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Review

The Purport of Space Telescopes in Supernova Research

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Abstract: The violent stellar explosions known as supernovae have received especially strong attention in both the research community and the general public recently. With the advent of space telescopes, the study of these extraordinary events has switched gears and it has become one of the leading fields in modern astrophysics. In this paper, we review some of the recent developments, focusing mainly on studies related to space-based observations.

Keywords: supernovae; stellar evolution; cosmic dust; distance measurement; space telescopes

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1. Introduction

This paper is intended to outline some of the recent developments in understanding the remarkably rich astrophysics of supernova explosions, focusing mostly, but not exclusively, on space-based observations, discoveries and their interpretations. Instead of giving a full, detailed review of this very diverse area, we highlight some important aspects of supernova studies that have recently attracted particular attention in both the scientific and popular domains.

First, a brief outline of the basics of supernovae is given, followed by the presentation of the selected topics, such as the progenitors of supernovae (Section 2), early-phase observations (Section 3), interactions with circumstellar material and dust formation around supernovae (Section 4) and distance measurements and their cosmological implications (Section 5). Finally, some of the future plans, related mostly to the application of the *James Webb Space Telescope* (*JWST*) in supernova research, are highlighted in Section 6.

1.1. The Importance of Supernovae in Astrophysics

Supernovae (SNe) played a literally spectacular role during the history of astronomy, starting from the earliest recorded observations of "Guest Stars" by Chinese and Korean astronomers ∼1000 years ago. The discovery of the "Nova Stella" by the Danish astronomer Tycho Brahe in 1576 provided the first direct evidence for Europeans about the non-static behavior of the cosmos that later facilitated the acceptance of the Copernican model. In the 20th century, the recognition of the extreme power of the nova-like transient S Andromedae occurred in 1885 in M31 by Walter Baade and Fritz Zwicky [1], who highlighted the possibility of stellar explosions and their roles in the fates of massive stars. More recently, the use of high-redshift Type Ia supernovae as distance indicators played a key role in the discovery of the accelerated expansion of the Universe [2,3], a result that led to the Nobel Prize in Physics in 2011.

Besides these historical milestones, the study of supernovae has been one of the most popular domains in astronomy and astrophysics. In brief, supernovae are very important in the chemical evolution of the Universe, as they are thought to be (at least partially) the source of heavy elements beyond the iron peak [4]. Supernovae are also thought to be major factories for cosmic dust (see Section 4), which is essential for star formation processes. Supernovae are responsible for producing massive compact objects, such as neutron stars and probably stellar-mass black holes [5]. They are also still one of the most reliable and widely used objects in measuring extragalactic distances, which very recently resulted in the discovery of the "Hubble tension", i.e., the discrepancy in the values of the Hubble constant inferred from local objects and from the fluctuations of the Cosmic Microwave Background (CMB) (see, e.g., [6], and Section 5), which may finally need new physics to resolve. Lastly, a rare type of supernova, called Superluminous Supernovae (SLSNe), which were discovered as a class only a decade ago [7], still represents an unsolved mystery of astrophysics, as neither their progenitors nor their explosion mechanism or power source(s) are known to date [8,9].

1.2. Supernova Types and Explosion Mechanisms

Essential differences in the spectral appearances of SNe were first recognized by Minkowski in 1941 [10], and refined later in 1965 by Zwicky [11]. They established the "Type I"/"Type II" categories based on the absence/presence of hydrogen in the optical spectra taken around maximum brightness. This is still the basis of the SN classification scheme, even though several subtypes have been introduced since then. For example, Type Ia refers to SNe having no hydrogen but strong lines of ionized silicon (Si II) in the spectrum. Similarly, Type Ib SN shows no H but strong He, while a Type Ic SN has neither H nor He and only weak Si lines.

Type II SNe can also be further divided into subgroups. The majority of them belong to the Type II-P category: they show a characteristic plateau in their optical light curves (LCs) extending up to 100–120 days past explosion. On the other hand, a few of them exhibit a nearly linear LC decline (on a magnitude scale); they are referred to as Type II-L. The optical spectra of these two sub-categories are similar; therefore, this distinction is purely photometric. A transition between Type II and Type Ib SNe is called a Type IIb SN: shortly after explosion, the spectrum resembles that of Type II, but later the H features become weaker while the He features become stronger. At late phases, the spectrum of a Type IIb SN is similar to that of Type Ib.

A fairly complete and detailed description of the spectral diversity of SNe can be found in the review paper by Filippenko [12] and in the comprehensive book of Branch and Wheeler [13]. Figure 1 shows examples of the classical sub-types, together with the identification of the strongest spectral features for each type.

SNe that exhibit signs of interaction with the circumstellar matter (CSM) in their spectra are usually denoted with an "n" attached to the type name. For example, interacting Type II SNe are called Type IIn, while interacting Type Ib SNe are referred to as Type Ibn. An example of a Type Icn SN has been discovered very recently [14]. These SNe generally show narrow features of H or He or C/O/Ne in their spectra, respectively, which cannot originate from the SN ejecta. Thus, they are formed in the CSM surrounding the site of the explosion.

Gamma-ray bursts (GRBs) have been thought to be associated with SNe for a long time, because the explosions of massive stars were strong candidates for at least the long GRBs showing pulse widths of longer than 2 s. The physical connection between these two types of explosive events was first confirmed by the discovery of GRB980425 and its optical counterpart, SN 1998bw [15,16], and later strengthened by the observations of SN2003dh/GRB030329 [17,18]. These SNe turned out to be members of a peculiar subclass of Type Ic SNe, called broad-lined Ic (Ic-BL), that are characterized by high ($\gtrsim$30,000 km s^{-1}) expansion velocities and very broad ($\gtrsim$80,000 km s^{-1}) spectral features. Referring to their high kinetic energies, these SNe were often termed "hypernovae" two decades ago, but, since then, the Ic-BL terminology (sometimes "relativistic SNe" or "jet-driven SNe") has become more common. The general model for these special SNe involves the core collapse of a very massive star having a rapidly rotating core that results in a relativistic jet, which breaks through the stellar envelope, causing a rapid, sometimes asymmetric expansion. These are certainly complex events, because, very often, such SNe have been discovered without any detected GRBs (e.g., SN 2009bb [19,20]). Nowadays, the number of spectroscopically confirmed GRB-SNe is ∼20 [21]. Note that, in addition to the rapidly rotating, jet-driven SN model, there exists a "binary-driven hypernova" model, in which the exploding star has a compact, relativistic companion (a neutron star or a black hole) and the GRB is due to the interaction between the rapidly expanding SN ejecta and the companion [22].

