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The Physics and Astrophysics of Neutron Stars

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The Physics and Astrophysics of Neutron Stars

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Cover illustration: Composite image of the Crab nebula with X-rays from Chandra (blue and white), NASA's Hubble Space Telescope (purple) and NASA's Spitzer Space Telescope (pink). Also shown with a cartoon is the structure of the compact star at the center of the nebula and showing the various parts of a neutron star: the core, the outer core and the crust. Credit: X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Infrared: NASA-JPL-Caltech; Cartoon: L. Rezzolla (GU)

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Foreword

Compact stars, such as neutron stars, strange stars, and hybrid stars, are unique laboratories that allow us to probe the building blocks of matter and their interactions at regimes complementary to terrestrial laboratories. These exceptionally complex astrophysical sources have already led to breakthrough discoveries in nuclear and subnuclear physics, QCD, general relativity, and high-energy astrophysics. The most recent landmark was the first gravitational wave detection from the merging of two neutron stars on August 17, 2017 (GW170817), 2 years after the first ever direct detection of gravitational waves, which has closed a chapter initiated almost one century ago, with the first paper of Albert Einstein on general relativity. With the observation of coalescing neutron stars, the gravitational-wave detectors LIGO and Virgo have demonstrated their potential to directly probe the properties of matter at the extreme conditions found in this scenario. Indeed, constraints have been placed on the tidal effects of the coalescing stars, which in turn constrain the neutron star radii and the equation of state of matter at twice the nuclear saturation density. These observations also mark the beginning of the multi-messenger astronomy era with the simultaneous detection of gravitational waves, gamma-ray burst, and electromagnetic emission from the same source. In the coming years, the predicted large number of new events will greatly improve our understanding of neutron star mergers and of neutron star internal structure. During 2019, the observatory NICER (Neutron Star Interior Composition Explorer) hosted by the International Space Station (ISS) will release its first one-year campaign of X-ray observations of a few neutron stars aiming at determining the radius of these stars within less than 10% accuracy. We shall also mention the GAIA satellite which is measuring the position of billions of objects in our universe with an unprecedented accuracy. We are confident that these measures will considerably help understanding the multiple faces of neutron stars and will provide a better picture of the neutron star jigsaw puzzle.

The nuclear and subnuclear experimental facilities, such as FAIR and GANIL in Europe, offer a complementary approach to explore the phase diagram of dense matter as well as reaction rates and transport properties. They have nurtured innovative and fundamental discoveries thanks to the synthesis of new radioactive elements, on one side, and to the production of new states of matter in heavy ion collisions, on the other side. Theoretical approaches in nuclear physics have also been greatly renewed over the last decade, mainly thanks to the new chiral EFT methods which have allowed to establish constraints on the properties of low-density nuclear matter—up to $1-2$ times the nuclear saturation density. The description of the nuclear equation of state at zero and finite temperature, in uniform or non-uniform matter, as well as reaction rates and transport properties has also made a big step during the last decade. The more systematic use of nuclear physics inputs in compact star modeling has contributed to reduce the uncertainties in the model predictions. The various constraints coming from both nuclear physics and astrophysics have been instrumental in improving our understanding of the dense matter equation of state. Detailed questions related to phase transitions and transport properties are now emerging, and future experiments and observations will provide even better data to keep improving the models.

The outstanding variety of observational properties of compact stars challenged observers and requires quite dedicated instruments. NICER is an example, but observations in the whole electromagnetic range, from radio to gamma rays, are crucial to understand the properties of compact stars. Future instruments, e.g., FAST, LOFT, ATHENA, and SKA, will provide an unprecedented amount of data on compact stars. One particular issue that has received significant attention is the astonishing large magnetic fields exhibited by neutron stars. From both the microphysics and the macrophysics sides, the relevance of strong magnetic fields in different processes has been acknowledged. Understanding their impact, for instance, in core-collapse supernovae, the long-term cooling of strongly magnetized neutron stars, the bursting activity of magnetars, the merger of neutron stars binaries, and the crustal cooling of quiescent low-mass X-ray binaries, among other scenarios, has been the object of many theoretical studies, improving our knowledge of these fascinating objects.

The book is meant to address a large spectrum of readers, from first-year PhD students up to senior researchers, who will find a thorough overview of the various facets of the physics and astrophysics of compact stars. The aim is that of summarizing the recent progress in the field and the many challenging questions which still remain to be answered; most importantly, the book aims at identifying effective strategies to explore, both theoretically and observationally, the open problems. To accomplish this goal, each of the 13 chapters of the book written by internationally renowned experts includes a brief overview of the historical context, a detailed review of the main theoretical achievements, experimental and observational results, and finally the present challenges, future prospects, and open questions.

