The rebirth of Supernova 1987A

a study of the ejecta-ring collision

Per Gröningsson
Cover image:
This is an image of the triple-ring nebula around SN 1987A taken in December 2006 with the Advanced Camera for Surveys (ACS) aboard the Hubble Space Telescope (HST).
Image credit: SAINTS team/Peter Challis/NASA
Abstract
Supernovae are some of the most energetic phenomena in the Universe and they have throughout history fascinated people as they appeared as new stars in the sky.

Supernova (SN) 1987A exploded in the nearby satellite galaxy, the Large Magellanic Cloud (LMC), at a distance of only 168,000 light years. The proximity of SN 1987A offers a unique opportunity to study the medium surrounding the supernova in great detail. Powered by the dynamical interaction of the ejecta with the inner circumstellar ring, SN 1987A is dramatically evolving at all wavelengths on time scales less than a year. This makes SN 1987A a great “laboratory” for studies of shock physics.

Repeated observations of the ejecta-ring collision have been carried out using the UVES echelle spectrograph at VLT. This thesis covers seven epochs of high resolution spectra taken between October 1999 and November 2007. Three different emission line components are identified from the spectra. A narrow ($\sim 10$ km s$^{-1}$) velocity component emerges from the unshocked ring. An intermediate ($\sim 250$ km s$^{-1}$) component arises in the shocked ring, and a broad component extending to $\sim 15,000$ km s$^{-1}$ comes from the reverse shock. Thanks to the high spectral resolution of UVES, it has been possible to separate the shocked from the unshocked ring emission.

For the unshocked gas, ionization stages from neutral up to Ne V and Fe VII were found. The line fluxes of the low-ionization lines decline during the period of the observations. However, the fluxes of the [O III] and [Ne III] lines appear to increase and this is found to be consistent with the heating of the pre-shock gas by X-rays from the shock interactions.

The line emission from the ejecta-ring collision increases rapidly as more gas is swept up by the shocks. This emission comes from ions with a range of ionization stages (e.g., Fe II-XIV). The low-ionization lines show an increase in their line widths which is consistent with that these lines originate from radiative shocks. The high-ionization line profiles (Fe X-XIV) initially show larger spectral widths, which indicates that at least a fraction of the emission comes from non-radiative shocks.
To my family and friends
This thesis is based on the following four scientific articles, re-printed in the second part of the thesis. All four articles present studies of the interaction between SN 1987A and its circumstellar medium.


III P. Gröningsson, C. Fransson, B. Leibundgut, P. Lundqvist, P. Challis, R. A. Chevalier, J. Spyromilio, 2008 “Time evolution of the line emission from the inner circumstellar ring of SN 1987A and its hot spots”, Accepted for publication in Astronomy & Astrophysics


The articles are referred to in the text by their Roman numerals.
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1 Introduction
1.1 An historical overview

The explosion of a star is one of the most spectacular events in the universe. A supernova (SN) becomes as bright as its entire host galaxy before it starts to fade and an explosion in our own Galaxy, the Milky Way, may even be visible in daylight. However, over the past thousand years only a few events have been identified in the Milky Way. The last one observed with the naked eye was discovered in year 1604 and was extensively studied by Johannes Kepler among other European astronomers. The SN which appeared in year 1572 was visible in daylight and the most detailed studies of this event in Europe were performed by the Danish astronomer Tycho Brahe. Other famous supernovae (SNe) in the Galaxy are SN 1181, which was extensively observed by Chinese and Japanese astronomers, SN 1054 which produced the Crab Nebula and the extremely bright SN 1006. The latter was visible for several years as reported by Chinese astronomers (Green & Stephenson 2003). Cassiopeia A (Cas A) in the constellation Cassiopeia is, after the Sun, the brightest radio source in the sky although very faint in optical emission. The remnant is at a distance of about 11000 ly and spans \( \sim 10 \) ly across. The expansion rate (\( \sim 4000 \text{ km s}^{-1} \)) together with the spatial extent of the remnant, suggest that the parent SN would have taken place around year 1681. Although, there are no available historical records of the SN event, observations of light echoes have revealed that it was a Type IIb (Krause et al. 2008).

The first systematic studies of the SN events were performed by Baade & Zwicky. They searched for SNe by comparing images of galaxies taken at two different occasions. By comparing the older image with the newer, any bright spot, that was present in the newer but not in the older image, was considered to be a SN candidate. Spectra showed two distinct types of SNe. The first type (Type I) shows no hydrogen emission lines, whereas the second type (Type II) has prominent hydrogen lines. Baade & Zwicky were also the first ones to suggest that SNe were results of the great energy release of collapsing stars (Baade & Zwicky 1934). The idea of the collapsing core of the star is today the accepted model for many, but not for all SN events. Hoyle & Fowler proposed in 1960 an alternative scenario for the explosion of Type I SNe (Hoyle & Fowler 1960). In their model, the explosion was a result of the ignition of degenerated nuclear material. Today, it is well established that the thermonuclear explosion scenario is indeed valid for one subclass of Type I events, i.e. Type Ia.

Figure 1.1 shows the discovery rates of SNe from year 1950 to year 2007. Until 1987, the discoveries were in the range of \( \sim 10 - 30 \) per year. However, after SN 1987A and onwards, there has been a large increase in the discoveries rates. Today, there are as many as about two SNe discovered per day.
Nevertheless, if one only considers the bright events, i.e. brighter than magnitude 15, there is no such increase in the SN rates, and they have been roughly constant at about 10 per year (Cappellaro 2003). This is due to the fact that nearly all bright, nearby SNe are discovered. With today's modern telescopes, a much larger volume of the Universe is sampled. The sharp increase in the total number of SNe, is therefore a result of deeper surveys of space to very high redshifts.

The studies of very distant SNe, especially Type Ia, have had major impacts on cosmology. Such observations have relatively recently shown that the Universe is expanding at an accelerating rate, which has introduced the mysterious dark energy as a concept.

With the modern space-based telescopes, astrophysical objects can now be studied in all energy bands, from radio emission to gamma-rays. This has for example made it possible to associate some SNe with some of the gamma-ray burst events.

![Figure 1.1: Supernova discovery rates. The data were collected from http://www.cfa.harvard.edu/iau/lists/Supernovae.html. Note the sharp increase from year 1988 to 2007.](image)
1.2 Classification

The classification of SNe is generally based on features of their optical spectra and shapes of the light curves. Originally, two different types of SNe were identified, based on the presence of hydrogen in their spectra (Minkowski 1941). The SNe that did not show any hydrogen lines were classified as Type I, while those with the presence of hydrogen were called Type II. Later on, these types have been divided into several subclasses (see Fig. 1.2).

![Classification scheme of supernovae (Turatto 2003).](image_url)

At the end of the 1980s it was realized that there are two to three different subclasses of Type I SNe, which we now know are fundamentally different events from a physical point of view. Many Type I SNe are characterized by a prominent Si II absorption feature at around 6150 Å. These are labeled Type Ia. Those which do not show this feature are members of the subclasses Ib or Ic. SNe Ib show clear presence of He I in their optical spectra in contrast to SNe Ic, where He I lines are almost absent. SNe Ia are observed in all types of galaxies, including those with an old population of stars, e.g. ellipticals. They are associated with the thermonuclear explosions of WDs. At very early times, their spectra are characterized by lines such as oxygen, magnesium, silicon, sulphur and calcium (Filippenko 1997, see Fig. 1.3). However, as the ejected matter starts to reveal itself, the spectra become dominated by iron lines. Type Ib and Ic, on the other hand, appear only in spiral galaxies with a young stellar population. They are believed to be produced by the
core-collapse of massive stars, which have lost their hydrogen envelope and in some cases also their helium envelope (Type Ic).

The Type II SNe are commonly divided into four subclasses. The two major subclasses, type IIP (Plateau) and IIL (Linear), are distinguished by the different shapes of their optical light curves. The light curve of SNe IIP forms a plateau shortly after maximum luminosity, which lasts for 50-90 days (see Fig. 1.4), while a recombination wave moves through the massive hydrogen envelope of $\sim 10M_\odot$ (Filippenko 1997). During this phase the luminosity remains within $\sim 1$ magnitude of maximum brightness. At very early times, the spectrum often shows very weak hydrogen and helium lines superimposed on a blue continuum. At later times, as the light curve declines, the continuum fades and hydrogen lines get stronger. In addition, oxygen and calcium lines appear. The exponential decline, following the plateau phase of the light curve, is powered by the energy release of the radioactive decay $^{56}\text{Co} \rightarrow ^{56}\text{Fe}$. The $^{56}\text{Co}$ is in turn the result of the decay $^{56}\text{Ni} \rightarrow ^{56}\text{Co} + \gamma$. 

![Early-time spectra for different supernova classes and subclasses (Filippenko 1997).](image)

**Figure 1.3:** Early-time spectra for different supernova classes and subclasses (Filippenko 1997).
The spectrum of SNe IIL is similar to SNe IIP. However, their progenitors are believed to have much smaller hydrogen envelopes (\( \lesssim 2 ~ \text{M}_\odot \)), presumably due to mass loss to a binary companion. As a consequence, the Type IIL light curves show no distinct plateau. Instead their luminosity drops linearly (in magnitudes) with time after maximum light. After \( \sim 100 \) days the SNe IIL light curve, also powered by the decay of \(^{56}\text{Co}\) into \(^{56}\text{Fe}\), resembles the exponential decline of SNe IIP.

A relatively recent subclass that has emerged is the Type IIn (narrow) (Schlegel 1990). The spectra of this subclass are characterized by strong Balmer emission lines without P-Cygni profiles, slow evolution and very blue continua at early times. For these events the ejected matter is believed to be strongly interacting with a dense circumstellar medium. Their spectra are dominated by strong emission lines that have relatively narrow profiles, hence the name of the subclass. The narrow line components (FWHM \( \lesssim 200 ~ \text{km s}^{-1} \)) are superimposed on intermediate (FWHM \( \sim 1000 - 2000 ~ \text{km s}^{-1} \)) emission components and occasionally on very broad components (FWHM \( \sim 5000 - 15000 ~ \text{km s}^{-1} \)) (Filippenko 1997). The narrow line components are believed to be produced by circumstellar gas, photoionized by the UV flash emitted at the time of shock breakout (see Sect. 2.2). The intermediate and broad emission components are believed to
arise from the interaction of the ejecta with a possibly clumpy circumstellar medium (Chugai & Danziger 2003).

The subclass Type IIb seems to be a link between SNe II and SNe Ib/Ic. The progenitors of type IIb are massive stars which have lost most of their hydrogen envelopes prior to explosion. Hence, near maximum light, the spectra show rather weak hydrogen lines. Later on, as the ejecta expand, the hydrogen layer becomes optically thin and the hydrogen lines become absent in the spectra. Instead, the spectra are dominated by emission from deeper layers and, similar to SNe Ib, oxygen and calcium are the most prominent emission lines.
2 Core-collapse supernovae
2.1 Explosion mechanisms

Core-collapse supernovae (CCSNe) are the most frequent kinds of SNe in the Universe. The explosion energy is \( \sim 10^{53} \) ergs and is released mainly as neutrinos (\( \sim 99\% \)). The rest of the energy, \( \sim 10^{51} \) ergs, is carried away by the SN ejecta in form of kinetic energy, and only about 1\% of this energy, or \( \sim 10^{49} \) ergs is transformed into light. In 1934, Baade & Zwicky (1934) first suggested that SNe were the results of stellar collapses into compact neutron stars. The collapse starts after a massive star (\( \gtrsim 8 \, M_{\odot} \)) has burnt its fuel through hydrogen all the way to iron in the central region. Figure (2.1) shows the final composition for 15 \( M_{\odot} \) star before the collapse of the iron core.