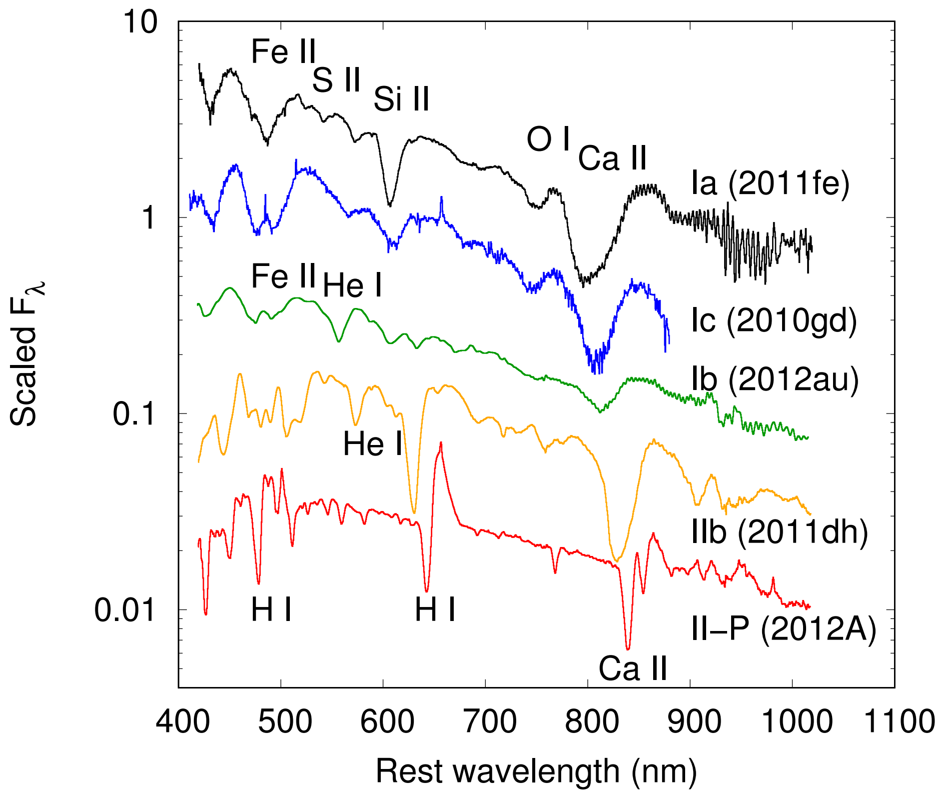

Figure 1. Optical spectra of different types of supernovae close to maximum light. Prominent spectral features are labeled with their contributing ions. Data were collected with the Hobby–Eberly Telescope at McDonald Observatory, Texas.

Recently, a number of new SN types and/or sub-types have been announced, thanks to the increasing amount of non-targeted SN surveys that have discovered previously unknown, unusual supernovae. A special sub-type of SNe Ia, called Iax, contains low-luminosity supernovae that show spectra similar to Ia, but the Si features are much weaker and the spectrum is dominated by ionized iron (Fe II) [23]. Superluminous supernovae (SLSNe), on the other hand, occupy the other end of the brightness distribution: their peak brightness is at least −21 magnitude, or brighter, in all wavelength bands, and they are characterized by unique spectral features that are different from those of any other classical SN types [7–9,24]. Pre-maximum spectra of hydrogen-poor SLSNe are dominated by ionized oxygen (O II and/or O III), but not all of them [25]), while, at later phases, their spectra are essentially similar to the late-time spectra of SNe Ic. Hydrogen-rich SLSNe, however, show spectral similarities to very bright Type IIn SNe.

2. Supernova Progenitor Scenarios

Considerable progress has been made in understanding the physics of exploding stars since the pioneering work of Baade and Zwicky [1]. The diversity among the observational properties discussed above implies that the physical nature of the exploding object (the progenitor star), as well as the physics of the explosion mechanisms, cannot be the same in all cases.

It was recognized long ago that catastrophic explosions of massive stars cannot explain all the observed SN types. In 1960, Hoyle and Fowler [26] proposed that, unlike all other types of SNe, Type Ia events are due to the thermonuclear explosion of hydrogen-poor compact objects, such as a carbon/oxygen white dwarf (C/O WD). The majority of the other SN types, however, can be explained by the gravitational collapse of their iron cores into a neutron star or a black hole and a subsequent shock wave following the bounce of the stellar envelope after infalling to the freshly born neutron star.

On the other hand, the progenitor scenarios of SLSNe are still debated. Although their slow photometric and spectroscopic evolution, extremely high peak luminosity and association with metal-poor compact galaxies having high star formation rates all suggest that they arise from the explosion of very massive ($M > 20\ \mathrm{M}_\odot$) stars [8], the observed diversity among hydrogen-poor SLSNe-I [24] has raised some doubts about their universal origin.

2.1. Core-Collapse SNe

The evolution of massive stars into the final stage having an inactive Fe-rich core close to its Chandrasekhar mass ($\sim$1.5–2 $\mathrm{M}_\odot$) has been extensively studied in the literature (see, e.g., the detailed reviews by Janka [27–29] and *Supernova Explosions* by Branch and Wheeler [13]). It is well known that stars having $M \gtrsim 8\ \mathrm{M}_\odot$ initial mass are able to reach the evolutionary stage of Si burning, thus forming an Fe core that is supported mostly by the pressure of degenerate electrons. While approaching the Chandrasekhar mass, the core becomes unstable due to either the loss of high-energy γ-photons by the photodisintegration of Fe nuclei into He, or the disappearance of electrons due to neutronization (inverse β-decay), i.e., the fusing of protons and electrons into neutrons [30]. The sudden lack of pressure supporting the core initiates a gravitational collapse that can be stopped only by the immense pressure of the degenerate neutrons in the freshly born neutron star.

The massive envelope of the star, outside the former Fe core, is infalling onto the neutron star, and its innermost part crashes into the surface of the neutron star. Since the degenerate pressure makes the neutron star practically incompressible, the infalling matter is bounced back, which drives a shock wave propagating outward into the infalling envelope. This shock wave is thought to be responsible for the ejection of most of the envelope, witnessed by observers as a supernova explosion, although details of the necessary physical mechanisms are still under intense study. The most problematic part is the explanation of how the shock continues to propagate up to the surface. Several energy injection mechanisms have been proposed to resolve this decade-long issue, including neutrino trapping, magneto-rotational effects and others [13]. The solution might be in building 3D simulations based on the up-to-date physics of the relevant phenomena [31].

Progenitors with initial masses in the 8–20 $\mathrm{M}_\odot$ range can retain their H-rich envelopes, at least partly; thus, they likely produce Type II (either II-P or II-L) SNe. The common (plausible) belief is that Type Ib/c SNe, often called "stripped-envelope supernovae" (SE SNe), result from the same core collapse, but the progenitor star loses its hydrogen-rich envelope (in Type Ib SNe) or even the helium-rich layer (in Type Ic SNe). Details of the mass-loss process are not clear, however, as multiple mechanisms, including stellar winds, mass transfer in binary systems, etc., have been proposed. Nevertheless, the observed spectral evolution of Type IIb SNe, i.e., the transition from a H-rich Type II SN spectrum to Type Ib after maximum light, can be well explained by the partial stripping of the original H-rich envelope, with only a thin H-rich layer remaining by the onset of core collapse [13].

