OBSERVATIONS OF SUPERNOVAE AND THEIR COMPACT OBJECTS

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Abstract:

The late time emission from core collapse supernovae is often powered by the decay of radioactive nuclei synthesized in the explosion itself. Observing supernovae at these phases provides information about the amount of ejected synthesized material, which also probes the explosion mechanism itself. This thesis presents observational studies of several core collapse supernovae, and discusses their interpretation.

For supernova (SN) 1994W we observed an unprecedented decline of the late light curve, an effect that we interpreted as due to a very low mass of ejected ^{56}Ni, $\lesssim$ 0.015 $M_{\odot}$. If SN 1994W had indeed a very massive progenitor, which we argue to be likely from the shape of the early light curve, this might imply that fall-back of material onto the newly formed neutron star occurred. If enough material fell back, a black hole would have formed.

The Type Ib SN 1996N was also followed to late phases, 337 days past discovery. The fast decline rate of the light curve ($\sim$ 1.75 mag/100 days) indicates γ-ray leakage from the radioactive decay, a likely scenario for a progenitor depleted of its hydrogen envelope. The spectral evolution is typical for Type Ib supernovae, but a feature redward of [O I] $\lambda\lambda$ 6300,6364 is similar to the Hα line seen in the well studied Type IIb SN 1993J. Moreover, many of the emission lines show considerable blueshifts ($\sim$ 1000 km s^{-1}), as was also seen in SN 1993J.

For the nearby SN 1987A we used the Infrared Space Observatory to search for [Fe II] 26 μm emission at very late times, 4000 days after explosion. The non-detection of this emission line, together with our detailed modeling of the supernova, indicates that no more than 1.5×10^{-4} $M_{\odot}$ of radioactive ^{44}Ti were ejected in the explosion.

Finally, we present a study of the Crab nebula and its pulsar. Using the Hubble Space Telescope in the ultraviolet (UV) we detected a broad absorption line of C IV λ 1550, extending out to $\sim$ 2500 km s^{-1}. This provides evidence for the long sought outer shell of the nebula, which can account for (some of) the missing mass and energy of the Crab nebula. Furthermore, we studied the far-UV pulse profile of the Crab pulsar and, by adding near-UV and optical data, we determined the power law index of the pulsar spectrum. Correcting for $E(B-V) = 0.52$ results in a good fit with a slope of $\alpha_{\nu} = 0.11$.

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Fly me to the moon
and let me play among the stars.
Let me see what spring is like
on Jupiter and Mars.

- Bart Howard

Contents

Preface

This thesis presents observational studies of supernovae, supernova remnants and some aspects of the central compact objects formed in supernova explosions. The observations have been collected during many runs at the ESO telescopes on La Silla, Chile, and at the Nordic Optical Telescope, La Palma, Spain. Space-borne observations have also been conducted with the Infrared Space Observatory (ISO) and the Hubble Space Telescope (HST), to reach wavelength regimes not accessible from the ground.

The thesis is divided into two sections. The first part introduces the reader to the subject and summarizes the publications. The second part consists of the included scientific papers themselves.

This thesis is based on the following four publications, which will be referred to in the text by their Roman numerals:

I. Jesper Sollerman, Robert J. Cumming, & Peter Lundqvist, *A Very Low Mass of* ^{56}Ni *in the Ejecta of SN 1994W*, ApJ, 493, 933 (1998)

II. Jesper Sollerman, Bruno Leibundgut, & Jason Spyromilio, *SN 1996N - A Type Ib supernova at late phases*, A&A, 337, 207 (1998)

III. Peter Lundqvist, **Jesper Sollerman**, Cecilia Kozma, Bengt Larsson, Jason Spyromilio, Arlin P. S. Crotts, John Danziger, & Dietmar Kunze, *ISO SWS/LWS Observations of SN 1987A*, A&A, 347, 500 (1999)

IV. Jesper Sollerman, Peter Lundqvist, Don Lindler, Roger A. Chevalier, Claes Fransson, Theodore R. Gull, Chun J. S. Pun, & George Sonneborn, *Observations of the Crab Nebula and its Pulsar in the Far-Ultraviolet and in the Optical*, submitted to ApJ

ApJ = Astrophysical Journal
A&A = Astronomy & Astrophysics

Page 27 lists a number of publications that I have also worked on. Although I have chosen not to include these in the thesis, they are sometimes referred to by their given Roman numbers in the introducing chapters.

