Supernova impostors and other gap transients

Besides supernovae, few astrophysical processes can release close to 10^{51} erg of energy. A growing number of stellar outbursts are now recognized to have energy releases matching those of faint supernovae. These transients can be triggered by various mechanisms, and their discrimination is sometimes a tricky issue.

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The death of a massive star in a supernova explosion represents the sudden release of about 10^{51} erg as radiation and kinetic energy. Ongoing all-sky transient surveys have now begun to find substantial numbers of less energetic transients that are fainter and have lower kinetic energy than normal supernovae, but are more luminous than classical novae (Fig. 1). These transients are often called 'gap transients'[1] and pose a fundamental question: are they also associated with terminal explosions of massive stars, or do they represent new physical classes of transient phenomena?

Among gap transients, stellar mergers can release around 10^{49} erg. Alternatively, some massive stars can also undergo non-terminal eruptions and outbursts (and these are termed supernova impostors). Some supernova impostors appear to presage the explosion of a massive star as a genuine core-collapse supernova: in such cases, the supernova impostor must be associated with an instability in the latter stages of stellar evolution. Other supernova impostors appear to be eruptions long before the star will undergo core collapse, as exemplified by the Great Eruption of Eta Carinae in the middle of the nineteenth century.

Distinguishing between faint hydrogen-rich core-collapse supernovae and the various classes of non-terminal eruptions or outbursts remains a key challenge in transient astronomy. Here we propose a physical characterization of the different subtypes of gap transients on the basis of some common observational properties (see also Fig. 1).

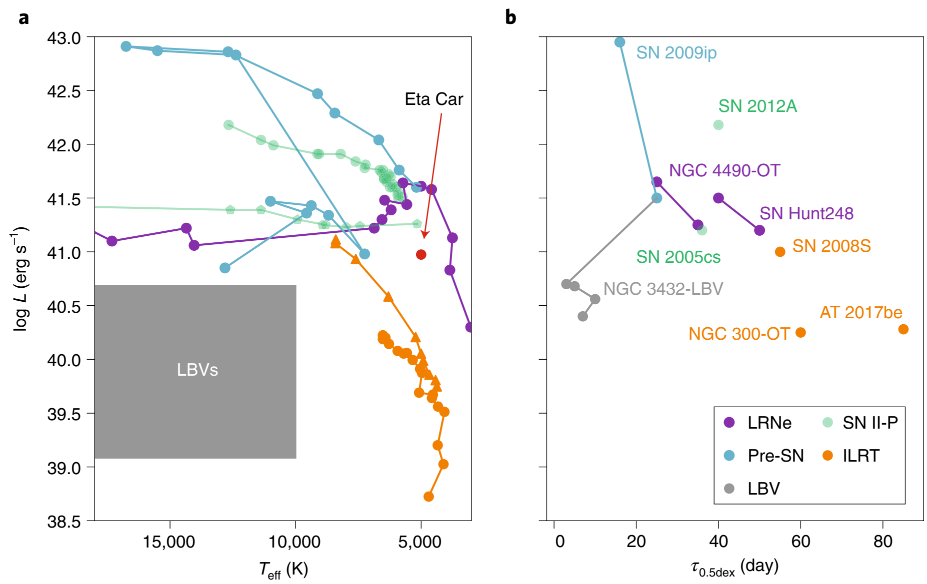

Fig. 1 | Summary of the main properties of gap transients. a, Luminosity versus effective temperature (T_{eff}). **b**, Timescale for a luminosity decline of 0.5 dex diagrams for the gap transients discussed here. For comparison, the reference parameters for two type II-P supernovae (2005cs and 2012A) are also shown. In both panels, the colour coding for the symbols is as follows: purple for luminous red novae (LRNe), blue for pre-SN outbursts (Pre-SN), grey for luminous blue variables (LBV), green for supernovae II-P (SN II-P) and orange for intermediate-luminosity red transients (ILRT). Only a few representative objects are shown in panel a: NGC 4490-OT (LRN), SN 2009ip (Pre-SN), Eta Car (LBV), SN 2012A (SN II-P, circles), SN 2005cs (SN II-P, pentagons), SN 2008S (ILRT, triangles) and AT 2017be (ILRT, circles).