The book is organized into three thematic blocks: the first part (Chaps. 1–4) covers the astrophysical context where neutron stars are formed (core-collapse supernovae), discusses the impact of strong magnetic fields in neutron stars (magnetars and transient phenomena), reviews tests of gravity with compact stars and the detection of gravitational waves, and studies the complexity of binary systems.

The second part (Chaps. 5–9) is dedicated to nuclear physics. Several decades ago, it was suggested that the neutron star equation of state could be directly determined from observations. As a transition from astrophysics to nuclear physics, a review is made of the constraints from electromagnetic observations. Then the nuclear equations of state at both zero and finite temperature are presented, followed by the connection with low-energy QCD and super-dense matter. Interestingly, since the nuclear interaction is attractive at long range, a part of the volume of neutron star core and crust could host superfluid neutrons, or charged particles in superconducting state. Pairing is believed to be responsible for glitches and can affect neutron star oscillations. Finally, the microphysics part of the book is concluded by addressing the questions related to transport phenomena and reaction rates in hadronic and quark matter.

The last part (Chaps. 10–13) is mainly focused on gravitational physics and kilonovae phenomena; the gravitational wave emission from merging neutron star binaries as well as the post-merging dynamics is discussed, and the electromagnetic emission of kilonovae and its engine—the nucleosynthesis—is described. Gravitational waves emitted by a single neutron star due to its quadrupolar "mountain" deformation are also discussed, as these could be the next new signals to look for in advanced terrestrial interferometers. Finally, this section is concluded with a presentation of universal relations arising in general relativity—the so-called I-Love-Q relations—and of alternative theories of gravity and their universal relations.

This book, the *NewCompStar White Book*, is the final deliverable of the MP1304 COST Action, which ran from 2013 to 2017 and was the natural extension of the ESF-funded RPN "CompStar" (2008–2013), which coordinated various initiatives at the national level such as EMMI in Germany and TeonGrav in Italy (still continuing), SN2NS continuing as MODE in France, and many more. After more than 10 years of continued networking at the highest European level, research on compact stars is more active than ever before and has reached maturity. The near future activities are also guaranteed by the new COST Action PHAROS which will operate until 2021. But NewCompStar did not end in Europe. It was also connected to research groups in non-EU countries, such as Armenia, Australia, the Russian Federation, and the USA. Many of the world leading experts in the field have participated in our international conferences and schools. NewCompStar has therefore been an important nexus acting as a global reference for compact star physics.

At this point, the *NewCompStar White Book* provides a timely summary of the enormous progress in our field during the last decade. As illustrated through the chapters of this book, progress has been possible thanks to the multidisciplinary interaction among astrophysicists, nuclear and particle physicists, and experts in gravitational physics. NewCompStar was the framework which allowed leading experts in these fields to work together and jointly address fascinating and challenging problems. The deep and rich interconnectivity between areas was stressed and exploited since the beginning of our European networking efforts, being one of the keystones of our project. In addition to the pure research agenda, Compstar and

NewCompStar also provided a dedicated training program for a new generation of scientists, which grew with a broader view and better skills than previous generations. This book also represents a synthesis of the many ideas transmitted to young researchers during the international schools.

To conclude, it is worth stressing again that, although this white book is a collection of contributions from NewCompStar community members, most of the discussed results have been obtained by large international, worldwide collaborations trying to understand the physics of compact stars. Given its pedagogical purposes and the very broad range of topics covered, we have no doubt that this volume will find its place among the few general books on neutron stars, and we hope it will further stimulate research on these fascinating celestial objects, accompanying a new generation of physicists.

Roma, Italy Valeria Ferrari
Seattle, WA, USA Jerome Margueron
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June 2018

Preface

Astrophysical objects have always inspired in us a deep sense of wonder, awe and inspiration. Astrophysical *compact* objects—such as neutron stars—obviously belong to this class and are, arguably, among the most exquisite example of what drives human fascination.

This sense of fascination has pervaded “NewCompStar”, a network that between 2013 and 2017 has collected scientists across Europe with very different backgrounds—astrophysics and gravitational and nuclear physics—in the common quest for a better understanding of neutron stars and of the fundamental physics behind them.

Numerous are the achievements of these scientists, who have met in a number of meetings—small and large—and who have collectively written hundreds of papers over 4 years only. More importantly, a legacy of collaborations, synergies and friendships has been passed over to “PHAROS”, the new and improved incarnation of this spirit.

As a way to cast on paper a small part of what NewCompStar has ultimately achieved, we have organised this collection of chapters that aim at providing the exciting portrait of our present understanding of neutron stars.

The authors of these chapters have been chosen for their extraordinary expertise and to reflect NewCompStar’s natural geographic and gender balance. More importantly, these authors are not only very active in their corresponding fields, but they will probably shape them in a permanent manner.

We trust that this book will be useful both as a reference for researchers working in the field and as a first introduction to the subject for the generation of young scientists willing to join the exciting adventure of understanding compact stars.