Direct observational detection of the progenitor star before explosion provides strong support for the theoretical scenario outlined above, at least for Type II-P/II-L and Type IIb events [32,33]. The identification of an SN progenitor on pre-explosion archive images was a major success in the case of SN 1987A as it turned out to be a blue supergiant (instead of a theoretically expected red supergiant) star that underwent a common envelope phase in a binary system [34].

The previously unprecedented spatial resolution and limiting magnitude of the *Hubble Space Telescope* (HST) has considerably extended the possibilities for progenitor detection. This resulted in the discovery of the progenitor object for Type II-P SNe in 13 confirmed cases, all of them being in the lower part of their mass distribution, i.e., between 7 and 16 $M_\odot$ [32]. More recently, the progenitors of SN 2017eaw (Type II-P) [35,36] and SN 2018aoq [37] have been successfully detected with HST in multiple bands.

In addition, upper limits for the luminosity and mass have been determined in another 13 cases, which are in the same mass range as the detected ones. It is interesting that the lack of observed progenitors in the $15 < M < 30\ M_\odot$ regime, the "red supergiant problem", still awaits explanation [33,38–40].

Surprisingly, only two nearby SN progenitors (SN 2004dj and SN 2004am) turned out to occur within young, compact star clusters, despite the expectation that massive stars should be spatially associated with star-forming regions. Although the direct detection of the progenitor was not possible due to crowding, fitting population synthesis models to the photometry of the cluster provided reasonable estimates for the age of the cluster, and hence the possible mass of the progenitor [33]. The population synthesis technique was also successfully applied to study the environments of 12 core-collapse (CC) SNe observed with HST [41]. They found that all studied SNe originated from a young stellar population, in accordance with expectations.

There are also four known examples (SNe 2008ax, 2011dh—see Figure 2—2013df and 2016gkg) of the pre-explosion detection of Type IIb SN progenitors (Figure 2), even though the uncertainty of the distance of SN 2016gkg prevented the accurate determination of the physical parameters [32,42]. The mass range in these cases is more difficult to estimate than for Type II-P/L SNe, because Type IIb SNe are thought to occur in binary systems, where the mass transfer between the components causes the partial stripping of the H-rich envelope of the exploding star. Nevertheless, the inferred temperatures and luminosities from the observed magnitudes and colors are consistent with binary evolution models of $M > 10\ M_\odot$ stars that produce a $\sim$4 $M_\odot$ He core after stripping most of the H-rich envelope.

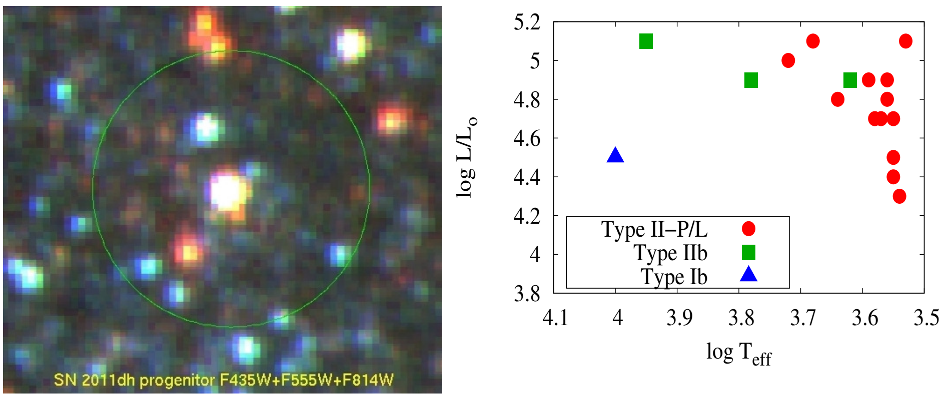

Figure 2. Left: The pre-explosion image of the progenitor star of the Type IIb SN 2011dh taken with *HST/ACS* (Program GO/DD 10452, P.I. Beckwith). **Right**: The positions of the detected core-collapse SN progenitors in the theoretical Hertzsprung–Russell diagram. Data are from [32].

Despite these successes, the direct observational detection of Type Ib/c SN progenitors turned out to be more challenging. Pre-explosion *HST* imaging resulted in the positive detection of a point source at the SN position only in a handful of cases: iPTF13bvn (Type Ib), SN 2017ein (Type Ic) and SN 2019yvr (Type Ib) [43–45]. In the first two ones, a blue, very luminous star was identified as the likely progenitor, while, in the case of SN 2019yvr, a yellow supergiant progenitor is assumed. Moreover, late-time *HST* observations of the environment of SN 2007gr (Type Ic) compared with population synthesis models also suggested a yellow supergiant having $M_{\mathrm{ZAMS}} \sim 40\ \mathrm{M}_{\odot}$ [46]. These results are in accordance with the theoretical expectations that Type Ib/c SNe occur from massive stars evolving through the Wolf–Rayet phase and exhibiting significant, violent mass loss immediately before explosion, even though the lack of more progenitor detection is in contrast with the observed Wolf–Rayet population in nearby galaxies [32].

2.2. Thermonuclear SNe

The explosion mechanism that powers thermonuclear (Type Ia) supernovae, as well as the physical nature of the progenitor, still remains an unresolved issue to date. Two main progenitor systems were proposed to account for the LCs and spectra of these events: the single-degenerate (SD) [47] and the double-degenerate (DD) [48] scenarios.

According to the SD scenario, a carbon–oxygen white dwarf (C/O WD) forms a binary system with a non-degenerate companion, either a red giant or a main-sequence star that transfers mass to the WD after overflowing its Roche lobe. As the WD approaches the Chandrasekhar mass ($M_{Ch} \sim 1.44\ \mathrm{M}_{\odot}$), spontaneous fusion starts inside the WD that converts carbon and oxygen into ^{56}Ni and other intermediate-mass elements. The fusion spark swiftly develops into a runaway burning and results in a thermonuclear explosion.

The start, as well as the progress, of the spontaneous fusion, however, is still uncertain regarding its details, and numerous possible scenarios have been suggested in the literature. One of the most popular is the delayed detonation explosion (DDE). In this model, the expansion of the burning front begins as a deflagration that transforms into a detonation wave in later phases [49–51].

A variant proposed for the DDE model is the pulsational delayed detonation (PDDE) explosion scenario, in which the progenitor star expels a small amount of material from its uppermost layers during the primeval deflagration phase, which expands and pulsates without burning. Then, after the bound material falls back onto the surface of the C/O WD, a subsequent detonation occurs [51].