Chapter 1

Introduction

1.1 Why are supernovae interesting?

A massive star ($\gtrsim$ 8 solar masses ($M_\odot$), 1 $M_\odot$ $\approx$ 2×10^{33} g) ends its life in a spectacular way, as a supernova explosion. This is one of the most energetic phenomena we know in the universe. The exploding star alone can outshine all the rest of the billion stars in its galaxy. Still, only about one part in 10,000 of the released energy comes out in the form of visible light. The major part of the energy, $\sim$ 99 %, is instead emitted as neutrinos, those ghostlike elementary particles that hardly interact with matter at all. About 1 % of the energy is used to eject the matter at a speed of $\sim 10,000$ kilometers per second. Due to their brightness, supernovae have become increasingly interesting for cosmology, simply because they can be seen at vast distances and thus probe the universe as it was a long time ago. By observing supernovae at large distances, astronomers today investigate whether the expansion of the universe will go on forever, or if it will turn into contraction in a very distant future.

But supernovae are not merely spectacular fireworks in the sky. They are far more interesting than that. Supernovae constitute an important part in the life cycle of stars. They do not only mark the death of a star, but the shock wave produced in the explosion is thought to trigger star formation in the surrounding gas clouds. These new stars will be born out of gas enriched in heavy elements. This is because the massive stars and their supernovae are the factories of the heavy elements in the universe. Only the lightest elements, mainly hydrogen and helium, were produced in the early universe. All other elements have been synthesized deep inside the stars. To produce the heavier elements, massive stars are needed. In fact, the oxygen you breath right now was once produced inside a massive star. In a supernova explosion this freshly synthesized material is expelled to the interstellar medium, and the enriched matter can then form new stars and planets. In this sense, we are truly children of the stars. Our bodies are literally made up of heavenly material. Some elements, especially those heavier than iron, cannot be produced inside the massive stars during their normal life cycle. To build up these heavy elements, for example gold, an additional energy source is needed. Supernovae are the sites for this production.