Frankfurt, Germany — Luciano Rezzolla
Milan, Italy — Pierre Pizzochero
Southampton, UK — David Ian Jones
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Contents

Chapter 1
Neutron Stars Formation and Core Collapse Supernovae

Pablo Cerda-Duran and Nancy Elias-Rosa

Abstract In the last decade there has been a remarkable increase in our knowledge about core-collapse supernovae (CC-SNe), and the birthplace of neutron stars, from both the observational and the theoretical point of view. Since the 1930s, with the first systematic supernova search, the techniques for discovering and studying extragalactic SNe have improved. Many SNe have been observed, and some of them, have been followed through efficiently and with detail. Furthermore, there has been a significant progress in the theoretical modelling of the scenario, boosted by the arrival of new generations of supercomputers that have allowed to perform multidimensional numerical simulations with unprecedented detail and realism. The joint work of observational and theoretical studies of individual SNe over the whole range of the electromagnetic spectrum has allowed to derive physical parameters, which constrain the nature of the progenitor, and the composition and structure of the star's envelope at the time of the explosion. The observed properties of a CC-SN are an imprint of the physical parameters of the explosion such as mass of the ejecta, kinetic energy of the explosion, the mass loss rate, or the structure of the star before the explosion. In this chapter, we review the current status of SNe observations and theoretical modelling, the connection with their progenitor stars, and the properties of the neutron stars left behind.

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1.1 Introduction

1.1.1 Core-Collapse Supernovae and Their Importance

Neutron stars (NS) appear at the end point of the evolution of massive stars ($M > 8\ M_{\odot}$). At this stage, most of these stars have grown an iron core that cannot be supported by hydrostatic pressure and collapses. In most of the cases it produces a supernova (SN), releasing a gravitational energy of about $\sim 10^{53}$ ergs (mainly in form of neutrino radiation), and leading to the complete destruction of the progenitor star (e.g. see Janka 2012). SNe leave behind compact remnants, such as neutron stars (NS) or black holes (BH) (e.g. see Heger et al. 2003). The first interpretation of a SN as a transition between massive stars and neutron stars was introduced by W. Baade and F. Zwicky in the 1930s (Baade and Zwicky 1934) in order to explain the extraordinary amount of energy liberated. It still holds nowadays (see Sect. 1.2.3 for a detailed description about how NS are born).

SNe are studied from multiple perspectives. They are crucial for a complete understanding of stellar evolution, being associated with NS and black holes (BH), as well as with other extreme events such as gamma-ray bursts (GRBs; e.g. Galama et al. (1998) or Woosley and Bloom (2006)) and X-ray flashes (XRFs; Pian et al. 2006), mainly connected to stripped-envelope core-collapse SNe. SNe are also among the most influential events in the Universe regarding their energetic and chemical contribution to the interstellar medium in galaxies (Thielemann et al. 1996). In fact, SNe are the major "factories" of heavy elements synthesized along the progenitors life and in the SN explosion itself, as well as sources of gravitational waves, neutrinos, and cosmic rays (e.g. Andersson et al. 2013; Hirata et al. 1987; Koyama et al. 1995). SNe also produce dust (e.g. Todini and Ferrara 2001), and induce star formation (e.g., Krebs and Hillebrandt 1983) since the shock waves generated in their explosion heat and compress interstellar molecular clouds. Finally, they can be used as cosmological distance indicators, and to set constraints on the equation of state of Dark Energy (e.g. Riess et al. 1998; Perlmutter et al. 1999; Hamuy and Pinto 2002).

1.1.2 Brief History of Supernova Observations

Temporary stars, comets and novae, as well as occasional supernovae, were fairly frequently recorded in East Asian history (Stephenson and Green 2005). Possibly, the first supernova for which written reports exist is SN 185, which took place in the year AD 185 in the Milky Way Galaxy (precisely it occurred in the direction of Alpha Centauri).

The birth of modern SN astronomy occurred in 1885, when the first extragalactic SN (S Andromedae or SN 1885A) was detected with a telescope (Hartwig 1885). In the 1920s scientists begun to realise that there was a particular class of very bright novae, and a decade later, Baade and Zwicky (1934) named this kind of event "supernova". The distinction between novae and supernovae was at first based on twelve objects discovered between 1895 and 1930, plus the galactic SN observed by Tycho in 1572. Between 1936 and 1941, the first systematic supernova search was started by W. Baade and F. Zwicky using the Palomar 18-in. Schmidt telescope and led to the discovery of 19 SNe. In the same years, SNe were first classified as Type I or Type II based on the lack or presence of hydrogen spectral lines, respectively (Minkowski 1941). This subdivision is still the basis of the SN classification used today (Sect. 1.2.1 and Turatto et al. 2003; Gal-Yam 2016).