![Figure 2.1: The final composition of a pre-supernova star (Woosley et al. 2002).](image)

Once the iron core in a massive star has been formed, it will continue to grow until it approximately reaches the so called Chandrasekhar mass, \( M_{\text{ch}} = 1.44(Y_e/0.5)^2 \, M_{\odot} \), where \( Y_e \) is the number of electrons per baryon. At this mass, electron degeneracy pressure can no longer withstand the gravitational forces and, as a consequence, the iron core starts to contract. Due to electron captures in the iron core, \( e^- + p \rightarrow n + \nu_e \), the number of electrons decreases and the pressure reduces accordingly. Furthermore, energetic photons in the core start to photodisintegrate iron into \( \alpha \)-particles and baryons. This process is endothermic and lowers the thermal energy and leads to a lower pressure support. This makes the iron core contract faster, and the increasing core density leads to higher rates of electron captures, which again reduces the degeneracy pressure. Hence, these processes will trigger a gravitational collapse of the core. Once the collapse is underway, the inner part of the core collapses subsonically and homologously (\( v \propto r \)), while the outer part collapses supersonically and can reach speeds of about
25% of the speed of light.

Because of the high temperature and density, most of the energy release is in the form of neutrinos during the core collapse. The neutrinos that are produced, are scattered by both free and bound neutrons and protons. For a core density exceeding $\sim 10^{12} \text{ g cm}^{-3}$, the diffusion time of the neutrinos is much longer than the dynamical time scale of the collapse. Hence, the neutrinos will be trapped and the collapse will proceed almost adiabatically. The collapse of the inner core continues until the density exceeds nuclear density ($\sim 2 \times 10^{14} \text{ g cm}^{-3}$). At this stage, the repulsive nuclear forces start to counteract the collapse and the equation of state becomes very stiff in a short period of time. This causes the infalling matter to bounce back and a shock wave is sent outwards through the infalling material.

As the shock plowes through the infalling material of the iron core, it disintegrates the iron nuclei into protons and neutrons. This endothermic process effectively reduces the shock energy. Once protons become available, they capture electrons which, in turn, produce neutrinos. These neutrinos will further drain the shock from its energy. Simulations indicate that, in most cases, this drain of energy will cause the shock to stall after some time after the bounce ($10 - 20 \text{ ms}$) and at a relatively small radius ($\sim 100 \text{ km}$) (e.g., Janka et al. 2008). Thus, an accretion shock will be set up at constant radius inside the iron core as the infall of matter continues. Hence, in most simulations, it has turned out that this so called prompt explosion scenario is not able to generate an explosion of the star (e.g., Baron et al. 1985; Woosley & Janka 2005). Thus, an additional source of energy is needed to re-accelerate the shock and make a succesful SN explosion.

Since the bulk of the released gravitational binding energy is carried away by neutrinos, a natural extra energy source would be the deposition of energy of the neutrinos in layers behind the accretion shock. Such a mechanism was first proposed by Colgate & White (1966). In this scenario, the neutrinos emerging from the neutrinosphere in the inner core, heat the post-shock gas through the reactions $\nu_e + n \rightarrow p + e^-$ and $\bar{\nu}_e + p \rightarrow n + e^+$. This heating will increase linearly with the density, whereas the cooling rate of the gas (by the inverse of these reactions) will scale with the density squared. Since the density scales with the radius as $\rho \sim r^{-3}$, it follows that beyond some radius there will be a net neutrino heating of the gas. Hence, if the neutrinos could deposit a fraction ($\sim 10\%$, Janka et al. 2008) of their total energy into this region behind the stalled shock, pressure could build up and ultimately lead to an explosion of the star. This scenario is often referred to as the delayed explosion mechanism. However, since both the mass accretion rate and the neutrino flux decrease with time, there will be a time window of a possible explosion, streching from a few tenths of a second to a few seconds.
Even though this delayed explosion mechanism is considered to be a plausible scenario, many details in the mechanism are uncertain. Nevertheless, it is believed that convection of the gas behind the accretion shock should play an important role for making the neutrino heating more efficient. Such convective motions would dredge up hot material from deeper regions and at the same time transport cooler gas close to the shock into deeper layers where it can be re-heated. However, detailed calculations of the neutrino transport indicates that the convection mechanism is not as efficient as was previously believed (Janka et al. 2008) and hence, it may not be strong enough to push the stalled shock further out.

Relatively recently, another type of hydrodynamic instability has been discovered (Blondin et al. 2003). This is the so-called standing accretion shock instability (SASI), which is able to grow efficiently, independent of convective motions. Due to the SASI, the accreted gas can stay longer in the heating layer interior of the shock, and is thus able to more efficiently absorb energy from the neutrino flux. Another consequence of this instability is a global asymmetry of the shock front. Such an asymmetry in the explosion can give the remnant a kick sufficiently large to explain the observed pulsar velocities of several hundred kilometers per second (Janka et al. 2008). In addition, this instability may also explain the spin of the pulsars without the need of introducing rotation of the progenitor star (Blondin & Mezzacappa 2007; Blondin & Shaw 2007).

Once the outgoing shock escapes the iron core, the density decreases and the shock will therefore suffer much less from energy losses. Hence, at this stage, the shock will be able to propagate through the whole star within hours or days. While the shock propagates through the star it will either accelerate or decelerate depending on changes in the quantity $\rho r^{-3}$, which is a measure of the swept-up mass. Hence, if the density declines at a slower rate than $r^{-3}$, the shock will decelerate and leave behind a region of Rayleigh-Taylor instabilities. Such instabilities will introduce mixing of the different burning zones. This kind of mixing is an important ingredient in order to explain the shapes of the observed SN light curves and spectral features (Woosley et al. 2002).
Figure 2.2: Schematic representation of the evolutionary stages from stellar core collapse leading to a supernova explosion (Janka et al. 2007).
2.2 Light curves of Type II SNe

The shapes of the light curves are important diagnostics of the physical nature of the SN events, such as the evolution of the progenitors as well as the explosion mechanisms.

The SN explosion becomes observable once the shock that was triggered by the collapse of the stellar core, reaches the surface. Most of the radiation will be emitted as EUV emission and soft X-rays. The duration of this pulse is dependent on the size of the star, but is normally less than an hour. For the case of SN 1987A, where the progenitor was a compact blue supergiant (BSG), the pulse lasted for only $3-4$ minutes and is roughly equal to the light travelling time over the progenitor $\sim R/c$ (e.g., Ensman & Burrows 1992). Due to the short time scales, direct observations of the shock breakouts are very rare, although recently SN 2008D provided a very nice example (Soderberg et al. 2008). For SN 1987A the effects of the burst could be seen in the line emission from the ring (see Sect. 4.4.1).

After the initial burst, the surface cools rapidly and since the luminosity is related to the effective temperture as $L \propto R_{ph}^2 T_{eff}^4$ where $R_{ph}$ is the radius of the photosphere, which can be considered nearly constant during the first hours, it follows that the luminosity will decline accordingly. After this, the material of the star is cooled by adiabatic expansion, and since the debris is opaque most of the internal energy is converted into kinetic energy. The internal energy is lowered by a factor proportional to the expansion from the radius of the progenitor to the radius when the diffusion time scale is equal to the expansion time scale at a radius of $\sim 10^{15}$ cm. It therefore follows that objects that are initially compact lose a lot of internal energy and will be subluminous. This was the case of SN 1987A.

The plateau emission phase that follows for the Type IIP SNe originates from a recombination wave that is initially formed in the outer parts of the hydrogen envelope. This wave will then propagate inwards (in mass coordinates) through the expanding ejecta. During this phase, the photosphere follows the recombination front and the radius of the photosphere remains roughly constant (in Eulerian coordinates). The temperature of the photosphere is determined by the recombination temperature of hydrogen ($\sim 4000$ K). Since $L \propto R_{ph}^2 T_{eff}^4$, it follows that the luminosity stays roughly constant during this period and hence the observed plateau in the light curve (Falk & Arnett 1977). This phase lasts until the recombination wave has reached the deeper hydrogen-free layers. Hence, the length of the plateau phase depends on the depth of the envelope and the mixing of hydrogen and lasts typically for two to three months. For SNe of Type III, on the other hand, the progenitors only have a small amount of hydrogen in their
When the plateau phase has come to an end, other energy sources start to dominate the powering of the light curve (Fig. 2.3). The major source of energy comes from radioactive decay of $^{56}\text{Ni}$, which is produced in the explosion. By electron capture, $^{56}\text{Ni}$ will decay to $^{56}\text{Co}$ ($^{56}\text{Ni} + e^- \rightarrow ^{56}\text{Co} + \nu_e + \gamma$) with a half-life of 6.1 days. The emitted $\gamma$-photons then transfer their energy to the stellar ejecta. Since the half-life of the decay is relatively short, this decay process will power the early phase (the first few weeks) of the light curve. The isotope of $^{56}\text{Co}$ is also unstable and decays via electron capture to $^{56}\text{Fe} + \gamma$ (81% of the decays) or by $\beta$-decay to $^{56}\text{Fe} + e^+$. The emitted $\gamma$-photons deposit their energy to the ejecta through Compton scattering and will eventually be re-emitted in optical or near-IR emission. This decay has a half-life of 77.3 days, and is therefore primarily responsible for the energy input at later phases (see Fig. 2.3).

A few years after the explosion, the energy input becomes dominated by the decay of $^{57}\text{Co}$ to $^{57}\text{Fe}$ with a half-life of 272 days. The isotope $^{57}\text{Co}$ is, in turn, the result of the decay of the short-lived $^{57}\text{Ni}$ (half-life 1.5 days) produced in the explosion. $^{44}\text{Ti}$, which is another radioactive rest product of the explosion, decays to $^{44}\text{Sc}$ and then quickly to $^{44}\text{Ca}$. This decay chain has a half-life of 60 years, and for SN 1987A it became the dominant energy source after about 5 years (see Fig. 2.3). The $\gamma$-rays dominate the energy budget for the decay of $^{44}\text{Sc}$, but part (25%) of the energy release is in the form of positrons. However, at this stage, the ejecta are so transparent that most of the $\gamma$-rays escape and the energy input is therefore dominated by the positrons. Due to the effective trapping of positrons, the bolometric light curve will stay almost flat at this late time.

Some SNe remain bright much longer than normal, and to account for the slower decline of their light curves, some extra energy source must be available. These events often display narrow hydrogen lines in their spectra and are accordingly labelled Type IIn (see Sect. 1.2). It is commonly believed that the appearance of these narrow lines is due to the interaction of the ejected envelope with a dense circumstellar wind emitted by the progenitor. The strength of these lines indicate that the mass loss rate could be very high. Hence, the additional source of energy is thought to arise from the interaction of the shock with the dense CSM. In this process a large fraction of the kinetic energy of the ejecta is transformed into light, which then explains the extended bright light curves of these events.
Figure 2.3: V-band light curve of SN 1987A (Leibundgut & Suntzeff 2003).
2.3 Mass loss processes

Mass loss plays an important role in the evolution of massive stars. Not only does it reduce the mass of the star, but also affects its convective core size, temperature, angular momentum and its luminosity. Hence, the amount of mass loss affects the stars evolutionary track and its time on the main-sequence (MS) phase (Smith & Owocki 2006). As we have seen in Sect. 2.2, the mass of the hydrogen envelope is crucial for the light curve of the SN. An understanding of the mass loss processes is therefore central for the SN taxonomy.

Blue supergiants (BSG) in the MS phase (stars of spectral types O and B) are very hot and bright stars. They have radiatively accelerated winds, driven by resonance line scattering of the UV radiation, that are relatively well understood. They typically experience mass loss rates of $\sim 10^{-7} - 10^{-6} \, M_\odot \, yr^{-1}$. This is about a hundred million times the mass loss rate of the Sun. In addition, since the wind velocity is roughly the same as the star’s escape velocity, the winds from these relatively compact objects are very fast with velocities in the range of $\sim 1000 - 3000 \, km \, s^{-1}$.

The driving mechanisms behind the winds during the post-MS phases are less well understood. Red supergiants (RSG) are very extended ($\sim 200 - 800$ times the radius of the Sun) cool stars with surface temperatures of $\sim 3000 - 4000 \, K$. Most likely, absorption of the radiation by dust is important for the driving of the wind. The formation of the dust probably takes place in a similar way as in lower mass AGB stars. Because of their large extension, and hence low escape velocity, the winds are slow with velocities of only $10 - 50 \, km \, s^{-1}$. The mass loss rates in this phase are typically $\sim 10^{-6} \, M_\odot \, yr^{-1}$, but there are strong indications, from radio observations, of short lived superwind phases with $\dot{M} \sim 10^{-4} - 10^{-3} \, M_\odot \, yr^{-1}$ for some stars.