Faint core-collapse supernovae

Some faint 'gap transients' can actually be genuine supernovae (making them 'supernova impostor impostors'). In particular, the class of intermediate-luminosity red transients (ILRTs; for example, ref. [2]) have attracted attention as possible examples of weak electron-capture supernovae. The prototypical ILRT SN 2008S (ref. [3]) had a slow rise to maximum light (with $M_R \approx -15$ mag), followed by a linear decline lasting about 4 months. Other objects peaked at −12 to −14 mag and have shown a post-peak plateau followed by a rapid decline 3–4 months later. When observed at late phases, the light curves settle onto a slower decline rate, close to that expected from the decay of ^{56}Co. These light curves resemble those of very faint type II-L or type II-P supernovae. The spectra of ILRTs are initially blue and become redder with time. They always show Balmer lines in emission, along with prominent Ca II features (in particular, the [Ca II] doublet at λλ7291, 7323 is always detected: see Fig. 2). Together, these properties have been taken as suggestive of a weak supernova explosion inside a dense cocoon of circumstellar material.

The progenitor stars of some ILRTs have been detected in quiescence in mid-infrared Spitzer archive images. In contrast, deep optical and near-infrared images (including data from the Hubble Space Telescope) obtained before outburst do not show any source at the ILRT position. Although most agree that the progenitors are 8–15$M_\odot$ stars embedded in dusty cocoons, the nature of the transients is controversial. Along with the faint supernova scenario, the ejection of a common envelope due to binary interaction, the eruptive formation of a relatively massive white dwarf or a super-Eddington event of a moderate-mass star were proposed as possible explanations for ILRT outbursts[4]. However, more recent Spitzer observations of sites of ILRTs a few years after outburst show that the residual flux at the transient position is much fainter than the quiescent progenitor, hence