In the following years, the improvement of the instrumentation, the construction of new telescopes and also the numerous progresses in the understanding of the stellar evolution, stimulated the research and cataloguing of the SNe. By the Eighties, with the introduction of the CCD and the construction of larger diameter telescopes, not only did the number of SNe observed grow but it was possible also to obtain spectra with better resolution and to study their luminosity evolution for long times. SNe classification became consequently more complex due mainly to more careful comparison among the SNe, and the previous types of SNe were further sub-categorised attending to the presence/absence of chemical elements other than hydrogen.

Computer controlled search programs of SNe were initiated in the following decade. Thanks to past and ongoing surveys (e.g. the All-Sky Automated Survey for SuperNovae—ASAS-SN; Shappee et al. (2014), the ESA Gaia transient survey—Hodgkin et al. (2013), or the Panoramic Survey Telescope & Rapid Response System—Pan-STARRRS; Kaiser et al. (2002), among numerous others), and to the efforts of amateur astronomers, the rate of SN discoveries has dramatically increased, going from less than 20 SNe at the beginning of the twentieth century, to more than $\sim$200 SNe per year in the first decade of the twenty-first century, and finding today up to 1000s of events per year.

These technological advances also allowed SN searches at $z > 0.2$ (e.g. Dark Energy Survey—DES[1]), and the multi-wavelength observation of SNe. The optical band has played a fundamental role in the knowledge and classification of the SNe, but with the technological progress, it has been possible to observe the SNe in the IR bands, and in the radio, ultraviolet (UV) and X-ray. In particular, with the explosion of the SN 1987A in the LMC, the closest extragalactic SN observed (50 kpc), it has been possible also to directly identify for the first time the SN progenitor in archival images and to detect the neutrino flux produced during the explosion (see e.g. Arnett et al. 1989; McCray 1993 for reviews).

To further complicate this scenario, these new generation of deep, and wide surveys, are discovering new types of transients with unprecedented observational characteristics, as we will describe in Sect. 1.3.1. For example, it has been found extreme SNe types such as superluminous SNe, hundreds of times brighter than those found over the last 50 years ($M_V < -21$ mag), whose energy regime is not

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[1] http://www.darkenergysurvey.org/.

explained by the standard core-collapse and neutrino-driven mechanisms. Or ultra-faint SNe ($M_V > -14$ mag), which are characterized by a very low explosion energy ($\sim 10^{49}$ ergs) and small amount of ^{56}Ni mass ($<10^{-3}$ $M_\odot$).

The wide variety of classes of SNe has also shown that core-collapse supernovae (CC-SNe) present observational heterogeneity, consequence of the different properties of the progenitor star at the moment of the explosion, their energetic, angular momentum, and environment. Thus, in the last decades SNe have been studied in order to better establish the link to their progenitor stars and thereby to clarify the evolution of massive stars. This make the SNe a very valuable probe of mass loss, circumstellar structure, and star formation rates. For nearby CC-events it has been possible to directly image the precursor star in pre-explosion images (mainly from the archive of the Hubble Space Telescope, *HST*) and to verify its disappearance years after the SN exploded (Smartt et al. 2009; Smartt 2015 and Sect. 1.2.2.2).

1.1.3 The Theoretical Perspective

In parallel to the observations, our theoretical understanding of the processes leading to the formation of a neutron star as a result of a supernova explosion has grow significantly in the last century. Although the basic scenario was set by Baade and Zwicky (1934), it was not until the 1960s, with the appearance of the first modern computers, that a significative progress was achieved. It was established that the collapsing core should bounce when reaching nuclear matter density (Colgate and Johnson 1960; Colgate et al. 1961) and suggested that the primary energy source in supernova explosions should be in form of neutrino radiation (Colgate and White 1966). The basics behind most advanced models nowadays was set by Bethe and Wilson (1985) in the so-called delayed neutrino-heating mechanism. They realised that, when included the most sophisticated microphysics, a prompt explosion after bounce was not possible, but the energy deposited by neutrino radiation could revive the shock and power the explosion. We know now that multidimensional effects play a primary role in the explosion, and that a comprehensive numerical modelling of the scenario including all relevant physical effects is a computational challenge (see e.g. Janka et al. 2007; Janka 2012; Burrows 2013; Müller 2016). Therefore, our current understanding of the supernova mechanism relies heavily in the results of numerical modelling and the progress in the field has tracked closely the improvements of modern supercomputers and the development of high performance computing.

However, in order to understand the plethora of observations it is not sufficient to be able to model numerically the collapse of massive stars. One also has to be able to link these explosions with their progenitor stars, make predictions of how common or uncommon each type of event is, and what are the consequences for the galactic environment in which they live. The complete picture can only be achieved with the help of the complementary discipline of stellar evolution (see e.g. Woosley et al. 2002). Even if more than 2500 CC-SNe have been discovered so far, it is still missing a complete picture of this progenitor-explosion link. In order to better understand the way in which these stars end their evolution, it is necessary to get stronger constrains of the physical characteristics of the progenitor stars alongside the explosion parameters through the observation of SNe, and thus test and constrain the models. At the same time, studying compact remnants like neutron stars, we can determinate explosion conditions and understand associated phenomena such as mass loss, r-process nucleosynthesis, gravitational waves and neutrino emission.