Because of strong mass loss in the RSG phase, the star may lose most or all of its hydrogen envelope, or even the helium envelope. The result will then be a hot, compact star with a radius of $\sim 10 \, R_\odot$, known as a Wolf-Rayet star. For single stars of solar metallicity this probably only happens for stars more massive than $22 - 30 \, M_\odot$ depending on the rotation (see Sect. 2.4). These stars have surface temperatures in the range of $\sim 25000 - 50000 \, K$, and have very strong stellar winds with mass loss rates of $\sim 10^{-5} \, M_\odot \, yr^{-1}$ and wind speeds of $\sim 2000 - 3000 \, km \, s^{-1}$. The driving force behind these strong winds is believed to be radiation pressure on resonance lines.

If a star is located in a binary system, mass loss can be greatly enhanced. Thus, if one of the stars at some point exceeds its Roche lobe, matter will be transferred to the companion star through what is called Roche lobe overflow.
This overflow of matter could either lead to a complete loss of the hydrogen envelope, resulting in a Wolf-Rayet star, or in a common envelope, which would ultimately lead to a merging of the two stars (Woosley et al. 2002).

One of the most well-studied examples of a binary system, leading to an explosion, is the SN 1993J, which was discovered on March 28, 1993 in the host galaxy M81. The light curve of SN 1993J did not show the plateau phase, which is common for many normal Type II SNe (i.e. Type IIP’s). The absence of the plateau suggested that the progenitor star had a hydrogen envelope mass of only $0.2 \, M_\odot$ (hence the classification Type IIb). However, the initial mass of the star was only $\sim 15 \, M_\odot$, which is considered too small for the star to lose much of the hydrogen envelope through stellar winds. Instead, the small envelope mass can be attributed if mass was transferred to a binary companion (Nomoto et al. 1993; Podsiadlowski et al. 1993; Woosley et al. 1994). This scenario implied that mass was transferred until only a fraction of the hydrogen envelope remained, i.e. that mass necessary to fill the Roche lobe.
2.4 Effects of mass loss on progenitors and SNe

The fate of a massive star is mainly determined by its initial mass and metallicity (i.e. the initial abundance of heavy elements), which in turn influence its mass loss history. Stellar winds are responsible for the mass loss of single stars and are expected to be related to the mass in such a way that, on the main-sequence (MS), the winds of massive stars are stronger than of stars with lower mass. Wind driven mass loss is also found to be dependent on the metallicity. The exact scaling of mass loss with the metallicity is likely to depend on the evolutionary stage of the star, but is normally assumed to follow \( M \propto Z^{0.5-0.7} \) (Heger et al. 2003). Thus, stars with low metallicity suffer to a lower extent from mass loss and have therefore larger helium cores and hydrogen envelopes at the end of their lives. The opposite is true for high-metallicity stars, where the radiation pressure on the envelope is higher.

For binary systems, however, mass loss can also occur due to mass transfer to the companion star. This process can greatly enhance the mass loss rate.

While the mass of the star’s helium core governs the explosion, for SNe of Type II, the hydrogen envelope determines much of the SN spectral features and the shape of the light curves. Stars that end their lives with a massive hydrogen envelope (\( \gtrsim 2 \, \text{M}_\odot \)), will result in a Type IIP. SNe of Type IIP are believed to arise in RSG progenitors of moderate mass (Smartt et al. 2003). According to the stellar evolution models presented by Heger et al. (2003), massive single stars with initial masses of up to \( \sim 25 \, \text{M}_\odot \), are expected to produce Type IIP events. If, however, the metallicity is low enough, Type IIP SNe are also possible in the mass range of \( 25 - 40 \, \text{M}_\odot \). Such events are expected to be faint because of the fallback of \( ^{56}\text{Ni} \) (see Fig. 2.4).

Stars with a less massive hydrogen envelope (\( \lesssim 2 \, \text{M}_\odot \)) will end their lives either as a Type IIL or as a Type IIb SN (see Sect. 1.2). Since the mass loss needs to be strong enough to remove a substantial part of the hydrogen envelope in order to produce Type III/Lb, a single star with at least a moderate metallicity as well as a high initial mass (\( \sim 25 - 40 \, \text{M}_\odot \)) is needed (see Fig. 2.4). As the initial mass must be high, black holes formed by fallback are expected and these SNe would thus be fainter than normal.

The majority (\( \sim 90\% \)) of the massive single stars are, according to the stellar models by Heger et al. (2003), forming SNe of Type II and out of these, the majority will produce normal Type IIP. Only a minority (\( \sim 10\% \)) of the Type II events will, depending on the metallicity, either produce scaled down Type IIP or Type III/Lb SNe.

For Type Ib/c SNe the entire hydrogen envelope is removed prior to explosion, making the observational features sensitive to the helium core mass of the progenitor. Clearly, a single star resulting in a Type Ib/c must meet the conditions of having both a high metallicity and a high initial mass.
Figure 2.4: Supernova population diagram showing the evolution of massive stars as a function of initial mass and metallicity (Heger et al. 2003).

For a non-rotating star with solar metallicity, the mass has been estimated to \( \gtrsim 34 \, M_\odot \) (Woosley et al. 2002). As is the case for Type IIL/b, many of the Type Ib/c SNe would leave behind a black hole by later fallback and are therefore expected to be subluminous.

To reduce the helium core enough for luminous Type IIL/b to be formed from a non-rotating single star, the metallicity would have to exceed solar. Bright Type Ib/c could, however, also be formed for a metallicity slightly less than solar if the progenitor’s initial mass exceeds \( \sim 60 \, M_\odot \) (see Fig. 2.4). One would therefore expect that these types of SNe are in most cases likely to be produced in binary systems where mass transfer through Roche lobe overflow occurs. In fact, this is a well-known channel to form Wolf-Rayet stars which, in turn, are the progenitors of Type Ib/c events. In addition, rotation is also likely to play an important role in the evolution of stars. This has not been accounted for in Fig. 2.4. Rotation has the effect of enhancing the mass loss which would lower the metallicity needed in order to produce Type IIL/b and Type Ib/c. For stars with rotation and solar metallicity, a lower mass limit of \( \sim 22 \, M_\odot \) has been estimated in order to produce Type Ib/c SNe (Meynet & Maeder 2005). Hence, when rotation is taken into account for single stars, one would expect more of these types of SNe to be strong explosions as
fewer of these events would produce black holes from fallback.

For very massive low-metallicity stars ($\sim 100 - 140 \, M_\odot$), pair instabilities occur in violent pulsations that will continue until enough mass has been lost and an iron core can be formed. Since the iron core is very massive, the likely outcome will be a black hole. The kinetic energy of the pulses is of the order of or even more than a normal supernova but they will be less bright since they lack any radioactive material to power the light curve. Nevertheless, the collision of the expelled shells could still be bright. If the mass is between $\sim 140 - 260 \, M_\odot$ the pair instabilities are so violent that only one pulse is enough to disrupt the star completely and hence, in this case, no remnant will be formed. Stars above $\sim 260 \, M_\odot$ are expected to directly form a black hole (see Fig. 2.4).

To test stellar evolutionary models of pre-supernova evolution, it is of special importance to detect stars before explosion. To date, this has only been possible for a small number of objects. This has, for instance, been done for the two most well studied SNe so far, SN 1987A (a peculiar Type IIP) and SN 1993J (Type IIb). Of the three normal Type IIP events for which the progenitor stars have been identified (SNe 2001du, 1999em and 1999gi), all have progenitor masses of $\lesssim 12 - 15 \, M_\odot$ and metallicities in the range of 1–2 times solar (Smartt et al. 2003). This fits well into the theoretical picture for single stars as presented in Fig. (2.4). However, for both SN 1980K (Type IIL) and the bright Type Ic event SN 2002ap, it appears that their progenitor metallicities (about half the solar) are too low to be consistent with the theoretical picture of single stars. Considering such low metallicities, SN 1980K would theoretically appear as a Type IIP and SN 2002ap would only be a weak Type Ic event, inconsistent with the observations. If, however, the progenitor was a binary system, high enough mass loss would still be possible to account also for these two objects (Smartt et al. 2003).
3 Shock physics
3.1 Shock waves

Because the properties of shocks are crucial for the interpretation of the observations of the ring collision in SN 1987A, we here review some of the basic properties of shocks.

A shock wave is a supersonically propagating, thin transition region, in which there is a sudden change in the density, pressure and velocity of the medium. Shocks can arise from various phenomena, e.g. from explosions and from supersonic motions of bodies. The changes of density, $\rho$, velocity, $v$ and pressure, $P$, across a shock front are described by a set of conservation relations. These are the so called Rankine-Hugoniot conditions (Landau & Lifshitz 1959), which conserve mass, momentum and energy, respectively,

\[ \rho_1 v_1 = \rho_2 v_2 \quad (3.1) \]
\[ P_1 + \rho_1 v_1^2 = P_2 + \rho_2 v_2^2 \quad (3.2) \]
\[ \frac{1}{2} v_1^2 + \frac{\gamma}{\gamma - 1} P_1 = \frac{1}{2} v_2^2 + \frac{\gamma}{\gamma - 1} P_2 \quad (3.3) \]

where $\gamma = 5/3$ for an ideal monatomic gas and $7/5$ for a diatomic gas. For the gas ahead of the shock (the upstream gas), the quantities are labeled with 1 and the quantities for the gas behind the shock front (downstream gas) are labeled with 2. From Eqs. (3.1)-(3.3) it then follows that

\[ \frac{\rho_2}{\rho_1} = \frac{v_1}{v_2} = \frac{(\gamma + 1) M_1^2}{(\gamma + 1) + (\gamma - 1)(M_1^2 - 1)} \quad (3.4) \]
\[ \frac{P_2}{P_1} = \frac{(\gamma + 1) + 2\gamma(M_1^2 - 1)}{(\gamma + 1)} \quad (3.5) \]

where $M_1 \equiv u_1/c_1$ denotes the Mach number and where $c_1 = \sqrt{\gamma P_1/\rho_1}$ is the speed of sound in the unshocked gas. For a strong shock ($M_1 \gg 1$), Eqs. (3.4) and (3.5) approach the limits

\[ \frac{\rho_2}{\rho_1} = \frac{v_1}{v_2} = \frac{\gamma + 1}{\gamma - 1} \quad (3.6) \]
\[ \frac{P_2}{P_1} = \frac{2\gamma M_1^2}{(\gamma + 1)} \quad (3.7) \]

which for a monatomic gas becomes, $\rho_2/\rho_1 = v_1/v_2 = 4$. Since $P_2 \gg P_1$ (Eq. 3.7), the downstream gas pressure, $P_2$, from Eq. (3.2) now becomes

\[ P_2 = \rho_1 v_1^2 - \rho_2 v_2^2 \quad (3.8) \]

Using this together with Eq. (3.6)
\[ P_2 = \frac{2}{(\gamma + 1)} \rho_1 v_1^2. \]  

(3.9)

The equation of state for a perfect gas reads, \( P = \rho kT/\mu \). Thus, the temperature of the shocked gas becomes

\[ T_2 = \frac{2(\gamma - 1) \mu}{(\gamma + 1)^2 k} v_1^2. \]  

(3.10)

In the rest frame of the shock, \( v_1 = -V_s \) (where \( V_s \) is the shock speed) and hence, \( v_2 = (1 - \gamma)/(\gamma + 1)V_s \). In the observers reference frame (where the unshocked gas is at rest), the gas behind the shock is moving with the speed

\[ v_{2obs} = v_2 - v_1 = \frac{2}{(\gamma + 1)} V_s \]  

(3.11)

which yields \( 3V_s/4 \) for a monatomic gas.