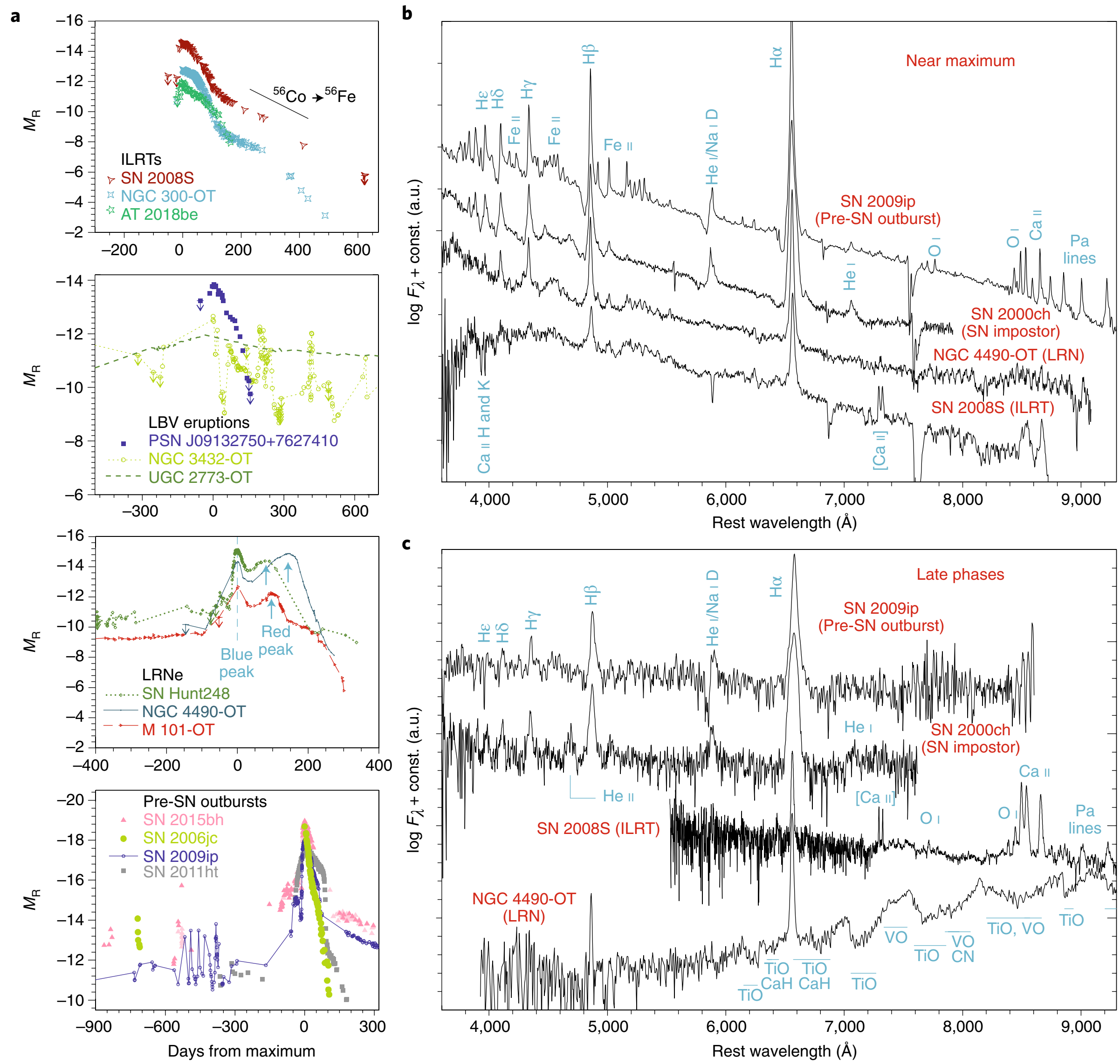

Fig. 2 | The diversity of gap transients. a, Representative light curves of gap transient subtypes. **b**, Spectral sample of gap transients near the maximum light, including a pre-supernova outburst (SN 2009ip), a supernova impostor in outburst (SN 2000ch), a luminous red nova (NGC 4490-OT; during the first, blue peak) and an ILRT (SN 2008S). **c**, Spectra of the above sample but obtained several months after the outburst maximum. The spectra of SN 2009ip were obtained about 3 and 2 years (respectively) before the putative supernova explosion. Data are from refs. [3,10,14–16,19,21,22,26–30,36–47], along with unpublished data from our team.

supporting terminal supernova explosions[5]. If ILRTs are core-collapse supernovae, they necessarily eject very modest ^{56}Ni masses (10^{-3} to $10^{-4}M_{\odot}$). This, and the clear evidence of circumstellar gas and dust, point towards all ILRTs resulting from an electron-capture supernova from super-asymptotic giant branch stars[6].

Mergers

Often referred to as 'luminous red novae', these transients display a slow rise over months to years, followed by a distinctive double-peaked light curve (see Fig. 2a). During the first peak, optical spectra appear blue and show prominent emission lines of H and Fe II (Fig. 2b). During the second peak, we observe a major metamorphosis in the spectrum, which becomes similar to a late G- to K-type star, with a forest of narrow metal lines in absorption (with velocity $v \approx 100$ km s^{-1}) and much weaker Balmer lines. Finally, at late phases, during the fast, late luminosity decline, the spectrum transitions to that of an M-type star, with Hα becoming prominent again, while the optical spectrum, now very red, shows strong molecular absorption bands (mostly TiO and VO; Fig. 2c).

The strongest evidence that such transients originate from mergers in binary systems comes from studies of the galactic transient V1309 Scorpii[7,8]. Crucially, periodic modulations in brightness were observed superimposed on a trend of slowly rising luminosity. The period seen in photometry slowly decreased over time, consistent with two in-spiralling stars in a binary system. The subsequent four-magnitude rise in the light curve in about 6 months and the disappearance of the photometric periodicity were interpreted as being due to the ejection of a common envelope. A sudden brightening by a further four magnitudes over a few days and the following double-peaked light curve were due to a violent gas ejection as a consequence of the stellar coalescence, with the gas outflow later interacting with the previously ejected common envelope.

Luminous red novae span a wide range of absolute magnitudes, from −4 to −15, with frequent faint events being produced by low-mass mergers, whereas rare luminous events are produced by the coalescence of stars in massive binaries (a few tens of solar masses[9,10]).

Supernova impostors

Supernova impostors[11,12] are non-terminal eruptions from massive stars and are often associated with luminous blue variables (LBVs). The LBV phase is a short-duration stage of stellar life, during which a very massive star ($\geq 40M_{\odot}$) becomes an evolved hypergiant with luminosity of several $10^5L_{\odot}$ (ref. [13]). LBVs may undergo long-lasting giant eruptions, as observed during past centuries in the Milky Way: Eta Car erupted during the second half of the nineteenth century, later producing the spectacular Homunculus nebula, and P Cygni experienced repeated outbursts around four centuries ago. In both cases, several to several tens of solar masses of material were ejected from the star.

