenko et al (2003). Later, thorough investigations were provided by Perets et al (2010) of SN 2005E, and Kasliwal et al (2012) who discovered several examples in PTF survey data.

Ca-rich transients have distinct He lines in their spectra during the first couple months of evolution and fall within the supernova Type Ib classification. However, Ca-rich transients are less luminous than normal SNe Ib and reach nebular stages much more rapidly (within two months post-explosion). Perhaps most intriguing is that Ca-rich transients are often located at large projected distances (as high as 150 kpc) from the centers of their host galaxies, implying that progenitors have traveled significant distances before exploding (Lyman et al 2014, Foley 2015). Many occur in early-type galaxies lacking obvious massive star populations (Kasliwal et al 2012), and examinations of explosion sites with deep, high resolution images have thus far failed to uncover any sign of in situ star formation (Lyman et al 2013, 2014, 2016, Lunnan et al 2017).

The progenitor systems of Ca-rich transients have been a source of contention. A variety of spectroscopic properties of Ca-rich transients, including the Type Ib classification, are most naturally understood as originating from explosions of massive star progenitors (Kawabata et al 2010). However, the prevailing view is that Ca-rich transients are somehow related to WD progenitor systems. The relatively large delay-time distribution required to travel large distances favors an older white dwarf (WD) population that also contributes to SNe Ia. Many explosion channels have been proposed involving helium detonations occurring on a helium-accreting WD (Shen and Bildsten 2009, Perets et al 2010, Woosley and Kasen 2011). Attempts to understand Ca-rich transients using models involving the tidal detonation of a low-mass WD by a neutron star or intermediate-/stellar-mass black hole have also been suggested (Rosswog et al 2008, MacLeod et al 2014, Sell et al 2015).

The discovery of iPTF15eqv – a “Peculiar Ca-rich Transient” – complicated the WD progenitor paradigm and corroborated suspicions that the observational classification may encompass multiple progenitor channels (Milisavljevic et al 2017). The close proximity and relatively slow decline rate of iPTF15eqv enabled spectroscopic observations of high signal-to-noise ratio at epochs > 200 days after explosion, which is among the latest epochs ever observed for a Ca-rich transient. The transient was originally
discovered by K. Itagaki, and then independently discovered and classified by the iPTF survey (Cao et al 2015). Initial spectra led Cao et al (2015) to classify iPTF15eqv as an SN IIb/Ib in the nebular phase. However, a multi-wavelength follow-up campaign supported by radio observations with the VLA and X-ray observations with Chandra showed a combination of properties that bridge those observed in Ca-rich transients and SNe Ib/c (Milisavljevic et al 2017).

Perhaps most revealing about iPTF15eqv is its conspicuous Type Ib/c and Type II spectroscopic signatures in late-time optical and NIR data (Figure 7). iPTF15eqv exhibits [O I], [Ca II], a blend of He I+Na I, and a “plateau” of emission spanning 3800-5600 Å associated with Fe-peak elements. To varying degrees these are all observed in Type IIb SN 2011dh (Ergon et al 2015), the GRB-SN SN 1998bw, and the Type IIP SN 2004et
Fig. 8 Emission line ratio of [Ca II] λλ7291, 7324 to [O I] λλ6300, 6364 for Type II, Type IIb/Ib/Ic, and Ca-rich transients. At all epochs where both lines are visible and the conditions can be reasonably assessed to be nebular, all Ca-rich transients have [Ca II]/[O I] > 2, and all Type Ib/c are < 2. Solid lines connect different epochs of the same object. iPTF15eqv stands out with the highest [Ca II]/[O I] ratio of ≈ 10. The gray silhouette of iPTF15eqv connected by dashed lines reflects the uncertainty in the explosion date. Adapted from Milisavljevic et al (2017).

(Sahu et al 2006). A broad emission feature redward of [O I] that is likely Hα but may include contribution from [N II] and/or Ca I λ6572, is also shared in some cases. In sharp contrast, iPTF15eqv does not share any conspicuous features with normal Type Ia that are dominated by blended forbidden and permitted Fe-peak lines between 4000-5500 Å and 7000-7600 Å.

On the one hand, the late-time spectra of iPTF15eqv are dominated by strong calcium emission lines, which is a defining characteristic of Ca-rich transients. Its [CaII]/[OI] ≈ 10 emission line ratio is among the highest encountered among Ca-rich events (Figure 8). On the other hand, iPTF15eqv differs from other Ca-rich transients in terms of its light curve evolution. iPTF15eqv was a slower evolving and potentially much more luminous object than Ca-rich transients (estimated to potentially be up to ~ 2 mag brighter than other examples; Kawahara et al 2018) and exhibited a light curve that resembles SNe Ib/c.
Analysis of the chemical abundances associated with observed line emission from iPTF15eqv is consistent with the supernova explosion of a $<10 M_\odot$ star that was stripped of its H-rich envelope via binary interaction. This result challenges the notion that spectroscopically classified Ca-rich transients only originate from WD progenitor systems. Milisavljevic et al. (2017) conclude that the relatively long delay-time distribution and distinguishable abundance patterns of electron capture supernovae from binary systems make them an attractive progenitor system for at least some Ca-rich transients.

4.3 Unusual Longevity: iPTF14hls

iPTF14hls (Arcavi et al. 2017) commanded recent attention for exhibiting both extremely normal and extremely peculiar characteristics simultaneously. iPTF14hls showed spectra that are identical to normal Type II-P explosions, yet persisted nearly unchanged for $\sim 600$ days while the light-curve experienced multiple re-brightenings (Figure 9). The absorption lines showed negligible decreases in velocity throughout the five peaks of the luminous light curve. A pre-explosion outburst in 1954 was also reported.

The spectral and temporal evolution of iPTF14hls is unprecedented. Possible frameworks to understand its nature include magnetar central engines and pulsational pair-instability supernovae (Dessart 2018, Woosley 2018), or common envelope jets (Soker and Gilkis 2018). High-energy $\gamma$-ray emission may have been detected (Yuan et al. 2017), which suggests very fast particle acceleration by the supernova explosion.