These relations are valid as long as no energy losses occur, i.e. the shock is adiabatic. However, since the shocked gas is heated according to Eq. (3.10), it will gradually cool until it returns to the temperature close to the original temperature, \( T_1 \). If the cooling time of the shocked gas is short compared to the dynamic time of the flow (see below), the transition region can be considered to be thin such that the physical parameters of the gas change discontinuously whereas the temperature is held fixed. Hence, for such an isothermal shock, the energy conservation equation (Eq. 3.3) is replaced by

\[ T_1 = T_3 \]  

(3.12)

where the region of complete cooling is labelled index 3. In the strong shock scenario, Eq. (3.8) is valid and can be written in the form

\[ v_2^2 - v_1 v_3 + c_T^2 = 0 \]  

(3.13)

where the isothermal sound speed, \( c_T \), has been introduced (\( c_T^2 = P_1/\rho_1 = P_3/\rho_3 \)). Equation (3.13) has the non-trivial solution

\[ v_1 v_3 = c_T^2 \]  

(3.14)

which can be re-written in terms of the upstream Mach number, \( M_1 \equiv v_1/c_T \)

\[ \frac{v_1}{v_3} = \frac{\rho_3}{\rho_1} = M_1^2. \]  

(3.15)

Hence, for a strong isothermal shock (\( M_1 \gg 1 \)) it follows that \( \rho_3 \gg \rho_1 \). The speed of the of the downstream gas in the observer’s rest frame becomes

\[ v_{3obs} = v_3 - v_1 = (1 - 1/M_1)V_s \approx V_s. \]  

(3.16)
Using Eq. (3.14), the downstream gas pressure, \( P_3 \), becomes

\[
P_3 = \rho_3 c_T^2 = \rho_1 v_1^2 \tag{3.17}
\]

The cooling time, \( t_c \), is defined as the time taken for the shocked gas to radiate away the thermal energy, that was gained by the passage of the shock front. If time dependent effects for the density and temperature are ignored, the cooling time can be estimated by

\[
t_c = \frac{3kT}{n\Lambda(T)} \tag{3.18}
\]

where \( \Lambda(T) \) is the cooling function. How this function scales with the temperature depends on the relevant cooling processes in the post-shock gas as well as the composition of the gas.

For temperatures in excess of \( \sim 2 \times 10^7 \) K, the gas is more or less completely ionized and no line cooling can occur. Consequently, for these temperatures, the cooling is inefficient and the only process of significance is the continuum emission arising from bremsstrahlung. This radiation is observed as X-ray emission. In this temperature region, the cooling function scales as \( \Lambda(T) \propto T^{1/2} \), which from Eq. (3.18) implies that \( t_c \propto T^{1/2} \propto V_s \).

In the temperature interval of \( \sim 1 \times 10^5 \) to \( 2 \times 10^7 \) K, the resonance emission lines in the EUV and soft X-ray spectral region are important for the cooling of the gas. Although most emission emerges in these spectral regions, a number of coronal lines, like [Fe X] \( \lambda 6375 \), [Fe XI] \( \lambda 7892 \) and [Fe XIV] \( \lambda 5303 \), are also found here. These lines are prominent in our UVES spectra, and are the most interesting discovery in paper I. The cooling function can in this temperature interval be approximated by the power law \( \Lambda(T) \propto T^{-\alpha} (\alpha > 0) \). Hence, the cooling time scales with the shock velocity as \( t_c \propto V_s^{2(\alpha+1)} \). For solar abundancies, \( \alpha \approx 0.90 \) (Nymark et al. 2006, see Fig. 3.1) which then yields \( t_c \propto V_s^{3.8} \) (see paper I). It therefore follows that for strong shocks, the cooling time is very sensitive to the shock velocity. Furthermore, since \( \Lambda(T) \) increases with decreasing temperature in this temperature range, the gas will be thermally unstable. As a consequence, a thin, cool, dense shell will develop behind the shock where most of the line emission will be produced. This is the origin of most of the optical emission lines observed from the ring collision, and is discussed especially in papers II–III.
3.1 Shock waves

Figure 3.1: Cooling functions for different compositions with corresponding analytical fits. (Nymark et al. 2006).
3.2 Circumstellar interaction

For a CCSN the explosion is induced in the stellar core. In such a scenario the outer parts of the ejecta would have a density profile which follows a steep power law, $\rho_{ej} \propto r^{-n}$ (Matzner & McKee 1999). Hence, in the standard model of circumstellar interaction (Chevalier 1982) it is assumed that a few days after the explosion, the density of the outer ejecta part will be described by

$$\rho_{ej} = \rho_0 (t/t_0)^{-3}(V_0 t/r)^n$$  \hspace{1cm} (3.19)

where $\rho_0$ is the density at time $t_0$ with expansion velocity $V_0$. The power law index, $n$, depends on the structure of the progenitor but for compact objects it is expected to be in the range of $7 - 12$.

The ejecta expand through the circumstellar medium (CSM), which was ejected at an earlier phase by the stellar wind or a more short-lived event by the progenitor. If this wind stays relatively constant in terms of mass loss rate, $\dot{M}$, and velocity, $u_w$, the density is given by

$$\rho_w = \frac{\dot{M}}{4\pi u_w r_0^2} \left(\frac{r_0}{r}\right)^s$$  \hspace{1cm} (3.20)

(Fransson et al. 1996). The dependence of $\rho_w$ on $u_w$ means that the density will be very different for a fast wind from a WR progenitor ($u_w \approx 2000 - 3000$ km s$^{-1}$) compared to a slow wind from a RSG ($u_w \approx 10$ km s$^{-1}$). The expansion velocity of the ejecta is $\gtrsim 10^4$ km s$^{-1}$ which is much higher than $u_w$. Hence, the interaction between the ejecta and the CSM will result in a strong forward moving shock propagating into the CSM and a reverse shock that will be driven back (in a Lagrangian coordinate system) into the ejecta.

Since the density of the ejecta is usually much higher than the wind density, it follows that the reverse shock that propagates into the ejecta will be much slower than the forward moving shock (see, however, later for SN 1987A where the opposite is the case). As a result, the temperature behind the reverse shock is much lower than the temperature behind the forward shock. The high density in combination with a low temperature makes the region behind the reverse shock suffer from radiative cooling and a cool dense shell will be set up between the reverse shock and the contact discontinuity, which separates the shocked ejecta from the shocked CSM (see Fig. 4.3 for a schematic description of the shock structure). In addition, the large differences between the ejecta density and the wind density give rise to Rayleigh-Taylor instabilities as the ejecta are plowing through the CSM.

If the assumption is made that the shocked region can be treated as a thin shell, a simple solution for the interaction can be found. As the shell moves
out into the CSM with a velocity, $V_s$, it will experience the ram pressure, $\rho_w V_s^2$, acting against its propagation. At the same time, however, the shell is gaining momentum as the ejecta are impacting on it. The ram pressure exerted by the ejecta on the shell is given by $\rho_e (V_{ej} - V_s)^2$. Thus, balancing of these pressures gives the momentum equation for the shell

$$M_s \frac{dV_s}{dt} = 4\pi R_s^2 \left[ \rho_e (V_{ej} - V_s)^2 - \rho_w V_s^2 \right]$$  \hspace{1cm} (3.21)

where $M_s$ is the sum of the swept-up gas of both the ejecta and the CSM. The swept-up gas behind the forward shock is given by

$$M_{cs} = 4\pi \int_{R_0}^{R_s} \rho_w r^2 dr = \frac{M}{(3-s)u_w} \frac{R_s^{3-s} - R_0^{3-s}}{r_0^{3-s}}$$  \hspace{1cm} (3.22)

where $R_0$ is the radius where the shock initiates which is approximately twice the progenitor radius (Fransson 1982). However, after a few expansion times, $R_s \gg R_0$ and $M_{cs}$ becomes

$$M_{cs} = \frac{\dot{M} R_s}{(3-s)u_w} \left( \frac{R_s}{r_0} \right)^{2-s}.$$  \hspace{1cm} (3.23)

In a similar way, using Eq. 3.19 for the density of the ejecta, the swept-up gas behind the reverse shock can be estimated to

$$M_{rev} = \frac{4\pi t_0^2 V_{ej}^n}{n-3} \left( \frac{t}{R_e} \right)^{n-3}.$$  \hspace{1cm} (3.24)

Under these assumptions, the solution to Eq. 3.21 reads

$$R_s(t) = \kappa t^{(n-3)/(n-s)}$$  \hspace{1cm} (3.25)

where

$$\kappa = \left( \frac{4\pi (4-s)(3-s)\rho_0 V_0^n u_w r_0^{2-s}}{(n-4)(n-3)\dot{M}} \right)^{1/(n-s)}.$$  \hspace{1cm} (3.26)

The ejecta are in free expansion and hence, it follows that the maximum ejecta velocity is given by

$$V_{ej} = \frac{R_s(t)}{t} = \kappa t^{-(3-s)/(n-s)}$$  \hspace{1cm} (3.27)

and for the forward shock velocity, $V_s$, it follows

$$V_s = \frac{dR_s}{dt} = \frac{n-3}{n-s} \kappa t^{-(3-s)/(n-s)} = \frac{n-3}{n-s} V_{ej}.$$  \hspace{1cm} (3.28)

The reverse shock velocity, $V_{rev}$, is related to $V_{ej}$ as

$$V_{rev} = V_{ej} - V_s = \frac{3-s}{n-s} V_{ej}.$$  \hspace{1cm} (3.29)
The temperature behind the forward shock is

\[ T_{cs} = \frac{3\mu}{16k} V_s^2, \]  

(3.30)

where \( \mu \) is the mean particle weight (Eq. 3.10). This can now be expressed in terms of \( V_{ej} \)

\[ T_{cs} = \frac{3\mu}{16k} \left( \frac{n-3}{n-s} \right)^2 V_{ej}^2. \]  

(3.31)

Similarly, it follows that the temperature behind the reverse shock can be written as

\[ T_{rev} = \frac{3\mu}{16k} V_{rev}^2 = \frac{3\mu}{16k} \left( \frac{3-s}{n-s} \right)^2 V_{ej}^2 = \left( \frac{3-s}{n-3} \right)^2 T_{cs}. \]  

(3.32)

The density behind the reverse shock, \( \rho_{rev} \), relates to the density behind the forward shock, \( \rho_{cs} \), according to

\[ \frac{\rho_{rev}}{\rho_{cs}} = \frac{(n-4)(n-3)}{(4-s)(3-s)} \]  

(3.33)

while the density behind the forward shock relates to the wind density as, \( \rho_{cs}/\rho_{w} = 4 \) (Sect. 3.1). Furthermore, the swept-up mass behind the reverse shock relates to that behind the forward shock as

\[ \frac{M_{rev}}{M_{cs}} = \frac{n-4}{4-s}. \]  

(3.34)

These relations apply to the expansion into a stellar wind, with \( \rho \propto r^{-s} \) for \( s < 3 \). For a free stellar wind \( s = 2 \). This, however, does not apply in all cases and in particular, for SN 1987A, a better approximation is a constant density CSM, i.e. \( s = 0 \), when the forward shock expands into the H II region interior to the rings.
SN 1987A
4.1 Introduction

SN 1987A was discovered on 24 February 1987 by Ian Shelton during his observations of the Large Magellanic Cloud (LMC) at the Las Campanas Observatory in Chile. From the detection of the neutrino burst by Kamiokande II (Hirata et al. 1987) and IMB (Bionta et al. 1987), the exact explosion time was later determined to be February 23.316 UT. This was the first SN that was visible to the human eye since Kepler’s SN in 1604, and the first ever to be detected by a neutrino detector. For an account of some of the early observations see Arnett et al. (1989) and Danziger & Bouchet (2007).

The SN location coincided with the location of the Sanduleak $-69^{\circ}202$ star system, and by the time the SN had become faint enough in the UV, it was found that the most luminous star of the system had indeed disappeared. This was the first case for which the progenitor could be identified prior to the explosion. The progenitor was classified as a B3 Ia BSG star with an estimated MS mass of $\sim 20 \, M_\odot$. This came as a great surprise as the conventional wisdom at the time was that stars, which end their lives as SNe, would be in a RSG phase. In fact, the progenitor radius was only $3 \times 10^{12}$ cm (about 40 times the radius of the Sun), which is more than 10 times less than what would have been the case if the progenitor would have been a RSG. Moreover, the SN light curve also revealed that the explosion did not take place in a RSG. Since the object was so compact, the SN lost most of the thermal energy in the adiabatic expansion of the supernova. As a consequence, SN 1987A turned out to be significantly dimmer than most Type II SNe. The classification of SN 1987A as a Type IIP is due to the fact that it showed hydrogen in the early spectra (Fig. 1.3) together with a plateau phase in the light curve during the first four months (Fig. 1.4). In Fig. 1.4, it is illustrated that the light curve of SN 1987A differs substantially from the light curve of a normal Type IIP in both flux level and shape. SN 1987A is thus often denoted as a peculiar Type IIP or simply IIp (“p” for peculiar).