Although very rare, giant eruptions can be also observed in other galaxies. Well-known cases include the LBV in NGC 3432 (also known as SN 2000ch; Fig. 2b,c) which has produced multiple outbursts up to M_R of about −14 mag in the past three decades[14]. Occasionally, long-term smooth variability or isolated outbursts are also observed in massive hypergiants[15,16]. Spectroscopically, such events are typified by blue continua and narrow (~10^2 to 10^3 km s^{-1}) emission lines. The emission lines result from the photoionization of the circumstellar material lost by the star. The mechanism behind such large mass-loss events is still unclear. Close stellar encounters in close binary systems is a viable explanation for some giant eruptions, whereas super-Eddington continuum-driven winds have been invoked for single stars[17], although what leads a star to suddenly exceed the Eddington luminosity/mass limit by a large amount is still a puzzle.

Pre-supernova outbursts

In some cases, supernova impostors probably heralded the death of a star (for example, refs. [18,19]; Fig. 2a). The supernovae that follow these outbursts are usually classed as type IIn (ref. [20]), with spectra dominated by narrow H emission lines (full-width at half-maximum about 10^3 km s^{-1}). These lines are indicative of the interaction of fast supernova ejecta with slower-moving H-rich circumstellar material ejected immediately before the supernova explosion.

However, impostors are not only observed before type IIn supernova explosions, nor solely from LBVs. A pre-supernova outburst of $M_R \approx -14$ mag, in fact, was observed by the amateur astronomer Itagaki two years before the explosion of SN 2006jc (refs. [21,22]; Fig. 2a). The supernova spectrum revealed narrow emission lines of He and no H, so it was classified as a type Ibn supernova (ref. [23]). The outburst was probably a dramatic mass-loss event from a Wolf–Rayet star that produced a He-rich cocoon. The Wolf–Rayet star later exploded as a stripped-envelope supernova, as confirmed by a post-death inspection of Hubble Space Telescope images[24].

At present, stellar evolutionary models do not predict outbursts immediately before a supernova explosion. However, the latter stages of stellar evolution are notoriously difficult to simulate, and recent work has suggested that violent convection and instabilities associated with late nuclear burning stages could lead to eruptions. With a better understanding of what drives pre-supernova outbursts, and how common they are, one may even envisage being able to predict stars that are just about to undergo core collapse.

Progress and outlook

Although the nature of gap transients is not yet fully understood, some firm markers have been posed over the last decade: all of them are linked to moderate- to high-mass stars; these stars are enshrouded by H-rich cocoons, and they show signatures of interaction between ejecta and circumstellar material; and in some cases, the outbursts are followed by a much brighter event which is possibly the terminal supernova explosion.

The object that perhaps most clearly illustrates these characteristics is supernova SN 2009ip, where a very massive star of over $40M_{\odot}$ (ref. [25]) was observed to erupt repeatedly for at least 3 years (hence it was formally a supernova impostor[26,27]). Then, in summer 2012, the object went into outburst again, with a light curve initially reaching a peak of −15.5 mag, before brightening further to −19 three weeks later[28–30]. Recently, a number of transients with properties similar to those of SN 2009ip have been discovered (ref. [31] and references therein). Several scenarios were proposed to explain the sequence observed in SN 2009ip-like events, including a giant outburst followed by the supernova explosion; a faint supernova explosion followed by major interaction between ejecta and circumstellar material; a giant outburst due to extreme binary interaction; or pulsational pair-instability in an LBV progenitor followed by collision between massive shells. Whether the progenitor of SN 2009ip really exploded as a supernova has still not been conclusively settled. However, the late-time light-curve evolution of SN 2009ip, with an almost linear decline to very faint magnitudes and no further outbursts, seems to support a terminal type IIn supernova explosion.

Ongoing all-sky surveys have considerably increased the number of known gap transients, and many more will be discovered in the era of the Large Synoptic Survey Telescope. Although good progress has been made in discriminating between the different types of gap transients (Fig. 2), the triggering mechanisms and the fate of their progenitor stars remain debated. Deep imaging of the explosion sites a few years after the outbursts with space facilities such as the Hubble Space Telescope and Spitzer, or future ground-based telescopes with adaptive optics such as the Extremely Large Telescope, should reveal whether the progenitor star of a gap transient has disappeared as a consequence of a dim supernova explosion or survived the outburst[5,32]. For the survivors, comparison of their magnitude and colour information with theoretical evolutionary tracks will provide crucial parameters such as zero-age main sequence mass, final mass and eventually binary signatures. Spectroscopy at very late phases (with 10-m class telescopes) or multi-domain monitoring, are also powerful tools to disentangle alternative scenarios for controversial events (ref. [33–35]). All of this will enable us to address the remaining uncertainty over the nature of gap transients. ❐

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