A growing number of recent observations support the sub-Chandrasekhar double-detonation (DUDE) model, which recently became popular. In this model, a thin He layer is accreted onto the surface of the WD, which leads to helium detonation after being compressed by its own mass. The He burning quickly triggers the explosion of the underlying C/O WD, which then explodes as a Type Ia SN [52–56].

Contrary to the previous cases, in the DD model, two or more degenerate objects (i.e., two WDs) collide or merge, which leads to a thermonuclear explosion engulfing the progenitor [57,58]. One way to distinguish between the different scenarios mentioned above is to infer the ejected mass (M_{ej}), which is one of the most important explosion parameters. The DD scenario requires super-Chandrasekhar or near-Chandrasekhar M_{ej}, while the "violent merger" or DUDE mechanisms may be the explanations for exploding sub-M_{Ch} white dwarfs [57].

As a further possibility, an SN Ia can be triggered during the coalescence itself in a double-WD system, if the He-rich surface layer of one of the WDs initiates the explosion via the double-detonation mechanism in the other one (called "dynamically driven double-degenerate double detonation" or the D^6 scenario). Based on recent results from *Gaia* DR2 observations, the D^6 model seems to be supported by the identification of several hypervelocity WDs as potential surviving companions [59].

Not surprisingly, observational attempts to detect the progenitors of Type Ia SNe with HST resulted in only upper limits and (important) constraints. For example, in the case of the nearby, but highly reddened SN 2014J, pre-explosion HST observations successfully ruled out the presence of a red supergiant progenitor [60], while post-explosion narrow-band HST imaging detected no sign of a hot, photoionized nebula around both SN 2014J and SN 2011fe [61,62], which is an important observational constraint for the SD models. Note, however, that, in the case of SN Iax 2012Z, a probable normal companion (a blue, He-rich star) has been identified with HST by McCully et al. [63,64].

2.3. Superluminous Supernovae (SLSNe)

The most probable progenitor candidates for the brightest stellar explosions ever seen are the most massive stars born mostly in irregular dwarf galaxies with high specific star formation rates (sSFR). However, the true nature of SLSNe still remains a puzzle. The main question is the following: what could be the engine powering these extremely bright and therefore slowly evolving events compared to traditional SNe?

The most commonly utilized model for SLSNe is the magnetar scenario, in which the main power source is the rotation energy of a newly born, swiftly spinning and highly magnetized ($B > 10^{14}$ G) neutron star (magnetar) that is converted into heat via magnetic braking while spinning down [65–67]. Numerous models fitted to the LCs of hydrogen-poor SLSNe resulted in a magnetic field of $B \sim 10^{14}$ G, a spin period of $P \sim 2$ ms and an ejected mass $M_{ej} \sim 5$ $M_\odot$ as typical values for the inferred physical parameters [68], consistently with the results derived using synthetic spectra during the photospheric as well as the nebular phase [69–71]. It was also found that the slower the LC decline, the larger the ejecta mass. Even though the magnetar model fits the observed properties of most SLSNe, it suffers from some disadvantages as well, such as the lack of explanation for the early-phase LC undulations, which is a challenge for this scenario. Since this model predicts a smoothly decreasing LC, it cannot naturally be accommodated to late-phase bumps after maximum light. Another controversy in this model is that it tends to under-predict the ejecta masses and over-predict the late-phase emission [68,72,73]. As there are numerous pieces of evidence for late-time interaction with the CSM [68,71], it is suggested that instead of pure magnetar models, the usage of some hybrid models containing magnetar *and* CSM interaction could be more appropriate.

The second model that utilizes a central engine as a power source is the black hole (BH) accretion model, in which the fallback accretion onto the surface of a newly born black hole may release gravitational energy to power this extremely luminous type of transient [74]. This scenario is quite similar to the magnetar model, as it uses a central engine as well, but, unlike the magnetar model, BH accretion cannot explain the observed LC with simple specifications, apart from the late-phase evolution. The comparison of SLSN observations with BH accretion models has demonstrated some advantages of this scenario [74]. For example, most BHs have unstable accretion rates that can naturally be the explanation for the bumps in the LC both before and after maximum light [75]. However, BH accretion models often require an unrealistically large fallback mass up to >100 $M_\odot$ [76] to obtain a reasonable energy–mass conversion.

The third alternative scenario to power SLSNe suggests the radioactive decay of a large amount of freshly synthesized ^{56}Ni in a pair instability (PI) explosion to account for the outstanding brightness. This can only occur in the core of the most massive ($M > 100$ $M_\odot$) stars [77,78], in which, after reaching a critical temperature inside the oxygen core, spontaneous e^-–e^+ pair creation leads to a rapid loss of pressure that subserves a thermonuclear explosion destroying the whole star. The PISN models predict an enormous amount of ^{56}Ni that may power the very bright SLSNe [78], together with extremely large ejecta masses and long LC timescales. Therefore, this model is favored in the case of the slowest evolving SLSNe, while it does not provide good fits for faster evolving events [7]. At the moment, radioactive and PISN models are relevant only in the case of a tiny group of hydrogen-poor SLSNe [79] that show the slowest LC rise and decline timescales, as >100 $M_\odot$ of ejecta mass seems to be inconsistent with the evolution timescales of most SLSNe.

The strong interaction with the surrounding CSM can be a potential mechanism to power SLSNe by converting the kinetic energy of the ejecta into radiation after colliding with CSM shells. Such a CSM could be produced by the mass loss of the progenitor years/decades before the explosion. Alternatively, the envelope of the progenitor may be lost due to huge outbursts or binary interactions in the later phase of stellar evolution [80,81]. The CSM interaction scenario most likely powers Type II SLSNe. However, it may also be relevant in the case of H-poor SLSNe-I as well, since the spectra of a few SLSNe-I show some H emission lines in the late nebular phase [82], suggesting the presence of CSM shells surrounding the progenitor. An advantage of this model is that it can explain the post-peak LC undulations of SLSNe-II and of some slow-evolving SLSNe-I [83]. A major caveat of the CSM interaction scenario is that, to date, there are no pure CSM models that can fit the spectra of SLSNe-I appropriately. Therefore, CSM interaction is usually applied as a component in hybrid models combining two or more specific models in order to obtain the best fits to the observations.

All of the proposed powering mechanisms outlined above require very massive stars as progenitors for SLSNe. The distribution of the ejected masses derived from observations spans a wide range starting from $\sim$10 $M_\odot$ and ending at $\sim$100 $M_\odot$ [25,84]. It is not clear how very massive stars can evolve to produce such a wide range of mass distribution immediately before explosion.

Since SLSNe are rare in the local Universe, they are usually discovered in galaxies beyond $z \sim 0.1$, i.e., at $D \gtrsim 400$ Mpc, which has so far prevented the direct detection of their progenitors with, e.g., HST. Future surveys reaching deeper detection limits may provide additional insights into this issue.