A significant breakthrough in constraining the nature of iPTF14hls came with an abrupt change in its spectral emissions observed in data obtained by Andrews and Smith (2017) three years after discovery. A double-peaked intermediate-width $H_\alpha$ line indicative of expansion speeds around 1000 km s$^{-1}$ was observed. A similar profile was also observed in the [O I] 6300, 6364 lines. Andrews and Smith (2017) interpreted this as clear evidence of interaction between the SN and dense CSM having a disc-like geometry, which is an important clue for understanding the nature of the explosion. They conclude that interaction with variations in the density structure of the CSM may be adequate to explain the peculiar evolution of iPTF14hls. A later epoch Keck spectrum obtained by Terreran et al. (in preparation) shows a combination of narrow and broad emission lines seen in strongly interacting Type IIn supernovae consistent with the Andrews and Smith (2017) SN-CSM interpretation (Figure 9). Further monitoring across wavelengths will hopefully continue to shed additional light on the nature of this exciting transient.

5 Special case: ASASSN-15lh

The transient ASASSN-15lh is an excellent example of how some phenomena fail to fit naturally into any known classification. Indeed, the properties of ASASSN-15lh are so peculiar that, at the time of writing, it is not even
clear if ASASSN-15lh is connected with a stellar explosion and might be the first (and only member so far) of its own class.

ASASSN-15lh was discovered (Dong et al 2016) by the All-Sky Automated Survey for Supernovae (ASAS-SN) at z=0.2326 (d = 1171 Mpc for standard Planck cosmology). The location of ASASSN-15ls is astrometrically consistent with the nucleus of its massive early type host galaxy (Dong et al 2016). The transient exhibited an extremely large peak luminosity $L_{pk} \sim 2 \times 10^{45}$ erg s$^{-1}$ and a blue, almost featureless spectrum with no apparent sign of H or He, leading Dong et al (2016) and Godoy-Rivera et al (2017) to suggest it to be the most luminous SLSN ever detected (Fig. 10). However, the spectral and temporal evolution of the transient, as well as its host galaxy, are unprecedented among SLSNe and other explanations have been proposed, including a tidal disruption event (TDE) by a super-massive BH (Leloudas et al 2016).

The observed properties of ASASSN-15lh challenge any classification scheme and can be summarized as follows:

- The peak luminosity of ASASSN-15lh and its total radiated energy ($E_{rad} \sim 2 \times 10^{52}$ erg) are extreme even among SLSNe, and require
Fig. 10 Left panel: Bolometric luminosity emission from ASASSN-15lh (black dots from Dong et al 2016, Margutti et al 2017b) compared to a sample of H-stripped SLSNe (from Inserra et al 2013, Nicholl et al 2016). ASASSN-15lh is > 10 times more luminous then the most luminous SLSNe known at peak and shows an unusually very mild decay at later times. Right panel: early-times spectral evolution of ASASSN-15lh in context with SLSNe (here we use the SLSN SN2010gx, which shows the typical features of the class). The 0 II ion “W-shaped” feature is typical of SLSNe (vertical dashed lines), and here we show how using the simple assumptions of SYN++ and a photospheric velocity of 19,000 km s$^{-1}$, the -4 day spectrum of the SLSN 2010gx can be reproduced. By contrast, we cannot reproduce +13 day spectrum of ASASSN-15lh. Even more importantly, ASASSN-15lh progressively evolves towards a featureless spectrum with time, which is the opposite evolution of SNe. Adapted from Margutti et al (2017b).

sources of energy that are different from the standard radioactive decay of $^{56}$Ni that powers normal H-stripped SNe in the local Universe (Dong et al 2016, Chatzopoulos et al 2016, Kozyreva et al 2016, van Putten and Della Valle 2016).

– ASASSN-15lh experienced a UV rebrightening beginning at $t \sim 90$-d (observer frame) after the primary peak and was followed by a $\sim 120$-d long plateau in the bolometric luminosity (Fig. 10), before starting to fade again. Throughout its initial decline, subsequent rebrightening and renewed decline, the spectra did not show evidence of interactions between the ejecta and CSM such as narrow emission lines. There are hints of weak H$\alpha$ emission at late-times, but Margutti et al (2017b) have shown that it is narrow line emission consistent with star formation in the host nucleus.

– Differently from SNe, ASASSN-15lh evolved towards a progressively featureless spectrum (Fig. 10).

– The host galaxy of ASASSN-15lh is old, massive $M_\ast \sim 2 \times 10^{11}$ M$_\odot$ and with limited star formation (Dong et al 2016). These properties are very different from galaxies that host core-collapse SNe and SLSNe, which are typically younger star forming galaxies with significantly lower stellar mass (Milisavljevic et al 2015b, Lunnan et al 2015, Perley et al 2016, Leloudas et al 2016). In the context of TDEs, the host galaxy properties...
are also unprecedented, and ASASSN-15lh would be the most luminous TDE ever observed, associated with a SMBH with mass $M \sim 10^{8.6}\,M_\odot$ significantly larger than the average TDE SMBHs (e.g. Komossa 2015). The large SMBH mass motivated speculation of a fast rotating SMBH, in order to disrupt the star outside the innermost stable stellar orbit (Leloudas et al 2016, Margutti et al 2017b). Coughlin and Armitage (2017) argue that its features, including its anomalous rebrightening at $\sim 100$ days after detection, are consistent with the tidal disruption of a star by a supermassive black hole in a binary system.

Debate has continued on whether ASASSN-15lh is an H-poor supernova or a tidal disruption event. It is clear that the properties of ASASSN-15lh and of its host galaxy are unprecedented in both scenarios. It is possible that a clue to the real nature of ASASSN-15lh has already been provided by its emission outside the optical range. A faint X-ray source has been detected at the location consistent with ASASSN-15lh (Margutti et al 2017b). The very soft spectrum of the source and its persistent emission are not consistent with SNe, and suggest instead an origin connected with the nucleus of the host galaxy. If ASASSN-15lh is a TDE, the expectation is fading of the X-ray source in the next few years.

Future multi-wavelength follow-up of ASASSN-15lh, and a larger sample of similar events, are the only way to advance our understanding of the physics of this extremely peculiar transient.

6 Concluding Remarks: what will be “peculiar” in the future?

In this chapter we have reviewed several examples of peculiar supernovae in an effort to understand what sets them apart from normal events. A general pattern emerged that classes of supernovae that were originally interpreted to have unusual properties are later seen as logical branches of phenomena that are already well understood. In some cases, the nature of a peculiar transient can remain debated, and we discussed the special case of ASASSN-15lh as an example of this contentious variety. The shift in interpretation from extraordinary to mundane has often been brought about by improvements in telescope and detector technology, and by observations that push into new phase spaces of luminosity, time scale, and wavelength.