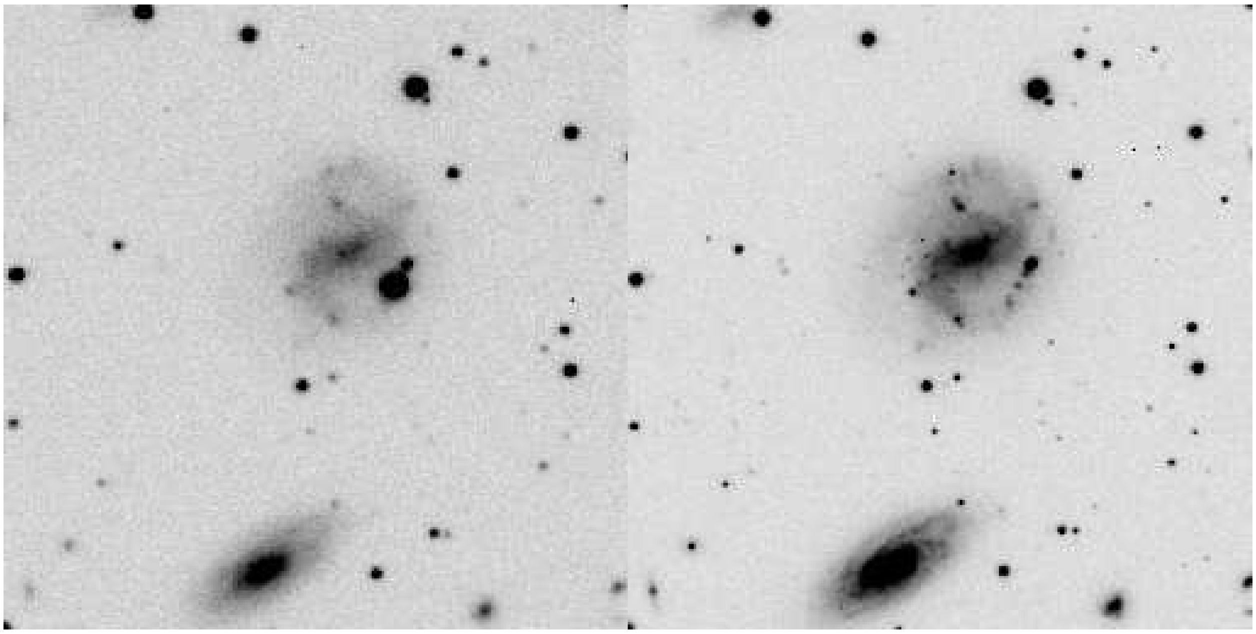

Figure 1.1: A supernova explosion. The left image was taken at the ESO 3.6m telescope one month after the explosion of SN 1998bw. A year later, the supernova had faded considerably, as seen on the right image taken at VLT.

Finally, supernovae create some of the most exotic and mind-boggling objects we know in the universe: neutron stars and black holes. These central compact objects represent the final destiny for the massive stars.

1.2 A historical overview

Nova is a Latin word that means new. For the ancient stargazers, who knew the night sky well, a new star appearing on the sky must have been an awesome phenomenon. Rather complete records of novae have been kept by Chinese astronomers for more than 2000 years. They recorded a handful of events we today recognize as supernovae, including the bright new stars of A.D. 185 and 1006. Most famous is perhaps the supernova that exploded in 1054 A.D., and which is the origin of the well studied Crab nebula. This supernova was visible in full daylight for 23 days, and during night for almost two years, according to the Chinese sources (Clark & Stephenson 1977). These ancient observations are still puzzling astronomers today (Chevalier 1977; Paper IV).

The latest bright supernovae to explode in our own galaxy, the Milky Way, were the supernovae A.D. 1572 and 1604. Both were visible on the night sky for a full year, and were observed by the contemporary astronomers, Tycho Brahe and Johannes Kepler, respectively. Tycho's observations of his supernova showed it to be more distant than the moon, in conflict with the prevailing Aristotelian cosmology. The appearance of these new stars thus provided observational evidence in favor of the coming Copernican revolution, which abandoned the geocentric conception of the world held since ancient times. These supernovae were shining proofs of a changing universe. Unfortunately they exploded just a few years before the invention of the telescope. We are still waiting for the next bright supernova to explode in the Milky Way.

The term supernova was coined in 1934 (Baade & Zwicky 1934). By then, the astronomers had begun to grasp the size of the universe. In particular, realizing that the spiral nebulae, like the Andromeda galaxy, were distant island universes (galaxies) rather than a part of our Milky Way clarified that a few novae were much, much more luminous than most others. The Swedish astronomer Knut Lundmark was, together with Edwin Hubble, one of the front figures in this debate, although his term for the most luminous novae, upper-class novae, never caught on (Lundmark 1925). Today we know that the common novae are thermonuclear explosions on the surface of a star in a binary system. They usually fade within a week. A supernova represents instead the fatal disruption of a massive star, it marks the end of the star's life and is a much more energetic phenomenon.

The 1934 papers by Baade & Zwicky also contain a remarkable piece of skilled speculation. They suggested that "a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons". This was only two years after the discovery of the neutron by James Chadwick, and few astronomers had even speculated about neutron stars. But the speculation survived and is today supported by both theory and observations.

Systematic observations of supernovae were started by Zwicky in 1934 and have helped astronomers understand these objects. To date, more than 1600 supernovae have been discovered. The evolution of their luminosity is displayed in their light curves (Fig. 1.2). More detailed physical information is obtained from their spectra (Fig. 1.3). Dispersing the light of the supernova with a spectrograph attached to the telescope provides a wealth of information about the elemental composition and enormous velocities of the expanding ejecta. The task of the astronomers is to understand and interpret this information written in the starlight.