3. Early-Phase Observations

For a few years, large-scale ground-based surveys—such as the Zwicky Transient Facility (ZTF) and its predecessor survey, the (intermediate) Palomar Transient Factory ((i)PTF [85]), the All-Sky Automated Survey for Supernovae (ASAS-SN [86]), the Asteroid Terrestrial-Impact Last Alert System (ATLAS [87]), the $D < 40$ Mpc SN Survey (DLT40 [88]), the High Cadence Transient Survey (HiTS) [89,90] or the Mobile Astronomical System of TElescope Robots (MASTER [91])—have been constantly monitoring the night sky, allowing one to discover and follow (tens of) thousands of transients, including SNe, each month. The *Gaia* space mission, started in 2013, also contributes to transient discoveries via regular alerts [92].

Combining these possibilities with rapid-response follow-up resources, either on the ground—e.g., the Las Cumbres Observatory global network of robotic telescopes [93], the Panoramic Survey Telescope and Rapid Response System [94] or the Public ESO Spectroscopic Survey of Transient Objects [95]—or even in space (e.g., the gamma–X-ray–optical–UV telescopes onboard the *Neil Gehrels Swift Observatory (Swift)* [96,97]), it is possible to gather unprecedented amounts of information starting from the very first days of the SN's evolution.

Thanks to these early-phase data, one can see into the initial *shock breakout* (SB): a bright, very short (a few seconds to tens of minutes) X-ray/UV flash occurring when the shock reaches the edge of the star. Photometric follow-up of this early excess flux, together with the following (day-long) UV/optical cooling of the expanding ejecta, is essential for determining the basic parameters (radius, atmospheric composition, mass loss history) of the progenitor star; see, e.g., [98]. It is important to mention here that compared to the large dataset of optical light curves and spectra of supernovae, there are considerably less SN observations in the UV bands. The main cause of this is that the UV flux is suppressed in the case of most SNe by the radiation processes and the large line opacities of the Fe lines below 3000 Å; thus, it is not easy to obtain UV light curves, particularly for SNe-Ia. However, apart from these difficulties, the International Ultraviolet Explorer (IUE) satellite presented UV LCs of SNe (see their summary in [99]), and several photometric observations were carried out using the UltraViolet/Optical Telescope (UVOT) on *Swift* as well (see, e.g., [100]).

Moreover, interactions of the SN ejecta with any companion star and/or any circumstellar material (CSM) close to the explosion site may also be revealed.

Nevertheless, given the shortness of the timescales, even the data of extended observational networks have provided a small number of SNe with well-covered early LCs (i.e., started within 1 day after explosion with a <1-day cadence). In a few cases, serendipitous ground-based observations have arisen within 1–3 days after explosion on some nearby (mainly Type Ia) SNe (see, e.g., [101] for a recent review); similarly, UV/X-ray SB flashes were detected in a few SNe II-P with *GALEX* [102,103], and in the SN Ib 2008D with *Swift/XRT* [104]. The earliest phases of the LCs were monitored in the case of a few SLSNe-I as well, revealing that some of these objects show one or more pre-maximum LC undulations, the so-called early bumps, contrary to normal Type Ic SNe [105–108]. Several hypotheses have been proposed to explain the physical mechanism behind the presence of the early bumps: for example, Leloudas et al. suggest that a recombination wave in the ejecta may be responsible for the LC undulations [105], while, according to Nicholl et al. and Piro, they are due to the post-shock cooling of the extended material that surrounds the progenitor [84,109]. Furthermore, the interaction with the CSM [110] and a magnetar-driven shock breakout [75] may explain the presence of the early bumps.

Recently, a very important contribution has been made by space telescopes such as *Kepler* and *TESS*, which have been monitoring selected regions of the sky continuously with an unprecedentedly short cadence and good photometric precision. While the primary goals of these missions are to detect extrasolar planets (using the transit method) and to perform asteroseismology by measuring oscillations in pulsating variable stars, their special datasets also allow studies of either galactic or extragalactic transients including SNe.

Kepler observed hundreds of galaxies during its primary mission and almost 10,000 galaxies in the subsequent K2 Campaign. Its dataset, having extremely high (30 min) cadence, allowed the follow-up of the very early evolution of two Type II SNe [111], one of which showed the plausible detection of an SB emission (Figure 3), as well as four SNe Ia. One of them, SN 2018oh, exhibited signs of possible interaction between the SN ejecta and a single-degenerate companion [112–114], while the three other objects did not show such a phenomenon [115].

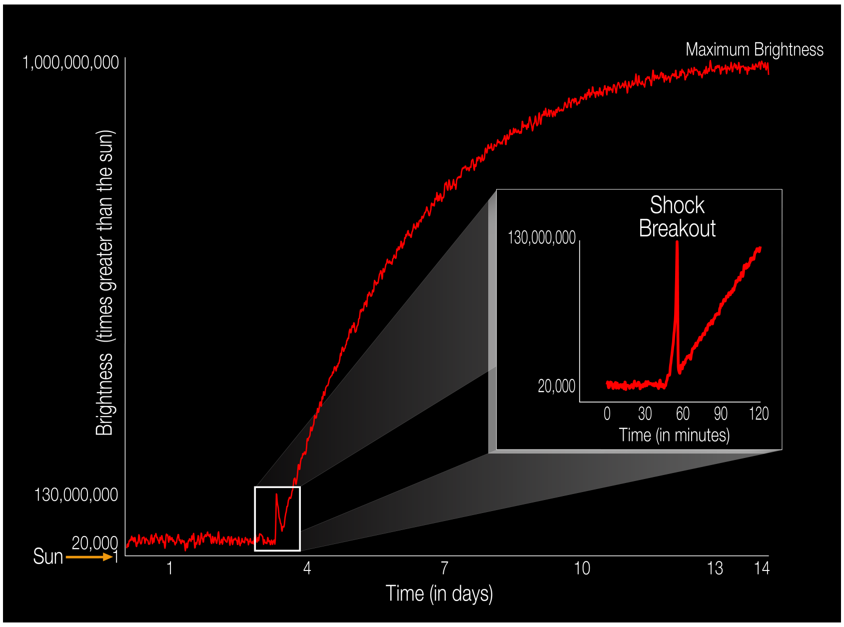

Figure 3. Early *Kepler* LC of the Type II-P KSN 2011d based on the results of [111]. For the first time, an SN shockwave has been observed in the optical wavelength as it reaches the surface of the star (called a shock breakout). Credit: NASA Ames/W. Stenzel.

Figure 4 shows the early-phase quasi-bolometric light curve of SN 2018oh from *Kepler* photometry compared to the radiation diffusion light curve models presented by Li et al. [112]. The models are shifted with respect to the moment of first light (T_0) inferred from the *Kepler* data by the amount indicated in the legend. The excess flux, as shown in the inset, is significant, at least during the first 5 days and maybe afterward, depending on the validity of the light curve model.