**What will be identified as peculiar in the future?** Observations of supernovae in the first hours to days following explosion have been limited thus far but provide enticing glimpses at the wealth of information that can be extracted at extremely early phases (Nugent et al 2011, Milisavljevic et al 2013a, Gal-Yam et al 2014, Nicholl et al 2015, Garnavich et al 2016). The Pan-STARRS, PTF, and $D < 40\,\text{Mpc}$ (DLT40) surveys have made commendable progress in this regard (Drout et al 2014, Yaron et al 2017, Tartaglia et al 2018), and the upcoming surveys Zwicky Transient Facility and Large Synoptic Survey Telescope (LSST) will allow even

---

1. [https://www.ptf.caltech.edu/ztf](https://www.ptf.caltech.edu/ztf)
2. [https://www.lsst.org/](https://www.lsst.org/)
greater exploration of these very early phases. Complementary to these advances will be explorations at very late epochs. This will be a particular strength of LSST, which will provide a deep, all-sky survey sampled in a consistent rapid cadence, and next-generation telescopes such as the Giant Magellan Telescope[^3], the Thirty Meter Telescope[^4] and the European Extremely Large Telescope[^5] that will revolutionize late-time investigations of supernovae both in the volume of space that can be sampled (and hence the number of objects to study) and the quality of data to be obtained. Particularly exciting will be the ability to carefully monitor the evolution of emission line widths in spectra, which can distinguish between sources of energy in extreme supernovae (Milisavljevic et al 2012). As these and other facilities, now operating in the multi-messenger era (Abbott et al 2017), move into uncharted frontiers of transient phase space, they are destined to continue finding new examples of supernovae that defy expectations and shape our understanding of the terminal stages of stellar evolution.

Acknowledgements  D. M. & R. M. thank ISSI organizers for their kind invitation to the Supernova Workshop in Bern. D. M. acknowledges support from NASA through grant number GO-14202 from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555. R. M. acknowledges partial support to her group from NASA through NuSTAR grants NNX17AI13G and NNX17AG80G. Partial support for this work was provided by the National Aeronautics and Space Administration through Chandra Award Number GO5-16064A and GO6-17054A issued by the Chandra X-ray Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of the National Aeronautics Space Administration under contract NAS8-03060. We especially thank Roger Chevalier for his help and patience preparing the manuscript. We thank J. Andrews and N. Smith for sharing their iPTF14hls spectrum before publication. We also thank G. Terreran for sharing Keck observations of iPTF14hls. This work is based in part on observations from the Low Resolution Imaging Spectrometer at the Keck-I telescope. We are grateful to the staff at the Keck Observatory for their assistance, and we extend special thanks to those of Hawaiian ancestry on whose sacred mountain we are privileged to be guests. The W. M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California, and NASA; it was made possible by the generous financial support of the W. M. Keck Foundation.

References

Abbott BP, Abbott R, Abbott TD, Acernese F, Ackley K, Adams C, Adams T, Adesso P, Adhikari RX, Adya VB, et al (2017) Multi-messenger Observations of a Binary Neutron Star Merger. ApJ 848:L12, DOI 10.3847/2041-8213/aa91c9, [1710.08833](https://arxiv.org/abs/1710.08833)

Anderson GE, Horesh A, Mooley KP, Rushton AP, Fender RP, Staley TD, Argo MK, Beswick RJ, Hancock PJ, Pérez-Torres MA, Perrott YC, Plotkin RM, Pretorius ML, Runsey C, Titterington DJ (2017) The peculiar mass-loss history of SN 2014C as revealed through AMI radio observations. MNRAS 466:3648-3662, DOI 10.1093/mnras/stw3310, [1612.06059](https://arxiv.org/abs/1612.06059)

[^3]: <https://www.gmto.org>
[^4]: <https://www.tmt.org>
[^5]: <https://www.eso.org/sci/facilities/eelt/>
Andrews JE, Smith N (2017) Strong late-time circumstellar interaction in the not-so-impossible supernova iPTF14hls. ArXiv e-prints 1712.00514

Arcavi I, Howell DA, Kasen D, Bildsten L, Hosseinzadeh G, McCully C, Wong ZC, Katz SR, Gal-Yam A, Sollerman J, Taddia F, Leloudas G, Fremling C, Nugent PE, Hicken A, Mooley K, Runyan C, Cenko SB, Graham ML, Perley DA, Nakar E, Shaviv NJ, Bromberg O, Shen KJ, Ofek EO, Cao Y, Wang X, Huang F, Rui L, Zhang T, Li W, Li Z, Zhang J, Valenti S, Guevel D, Shappee B, Kochanek CS, Holoien TWS, Filippenko AV, Fender R, Nyholm A, Yaron O, Kasliwal MM, Sullivan M, Blagorodnova N, Walters RS, Lunnan R, Kazov D, Andreoni I, Laher RR, Konidaris N, Wozniak P, Bue B (2017) Energetic eruptions leading to a peculiar hydrogen-rich explosion of a massive star. Nature 551:210–213, DOI 10.1038/nature24030, 1711.02671

Arnett WD, Meakin C (2011a) Toward Realistic Progenitors of Core-collapse Supernovae. ApJ 733:78, DOI 10.1088/0004-637X/733/2/78, 1101.5646

Arnett WD, Meakin C (2011b) Turbulent Cells in Stars: Fluctuations in Kinetic Energy and Luminosity. ApJ 741:33, DOI 10.1088/0004-637X/741/1/33, 1012.1848

Arcavi I, Howell DA, Kasen D, Bildsten L, Hosseinzadeh G, McCully C, Wong ZC, Katz SR, Gal-Yam A, Sollerman J, Taddia F, Leloudas G, Fremling C, Nugent PE, Hicken A, Mooley K, Runyan C, Cenko SB, Graham ML, Perley DA, Nakar E, Shaviv NJ, Bromberg O, Shen KJ, Ofek EO, Cao Y, Wang X, Huang F, Rui L, Zhang T, Li W, Li Z, Zhang J, Valenti S, Guevel D, Shappee B, Kochanek CS, Holoien TWS, Filippenko AV, Fender R, Nyholm A, Yaron O, Kasliwal MM, Sullivan M, Blagorodnova N, Walters RS, Lunnan R, Kazov D, Andreoni I, Laher RR, Konidaris N, Wozniak P, Bue B (2017) Energetic eruptions leading to a peculiar hydrogen-rich explosion of a massive star. Nature 551:210–213, DOI 10.1038/nature24030, 1711.02671