The distance to SN 1987A has been estimated to $51.4 \, \text{kpc}$ (Panagia 1999) or $168,000$ light years, which is extraordinarily nearby compared to most other SNe that are discovered at distances of millions of light years. Hence, the proximity of SN 1987A gives a unique opportunity to study the explosion mechanism, the ejecta and the surrounding medium in great detail.

The detection of the 19 neutrinos (11 detections by Kamiokande II and 8 detections by IMB) from this explosion was consistent with the expected neutrino flux from the outer parts of a proto-neutron star. Also, the fact that these neutrinos were detected over a time span as long as about ten seconds indicated that the remnant should be a neutron star and not a black hole. A black hole would trap all neutrinos on a shorter time scale. To date, however, no evidence of a neutron star remnant has been found. This could either be
due to low transparency of the ejecta or to the possibility that a black hole was formed through later fall-back of matter.
4.2 The progenitor

Studies of the SN 1987A event confirmed many of the predictions regarding core-collapse SNe. From the bolometric luminosity it was, for example, clear that the progenitor was a massive star of about $20 \, M_\odot$ (e.g., Arnett et al. 1989). It was also found that the outer layers of the star were highly enriched in helium and CNO processed material (Fransson et al. 1989). This suggested that material from the core of the star was mixed into the envelope.

However, it came as a major surprise to find that the progenitor star was a BSG, and not a RSG as stellar evolution theories predicted for massive stars at that time. Yet, the presence of narrow emission lines in the vicinity of SN 1987A strongly indicated that the progenitor star had been in a RSG phase during its evolution. Thus, the star must have evolved from the RSG phase to a BSG phase shortly before the explosion.

During the years, many models have been developed in order to explain the progenitor and its many surprising properties. Some of the models are based upon a single star scenario, while other models involve binary star systems.

4.2.1 Single star models

One class of models considers non-rotating single stars. Some of these models, explain the blue progenitor as a result of the low metallicity of the LMC (e.g., Truran & Weiss 1987; Hillebrandt et al. 1987). In this scenario, the progenitor never enters a RSG phase. However, such a model is inconsistent with the color distribution of massive stars in the LMC. In particular, the model would predict a lower number of RSGs than is actually observed in the LMC. In addition, the model fails to explain the progenitor’s RSG phase of SN 1987A.

Other models have pointed to mass loss as the primary reason for the progenitor’s blue color (e.g., Maeder 1987). In such models, the progenitor first evolves to a RSG before it becomes a BSG and after most of the hydrogen envelope has been lost. Hence, these mass loss models can explain the progenitor evolution from a RSG phase to the BSG phase, and also possibly give an explanation for the overabundance of core processed material. However, despite this apparent success, the low mass of the remaining hydrogen envelope cannot account for the shape of the light curve of SN 1987A. In addition, for slight changes in the mass loss rate, the star would instead either end its life as a RSG or a WR star. The WR star solution is in any case very controversial considering the low initial progenitor mass. Hence, extreme fine-tuning of the mass loss rate would be needed for such models to work.

Another proposed way of arriving at a BSG solution at the time of explosion would be to invoke some kind of mixing of helium into the hydrogen-rich envelope (Saio et al. 1988). This would result in a lower opacity in the envelope, which in turn would cause the envelope to contract. Hence, such a mixing would result in a BSG instead of a RSG and perhaps also explain the
4.2 The progenitor

dredge-up of core-processed material and in particular the CNO enrichment. The mixing in these models is, however, only invoked in an ad hoc way. Thus, as long as the mixing mechanism remains unexplained, the whole scenario must be considered to be uncertain.

Other models have considered the effects of suppressed semiconvection (Woosley et al. 1988, 1997). These models have shown that for low metallicity and helium abundancies it is possible for the star in the RSG phase to enter a BSG phase in a short time prior to the explosion. While the models give a satisfactory explanation of the explosion mechanism, as well as the distribution of RSGs in the LMC, they may possibly fail to account for the overabundance of processed material (Podsiadlowski 1992).

While the non-rotating single star models have problems in explaining all of the observed features of the progenitor, the identification of the non-spherical triple-ring nebula is clearly the strongest argument against these scenarios. Since the nebula structure implies that spherical symmetry is broken, rotation is likely to have played a crucial role.

Rotating single-star models have been proposed (e.g., Langer 1991; Eriguchi et al. 1992; Woosley et al. 1997). In these models it is found that a rapidly rotating star may end its life as a BSG. However, whether this happens or not depends on the amount of helium in the envelope and the metallicity. Such models are able to explain not only the apparent BSG, but also the overabundance of nuclear-processed material, and perhaps even account for the formation of the non-spherical ring system (Meyer 1997).

4.2.2 Binary solutions

Approximately half of all stars occur in binary systems. In most cases, however, these stars are at such distance from each other that their evolution is not affected by the companion. Still, in a many of the cases, the companion is in fact close enough to influence the evolution of the progenitor star before it explodes.

An early idea, that was proposed, was that the exploding star was not the BSG Sk $-69^\circ$ 202. Instead, according to this idea, the actual star that exploded should be a previously undetected companion (Fabian et al. 1987; Joss et al. 1988). In this scenario, Sk $-69^\circ$ 202 was originally the less massive star of the binary system, but accreted a substantial amount of matter from the more evolved companion star. The companion could then either become a WR star (if the hydrogen envelope was completely stripped off) or become a RSG where some of its hydrogen envelope remained. The classification of the SN as a Type II would then be due to the hydrogen-rich material that was stripped from Sk $-69^\circ$ 202. A reappearance of Sk $-69^\circ$ 202 would, of course, be the natural result of this idea. However, since this never happened, the scenario can be ruled out.
Since it is clear that it was indeed Sk $-69^\circ$ 202 that actually exploded, for the binary solutions, it is the accretion of matter from a companion star, after the hydrogen-core burning phase, that makes the progenitor end its life as a BSG and not as a RSG. However, also within this scenario there is room for several possibilities.

The first possibility is that the progenitor simply accretes matter from the companion until it explodes. In this case, the companion to the BSG progenitor is likely to be a compact star at the time of explosion. (Podsiadlowski 1992). The accretion of mass may be a mechanism for the dredge-up of core processed material, as seen in the CNO and He abundancies. Furthermore, since angular momentum is transferred in the mass accretion, it follows that the progenitor will rotate rapidly in the final stage of its life. This could then provide the necessary rotational asymmetry to explain the origin of the ring system.

The other possiblity is that the companion star merges with the progenitor before the explosion takes place (Morris & Podsiadlowski 2007; Podsiadlowski et al. 2007). This binary merger scenario provides a natural way of converting the systems orbital angular momentum into a spin angular momentum of the resulting single progenitor. In fact, such a merger model is, according to most of the recent papers on this subject, one of the most promising models to explain all of the observational features of the progenitor of SN 1987A, including the triple-ring system. As a specific example, the two stars in the binary system have initial masses of $\sim 15 - 20$ $M_\odot$ and 5 $M_\odot$, respectively. Because of the large mass ratio, the transfer of mass will be unstable and lead to a common envelope phase, where the less massive star will be engulfed by the envelope of the more massive star. The transfer of orbital angular momentum of the binary system will cause the rotation of the common envelope to increase. During this process, part of the envelope will be ejected. Hence, the result of this merger will be a very extended RSG that will later on shrink to become a BSG. The fast BSG wind will then sweep up the gas structure that was previously ejected by the merger, giving its final shape before the explosion.

Despite the success of the binary merger model, there are still some remaining questions that need to be addressed (Smith & McCray 2007). For example, the final BSG is expected to rotate very fast. However, spectra of Sk $-69^\circ$ 202 showed no indication of such rapid rotation. Furthermore, the mechanism behind the larger bipolar nebula structure around SN 1987A (identified from analysis of light echoes) is still unclear. Finally, the path leading up to this kind of binary systems has a small probability of only $\sim 5\%$ (Podsiadlowski et al. 1992), which is a clear problem for this scenario. In summary, it is fair to say that the exact nature of the progenitor is still unclear. The fact that more and more of the CSM outside the ring may be ionized by the ejecta-ring col-
4.2 The progenitor

...ision, as discussed in paper III, may here give additional information about the nature of the progenitor.
4.3 Nebular structure

A few months after the SN explosion came the first evidence of the presence of circumstellar gas around SN 1987A. Narrow optical lines (Wampler et al. 1988) and UV emission lines were detected with the International Ultraviolet Explorer (IUE) (Fransson et al. 1989). The presence of high ionization lines indicated that the gas had been photoionized by the EUV/X-ray flash that resulted from the shock breakout of the SN. The distance between this gas and the SN could (from the rise time of these lines) be estimated to be of the order of \( \sim 1 \) pc. In addition, the decay time of the lines implied a density range of \( \sim 3 \times 10^3 - 3 \times 10^4 \) cm\(^{-3}\) for the glowing gas (Lundqvist & Fransson 1996). Furthermore, the high nitrogen abundance of the relatively dense surrounding gas was a strong signal that the circumstellar gas had been processed through the CNO nuclear burning. This, together with the low expansion velocity of the gas, indicated that it had been ejected from the progenitor star only \( \sim 2 \times 10^4 \) years before the SN explosion.

Observations with the Hubble Space Telescope (HST) later revealed the detailed structure of the circumstellar gas. It was found that the expanding debris of SN 1987A is at a center of three elliptical rings (Burrows et al. 1995, see Fig. 4.1), where the SN is located at the center of the inner circumstellar ring, denoted the equatorial ring (ER). The ER is close to circular in shape and inclined by 43° (Sugerman et al. 2002, 2005). The northern part of the ring is tilted toward earth, whereas the southern part is tilted away. The ring has a radius of 0.6 ly and is expanding with 10.3 km s\(^{-1}\) (Crotts 2007). Combining these measurements (and assuming a constant expansion velocity) gives an estimate of \( \sim 2 \times 10^4 \) years since the ER gas was ejected.

The presence of the ER and especially the outer rings has been challenging to explain theoretically. The outer rings were originally thought to manifest the limb brightening of the nebula (Wampler et al. 1990; Blondin & Lundqvist 1993; Martin & Arnett 1995). However, it turned out that the outer rings are actually too bright and thin to be explained by such a line-of-sight projection effect. Instead, it is now well-established that they constitute an almost stationary nebula, which was photoionized by the flash from the SN outbreak (Lundqvist 2007).

The outer rings are approximately co-axial with the ER and are displaced by \( \sim 1.3 \) ly on either side of the equatorial plane. The southern outer ring is located in front of the ER whereas the northern outer ring is situated behind it. The radii of the outer rings are about 2.5 times the radius of the ER (Burrows et al. 1995). This size, together with the expansion velocity of \( \sim 26 \) km s\(^{-1}\), makes a dynamical time scale of \( \sim 2 \times 10^4 \) years for the outer rings, i.e., the same as for the ER (Crotts 2007). In other words, the ring kinematics suggest that the outer rings and the ER were ejected at roughly
Early ground-based observations of SN 1987A gave evidence that the triple-ring system was part of a more extended nebula (Wang & Wampler 1992). In these observations, light echoes were detected that arose from the scattering of the optical light from the SN by dust grains in the surrounding gas. The light echoes provide evidence of a much greater mass than that ionized by the SN flash. Mappings of these echoes have shown that this gas is located within a distance of several light years from the SN. Thus, the triple-ring system may in fact be a result of the ionization-limited inner rim (∼ 0.07 M⊙, Lundqvist 2007) of a much greater mass, which never became ionized by the flash (McCray 2007).

The increase of the X-ray and radio emission after ∼ 1000 days (see Sect. 4.6.2) have indicated that an H II region is present interior to the bipolar nebula (Chevalier & Dwarkadas 1995). The size of the radio source showed that the inner edge of the H II region is located ∼ 4.3 × 10^{17} cm from the SN and extending out to the inner edge of the ER at ∼ 6 × 10^{17} cm. To account for the X-ray emission produced as the forward shock sweeps through this gas, its density must be of the order of 10^2 cm^{-3}. The H II region is believed to
be composed by swept-up RSG wind, photoionized by the radiation from the BSG (Chevalier & Dwarkadas 1995).