In February 1987, the first supernova visible to the unaided human eye in 383 years appeared on the southern sky. It did not explode in our Galaxy, but in a nearby, unobscured satellite galaxy, the Large Magellanic Cloud (LMC), only 170,000 light years away. This supernova, SN 1987A, came at a time when astronomers were ready with modern telescopes, satellites and even neutrino detectors. The wealth of information from this explosion allowed detailed models of the supernova to be compared to actual observations (Arnett et al. 1989; McCray 1993). This was a breakthrough for supernova research, and although SN 1987A offered some surprises, it basically confirmed the general scenario that supernovae are the result of a catastrophic gravitational core collapse. The LMC is close enough that many of its individual stars have been studied. For the first time one was therefore able to identify the progenitor of a supernova explosion. The most striking observation of SN 1987A was perhaps the detection of neutrinos from the supernova (Hirata et al. 1987; Bionta et al. 1987). This was the first time that neutrinos were detected from a source outside the solar system, and can perhaps be seen as the starting point for neutrino

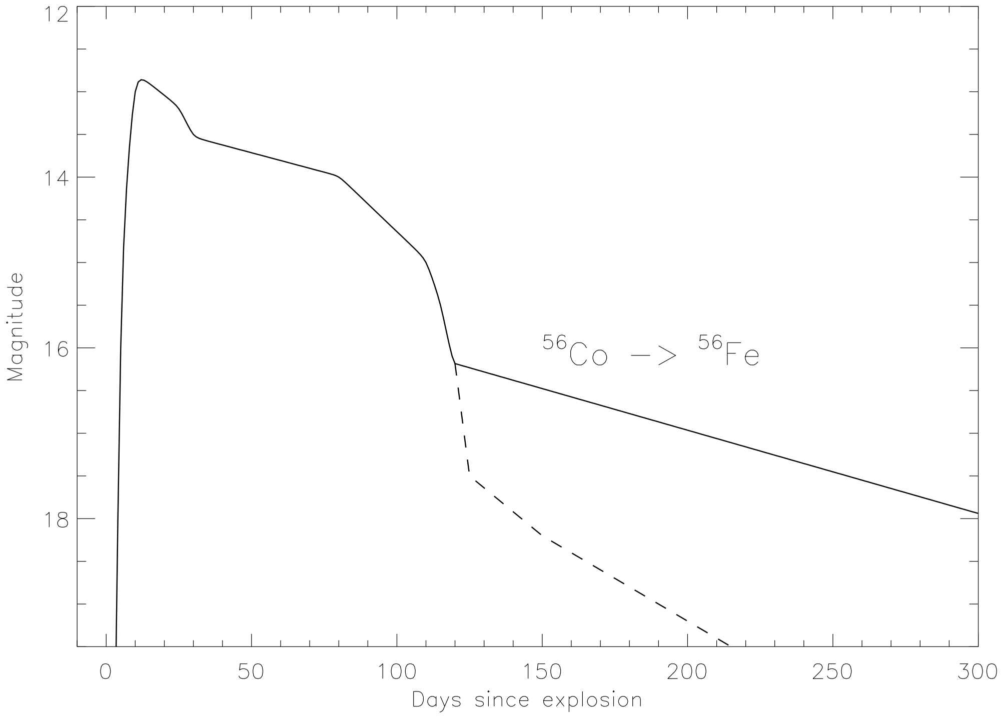

Figure 1.2: A light curve cartoon for a Type II supernova. At explosion, the brightness increases quickly, and then the supernova stays bright for a few months as the thermal radiation diffuses out through the envelope. At later stages, the emission is powered by the radioactive decay of ^{56}Co, and follows the full straight line with a slope determined by the decay time of this nucleus. For a supernova without ejected nickel (dotted line), the light curve would quickly plummet to very low luminosities (Woosley & Weaver 1986). Compare this to the light curve of SN 1994W (Paper I).

astronomy. In total 19 of these elusive particles were registered by detectors on earth, which agreed well with the theoretical framework of core collapse supernovae. SN 1987A continues to provide information about the supernova phenomenon as it ages. Sitting at close distance, we can follow the formation of a supernova remnant and perhaps eventually see a glimpse of the compact object formed in the center.