Arnett WD, Meakin C (2011b) Turbulent Cells in Stars: Fluctuations in Kinetic Energy and Luminosity. ApJ 741:33, DOI 10.1088/0004-637X/741/1/33, 1012.1848

Baltay C, Rabinowitz D, Hadjiyska E, Walker ES, Nugent P, Coppi P, Ellman N, Feindt U, McKinnon R, Horowitz B, Effron A (2013) The La Silla-QUEST Low Redshift Supernova Survey. PASP 125:683, DOI 10.1086/671198

Barbon R, Ciatti F, Rosino L (1979) Photometric properties of type II supernovae. A& A 72:287–292

Bauer FE, Dwarkadas VV, Brandt WN, Immler S, Smartt S, Bartel N, Bietenholz MF (2008) Supernova 1996cr: SN 1987A’s Wild Cousin? ApJ 688:1210–1234, DOI 10.1086/589761, 0804.3597

Beigman MC, Sarazin CL (1986) SN 1985f - Death of a Wolf-Rayet star. ApJ 302:L59–L62, DOI 10.1086/184637

Bersten MC, Benvenuto OG, Orellana M, Nomoto K (2016) The Unusual Supernovae SN 2011kl and ASASSN-15lh. ApJ 817:L8, DOI 10.3847/2041-8205/817/1/L8, 1601.01021

Bertola F (1964) The Supernovae in NGC 1073 and NGC 1058. Annales d’Astrophysique 27:319

Blumenthal OG, Bolte M, Nomoto K (2016) The Unusual Supernovae SN 2011kl and ASASSN-15lh. ApJ 817:L8, DOI 10.3847/2041-8205/817/1/L8, 1601.01021

Branch D, Wheeler JC (2017) Supernova Explosions. Springer, DOI 10.1007/978-3-662-55054-0

Bocchenek CD, Dwarkadas VV, Silverman JM, Fox OD, Chevalier RA, Smith N, Filippenko AV (2018) X-ray emission from SN 2012ca: A Type Ia-CSM supernova explosion in a dense surrounding medium. MNRAS 473:336–344, DOI 10.1093/mnras/stx1429, 1708.07181

Chambers KC, Magnier EA, Metcalfe N, Frewelling HA, Huber ME, Waters CZ, Denneau L, Draper PW, Farrow D, Finkbeiner DP, Holmberg C, Koppenhoefer J, Price PA, Saglia RP, Schlappy EF, Smartt SJ, Sweeney W, Wainscoat RJ, Burgett WS, Grav T, Heasley JN, Hodapp KW, Jedicke R, Kaiser N, Kupeitzki RP, Luppino GA, Lupton RH, Monet DG, Morgan JS, Onaka PM, Stubbs CW, Tonry JL, Banados E, Bell EF, Bender R, Bernard EJ, Botticella MT, Castelino S, Chastel S, Chen WP, Chen X, Cole S, Deacon N, Frenk C, Fitzsimmons A, Gezari S, Goessl C, Goggia T, Goldman B, Grebel EK, Hamblet NC, Hasinger
G, Heavens AF, Heckman TM, Henderson R, Holman M, Hopp U, Ip WH, Isani S, Keyes CD, Koekemoer A, Kotak R, Long KS, Lucey JR, Liu M, Martin NF, McLean B, Morganson E, Murphy DNA, Nieto-Santisteban MA, Norberg P, Peacock JA, Pier EA, Postman M, Primak N, Rae C, Rest A, Riess A, Riffeser A, Rix HW, Roser S, Schilbach E, Schultz ASB, Scolnic D, Szalay A, Seitz S, Shiao B, Small E, Smith KW, Soderblom D, Taylor AN, Thakar AR, Thiel J, Thilker D, Urata Y, Valenti J, Walter F, Waters SP, Werner S, White R, Wood-Vasey WM, Wyse R (2016) The Pan-STARRS1 Surveys. ArXiv e-prints 1612.05560
Chatzopoulos E, Wheeler JC, Vinko J, Nagy AP, Wiggins BK, Even WP (2016) Extreme Supernova Models for the Super-luminous Transient ASASSN-15lh. ApJ 828:94, DOI 10.3847/0004-637X/828/2/94, 1603.06926
Chevalier RA (1976) Cassiopeia A, faint supernovae, and heavy-element ejection by supernovae. ApJ 208:826–828, DOI 10.1086/154669
Chevalier RA (1986) Supernovae and stellar mass loss. Highlights of Astronomy 7:599–609
Chevalier RA, Fransson C (2016) Thermal and non-thermal emission from circumstellar interaction. ArXiv e-prints 1612.07459
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. ApJ 821:119, DOI 10.3847/0004-637X/821/2/119, 1510.07662
Chugai NN (1986) Normal and Peculiar Type-I Supernovae - why do they Differ. Soviet Astronomy Letters 12:192–195
Chugai NN, Chevalier RA (2006) Late Emission from the Type Ib/c SN 2001em: Overtaking the Hydrogen Envelope. ApJ 641:1051–1059, DOI 10.1086/500539, astro-ph/0510362
Claeys JSW, de Mink SE, Pols OR, Eldridge JJ, Baes M (2011) Binary progenitor models of type IIb supernovae. A&A 528:A131, DOI 10.1051/0004-6361/201015410, 1102.1732
Coughlin ER, Armitage PJ (2017) Tidal disruption by extreme mass ratio binaries and application to ASASSN-15lh. ArXiv e-prints 1705.04689
Dessart L (2018) A magnetar model for the hydrogen-rich super-luminous supernova iPTF14hls. ArXiv e-prints 1801.05340
Dittmann JA, Soderberg AM, Chomiuk L, Margutti R, Goss WM, Milisavljevic D, Chevalier RA (2014) A Mid-life Crisis? Sudden Changes in Radio and X-Ray Emission from Supernova 1970G. ApJ 788:38, DOI 10.1088/0004-637X/788/1/38, 1403.6825
Djorgovski SG, Drake AJ, Mahabal AA, Graham MJ, Donalek C, Williams R, Beshore EC, Larson SM, Prieto J, Catelan M, Christensen E, McNaught RH (2011) The Catalina Real-Time Transient Survey (CRTS). ArXiv e-prints [1102.3004]
Dong S, Shappee BJ, Prieto JL, Jha SW, Stanek KZ, Holoién TWS, Kochanek CS, Thompson TA, Morrell N, Thompson IB, Basu U, Beacom JF, Bersier D, Brinacombe J, Brown JS, Bufano F, Chen P, Conseil E, Danilet AB, Falco E, Grupe D, Kiyota S, Masi G, Nicholls B, Olivares E F, Pignata G, Pojmanski G, Simonian GV, Szczygieł DM, Woźniak PR (2016) ASASSN-15lh: A highly super-luminous supernova. Science 351:257–260, DOI 10.1126/science.aad9613, 1507.03010
Drout MR, Chornock R, Soderberg AM, Sanders NE, McKinnon R, Rest A, Foley RJ, Milisavljevic D, Margutti R, Berger E, Calkins M, Fong W, Gezari S, Huber ME, Kankare E, Kirshner RP, Leibler C, Lunnan R, Mattila S, Marion GH, Narayan G, Riest AG, Roth KC, Scolnic D, Smartt SJ, Tonry JL, Burgett WS, Chambers KC, Hodapp KW, Jedicke R, Kaiser N, Magnier EA, Metcalfe N, Morgan JS, Price PA, Waters C (2014) Rapidly Evolving and Luminous Transients from Pan-STARRS1. ApJ 794:23, DOI 10.1088/0004-637X/794/1/23, 1405.3868
Eldridge JJ, Stanway ER, Xiao L, McClelland LAS, Taylor G, Ng M, Greis SML,
Bray JC (2017) Binary Population and Spectral Synthesis Version 2.1: Construction, Observational Verification, and New Results. PASA 34:e058, DOI 10.1017/pasa.2017.51.