1.1.4 Aim

The aim of this work is to review the current knowledge about supernovae as the place of birth of neutron stars from both an observational and a theoretical perspective. In Sect. 1.2 we review the status of observations of core-collapse supernovae and our current knowledge about the scenario in which these explosions are produced. In Sect. 1.3 we discuss the present challenges and future perspectives in the field.

1.2 Current Status of Supernova Observations and Modelling

1.2.1 Traditional Supernova Types

As we see in Sect. 1.1.2, the first fundamental classification was given by Minkowski (1941) who distinguished the SNe in two different classes based on the lack (SNe I) or presence (SNe II) of hydrogen lines such as Hα 6563 Å and Hβ 4861 Å in their early spectra. Since SNe can be very different one from another as to spectral features (i.e. chemical composition, physical conditions), photometry, overall SED (spectral energy distribution), time evolution, radio and X-ray properties, in the 1980s sub-classes were introduced such as Ib, Ic, II-P, II-L, IIn, IIb which are related to characteristics of their spectra (small letter) or light curves (capital letter).

The SNe of type I are subdivided in three subclasses, depending basically on the presence or absence of Si II and He I in the spectra (see left panel of Fig. 1.1). Type Ia SNe spectra present the line of Si II (rest wavelength 6347, 6371, and 6150 Å) in absorption, while the spectra of the SNe Ib do not have these features but are characterized by pronounced lines of He I, such as those at 5876, 6678 and 7065 Å. Finally, the SNe Ic do not show Si II nor He I lines (or He I is very weak). Within this last subclass, we can distinguish events with fast-expanding ejecta ($v \sim 20{,}000\,\mathrm{km\,s^{-1}}$), named broad-line SNe Ic (Ic-BL) or hypernovae. These transients are sometimes related to long gamma-ray burst or X-ray flashes (SN 1998bw is the prototypical SN Ic-BL, discovered at the same time and location as GRB 980425; Galama et al. 1998). Currently, it is known that type

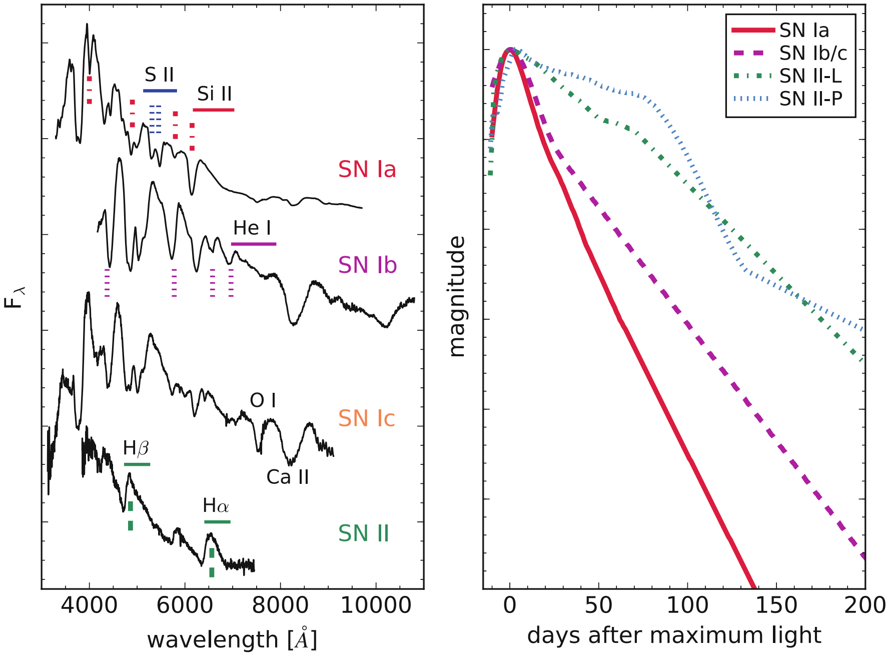

Fig. 1.1 *Left:* Representative spectra near maximum light of the main SN types (SN Ia 2011fe (Pereira et al. 2013), Type Ib iPTF13bvn (Cao et al. 2013), Type Ic SN 2007gr (Valenti et al. 2008), and Type II-P SN 1999em (Leonard et al. 2002)). The most prominent spectral features are indicated. The spectra are available in the public WISeREP repository (Yaron and Gal-Yam 2012). *Right:* Average light curves of the main SN types (Li et al. 2011)

Ia SNe arise from the thermonuclear runaway of an accreting white dwarf (WD), whereas Type Ib and Ic originate from the core collapse of massive stars that had lost their hydrogen, or hydrogen plus helium envelopes before explosion, respectively.