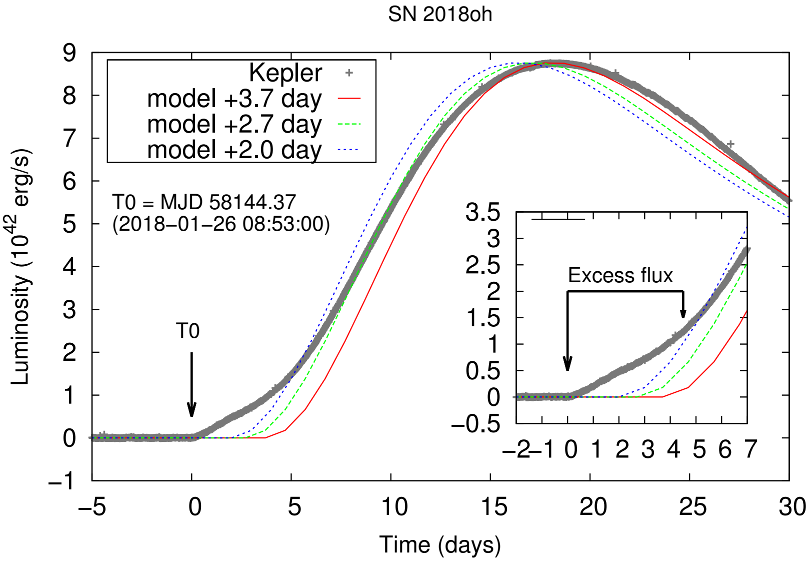

Figure 4. The *Kepler* bolometric light curve compared to SN light curve models [112], shifted horizontally to match different parts of the observed light curve. The amount of shift is indicated in the upper left corner. The excess flux, shown in the inset, is significant at least during the first 5 days.

The explanation for the excess emission is still heavily debated. Besides the ejecta–companion interaction [112,113], other possibilities have also been raised, including the non-central distribution of radioactive ^{56}Ni [114,116] or an interaction between the ejecta and a disk created by the merging of two WDs during the DD scenario [117]. Since the number of positive detections is still small, more observations are highly important to resolve this issue.

Even more recently, 30-min cadence *TESS* data on larger samples of both thermonuclear and CC SNe have been also published [101]. Fausnaugh et al. presented the photometry of 24 SNe Ia, six of them having complete coverage of the early-time LCs that allowed them to obtain upper limits on the radii of the possible companion stars. Additionally, Vallely et al. [118] published observations of 20 bright CCSNe. While the usefulness of these LCs is unquestionable, they do not allow direct confirmation of the presence of a SB, because *TESS* is sensitive only in the red and near-IR bands, rather than in the blue/UV region (note, however, that combined fitting residuals show an early flux excess). Since, during its upcoming extended mission, an even higher cadence (10-minute) *TESS* dataset will be available, further important discoveries regarding various types of SNe are expected in the near future.

4. Circumstellar Interaction and Dust Formation in SN Environments

Multichannel follow-up observations of SN–CSM interaction can provide essential details about the environments of SNe, and, thus, about the pre-explosion mass loss history of either their progenitors or their companions (see recent reviews by, e.g., Chevalier and Fransson [119] and Smith [120]). Moreover, physical processes during collisional or radiative interactions between SN shock waves and the ambient medium usually lead to phenomena of general astrophysical interest, e.g., the formation/heating of dust grains in SN environments.

Both the timescale and the degree of ejecta–CSM interaction may vary from event to event, and, specifically, among SN types and sub-classes. Type IIn—as well as Ibn or Icn—SNe usually produce narrow emission lines in their optical spectra, as well as strong X-ray and radio emission (produced by relativistic electrons accelerated by shock waves and moving in the strong magnetic fields) within days after explosion.

At the same time, progressively more "normal" CC or thermonuclear SNe are found to eventually start producing moderate (or even strong) signs of interaction months/years later, presumably occurring in CSM shells at larger distances from the explosion site. Such events include, e.g., strongly interacting Type Ib/c events such as SNe 2001em [121,122], 2004dk [123,124] and 2014C [125,126], as well as the Type IIb SN 1993J, e.g., [127–129], Type II-L SNe 1979C and 1980K [130,131] and the Type II-P SNe 2004et [132], 2011ja [133], 2013ej [134] or 2017eaw [135]. An especially interesting group is that of SNe Ia-CSM: this sub-class is thought to arise from thermonuclear explosions surrounded by dense, H-rich shells of ambient CSM producing SN IIn-like emission features in their late-time spectra [136–138].

4.1. A Detailed View of Interaction Processes: SN 1987A

A very unique and spectacular example of SN–CSM interaction was the detection of a circumstellar ring around the very nearby SN 1987A appearing in the Large Magellanic Cloud (LMC). The ring-shaped matter heated by the SN shock waves was first imaged in detail using the Faint Object Camera onboard the HST [139], while the narrow UV spectral lines of the SN, indicating the presence of photoionized circumstellar gas, were already monitored with the (*Réka*) IUE satellite [140,141]. In the last ∼35 years, SN 1987A has been intensively followed up by many space- and ground-based instruments covering the whole electromagnetic spectrum. These data—including measurements obtained by the optical/UV/near-IR detectors of HST, as well as of, e.g., the *ROSAT*, *Chandra* [142] and *XMM-Newton* [143] X-ray telescopes, or the mid-infrared *Spitzer Space Telescope* [144–146]—have allowed us to obtain a detailed view of the evolution of the object during the transition into the SN remnant phase, and revealed the interaction between the SN blast wave and the circumstellar medium, having a complex ring structure (Figure 5).

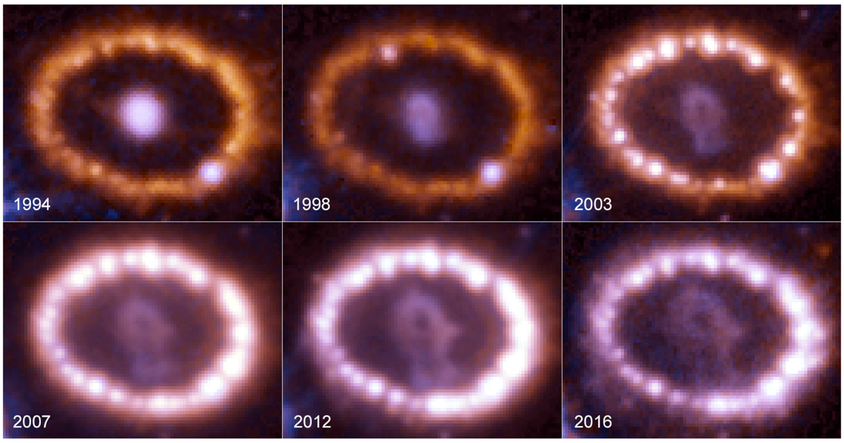

Figure 5. Evolution of the inner ring of SN 1987A followed by HST. Credit: NASA, ESA and R. Kirshner (Harvard–Smithsonian Center for Astrophysics and Gordon and Betty Moore Foundation) and P. Challis (Harvard–Smithsonian Center for Astrophysics).