Ergon M, Jerkstrand A, Sollerman J, Elias-Rosa N, Fransson C, Fraser M, Pastorello A, Kotak R, Taubenberger S, Tomassella L, Valenti S, Benetti S, Helou G, Kasliwal MM, Maund J, Smartt SJ, Spyromilio J (2015) The Type IIn Ib SN 2011dh: Two years of observations and modelling of the lightcurves. A&A 580:A142, DOI 10.1051/0004-6361/201424592.

Ergon M, Jerkstrand A, Sollerman J, Elias-Rosa N, Fransson C, Fraser M, Pastorello A, Kotak R, Taubenberger S, Tomassella L, Valenti S, Benetti S, Helou G, Kasliwal MM, Maund J, Smartt SJ, Spyromilio J (2015) The Type IIn Ib SN 2011dh: Two years of observations and modelling of the lightcurves. A&A 580:A142, DOI 10.1051/0004-6361/201424592.

Fesen RA, Becker RH (1988) Optical Detection of the Remnant of SN 1980K in NGC 6946. In: Bulletin of the American Astronomical Society, BAAS , vol 20, p 962.

Filippenko AV (1997) Optical Spectra of Supernovae. ARA&A 35:309–355, DOI 10.1146/annurev.astro.35.1.309.

Filippenko AV, Sargent WLW (1985) A peculiar supernova in the spiral galaxy NGC4618. Nature 316:407–412, DOI 10.1038/316407a0.

Filippenko AV, Sargent WLW (1986) The unique supernova (1985f) in NGC 4618. AJ 91:691–696, DOI 10.1086/114051.

Filippenko AV, Porter AC, Sargent WLW (1990) The type IC (helium-poor Ib) supernova 1987M - Transition to the supernuclear phase. AJ 100:1575–1587, DOI 10.1086/115618.

Filippenko AV, Richmond MW, Branch D, Gaskell M, Herbst W, Ford CH, Treffers RR, Matheson T, Ho LC, Dey A, Sargent WLW, Small TA, van Breugel WMJ (1992a) The subluminous, spectroscopically peculiar type IA supernova 1991bg in the elliptical galaxy NGC 4374. AJ 104:1543–1556, DOI 10.1086/116339.

Filippenko AV, Richmond MW, Matheson T, Shields JC, Burbidge EM, Cohen RD, Dickinson M, Malkan MA, Nelson B, Pietz J, Schlegel D, Schmeer P, Spinrad H, Steidel CC, Tran HD, Wren W (1992b) The peculiar Type IA SN 1991T - Detonation of a white dwarf? ApJ 384:L15–L18, DOI 10.1086/186252.

Filippenko AV, Chornock R, Swift B, Modjaz M, Simcoe R, Rauch M (2003) Supernovae 2001co, 2003H, 2003dg, and 2003dr. IAU Circ. 8159.

Foley RJ (2015) Kinematics and host-galaxy properties suggest a nuclear origin for calcium-rich supernova progenitors. MNRAS 452:2463–2478, DOI 10.1093/mnras/stv789, 1501.07607.

Foley RJ, Smith N, Ganeshalingam M, Li W, Chornock R, Filippenko AV (2007) SN 2006jc: A Wolf-Rayet Star Exploding in a Dense He-rich Circumstellar Medium. ApJ 657:L105–L108, DOI 10.1086/513145, astro-ph/0612711.

Foley RJ, Narayan G, Challis PJ, Filippenko AV, Kirshner RP, Silverman JM, Steele TN (2010) SN 2006bt: A Perplexing, Troublesome, and Possibly Misleading Type Ia Supernova. ApJ 708:1748–1759, DOI 10.1088/0004-637X/708/2/1748, 0912.0263.

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, Krshner RP, McCully C, Persson SE, Phillips MM, Reichart DE, Soderberg AM (2013) Type Iax Supernovae: A New Class of Stellar Explosion. ApJ 767:57, DOI 10.1088/0004-637X/767/1/57, 1212.2209.

Fox OD, Silverman JM, Filippenko AV, Mauerhan J, Becker J, Borish HJ, Cenko SB, Cobb RL, Graham M, Hsiao E, Kelly PL, Lee WH, Marion GH, Milisavljevic D, Parrent J, Shrivers I, Skrutskie M, Smith N, Wilson J, Zheng W (2015) On the nature of Type IIb/II-LSM supernovae: optical and near-infrared spectra of SN 2012ca and SN 2013dn. MNRAS 454:772–785, DOI 10.1093/mnras/stu2435, 1408.6239.

Fransson C, Chevalier RA (1989) Late emission from supernovae - A window on stellar nucleosynthesis. ApJ 343:293–312, DOI 10.1086/167707.

Gal-Yam A (2012) Luminous Supernovae. Science 337:927–, DOI 10.1126/science.1203601.

Gal-Yam A (2016) Observational and Physical Classification of Supernovae. ArXiv e-prints 1611.09353.