The SNe II are also believed to be CC-SNe whose progenitors have retained (at least part of) their outer envelopes before exploding, reason for which their spectra are dominated by hydrogen lines all the time. As shown in the right panel of Fig. 1.1, SNe II are sub-classified as SNe II-P and SNe II-L, based on their light curve shape. The former exhibit light curves that decrease slowly after maximum for about three months displaying a “plateau”. The light curve of SNe II-L shows instead, a linear decline starting shortly past maximum. Recently, it has been argued that these two subclasses are at the extremes of a continuous distribution of SNe with different light-curve slopes (e.g. Anderson et al. 2014).

This classification, based on early phase spectra, is normally used when a new SN candidate is confirmed, but it is not always accurate, as it can also be that the appearance of a SN can change in time due to the characteristics of the progenitor or to those of the circumstellar material (CSM).

During the last part of the 1980s and the 1990s, the family of CC-SNe begun to grow with the identification of various sub-types. The SNe IIn (named after the detection of narrow emission lines in their spectra) present blue continuum spectra, with Balmer emission lines formed by several components that evolve in the time in various ways (Schlegel 1990). The narrow component, with inferred full-width-at-half-maximum (FWHM) velocities from a few tens to a few hundreds $\mathrm{km\,s^{-1}}$, are believed to arise from photoionised, slowly expanding gas which recombines and emits photons. This gas, most likely expelled by the progenitor star during the last phases of its evolutions, is located in the outer CSM and is not perturbed by the SN ejecta, at least during the early phases of the SN evolution. At later phases, intermediate-velocity line components (FWHM of a few thousands $\mathrm{km\,s^{-1}}$) may be generated when the high velocity SN ejecta (a few 10^{-4}) collides with the dense pre-existing CSM. Although the interaction may mask the innermost ejecta (as well as the explosion mechanism; Chevalier and Fransson 1994), in some cases, particular geometric configurations may also favour the detection of high-velocity components (a few $10^{-4}\,\mathrm{km\,s^{-1}}$) arising from the photoionised SN ejecta. SNe IIn light curves are instead quite heterogeneous, showing both slow and fast declining SNe, as well as faint ($M_R \gtrsim -16$ mag) and very bright ($M_R \lesssim -19$ mag) objects (e.g. Kiewe et al. (2012) for a sample of SNe IIn). Note that recently it has been discussed that SNe IIn are not really a SN type, but an external phenomena where any type of SN (due to thermonuclear or core-collapse explosion) or not terminal outburst with fast ejecta and sufficient energy, interact with a slower and denser CSM. It produces a phenomena which appears or mimic what we know as a SN IIn. Therefore this sub-class is more commonly named “interacting SNe” (e.g. see Smith 2016).

Finally, the spectrum of the SNe IIb is similar to that of the SNe II-P and II-L during maximum light, i.e. it has strong lines of H, but in the following week it metamorphoses to that of SNe Ib. This points out a physical link between these two classes (SN 1993J represents the prototypical object of this subclass; Richmond et al. 1994), suggesting that SNe II and SNe Ib/c share a common origin, i.e., the CC of a massive star, but with just different amounts of stripping on the progenitors' outer layers.

Together the Type II-P and II-L represent the majority of CC-SNe (considering a volume-limited rate in the local Universe; Li et al. 2011). Almost 9% is formed by interacting SNe. H-poor SNe (SNe IIb, Ib, Ic) constitute instead the remaining ∼37%. Recently, Cappellaro et al. (2015) find similar rates for CC-SNe groups considering a redshift range $0.15 < z < 0.35$. Rare events like SN 1987A-like objects are estimated to form ∼3% of the CC-SN population (Pastorello et al. 2012).

1.2.2 Observational Constraints on the Progenitors of Core-Collapse Supernovae

In the last decades SNe have been studied in order to better establish the link to their progenitor stars and thereby to clarify the evolution of massive stars.

1.2.2.1 Observables of Core-Collapse Supernovae

Indirect clues about the SN origin can be derived from the interaction of the material dismissed during the explosion with dense circumstellar medium lost by the progenitor during its turbulent life, or as said before, from their light curve and spectral evolution.

Light Curves

The first observable of electromagnetic radiation from a SN is the shock-breakout. It is a short time scale (minutes for SNe with compact progenitors) in which the shock wave produced during the collapse of the stellar core, reaches the stellar surface. In this instant a flash of soft X-rays and ultra-violet (UV) photons are released. The shock-breakout was directly observed in X-rays for the type Ib SN 2008D (Soderberg et al. 2008), whereas the fast cooling tail (due to the adiabatic expansion of the ejecta) after the shock-breakout has been observed in optical and UV bands for a few other objects (e.g. SNe 1993J and 2013df (Morales-Garoffolo et al. 2014)). This post shock-breakout phase mainly depends on the progenitor radius (e.g. Chevalier 1992).