In the interior of the H II region there is a freely expanding low-density BSG wind with a velocity of $550 \text{ km s}^{-1}$ (implying a mass loss rate of $\sim 5 \times 10^{-9} \text{ M}_\odot \text{ yr}^{-1}$, Chevalier & Fransson 1987). Between this region and the H II region, there is a zone of shocked wind, separated from the free wind by a wind-termination shock (Dwarkadas 2007, see Fig. 4.2). The radius of this termination shock is estimated to be $\sim 20\%$ of that of the ER (Lundqvist 1998).

**Figure 4.2:** Schematic picture of the wind regions around SN 1987A (Chevalier & Dwarkadas 1995).
4.4 Circumstellar interaction

4.4.1 Flash ionization

The earliest form of circumstellar interaction occurred when the burst of EUV and X-rays from the shock break-out reached the surrounding gas (see Sect. 2.2). This burst of photons ionized the gas in the ER and a number of highly ionized narrow emission lines could be detected in UV and later on in the optical wavelength region (Wampler et al. 1988; Fransson et al. 1989). The recombination time scale depends on the density of the ER, but is of the order of years (Lundqvist & Fransson 1996). The higher density gas of the ER dominated the emission at early times. Later on, gas with lower density became more dominant since this gas cools and therefore fades less rapidly than the higher density gas. Thus, because of the long cooling time of the low density gas in both the ER and the outer rings, emission from this early interaction can still be observed, more than 20 years after the outburst. The physical conditions and evolution of these narrow lines are discussed in papers II–III.

4.4.2 First evidence of the ejecta–CSM collision

The first evidence that the SN ejecta had started to collide with the circumstellar medium (CSM) came from the re-detection of radio and X-ray emissions around day 1200 (Staveley-Smith et al. 1992). Imaging by the Australia Telescope Compact Array (ATCA) revealed that the radio source was located inside the ER, and from subsequent observations it was found that the source was expanding with a velocity of $\sim 3500 - 4000$ km s$^{-1}$ (see Sect. 4.6.2).

When the SN blast wave impacts on the surrounding medium, a shock structure forms comprising a forward shock moving into the CSM and a reverse shock moving back into the ejecta (see Fig. 4.3).

4.4.3 The reverse shock

Due to the recombination caused by radiative cooling and adiabatic expansion, the freely expanding ejecta of SN 1987A are mostly consisting of neutral hydrogen (Heng 2007). Hence, as these fast moving hydrogen atoms cross the reverse shock, they will be excited and the subsequent radiative decay will produce broad ($\sim \pm 15000$ km s$^{-1}$) Ly$\alpha$ and H$\alpha$ emission lines (see Fig. 4.4). Since roughly one Ly$\alpha$ photon and 0.21 H$\alpha$ photon are created per hydrogen atom crossing the reverse shock (Michael et al. 2003), the flux of these lines will directly trace the number of hydrogen atoms crossing the shock.

Due to the fact that the debris is freely expanding, there is a unique correspondence of the Doppler shift of the emitting photons to the depth of the
Figure 4.3: Ejecta interaction with the circumstellar medium (Fischer et al. 2002b).

Figure 4.4: VLT/UVES spectrum of the emission from the circumstellar interaction in SN 1987A from October 2002. The broad (extending to $\sim \pm 15000$ km s$^{-1}$) component is H$\alpha$ emission from the reverse shock. The emission lines from the circumstellar ring are superimposed and are composed of a narrow ($FWHM \sim 10 - 30$ km s$^{-1}$) velocity component arising from the unshocked ER and an intermediate ($FWHM \sim 250$ km s$^{-1}$) velocity component originating from the shocked gas in the ER.

Debris. Therefore, the shape of the emission lines can be used to trace out the surface of the reverse shock (Heng 2007).
The result from series of mappings, performed with the The Space Telescope Imaging Spectrograph (STIS) aboard the HST, of the shock surface shows that the reverse shock is brightest near the plane of the ER (Michael et al. 2003). This can be understood from the fact that the emissivity of the shock surface is proportional to the mass flux crossing it. Hence, since the reverse shock has a smaller radius near the equatorial plane than near the polar directions, it implies that the shock surface reaches deeper into the denser layers in the debris in that plane.

In addition to the spherical asymmetry, the results from these mappings also reveal a cylindrical asymmetry of the shock surface brightness. This asymmetry can neither solely be explained as a light-traveling delay, nor by the resonant scattering of the Ly$\alpha$ photons (since the asymmetry is also seen for the H$\alpha$ line of which the envelope is optically thin). Instead, it is likely to reflect a real asymmetry either in the ejecta density distribution, or is possibly a result of a denser CSM that the reverse shock encounters in the direction of the higher surface brightness (Michael et al. 2003).

In addition to the surface emission, spectroscopic observations have identified an emission component arising from lower velocity gas (different from the emission from the SN’s central core, which is powered by the decay of $^{44}$Ti). If this gas comes from the freely expanding debris, then it must clearly originate from a location between the reverse shock surface and the SN core. The emission mechanism that produces these photons is debated, but could in principle be a result of excitation by X-rays from the shock interactions, or by relativistic particles accelerated by the reverse shock. Another possibility is that the photons are in fact produced in the slower, shocked gas beyond the reverse shock. This emission would then come from hydrogen atoms resulting from charge transfer between the freely streaming atoms and the protons in the hot shocked gas. Since these atoms will have a similar velocity distribution as protons, the doppler-shifted photons emitted by the subsequent excitations of these atoms would not be distinguished from photons emitted from the interior regions of the freely expanding debris (Heng et al. 2006).

Roughly half of the ionizing UV and X-ray photons, that are created in the hot shocked plasma outside the reverse shock surface, will propagate inwards and hence ionize the hydrogen atoms before they cross the reverse shock. These photons will therefore suppress the emission from the reverse shock, and when the number of ionizing photons exceeds that of the hydrogen atoms, the broad emission lines of Ly$\alpha$ and H$\alpha$ will completely vanish (Smith et al. 2005). This turn off of the broad emission lines has been estimated to occur sometimes between the years 2012 and 2014 (Heng et al. 2006; Heng 2007).
4.5 The ejecta–ring collision

The expansion rate of the debris (about 10% of the speed of light) and radius of the ER (∼0.6 ly) implied that there should be a collision between the ejecta and the inner ring about a decade after the explosion. Indeed, the first indication of the collision came in April 1997 when HST detected a bright spot located at 29° (north-east) on the ER (Pun et al. 1997; Sonneborn et al. 1998). However, later on it was found that this spot (called Spot 1) was present on HST images already in March 1995 (Lawrence et al. 2000). Since then, Spot 1 increased in luminosity and revealed itself in HST/STIS spectra as blueshifted (velocity of the peak ≈ −80 km s⁻¹) and broadened (FWHM ≈ 250 km s⁻¹) emission lines. Spot 1 is located on the inner edge of the ER and is considered to be the result of the interaction between the blast wave and a finger of dense ring material protruding inwards toward the SN (see Fig. 4.5). Hence, in this view, Spot 1 marked the region where the blast wave first encountered the ER. It took more than three years before the appearance of other so called hot spots (Sugerman et al. 2002). Several new hot spots then appeared and eventually the entire ER became fully encircled by the these, making it resemble a necklace (see Fig. 4.6).

![Figure 4.5: Schematic illustration of the shock interaction region around SN 1987A (Pun et al. 2002).](image-url)

The inward pointing protrusions were likely formed by the action of the different phases of the stellar winds and are presumably a result of Rayleigh-Taylor instabilities (Crotts 2007). Since the hot spots are unresolved even with the high spatial resolution of HST, there is, however, no information about their morphology. Nevertheless, the fact that Spot 1 has not yet merged with...
the neighboring hot spots suggests that it must be very elongated. It is not clear, however, if the ring is continuous or if it consists of individual blobs. The evolution of the flux from the spots, as studied in paper III may here give some valuable information.

As the forward shock with a velocity of $\sim 3500 - 4000 \text{ km s}^{-1}$ encounters the protrusions of dense ring gas (Fig. 4.7), slower shocks are transmitted into them. The exact velocities of the transmitted shocks depend on the density structure as well as the angle of incidence (Pun et al. 2002). The fastest transmitted shocks will give rise to soft X-ray emission whereas the optical emission comes from shocks of relatively low velocities (see Sect. 4.5.1 for a detailed description of this process).

### 4.5.1 Shock structure

The post-shock gas is a great source of ionizing UV and X-ray photons. These photons will ionize not only the post-shock gas but also the pre-shock gas. Hence, due to this pre-ionization, the unshocked regions of the ER (as well as material outside the visible ring) will be heated before it is reached by the blast wave. The extent of the pre-shock region is $\sim 10^{17} \text{ cm}$ (assuming a ring density of $10^4 \text{ cm}^{-3}$). This length is comparable to the size of the ER, which has a radius of $\sim 6 \times 10^{17} \text{ cm}$ (see Sect. 4.3).

Figure (4.8) shows the ionization structure, as well as the density and temperature profiles of a fast shock (500 km s$^{-1}$) for both the photoionized precursor and for the post-shock recombination region (Allen et al. 2008).
The lower panel of Fig. 4.8 shows the ionization structure of oxygen. As can be seen, the high ionization lines and the strong cooling lines of [O III] in particular, are the most efficient emitters in the pre-shock gas.

When the blast wave reaches the ring, the velocity of the transmitted shock immediately behind the surface of the ring, $V_s$, is given by the jump condition

$$V_s \approx V_b \left( \frac{\rho_{\text{HII}}}{\rho_{\text{ring}}} \right)^{1/2}$$

(4.1)

where $V_b$ is the velocity of the blast wave, $\rho_{\text{HII}}$ is the density of the H II region ($\sim 10^2$ cm$^{-3}$) and $\rho_{\text{ring}}$ is the pre-shock density ($\sim 10^4$ cm$^{-3}$) of the ring. Hence, as the blast wave propagating through the H II region with a velocity of 3500 – 4000 km s$^{-1}$ hits the dense ring, slower shocks with velocities of $\sim 300$ km s$^{-1}$ are transmitted into the ring. The exact velocity of a transmitted shock depends on the angle between the blast wave direction and the normal to the ring surface. The fastest shock velocities occur for head-on collisions while the velocities of the transmitted shocks decrease monotonically as the obliquity increases. As a result, the blast wave will compress the geometric ring structure in the direction of propagation.

As the transmitted shock (with a Mach number much larger than unity) sweeps through the ring gas, the gas becomes compressed by a factor of four at the shock front (Eq. 3.6) provided that the magnetic field is negligible. For
4.5 The ejecta–ring collision

Figure 4.8: Ionization structure of hydrogen (upper panel) and oxygen (lower panel) for a fast-shock (500 km s$^{-1}$) model with solar abundances. The time since the passage of the shock front is indicated by the horizontal axis. Negative values are for the precursor (pre-shock region) whereas positive values mark the post-shock region. The vertical axis indicates the ionization fraction, the hydrogen density as well as the electron temperature (Allen et al. 2008).

In a non-negligible magnetic field, the compression factor will be less than four and the factor will depend on the strength of the field line components that are parallel to the shock front. The temperature of the gas after it has passed the shock front is given by $T_s = 3\mu V_s^2/16k$ (Eq. 3.10). In this region, just behind the shock front, the atoms are collisionally ionized and since the cooling processes are inefficient in removing the thermal energy of the hot gas, this region is called the adiabatic or nonradiative zone. However, after some time, the gas temperature will drop enough for resonance lines in the EUV and X-ray emission to become important for the cooling of the gas. The coronal lines also appear in this region and these emission lines were studied in detail in paper I. Once the temperature drops below $\sim 10^6$ K, the radiative processes become
very efficient in removing the thermal energy and the post-shock gas undergoes a thermal collapse. As this happens, the gas temperature quickly drops to $\sim 10^4$ K and in order to maintain pressure equilibrium across the shock, it follows that this region is highly compressed and if magnetic fields can be neglected, density is given by

$$\frac{\rho_c}{\rho_{\text{ring}}} = \frac{16T_s}{3T_c}$$

Hence, the gas becomes compressed by a factor of $500 - 600$ in this zone. This cool and dense region is optically thick to the downstream propagating X-ray and EUV photons. Thus, the radiative cooling will be balanced by the heating from the photoionizing radiation. This region is therefore called the photoionization zone. In this zone, most of the optical emission lines arise as the ionizing EUV and X-ray photons created in the upstream gas are re-emitted in the optical wavelength range.