Today, more than 100 supernovae are discovered every year. A handful of these explode in galaxies that are close enough to allow more detailed observations. Most of the supernovae that can be studied in detail are shown to be unique in some respect, and understanding these differences in terms of progenitors and explosion mechanisms, remains a major task for the supernova researchers.

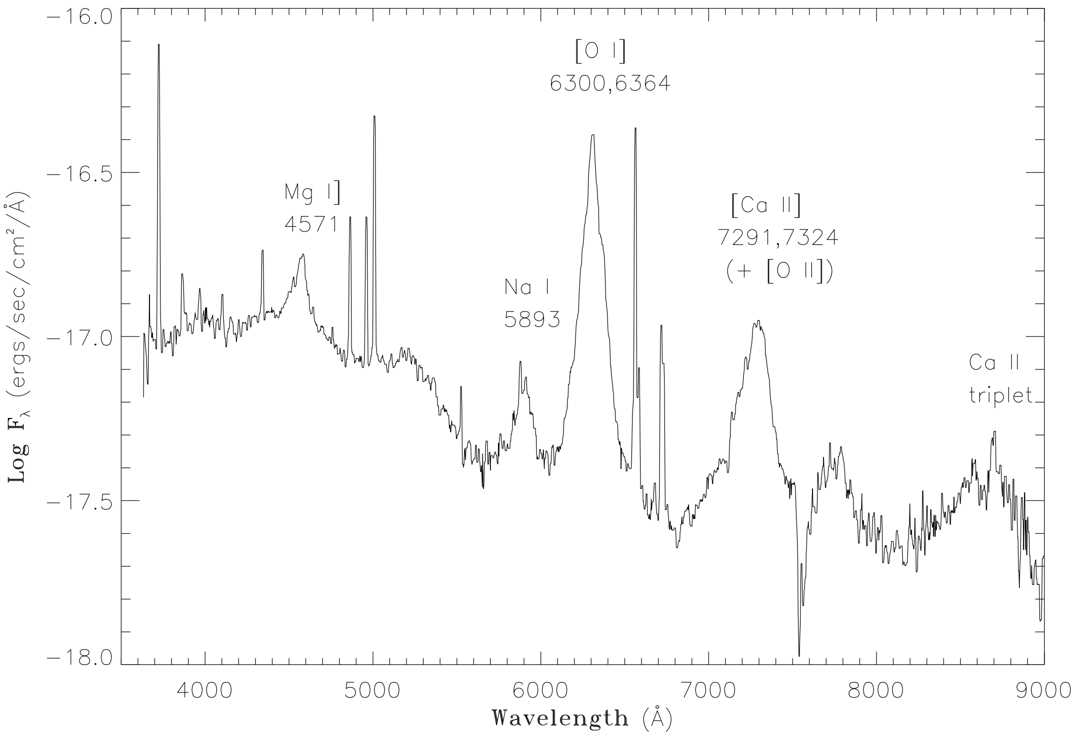

Figure 1.3: A supernova spectrum. This spectrum of the Type Ic SN 1998bw was taken at VLT, 414 days past explosion. Some of the stronger emission lines have been identified. The narrow lines are from the host galaxy.

1.3 The zoo of supernovae

Supernovae come in different flavors. They differ in a variety of observational parameters, such as maximum brightness, spectra, light curve, and explosion site (e.g., Filippenko 1991; Filippenko 1997). These differences reflect differences in the progenitor stars, their circumstellar environment and in the explosion physics. The objective of classification is to understand which features are important to derive some of the underlying physical parameters.

The classification of supernovae is based on observational parameters, and is today rather confused and even inappropriate. The supernovae are spectroscopically classified and the present types are Type Ia, Ib, Ic, II and IIn, of which the Type II's can show either linear (IIL) or plateau-like (IIP) light curves.

In this thesis I will not discuss supernovae of Type Ia. These are associated with thermonuclear explosions, presumably of white dwarfs in binary systems. As these explosions are all very similar, Type Ia supernovae are used as standard candles for determining cosmological distances.