Successively, the photons gradually leak out of the photosphere in a diffusion time scale ($t_{diff} \propto \rho \kappa R^2$, where ρ is the density, κ the opacity, and R the SN radius) shorter than the expansion time scale ($t_{exp} = R/V$, where V is the expansion velocity). During this period (tens to days) the thermal shock energy decreases as the ejecta expands, and the radioactive decay of ^{56}Ni (produced in the explosion, which has a lifetime of 8.8 days) and ^{56}Co (lifetime of 111.3 days) becomes important, reaching a peak of luminosity. After this maximum the SN ejecta continue to expand and cool, eventually arriving to the hydrogen recombination temperature of the ejecta. While the recombination wave moves inward through the ejecta, the temperature remains practically constant. Hence, depending on the mass of the hydrogen envelope and the radius of the SN progenitor star, the SN luminosity could show a constant or plateau phase (e.g. the case of the SNe Type II-P), or a steep decline after maximum light (e.g. the SNe Type II-L).

Once all the hydrogen has recombined, i.e. at late time ($t > 100$ days), the light curve declines at the rate of the decay of $^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$ (0.0098 mag day^{-1}). The late time light curve observations are useful to determine the mass of ^{56}Co (and hence synthesized ^{56}Ni). At times later than 1000 days past explosion, other radioactive elements with longer half-lives such as ^{56}Co and ^{56}Ti power the luminosity evolution of the CC-SNe.

Physical parameters from the SN explosion like the kinetic energy of the explosion, the total ejected mass, the mass of ^{56}Ni synthesized and the radius of the progenitor, can be estimated through the fit of the SN bolometric light curves by semi-analytic functions (e.g. Arnett 1982) or more sophisticated hydrodynamical models (e.g. Blinnikov et al. 2000). More details about the SN modelling can be found in Sect. 1.2.3.2.

Spectral Evolution

SN spectral time evolution are a scan through the SN ejecta. They are important to study the chemical compositions of SNe and their progenitors, and the kinematic of the SN ejecta. A clear example is their utility is to classify SNe.

During the early phases or photospheric phase, the SN ejecta are not completely transparent and only the outer layers of the ejecta are observed. Consequently, spectra are characterized by showing a black-body continuum superposed by absorption and/or emission lines (e.g. see Filippenko (1997) for a detailed review). These features are broad because the SN ejecta is expanding at high velocity. They often show P-Cygni profiles with blue-shifted absorption and red-shifted emission components. Precisely via the absorption component of the P-Cygni profile it is possible to measured the velocity of the region at which the line predominantly forms (through the Doppler effect).

Late-time (nebular) SN spectra, taken several months after the explosion, are a unique way to peer into the very centre of the exploded stars. At those phases the opacity for optical photons has dropped substantially due to the expansion of the ejecta, so that the innermost parts, which were previously shielded by an effective photosphere, are now uncovered. The inner ejecta composition, unveiled by the nebular emission lines, is one of the most powerful tools to constrain the mechanism that gave rise to an explosion, since they all have a characteristic and widely unique nucleosynthesis. Late time spectra are characterized by strong emission lines on top of a faint continuum. Also the profile of a nebular emission line carries important information. The width of an emission line is a measure for the radial extent of the emitting species, and the detailed shape encodes asymmetries in its spatial distribution (e.g. Taubenberger et al. 2009).

When the SN ejecta interact with the CSM, the spectra present a blue continuum with superposed narrow emission lines, arisen from the CSM ionized by the shock interaction emission. If the CSM is thin, it is also possible to observe broader emission lines from the ionized ejecta.

The radiative-transport modelling of the SN late-time spectra can give us information about the kinematics of the ejecta and constrain the SN progenitor masses (e.g. Jerkstrand 2017). For example, considering the sensitive dependency of the oxygen nucleosynthesis with the main-sequence mass of the star, the modelling of the [O I] 6300, 6364 Å features helps us to constrain the progenitor mass (e.g. Morales-Garoffolo et al. 2014).

Supernova Remnants

Studying the observed properties of young SN remnants (SNR) is also an indirect path to connect with the SN progenitors (e.g. see the reviews Chevalier (2005), Patnaude and Badenes (2017)). The remnant phase begins when, after the light from a SN fades away, the ejecta in expansion, cools down, and strongly interacts with the surrounding material, either the interstellar medium (ISM) or a more or less extended CSM modified by the SN progenitor. Thus SNR provide detailed information on the chemical composition of the ejecta, the explosion dynamics, and the progenitor star mass loss distribution. The most notable cases are the Galactic SNR Cassiopeia A, and the youngest know remnant, SN 1987A, in the Large Magellanic Cloud. The advantage of the study of Galactic SNR is that they can be resolved in fine detail. However, their link with CC-SN is complex given the large diversity of the CC-SN explosions and circumstellar environment, and the large mass range of the progenitors.