The time it takes for a shock to develop a cool and dense layer, $t_{\text{cool}}$, in the CNO-enriched ring (i.e., to become radiative) depends on the shock velocity, $V_s$, as well as the density of the pre-shock gas, $\rho_{\text{ring}}$, according to

$$t_{\text{cool}} \approx 8.3 \left( \frac{\rho_{\text{ring}}}{10^4 \text{ cm}^{-3}} \right)^{-1} \left( \frac{V_s}{300 \text{ km s}^{-1}} \right)^{3.4} \text{ years}$$

(4.3)

(see paper I). The downstreaming collisionally ionized gas has the velocity $V_s/4$ relative to the shock front (see Eq. 3.11). The extent of the cooling region, $D_{\text{cool}}$, is therefore $\approx V_s t_{\text{cool}}/4$, and hence,

$$D_{\text{cool}} \approx 2.4 \times 10^{14} \left( \frac{\rho_{\text{ring}}}{10^4 \text{ cm}^{-3}} \right)^{-1} \left( \frac{V_s}{300 \text{ km s}^{-1}} \right)^{4.4} \text{ cm}.$$  

(4.4)

Thus, at this distance behind the shock front, the optical lines of the post-shock gas appear in cool ($\sim 10^4$ K), dense ($10^6 - 10^7$ cm$^{-3}$) layers. The macroscopic motion of these layers will substantially broaden the emission lines. The shapes of the line profiles are therefore determined by the shock dynamics. Due to the longer cooling times of the faster shocks (Eq. 4.3), these may not have time to develop radiative layers. Given enough time, however, also these shocks become radiative. In paper III, this process is monitored as a gradual increase of the extent of the optical emission lines. These lines are compared with the coronal lines which also arise behind non-radiative shocks.
4.6 Observational summary of the ejecta–CSM interaction

4.6.1 Soft X–ray emission

Soft X–rays were expected to appear early on after the explosion, as the blast wave would overtake the surrounding medium and later by the reverse shock within the expanding ejecta. The first X–ray observations were performed in August 1987 (Aschenbach 2007). However, the X–ray flux was below the detection limit and one could therefore exclude the presence of any dense material in the vicinity of the SN, consistent with the low density of the wind of the BSG.

Observations carried out with ROSAT in 1991 and 1992 (Gorenstein et al. 1994) were able to detect an X–ray source at the location of SN 1987A. The frequent monitoring in the following years showed a steady increase in flux until the end of the ROSAT satellite mission in 1995 (Hasinger et al. 1996). However, the monitoring of SN 1987A continued after the launch of the Chandra X–ray observatory in July 1999 (e.g., Zhekov et al. 2006; Park et al. 2006, 2007; Dewey et al. 2008) and XMM-Newton in December 1999 (e.g., Haberl et al. 2006; Heng et al. 2008).

Figure (4.9) shows a compilation of light curves in soft (0.5 – 2 keV) and hard (3 – 10 keV) X–ray emission, as well as radio emission. Until day $\sim 3500 – 4000$ (1996 – 1998), the fluxes evolved in a similar way, but after that the light curve in the soft X–ray energy band shows a clear upturn and differs significantly from the evolution of both hard X–rays and radio fluxes. This indicates that the soft X–rays have a different origin than the hard X–rays and the radio emission (see Sect. 4.6.2). The soft X–rays are thought to be produced where the forward shock sweeps up the dense ER (Park et al. 2007). Hence, the upturn at $\sim 3500 – 4000$ days is believed to reflect the first impact between the blast wave and the dense protrusions (Spot 1) (Park et al. 2005). The velocities of the transmitted shocks would, however, be too low to be able to produce any significant hard X–rays. The soft X–ray observations by the Chandra and XMM-Newton satellites are very useful as complements to the optical observations described in this thesis. In particular, the spectroscopic X–ray observations show lines from high ionization ions such as Si XIII-XIV, Mg XI-XII, Ne IX-X, O VII-VIII, Fe XVII and N VII produced immediately behind the transmitted shocks moving into the hot spots. Most likely, these lines come from the same region as the coronal emission lines, discussed in paper I (see Fig. 4.10).

The steep increase of the flux in the soft X–ray band at $\sim 6000 – 6200$ days (year 2003 – 2004) (Fig. 4.9) has been interpreted to signal the time when the blast wave reached the main structure of the ER (Park et al. 2005). The shallower increase of the light curve after day $\sim 6700$ (June 2005) may reflect that the forward shock has started to interact with lower density gas...
4.6.2 Radio– and hard X–ray emission

SN 1987A is the most sub-luminous SN that has been discovered so far in the radio band (Staveley-Smith et al. 2007). Yet, radio emission was detected within 2 days after outburst at the Australian observatories (Turtle et al. 1987). After the initial rise, the radio emission peaked on day 4. This was followed by a rapid decline and the radio source became undetectable after some months (Gaensler et al. 2007). This decline was the result of a
fast-moving blast wave (~30000 km s\(^{-1}\)) (driven by the freely expanding ejecta) interacting with the inner parts of the CSM consisting of a low density stellar wind from the BSG (Chevalier & Fransson 1987).

However, the radio emission re-appeared after 1000 days (mid-1990), and since then, frequent monitoring with ATCA has shown a monotonic increase in the radio flux (Manchester et al. 2002, 2005). From these observations it was also clear that the detected radio source was spatially extended and from the evolution of the estimated diameter it was found that the expansion of the radio emitting region had slowed down considerably to about 3000 km s\(^{-1}\). In addition, the re-discovery of the radio emission occurred almost simultaneously with the turn-on of the X-ray emission (Staveley-Smith et al. 2007). These facts strongly indicated that the blast wave had reached out to a denser medium interior of the ER. The increasing radio emission was interpreted as synchrotron radiation generated as the ejecta interact with an H II region located inside the ER formed by the BSG progenitor (Chevalier & Dwarkadas 1995, see Sect. 4.3).

The evolution of the radio- and X-ray fluxes were similar up to day ~4500. Then, the soft component of the X-ray flux (0.5 – 2 keV) started to increase much more rapidly than the radio flux. This upturn of the soft X-ray flux coincides with the first interaction of the shock front with the ER (Spot 1, see Sect. 4.6.1). The hard X-ray flux (3 – 10 keV) continued, however, to evolve in a similar way to that of the radio.

The prompt deceleration of the X-ray remnant from ~6100 km s\(^{-1}\) to ~1400 km s\(^{-1}\) around days 6100–6200 (Park et al. 2007) has not been observed for the radio remnant. Instead, the expansion rate of the radio remnant over the period 1992–2008 has been relatively constant with a velocity of 4000 ± 400 km s\(^{-1}\) (Ng et al. 2008). In fact, this expansion velocity is similar to that of the reverse shock of ~3700 km s\(^{-1}\) (Michael et al. 2003).

The differences in evolution are consistent with the fact that the soft X-ray component traces the optical hot spots whereas instead both the hard X-ray source and the radio remnant show two lobes on either side of the ER. Thus, both the hard X-rays and the radio emission are likely to arise from the high-velocity shocked ejecta between the reverse shock and the forward shock and not from the dense ER. The reverse shock is thought to give rise to both the radio synchrotron emission and the high-temperature shocked gas from which the hard X-ray emission originates.

Figure (4.11) shows a comparison of the ring taken in optical, hard X-ray and radio emission. Both the radio emission and hard X-rays show the bright lobes on the east (left) and west (right) sides of the ER. It is also clear that the eastern lobe is brighter than the western one. In addition, the morphologies of the radio- and hard X-ray sources are also uncorrelated to the distribution
of the optical hot spots around the ER. Nevertheless, the fact that the two lobes are aligned along the major axis of the optical ring is consistent with an inclined thick ER, which likely manifests that the interaction between the ejecta and the CSM occurs primarily in the equatorial plane where the wind from the progenitor RSG has the highest density (Gaensler et al. 2007).

The latest observations indicate that the radio remnant now extends even outside the inner ring. The encounter between the ejecta piston and the ring may now be underway and, as a consequence, a significant deceleration also of this gas is expected to follow shortly (Park et al. 2007; Ng et al. 2008).

Figure 4.11: Multi-wavelength image of SN 1987A. HST-F656N (red image), Chandra (green image) and ATCA (blue image) (Gaensler et al. 2007).

4.6.3 Infrared emission

Infrared (IR) observations enable studies of abundances, and the composition and distribution of the size of the dust grains in the CSM, as well as various destruction processes of the grains. Such processes are the sputtering in the downstreaming gas behind the shocks and evaporation of the dust by the EUV/X–ray flash that followed from the SN outbreak.

IR dust emission became the most important emission mechanism of the ejecta after day $\sim 500$ (see Fig. 2.3). This was a result of the dust formation in the ejecta at this epoch. The first indications of dust came from blue shifts in several emission lines (Lucy et al. 1989). At the same time a strong IR
excess developed, which clearly showed that most of the emission from the ejecta was thermalized by the dust (Danziger et al. 1989; Wooden et al. 1993). However, even though later mid-IR ISO observations of SN 1987A at days 4100 and 4300 (Fischera et al. 2002a) indicated that dust was still the dominant emitter of the ejecta’s total flux, it was discovered that at least part of the dust emission was likely to come from the ER. Indeed, the correlation between the soft X-ray and the mid-IR images obtained by Gemini-South at day 6526 (Bouchet et al. 2006) suggests that both IR and X-ray emission originate from the same region. This is therefore a strong indication that the dust is heated by collisions or possibly by the X-rays in the shocked X-ray emitting gas behind the blast wave (Fischera et al. 2002a). The dust grains in the ER are likely to have been pre-existing and formed in the winds from the progenitor prior to explosion (Bouchet et al. 2004).

If the dust grains are collisionally heated by the gas, then the IR to X-ray flux ratio (IRX) is an import diagnostic for the IR cooling in the X-ray emitting gas. This ratio depends on the dust-to-gas mass ratio as well as the gas temperature. For a dust-to-gas mass ratio of 1% and a gas temperature in the range of $\sim 5 \times 10^6 - 10^8$ K, the IRX is expected to be in the range $\sim 10^2 - 10^3$ for grain sizes between 0.01 $\mu$m and 0.1 $\mu$m (Dwek & Arendt 2007). Yet, the IR flux at day 6190 obtained by Spitzer (Bouchet et al. 2006) indicated an IRX of less than one. This large discrepancy therefore indicates that the dust-to-gas mass ratio in the SN 1987A is much lower than what is normally found in the LMC. The reason for this could, in principle, be either a very inefficient dust formation in the progenitor wind or the dust being destroyed in the shocked gas. However, observations obtained by Spitzer at day 7137 (Dwek & Arendt 2007) showed that the IR flux between days 6190 and 7137 had increased by a factor of 2, whereas both the composition and temperature of the dust remained unchanged during this period. Yet, during the same period, the X-ray flux increased by a factor of 3. This decrease in the IRX favors a scenario where dust grains are being destroyed in the shocked gas behind the blast wave (Dwek et al. 2008).
Figure 4.12: Evolution of the inner ring of SN 1987A in the optical (HST), X–ray (Chandra), radio (ATCA) and infrared (Gemini) (McCray 2007).
5 Summary of the papers included in the thesis

This thesis is based on four publications. All four papers are on SN 1987A and the interaction with its circumstellar medium. The analysis is based on observations carried out by the Very Large Telescope (VLT) at the European Southern Observatory (ESO) at Paranal, Chile. Papers I–III present data taken with the Ultraviolet and Visual Echelle Spectrograph (UVES). These data have been complemented with data taken with the Hubble Space Telescope (HST). Paper IV is based on integral field spectroscopy taken with the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) at VLT.