4.2. A Multiwavelength Picture of SN–CSM Interaction

Apart from SN 1987A, interaction phenomena in more distant extragalactic SNe cannot be directly imaged. Nevertheless, long-term multiwavelength monitoring of these events may bring us closer to revealing important details of the interaction processes acting in various SN environments. These findings are also essential for the understanding of the pre-explosion mass loss processes of progenitors (or of their companions).

As mentioned above, signs of ongoing circumstellar interaction can be most efficiently detected and traced in the form of Hα, radio or X-ray emission; however, the amount of these long-term data is quite limited. Focusing here only on space-based observations, the top panel of Figure 6 shows a set of published X-ray LCs of various types of SNe [147]. Most of these data have been obtained in the 0.2–10 keV range using *Chandra*, *XMM-Newton* or *Swift/XRT*, complemented, in a few recent cases, by higher-energy data from *NuSTAR* (see a review in [148]). As is clearly seen, SNe IIn represent by far the most energetic events in X-ray due to the intense interaction processes between the SN ejecta and the dense ambient CSM.

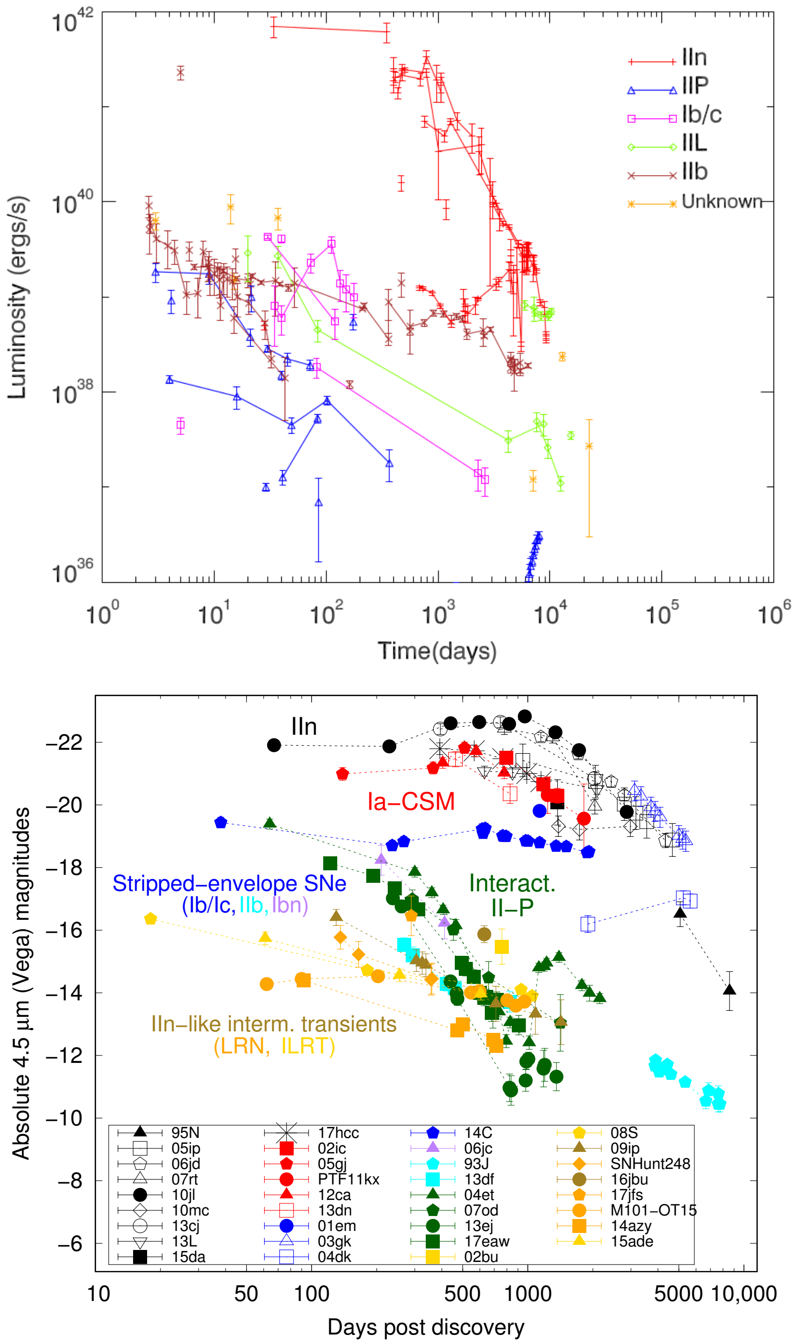

Figure 6. Top: Compilation of X-ray light curves of various SN types, adopted from [147]. **Bottom**: Mid-infrared (4.5 μm) evolution of various types of interacting SNe. (Source: Figure 2 in Szalai et al. [149]).

Taking a look at the much longer mid-infrared (mid-IR) wavelengths (also available only from space), we can see a similar picture (Figure 6, bottom panel): in general, Type IIn SNe represent the brightest sources, while the observed luminosities of other SNe scatter over a wide range [149]. In the last two decades, the missions of the *Spitzer Space Telescope* and *Wide-Field Infrared Survey Explorer* (*WISE/NEOWISE*) have resulted in a large amount of mid-IR SN data, revealing the strong connection between the interaction processes and the presence of dust in SN environments.

4.3. Dust in SNe and in SN Remnants

CC SNe have long been considered as possible sources of cosmic dust. However, dust masses based on infrared observations of nearby, young SNe were found to be 2–3 orders of magnitude smaller than values derived from models or seen in older SN remnants (SNRs). Moreover, since SN shock waves can also effectively destroy dust grains, there is a long-term debate regarding whether SNe are actually net creators or rather net destroyers of cosmic dust.

The origin and the heating mechanism of SN dust is usually not obvious, as the dust may be newly formed or pre-existing in the CSM. Newly condensed dust may be formed in either the ejecta or in a cool dense shell (CDS) between the shocked CSM and shocked ejecta where material cools. Pre-existing dust may be radiatively heated by the peak SN luminosity or by the radiation from the shock breakout, or by energetic photons generated during late-time CSM interaction, thereby forming an IR echo. In this case, the dust is a useful probe of the CSM characteristics and the pre-SN mass loss from either the progenitor or companion star. Detailed reviews on the SN–dust connection can be found, e.g., in [150–154].

Direct observational evidence for SN-connected dust, as with signs of circumstellar interaction, was first found in SN 1987A. Spectral observations obtained with the Kuiper Airborne Observatory (KAO) [155–158] and references therein indicated an excess at mid-IR wavelengths, which was also observed years later by *ISO* and *Spitzer*.