Gal-Yam A, Mazziar P, Ofek EO, Nugent PE, Kulkarni SR, Kasliwal MM, Quimby
RM, Filippenko AV, Chenko SB, Chornock R, Waldman R, Kasen D, Sullivan M, Beshore EC, Drake AJ, Thomas RC, Bloom JS, Poznanski D, Miller AA, Foley RJ, Silverman JM, Arcavi I, Ellis RS, Deng J (2009) Supernova 2007bi as a pair-instability explosion. Nature 462:624–627, DOI 10.1038/nature08579, [1003.1156]

Gal-Yam A, Arcavi I, Ofek EO, Ben-Ami S, Chenko SB, Kasliwal MM, Cao Y, Yaron O, Tal D, Silverman JM, Horesh A, De Cia A, Taddia F, Sollerman J, Perley D, Vreeswijk PM, Kulkarni SR, Nugent PE, Filippenko AV, Wheeler JC (2014) A Wolf-Rayet-like progenitor of SN 2013cu from spectral observations of a stellar wind. Nature 509:471–474, DOI 10.1038/nature13304, [1406.7640]

Garnavich PM, Tucker BE, Rest A, Shayaa EJ, Olling RP, Kasen D, Villar A (2016) Shock Breakout and Early Light Curves of Type II-P Supernovae Observed with Kepler. ApJ 820:23, DOI 10.3847/0004-637X/820/1/23, [1603.05657]

Gaskell CM, Cappellaro E, Dinerstein HL, Garnett DR, Harkness RP, Wheeler JC (1986) Type Ib supernovae 1983n and 1985f - Oxygen-rich late time spectra. ApJ 306:L77–L80, DOI 10.1086/184709

Granot J, Ramirez-Ruiz E (2004) The Case for a Misaligned Relativistic Jet from SN 2001em. ApJ 609:L9–L12, DOI 10.1086/422516, [astro-ph/0403421]

Harkness RP, Wheeler JC, Margon B, Downes RA, Kirshner RP, Uomoto A, Barker ES, Cochran AL, Dinerstein HL, Garnett DR, Levreault RM (1987) The early spectral phase of type Ib supernovae - Evidence for helium. ApJ 317:355–367, DOI 10.1086/165283

Inserra C, Smartt SJ, Jerkstrand A, Valenti S, Fraser M, Wright D, Smith K, Chen TW, Kotak R, Pastorello A, Nicholl M, Bresolin F, Kudritzki RP, Benetti S, Botticella MT, Burgett WS, Chambers KC, Ergon M, Flewelling H, Fynbo JPU, Geier S, Hodapp KW, Howell DA, Huber M, Kaiser N, Leloudas G, Magill L, Magnier EA, McCrum MG, Metcalfe N, Price PA, Rest A, Sollerman J, Sweeney W, Taddia F, Taubenberger S, Tonry JL, Wainscoat RJ, Waters C, Young D (2013) Super-luminous Type Ic Supernovae: Catching a Magnetar by the Tail. ApJ 770:128, DOI 10.1088/0004-637X/770/2/128, [1304.3425]

Jha S, Branch D, Chornock R, Foley RJ, Li W, Swift BJ, Cascone D, Filippenko AV (2006) Late-Time Spectroscopy of SN 2002cx: The Prototype of a New Subclass of Type Ia Supernovae. AJ 132:189–196, DOI 10.1086/505499, [astro-ph/0602250]

Kamble A, Soderberg AM, Chomiuk L, Margutti R, Medvedev M, Milisavljevic D, Chakraborti S, Chevalier R, Chugai N, Dittmann J, Drout M, Fransson C,
Lunnan R, Kasliwal MM, Cao Y, Hangard L, Yaron O, Parrent JT, McCully C, Gal-Yam A, Mulchaey JS, Ben-Ami S, Filippenko AV, Fremling C, Fruchter AS, Howell DA, Koda J, Kupfer T, Kulkarni SR, Laher R, Masri F, Nugent PE, Ofek EO, Yagi M, Yan L (2017) Two New Calcium-rich Gap Transients in Group and Cluster Environments. ApJ 836:60, DOI 10.3847/1538-4357/836/1/60, [1512.00454]

Lyman JD, James PA, Perets HB, Anderson JP, Gal-Yam A, Mazzali PA, Percival SM (2013) Environment-derived constraints on the progenitors of low-luminosity Type I supernovae. MNRAS 434:527–541, DOI 10.1093/mnras/stt1038, [1306.2474]

Lyman JD, Levan AJ, Church RP, Davies MB, Tanvir NR (2014) The progenitors of calcium-rich transients are not formed in situ*. MNRAS 444:2157–2166, DOI 10.1093/mnras/stt1574, [1408.1424]

Lyman JD, Levan AJ, James PA, Angus CR, Church RP, Davies MB, Tanvir NR (2016) Hubble Space Telescope observations of the host galaxies and environments of calcium-rich supernovae. MNRAS 458:1768–1777, DOI 10.1093/mnras/stw477, [1602.08098]

Lyman JD, Goldstein J, Ramirez-Ruiz E, Guillochon J, Samsing J (2014) Illuminating Massive Black Holes with White Dwarfs: Orbital Dynamics and High-energy Transients from Tidal Interactions. ApJ 794:9, DOI 10.1088/0004-637X/794/1/9, [1405.1426]

Maeda K, Tanaka M, Nomoto K, Tominaga N, Kawabata K, Mazzali PA, Umeda H, Suzuki T, Hattori T (2007) The Unique Type Ib Supernova 2005bf at Nebular Phases: A Possible Birth Event of a Strongly Magnetized Neutron Star. ApJ 666:1069–1082, DOI 10.1086/520054, [0705.2713]

Maeda K, Kawabata K, Mazzali PA, Tanaka M, Valenti S, Nomoto K, Hattori T, Deng J, Pian E, Taubenberger S, Iye M, Matheson T, Filippenko AV, Aoki K, Koegi G, Ohyama Y, Sasaki T, Takata T (2008) Asphericity in Supernova Explosions from Late-Time Spectroscopy. Science 319:1220, DOI 10.1126/science.1149437, [0801.1100]

Margutti R, Soderberg AM, Chomiuk L, Chevalier R, Hurley K, Milisavljevic D, Foley RJ, Hughes JP, Slane P, Fransson C, Moe M, Barthelmy S, Boynton W, Briggs M, Connaughton V, Costa E, Cummings J, Del Monte E, Enos H, Felkows C, Feroci M, Fukazawa Y, Gehrels N, Goldsten J, Golovin D, Hanabata Y, Harshman K, Krimm H, Litvak ML, Makishima K, Marisaldi M, Mitrofanov IG, Murakami T, Ohno M, Palmer DM, Sanin AB, Starr R, Svinck D, Takahashi T, Tashiro M, Terada Y, Yamaoka K (2012) Inverse Compton X-Ray Emission from Supernovae with Compact Progenitors: Application to SN2011fe. ApJ 751:134, DOI 10.1088/0004-637X/751/2/134, [1202.0741]