My contributions to papers I–III have mainly been to the observational aspects such as reduction, analysis and interpretation of the data. Most of the shock emission calculations in paper I were done by Tanja Nymark. I am responsible for most of the written text of papers I–III. For paper IV, I have mainly contributed with the UVES data and its relation to the SINFONI observations.

5.1 Paper I
Coronal emission from the shocked circumstellar ring of SN 1987A

In this paper we present four epochs of VLT/UVES data ranging from 2000 December to 2005 November. Three different velocity components are identified from the spectra. A narrow velocity component, $FWHM \sim 10 \, \text{km} \, s^{-1}$, comes from the unshocked circumstellar ring (ER), an intermediate velocity component arises in the shocked ER extending to $\sim 300 \, \text{km} \, s^{-1}$ and finally a very broad component extending up to $\sim 15000 \, \text{km} \, s^{-1}$ emerges from the reverse shock resulting from the ejecta interaction with the circumstellar medium. Here we concentrate on the evolution of the intermediate velocity component. The main result of this paper is the discovery of a number of high-ionization coronal emission lines, such as $[\text{Fe X}] \lambda 6375$, $[\text{Fe XI}] \lambda 7892$ and $[\text{Fe XIV}] \lambda 5303$. The flux of these lines are only $\sim 1\%$ of the H$\alpha$ flux, but thanks to the excellent resolution and high S/N of UVES these lines could be detected. The lines are excellent probes of the shocked gas.

By comparing fluxes from different epochs we found an increase in the fluxes of all lines over the range of the observations. Over this period the
[Fe X], [Fe XI] and [Fe XIV] line fluxes have increased by a factor of $\sim 24 - 30$, and their fluxes were found to evolve similarly to the flux evolution of the soft X-rays, but considerably faster than the hard X-ray flux and the radio emission. In contrast, the line fluxes from ions with lower ionization potential such as [Ne V], [Ar V] and [Fe VII] increase considerably slower.

The similar evolution of the flux of soft X-rays and high ionization optical lines led us to propose that most of the emission from [Fe X-XIV] comes from the same regions that produce the soft X-rays. The slower evolution of the lower ionization lines could be explained if some fraction of the [Fe X-XIV] emission arises from non-radiative shocks. Such shocks would not contribute to the lower ionization lines.

The [Fe XIV] $\lambda 5303$ line shows a width of $\sim 350$ km s$^{-1}$ while low ionization lines like [Fe II] only extend to $\sim 250$ km s$^{-1}$. This may indicate that the low ionization lines have a dominant contribution from oblique shocks with lower velocity, while the high ionization lines also arise from shocks parallel to the blast wave, having a higher velocity.

Using the shock code of Nymark et al. (2006) it was found that the high ionization lines come from a gas with a temperature of $\sim 2 \times 10^6$ K. The similar line profiles over a large range in ionization stages indicate that most of the emission comes from radiative shocks with velocities in the range of 310 – 390 km s$^{-1}$. The shock velocities from our spectral models are consistent with the observed line widths of $\sim 350$ km s$^{-1}$.

We find that the low and intermediate ionization lines, like [O III], [Ne V], [Ar V] and [Fe VII] all have narrow velocity components. The higher ionization lines, [Fe X], [Fe XI] and [Fe XIV] lack such a velocity component. This indicates that the pre-ionization of the unshocked gas by the X-rays from the shocks does not reach further than the former ionization stages.

5.2 Paper II
High resolution spectroscopy of the inner ring of SN 1987A

This paper discusses a full analysis of the UVES spectrum from a single epoch (2002 October). An advantage of this relatively early epoch is that the emission from the northern part of the inner ring (ER) is dominated by relatively few spots where Spot 1 is the strongest one. A large number of emission lines were identified (188) arising from both the unshocked– and shocked gas of the ER.

For the unshocked ring ionization stages from neutral up to Ne V and Fe VII were found. A nebular analysis of the unshocked ring gas indicated densities in the range of $(1.5 - 5) \times 10^3$ cm$^{-3}$ (except for [O III] which mainly comes from gas with an electron density lower than $\sim 1.5 \times 10^3$ cm$^{-3}$) as well as
temperatures in the interval of $6.5 \times 10^3 - 2.4 \times 10^4$ K, which is consistent with the thermal line widths of ($\sim 10 - 30$ km s$^{-1}$).

Also for the shocked gas the measured flux ratios were used as inputs to the model atoms to probe temperatures and densities. From this the electron density in the [O III] emitting region was found to be in the range of $10^6 - 10^7$ cm$^{-3}$ for a temperature in the interval of ($\sim 1 - 4$) $\times 10^4$ K for both the northern and southern parts of the ER. These densities are consistent with the large compression in radiative shocks.

The origin of the optical lines from the shocked gas is discussed within the context of radiative shock models. The low ionization lines originate from the photoionization zone behind the radiative shocks with a temperature of $\sim 10^4$ K, whereas [Ne V] as well as the coronal lines come from the collisionally ionized region with temperatures in the range of $(1 - 3) \times 10^5$ K. The [O III] and [Ne III] emission lines originate from the photoionized as well as the collisional ionized zones and therefore arise from a wide range of temperatures.

The shapes of the line profiles are dominated by the shock dynamics and the exact nature of the profiles is therefore sensitive to the forward shock velocity as well as the density and geometries of the shocked clumps. In addition, the line profiles only reflect the projected shock velocities along the line-of-sight and the profiles are therefore also sensitive to the locations of the blobs on the ER. From the FWZI of the H$\alpha$ line profile, shocks with velocities of $< \sim 260$ km s$^{-1}$ were estimated to have had enough time to cool to become radiative for this epoch.

A comparison of the profiles of different lines shows that the low ionization ions such as H$\alpha$ and He I up to [Ne V] and [Fe VII], all have similar profiles. The coronal lines, on the other hand, show considerably higher velocities (with an extent of almost 400 km s$^{-1}$ for [Fe XIV]) which indicates that these groups of lines arise from not exactly the same regions.

We argue that the wings of the line profiles trace the shocks with the highest observed velocities, where only the fraction of the gas with the highest densities has had time to cool. Some of the coronal emission lines, with their larger extent in the range of velocities, may therefore originate from non-radiative shocks, which are also likely to give rise to some of the soft X-ray emission. Thus, in this picture, one expect especially the low ionization lines to increase with time.

Since the shock velocity should be $\sim 4/3$ times the gas velocity immediately behind the shock, an observed extent of $\sim 400$ km s$^{-1}$ of the coronal lines indicates shock velocities above 500 km s$^{-1}$. Although the emission from the coronal lines clearly comes from higher velocities than the lower ionization lines we found evidence for some high velocity gas also in these. For the H$\alpha$ line, with the best S/N, we could trace gas up to $\sim 450$ km s$^{-1}$ for the northern part of the ER. The southern part, on the other hand, lack emission beyond $300 - 350$ km s$^{-1}$. We argue that this difference can be explained by the dif-
ference in cooling time between the two parts of the ER. The bulk emission at this epoch should originate from shocks with velocities of $\lesssim 300 \text{ km s}^{-1}$ and most of the weak high-velocity emission, seen on the northern side, must be old enough to come from Spot 1, which marks the place were the blast wave first encountered the ER.

### 5.3 Paper III

**Time evolution of the line emission from the inner circumstellar ring of SN 1987A and its hot spots**

This paper focuses on the time evolution of the optical emission lines from the unshocked ring as well as the lines originating from the collision between the ejecta and the inner circumstellar ring (ER). Our analysis is based on VLT/UVES spectra taken at seven epochs ranging from 1999 October to 2007 November.

Although the northern and southern parts of the ER can be separated, the limited spatial resolution of the ground-based UVES instrument makes it impossible to distinguish between different shocked clumps, located on the same side of the ER. Hence, in connection to these data studies were also performed on HST imaging taken with the WFPC2 and ACS instruments at roughly the same epochs as for the UVES data. With the HST data, it was possible to identify the number of hot spots covered by the slit for each epoch and each side of the ring. The HST images reveal that for the first epoch, only Spot 1 contributes to the shocked emission over the entire ring. For later epochs, however, multiple hot spots on both sides of the ring contribute.

The systemic velocity of SN 1987A was determined from the velocity at the peak flux of the narrow emission lines from the unshocked ring gas. The obtained value for the center of mass velocity was $286.7 \pm 0.1 \text{ km s}^{-1}$. The ring expansion velocity, also determined from the narrow lines, was found to be $10.3 \pm 0.3 \text{ km s}^{-1}$. These values are consistent with earlier estimates.

The line fluxes of the low-ionization lines from the unshocked ring decline during the observation period and especially so after day $\sim 6800$. Nevertheless, the higher ionized [O III] and [Ne III] lines appear to increase in flux until day $\sim 6800$. Thereafter they are constant or slowly decreasing.

The increase in flux of the [O III] and [Ne III] lines up to day $\sim 6800$ is consistent with the structure of a radiative shock where the soft X–rays from the shock interaction ionize and heat the pre-shock gas and are subsequently re-emitted as UV and optical lines. Shock models show that the [O III] lines are by far the strongest optical lines from this region. This picture is also supported by the declining diagnostic flux ratios of the low-ionization lines, which indicates an increasing temperature in this zone. The low flux ratio for [O III] at Epoch 2, on the other hand, indicates a much higher temperature than that
found at later epochs. This high temperature at Epoch 2 is inconsistent with what is expected from a shock precursor. The most likely reason for this is that the emission from the unshocked gas at early epochs mainly comes from a low-density region ($\sim 1 \times 10^3 \text{ cm}^{-3}$) that was flash-ionized in connection with the supernova explosion.

The line emission from the shocked gas increases rapidly as more gas in the ring is being swept up the shock. This is found to be a general feature for all lines although the rate varies for different lines. The Balmer lines and the low-ionization lines as well as the [Fe XIV] line are all increasing in a similar way.

The intermediate ionization lines such as [O III] and [Ne III] show a break in their light curves between day 6500 and day 7000. We argue that this is due to the fact that with time, the gas will recombine to lower ionization stages until the lowest stage is reached. A decline in the fluxes of the optical lines may also indicate that the shock has started to interact with gas of lower density.

One important result is that the shocked, intermediate velocity component of the low-ionization lines shows an increase in the line widths. This behavior is consistent with that these lines originate from radiative shocks, where faster shocks become radiative over time.

The coronal lines show consistently larger widths than the low-ionization lines throughout these observations, which indicates that at least a fraction of the emission comes from non-radiative shocks. At later epochs, however, the maximum velocities of the low-ionization lines are approaching the widths of the coronal lines, and in the last spectrum from 2007, the Hα line can be traced to $\sim 500 \text{ km s}^{-1}$, i.e. similar to that of the coronal lines. Together with the X-rays, this represents the most detailed information about the emission from a radiative shock.

\section{Paper IV}

\textbf{Infrared integral field spectroscopy of SN 1987A}

In this paper, near-infrared spatially resolved spectroscopy of the inner circumstellar ring taken with VLT/SINFONI is presented. The observations were carried out in 2004 November.

Integral field spectroscopy with adaptive optics allows us to trace the shock interaction in spatially separated emission sites around the ER. However, the spectral resolution does not allow for a separation between the narrow unshocked ER lines from the intermediate velocity components arising from the shocked ring. Nevertheless, it is still possible to separate the ER emission from the broad interior velocity component of the ejecta (extending to $\sim \pm 4000 \text{ km s}^{-1}$). This was done for the strong [Fe II] $\lambda 1.644 \mu \text{m}$ line. The flux of the broad [Fe II] component varies considerably with the azimuthal
angle around the ring. In fact, the line is only pronounced on the eastern side of the ER and with peak flux around Spot 1 (P.A. = 29°). Furthermore, the shape of the line is found to change around the ring. Close to Spot 1, the blue part of the line profile is slightly more luminous than the red part, whereas the opposite is found for the eastern part of the ER. This is a clear indication of an asymmetry in the outflow of the ejecta or perhaps a difference in the density of the circumstellar medium. This result is consistent with earlier results obtained from X-rays and radio observations.
Publications not included in this thesis

“Optical and near-IR observations of SN 1987A”

“SN 1987A at the end of its second decade”

“Twenty Years of Supernova 1987A”
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