1.2.2.2 Searching for SN Progenitor Stars

Still, the killer case is made with the *direct identification* of the star prior to explosion. Until the early 90s, only nearby events such SNe 1987A (∼50 kpc; White and Malin 1987) and 1993J (∼3.6 Mpc; Aldering et al. 1994) have allowed the direct progenitor identification in pre-explosion images. In recent years over a dozen CC-SN progenitors have been identified based on the inspection of archival, pre-explosion images. The identification relies on the positional coincidence between the candidate precursor and the SN transient. This requires high spatial resolution and very accurate astrometry because, at the typical distance of the targets ($>$30 Mpc[2]), source confusion becomes an issue. In practice, only *HST* or 8-m ground-based telescopes mainly provided by adaptive optics images can be used to accurately pin-point (with a typical uncertainty of a few tens mas) the progenitor candidate. Even so, there is always the chance of mis-identification with foreground sources or associated companion stars. Thus, a final approach is visiting the SN field when the SN has weakened: if the candidate star has disappeared, then it was indeed the progenitor, otherwise it was a mis-identification (e.g. see Maund and Smartt 2009, Van Dyk et al. 2013, and Fig. 1.2).

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[2] This distance limit is based on practical experience. Smartt et al. (2009) and Eldridge et al. (2013) set to 28 Mpc the distance limit for a feasible search of SN progenitors, although there are exceptions such as the massive progenitor of SN 2005gl at 60 Mpc (Gal-Yam et al. 2007).

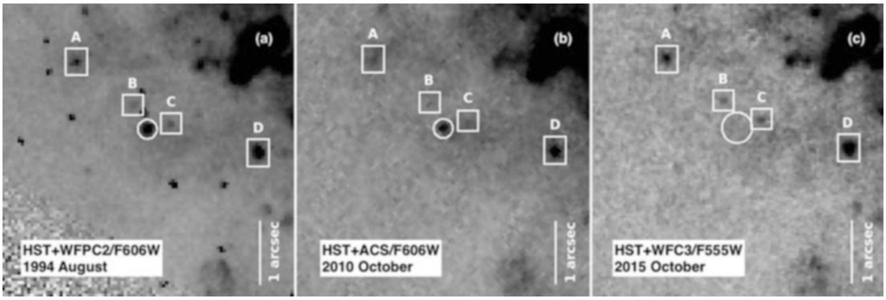

Fig. 1.2 Subsections of the pre-explosion (*panel* **a**), post-explosion (*panel* **b**), and late-time (*panel* **c**) *HST* image of the SN 2010bt site. SN 2010bt is likely a Type IIn SN and its progenitor was a massive star that experienced a powerful outburst. The positions of the SN candidate progenitor and SN are indicated by *circles* each with radius of 3 pixels (between 0.08 and 0.15 arcsec), except for *panel* **c**, for which the radius is 6 pixels (∼0.23 arcsec). The positions of three neighbouring sources of SN 2010bt, "A", "B", "C", and "D" are also indicated

Once a progenitor star candidate is identified, its initial mass and evolutionary state before the CC can be estimated by comparing its brightness and colour (if multi-colour imaging is available) measured with stellar evolution models. These models are chosen taking into account the metallicity in the SN environment, and the distance and the extinction to the star, derived from detailed light curves and spectral evolution of the SN with ground-based data (see Sect. 1.2.4 for a discussion about stellar evolution models).

Taken together, the availability and depth of archive images of nearby galaxies is a determining factor that delimits the rate of SN progenitor stars identified. There is an approximate probability of about 25% to find an image of the host galaxy of a nearby SNe in the HST archive (Smartt et al. 2009).

Following the above or similar steps, direct detections or upper mass limits have been established for progenitors of some types of SNe:

- *Type II-P:* Based on the statistics of around 15 SNe II-P, it appears that all of these progenitors exploded in the red supergiant phase from stars with initial mass range of 8–18 $M_\odot$, as we would theoretically expect (see Sect. 1.2.4.2). However there has been no detection of a higher mass stars in the range 20–40 $M_\odot$, which should be the most luminous and brightest stars in these galaxies. This has led to the intriguing possibility that higher mass stars undergo core-collapse, but form black-holes which prevents much of the stellar mass escaping the explosion (Reynolds et al. 2015). Theoretically, such quenched, low energy explosions have been proposed. Our lack of detection of high mass progenitors could be evidence for this missing population (Kochanek et al. 2008; Smartt et al. 2009). But exceptions exist as the case of SN 1987A, considered a peculiar SN Type II because in spite of exhibiting prevalent hydrogen P-Cygni profiles in the early spectra, it had slow rise to maximum, faint, and broad light curves. Its