Margutti R, Kamble A, Milisavljevic D, Soderberg AM, Chornock R, Zauderer BA, Murase K, Guidorzi C, Sanders NE, Kuin P, Fransson C, Levesque EM, Chandra P, Berger E, Bianco FB, Brown PJ, Challis P, Chatzopoulos E, Cheung CC, Choi C, Chomiuk L, Chugai N, Contreras C, Drout MR, Fesen R, Foley RJ, Fong W, Friedman AS, Gall C, Gehrels N, Hjorth J, Hsiao E, Kirshner R, Im M, Leloudas G, Lunnan R, Marion GH, Martin J, Morrell N, Neugent KF, Omodei N, Phillips MM, Rest A, Silverman JM, Strader J, Stritzinger MD, Szalai T, Utterback NB, Vinko J, Wheelar JC, Arnett D, Campana S, Chevalier R, Ginsburg A, Kamble A, Roming PWA, Pritchard T, Stringfellow G (2014a) A Panchromatic View of the Restless SN 2009ip Reveals the Explosive Ejection of a Massive Star Envelope. ApJ 780:21, DOI 10.1088/0004-637X/780/1/21, [1306.0038]

Margutti R, Parrent J, Kamble A, Soderberg AM, Foley RJ, Milisavljevic D, Drout MR, Kirshner R (2014b) No X-Rays from the Very Nearby Type Ia Supernova 2014J: Constraints on Its Environment. ApJ 790:52, DOI 10.1088/0004-637X/790/1/52, [1408.1488]

Margutti R, Kamble A, Milisavljevic D, Zapartas E, de Mink SE, Drout M, Chornock R, Risaliti G, Zauderer BA, Bietenholz M, Cantillo M, Chakraborti S, Chomiuk L, Fong W, Grefenstette B, Guidorzi C, Kirshner R, Parrent JT, Patnaude D, Soderberg AM, Gehrels NC, Harrison F (2017a) Ejection of the Massive Hydrogen-rich Envelope Timed with the Collapse of the Stripped SN
2014C. ApJ 835:140, DOI 10.3847/1538-4357/835/2/140, [10.1088/1538-4357/835/2/140]

Margutti R, Metzger BD, Chornock R, Milisavljevic D, Berger E, Blanchard PK, Guidorzi C, Migliori G, Kamble A, Lunnan R, Nicholl M, Coppejans DL, Dall’Osso S, Drout MR, Perna R, Sbarufatti B (2017b) X-Rays from the Location of the Double-humped Transient ASASSN-15lh. ApJ 836:25, DOI 10.3847/1538-4357/836/1/25, [10.3847/1538-4357/836/1/25]

Matheson T, Filippenko AV, Li W, Leonard DC, Shields JC (2001) Optical Spectroscopy of Type Ib/C Supernovae. AJ 121:1648–1675, DOI 10.1086/319390, [10.1086/319390]

Matheson T, Filippenko AV, Li W, Leonard DC, Shields JC (2001) Optical Spectroscopy of Type Ib/C Supernovae. AJ 121:1648–1675, DOI 10.1086/319390, [10.1086/319390]

Meakin CA (2006) Hydrodynamic modeling of massive star interiors. PhD thesis, The University of Arizona, Arizona, USA

Meakin CA, Arnett D (2007) Turbulent Convection in Stellar Interiors. I. Hydrodynamic Simulation. ApJ 667:448–475, DOI 10.1086/520318, [10.1086/520318]

Meakin CA, Arnett D (2007) Turbulent Convection in Stellar Interiors. I. Hydrodynamic Simulation. ApJ 667:448–475, DOI 10.1086/520318, [arXiv:astro-ph/0611315]

Milisavljevic D (2013) The Progenitor Systems and Explosion Mechanisms of Supernovae. In: New Horizons in Astronomy (BASH 2013), p 9

Milisavljevic D, Fesen RA, Leibundgut B, Kirshner RP (2008) The Evolution of Late-Time Optical Emission from SN 1986J. ApJ 684:1170–1173, DOI 10.1086/590426, [10.1086/590426]

Milisavljevic D, Fesen RA, Gerardy CL, Kirshner RP, Challis P (2010) Doublets and Double Peaks: Late-Time [O I] λλ 6300, 6364 Line Profiles of Stripped-Envelope, Core-Collapse Supernovae. ApJ 709:1343–1355, DOI 10.1088/0004-637X/709/2/1343, [10.1088/0004-637X/709/2/1343]

Milisavljevic D, Fesen RA, Chevalier RA, Kirshner RP, Challis P, Turatto M (2012) Late-time Optical Emission from Core-collapse Supernovae. ApJ 751:25, DOI 10.1088/0004-637X/751/1/25, [10.1088/0004-637X/751/1/25]

Milisavljevic D, Margutti R, Soderberg AM, Pignata G, Chomiuk L, Fesen RA, Bufano F, Sanders NE, Parrent JT, Parker S, Mazzali P, Pian E, Pickering T, Buckley DAH, Crawford SM, Gulbis AAS, Hettlage C, Hooper E, Nordieck KH, O’Donoghue D, Husser TO, Potter S, Kniazev A, Kotze P, Romero-Colmenero E, Vaisanen P, Wolf M, Bietenholz MF, Bartel N, Fransson C, Walker ES, Brunthaler A, Chakraborti S, Levesque EM, MacFadyen A, Drescher C, Bock G, Marples P, Anderson JP, Benetti S, Reichart D, Ivarsen K (2013a) Multi-wavelength Observations of Supernova 2011ei: Time-dependent Classification of Type Ib and Ib Supernovae and Implications for Their Progenitors. ApJ 767:71, DOI 10.1088/0004-637X/767/1/71, [10.1088/0004-637X/767/1/71, 1207.2152]