In the case of SN 1987A [159,160], as well as of SNRs in our own Galaxy and in the Magellanic Clouds, far-IR and sub-mm observations—carried out by the *Herschel Space Observatory*, as well as by the ground-based ALMA and airborne SOFIA observatories—have allowed us to reveal larger amounts ($\sim$0.1$-$1 $M_\odot$) of very cold ($T \lesssim 50$ K) SN dust formed after explosion (moreover, researchers have also found various types of molecules in these places); see a detailed and recent summary of these efforts in [151].

Regarding more distant extragalactic explosions, only much warmer dust can be studied within a few years after explosion (mainly at 3.6–4.5 micron by *Spitzer* and *(NEO)WISE*). These observed (warm) dust masses are orders of magnitudes lower than theoretical predictions and are also hardly connectable with the large (cold) dust masses found in older SNRs and/or high-redshift galaxies. Several ways to reconcile this inconsistency include the imperfections of grain condensation models, the probability of clumping dust formation or significant grain growth in the interstellar matter. In the very near future, (*JWST*) could help in resolving this mystery.

Further spectacular manifestations of light–matter interactions are light echoes, when optical/UV SN light is reflected by the dust in the surrounding (or even distant) interstellar matter. Such scattered light echoes (appearing as nearly circular rings) have been observed not only in the case of SN 1987A (discussed above), but—due to the imaging capabilities of HST—also in further nearby CC (e.g., 1980K, 1993J or 2003gd [161–163]) and Type Ia SNe (e.g., 2006X and 2014J [164,165]).

5. SNe as Distance Indicators, and Cosmological Implications

The idea that supernovae can be very effective indicators of extragalactic distances dates back to the 1970s, when Kirshner and Kwan [166] proposed the application of the Expanding Photosphere Method (EPM), a variant of the famous Baade-Wesselink method for pulsating stars, to measure the distances to Type II SNe based on simple physics that connects blackbody radiation and the kinematics of the expanding ejecta with measurable fluxes, temperatures and velocities. Shortly after this, the correlation between the light curve shape and the peak absolute magnitude of Type Ia SNe was discovered by Kowal [167] and Pskovskii [168], which, although not widely recognized at that time, opened up the possibility of obtaining reliable distances to galaxies via photometric measurements of Type Ia SNe.

The potential in space-based measurements to obtain distances to high-redshift galaxies via SNe was also quickly recognized: Colgate [169] and Tammann [170] proposed the photometry of Type Ia SNe with the *Hubble Space Telescope* to obtain luminosity distances to galaxies up to $z \sim 1$. The discovery of the Phillips relation, i.e., the quantitative connection between the SN Ia peak absolute brightness (M_B) and the decline rate of the B-band light cure ($\Delta m_{15}(B)$: the magnitude difference between the peak and at 15 rest-frame days later) [171], together with the start of large-scale sky surveys to locate supernovae, eventually led to the discovery of the accelerated expansion of the Universe [2,3]. Since then, Type Ia SNe have become the *de facto* standard and perhaps the most accurate distance indicators for galaxies in the local Universe and beyond ($D_L > 100$ Mpc).

More recently, second- and third-generation supernova surveys aimed at measuring the Hubble constant (H_0) led to significant disagreement regarding its value measured from either local distance indicators (including SNe Ia) or in the early, high-redshift Universe (via the fluctuations of the Cosmic Microwave Background, *CMB*): the former method leads to H_0 values between 70 and 75, while the latter consistently gives values between 67 and 68. At the time of writing this review, this "Hubble tension" is still unexplained, and there is a possibility that its resolution may need essentially new physics. The current status of the local H_0 estimates, based on *HST* and Gaia data on SNe Ia and Cepheids in local galaxies (the *SH0ES* program), is summarized in [172].

Meanwhile, Type II supernovae also turned out to be useful distance indicators, despite their lower peak absolute brightness and being more affected by dust extinction within their host galaxies. In addition to improvements in the implementation of EPM, Type II-P SNe were also found to be "standardizable" candles by combining their mid-plateau absolute brightness (measured at $\sim$50 days after explosion, i.e., around the middle of the plateau phase) and photospheric velocity taken at the same phase [173]. This Standard Candle Method (SCM) has been successfully applied to a growing sample of Type II-P SNe in the Hubble flow ($z > 0.01$), resulting in $\sim$5 percent accuracy in a recent estimate of H_0 [174].

Although we are far from having all the issues with extragalactic distance measurements resolved, significant improvements have been made in the last 50 years, and supernovae have played an incontestable role in this. This field will certainly benefit from the upcoming large all-sky survey programs aimed at exploring the transient sky and/or the very-high-redshift Universe. In addition to the traditional supernova types, SLSNe may also play a significant role by constraining the $z > 1$ volume [175,176]. A recent, thorough review on the roles of SNe as distance indicators can be found in the Supernova Handbook by B. Leibundgut [177].

6. Future Plans

At the time of submitting this manuscript, the *JWST* has recently started its scientific mission and the first results have been already published. As already mentioned, one of the expected results of *JWST* is to obtain a deeper insight into the CSM interaction and dust formation processes in SN environments. Starting in July 2022, *JWST* aims to obtain near- and mid-IR images and spectra on SN 1987A, on several more distant dusty extragalactic Type II-P and IIn SNe, as well as on historical Galactic SNRs Crab Nebula and Cassiopeia A.

Beyond dust and CSM interactions, the SN community also expects to find strong clues from *JWST* for the possible SN Ia explosion mechanisms reviewed in Section 2. Moreover, there are also expectations of finding signs of the first SNe, i.e., the exploded outcomes of massive Population III stars, at very high redshifts, with *JWST*.

Another expected flagship program, starting in the second half of the 2020s, will be the Nancy Grace Roman Space Telescope (*NGRST*, formerly called the Wide-Field Infrared Survey Telescope, WFIRST). Operating in the optical–near-IR regime (0.5–2.3 μm), with similar sensitivity but a $\sim$100 times larger field of view (FOV) than that of HST, NGRST will be a highly effective tool for large-scale sky surveys targeting also extragalactic SNe. Results from this mission will represent a huge step in SN Ia cosmology, leading to the far more precise determination of the contribution of dark energy to the mass–energy content of the Universe than our present knowledge.

Beyond IR telescopes, there are also great plans for the enhancement of space-based observations of extragalactic transients, both in the optical and high-energy ranges. The *Chinese Space Station Telescope* (CSST), with its 2-m aperture, could be the next flagship mission of optical space astronomy, giving, e.g., support to efforts toward SN-based cosmological parameter determinations [178]. In the UV range, the extremely large FOV *Ultraviolet Transient Astronomy Satellite* (ULTRASAT) mission could be able to revolutionize our understanding of the hot transient Universe [179]; this pursuit is also expected to obtain effective support from intelligent constellations of micro- or nanosatellites operating at either X-ray or gamma wavelengths [180,181].

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