Milisavljevic D, Soderberg AM, Margutti R, Drout MR, Howie Marion G, Sanders NE, Hsiao EY, Lunnan R, Chornock R, Fesen RA, Parrent JT, Levesque EM, Berger E, Foley RJ, Challis P, Kirshner RP, Dittmann J, Bieryla A, Kamble A, Chakraborti S, De Rosa G, Fausnaugh M, Hainline KN, Chen CT, Hickox RC, Morrell N, Phillips MM, Stritzinger M (2013b) SN 2012au: A Golden Link between Superluminous Supernovae and Their Lower-luminosity Counterparts. ApJ 770:L38, DOI 10.1088/0004-637X/770/2/L38, [10.1088/0004-637X/770/2/L38]

Milisavljevic D, Margutti R, Kamble A, Patnaude DJ, Raymond JC, Eldridge JJ, Fong W, Bietenholz M, Challis P, Chornock R, Drout MR, Franxsen C, Fesen RA, Grindlay JE, Kirshner RP, Lunnan R, Mackey J, Miller GF, Parrent JT, Sanders NE, Soderberg AM, Zauderer BA (2015a) Metamorphosis of SN 2014C: Delayed Interaction between a Hydrogen Poor Core-collapse Supernova and a Nearby Circumstellar Shell. ApJ 815:120, DOI 10.1088/0004-637X/815/2/120, [10.1088/0004-637X/815/2/120, 1511.01907]

Milisavljevic D, Margutti R, Parrent JT, Soderberg AM, Fesen RA, Mazzali P, Maeda K, Sanders NE, Cenko SB, Silverman JM, Filippenko AV, Kamble A, Chakraborti S, Drout MR, Kirshner RP, Pickering TE, Kawabata K, Hattori T, Hsiao EY, Stritzinger MD, Marion GH, Vinko J, Wheeler JC (2015b) The Broad-lined Type Ic SN 2012ap and the Nature of Relativistic Supernovae Lacking a Gamma-Ray Burst Detection. ApJ 799:51, DOI 10.1088/0004-637X/799/1/51, [10.1088/0004-637X/799/1/51]
S, Reichart DE, Rojas-Bravo C, Smartt SJ, Smith KW, Sollerman J, Stritzinger MD, Sullivan M, Taddia F, Young DR (2018) The Early Detection and Follow-up of the Highly Obscured Type II Supernova 2016ija/DLT16am. ApJ 853:62, DOI 10.3847/1538-4357/aaa014, [1711.03940]

Taubenberger S (2017) The Extremes of Thermoneural Supernovae. ArXiv e-prints [1703.06528]

Taubenberger S, Valenti S, Benetti S, Cappellaro E, Della Valle M, Elias-Rosa N, Hachinger S, Hillebrandt W, Maeda K, Mazzali PA, Pastorello A, Patat F, Sim SA, Turatto M (2009) Nebular emission-line profiles of Type Ib/c supernovae - probing the ejecta asphericity. MNRAS 397:677–694, DOI 10.1111/j.1365-2966.2009.15003.x, [0904.4832]

Tominaga N, Tanaka M, Nomoto K, Mazzali PA, Deng J, Maeda K, Umeda H, Modjaz M, Hicken M, Challis P, Kirshner RP, Wood-Vasey WM, Blake CH, Bloom JS, Krustskie MF, Szentgyorgyi A, Falco EE, Inada N, Minezaki T, Yoshii Y, Kawabata K, Iye M, Anupama GC, Sahu DK, Prabhu TP (2005) The Unique Type Ib Supernova 2005bf: A WN Star Explosion Model for Peculiar Light Curves and Spectra. ApJ 633:L97–L100, DOI 10.1086/498570, [astro-ph/0509557]

Turanat M, Cappellaro E, Danziger IJ (1989) The remnant of SN 1957d in M83. The Messenger 56:36–37

van Putten MHPM, Della Valle M (2016) On extreme transient events from rotating black holes and their gravitational wave emission. ArXiv e-prints [1610.05535]

Weiler KW, Williams CL, Panagia N, Stockdale CJ, Kelley MT, Sramek RA, Van Dyk SD, Marcaide JM (2007) Long-Term Radio Monitoring of SN 1993J. ApJ 671:1959–1980, DOI 10.1086/522558, [0709.1136]

Wheeler JC, Levreault R (1985) The peculiar Type I supernova in NGC 991. ApJ 294:L17–L20, DOI 10.1086/184500

Wheeler JC, Harkness RP, Barker ES, Cochran AL, Wills D (1987) Supernovae 1983i and 1983v - Evidence for abundance variations in type Ib supernovae. ApJ 313:L69–L73, DOI 10.1086/184833

Woosley SE (2010) Bright Supernovae from Magnetar Birth. ApJ 719:L204-L207, DOI 10.1088/2041-8205/719/2/L204, [0911.0698]

Woosley SE (2018) Models for the Unusual Supernova iPTF14hls. ArXiv e-prints [1801.08646]

Woosley SE, Kases D (2011) Sub-Chandrasekhar Mass Models for Supernovae. ApJ 734:38, DOI 10.1088/0004-637X/734/1/38, [1010.5292]

Woosley SE, Heger A, Weaver TA (2002) The evolution and explosion of massive stars. Reviews of Modern Physics 74:1015–1071, DOI 10.1103/RevModPhys.74.1015

Yaron O, Gal-Yam A (2012) WISEREP - An Interactive Supernova Data Repository. PASP 124:668–681, DOI 10.1086/666656, [1204.1891]

Yaron O, Perley DA, Gal-Yam A, Groh JH, Horesh A, Ofek EO, Kulkarni SR, Sollerman J, Fransson C, Rubin A, Szabo P, Sapir N, Taddia F, Cenko SB, Valenti S, Arcavi I, Howell DA, Kasliwal MM, Vreeswijk PM, Khazov D, Fox OD, Cao Y, Gnat O, Kelly PL, Nugent PE, Filippenko AV, Lauer RR, Wozniak PR, Lee WH, Rebbapragada UD, Maguire K, Sullivan M, Soumagnac MT (2017) Confined dense circumstellar material surrounding a regular type II supernova. Nature Physics 13:510–517, DOI 10.1038/nphys4025, [1701.02596]

Yoon SC, Woosley SE, Langer N (2010) Type Ib/c Supernovae in Binary Systems. I. Evolution and Properties of the Progenitor Stars. ApJ 725:940–954, DOI 10.1088/0004-637X/725/1/940, [1004.0843]
Yuan Q, Liao NH, Xin YL, Li Y, Fan YZ, Zhang B, Hu HB, Bi XJ (2017) Fermi Large Area Telescope detection of gamma-ray emission from the direction of supernova iPTF14hls. ArXiv e-prints [1712.01043]