All other supernovae are associated with the death of a highly evolved, initially massive star and are caused by the catastrophic gravitational collapse of the stellar core. I refer to these as core collapse supernovae. They are called Type II if the early spectra show hydrogen lines. If not, they are called Type Ib if they show helium lines, and Type Ic if there is neither hydrogen nor helium in the early spectra. This division is generally believed to be related to the nature of the progenitor star. Type II supernovae mark the explosion of massive stars, which still hold a (massive) hydrogen atmosphere at the time of explosion. Type Ib(c) supernovae may be the explosion of originally massive stars that have lost their outer hydrogen (and helium) layers. This depletion might be due to interaction with a binary companion, or due to mass loss in the form of a strong stellar wind.

Some supernovae have been difficult to classify. Most famous is the nearby SN 1993J which was discovered in the galaxy M81 in March 1993. This supernova started out as a Type II, with hydrogen lines in the early spectra, but later it showed spectroscopic properties similar to Type Ib/c supernovae. At later phases, these show strong emission lines of intermediate mass elements, such as oxygen and calcium (see Fig. 1.3). In SN 1993J the only sign of its Type II origin at late phases was a very weak hydrogen-line (Hα), which in Type II's normally dominates the late time spectra. This was an important clue to the similar nature of Type II and Type Ib/c progenitors (Filippenko, Matheson, & Ho 1993; Filippenko, Matheson, & Barth 1994), and the crossover term Type IIb was coined.

Another subclass is the Type IIn supernovae (e.g., Schlegel 1990). Their spectra contain hydrogen like ordinary Type II's. The emission lines are, however, narrow, giving rise to the label IIn. The width of the spectral lines reflects the expansion velocity of the emitting gas, and for the Type IIn's the lines indicate velocities $\lesssim$ 1000 km s^{-1}. This is about ten times slower than for normal supernovae. These lines probably originate from interaction of the ejecta with a dense circumstellar medium (CSM). Study of these supernovae can thus provide information on the material outside the exploding star. As most of this material was probably blown off the progenitor by a stellar wind in earlier phases of its life, studies of CSM interaction might provide information on the nature of the progenitor star.

Chapter 2

Supernovae

In this chapter I will make a short, popular introduction to supernovae. We will follow the life and death of a massive star, see it collapse and explode. Then we will discuss why supernovae shine at all, and finally get acquainted with two of the most exotic objects in the universe.

2.1 A quick tour through the life of a massive star

Massive stars live hard and die young. Shining brightly they quickly use up their fuel, they are kings for a day. While our sun consumes its hydrogen in a time span of 10 billion years, a 25 $M_\odot$ star finishes its (larger) reservoir in less than 10 million years. It thus leads a 1000 times shorter life.

A star is a giant sphere of hot gas and its life is a constant struggle between gravity and pressure. Gravity tries to squeeze the material together while the pressure from the hot interior wants to expand the gas. The major part of its lifetime, the star stays in a stable equilibrium between these competing forces. The pressure in the interior is maintained by the energy released in the conversion of hydrogen to helium. This process, where lighter elements are transformed to heavier elements, is called fusion. The helium nucleus is somewhat lighter than the four hydrogen nuclei it was made from, and the tiny excess mass (ΔM) is converted to energy according to the famous Einstein formula $E = \Delta M c^2$. In this way the star can keep its interior hot although it continuously loses energy by shining. Fusion is a very efficient way of producing energy, and physicists work hard to find a way to use this as an energy source also on earth. The sun has shone steadily for five billion years fusing hydrogen in its core, and it will continue to do so for another five billion years.

Eventually, however, all the hydrogen in the stellar core will be used up. Fusion stops, the pressure drops, and gravity forces the core to shrink. This makes the core temperature increase and when it is high enough, in this case $\sim$ 200 million degrees, fusion starts again. This time helium is converted to carbon (and oxygen). In the meantime, hydrogen is burnt in a shell around the central core. This is as far as our own sun will go. More massive stars

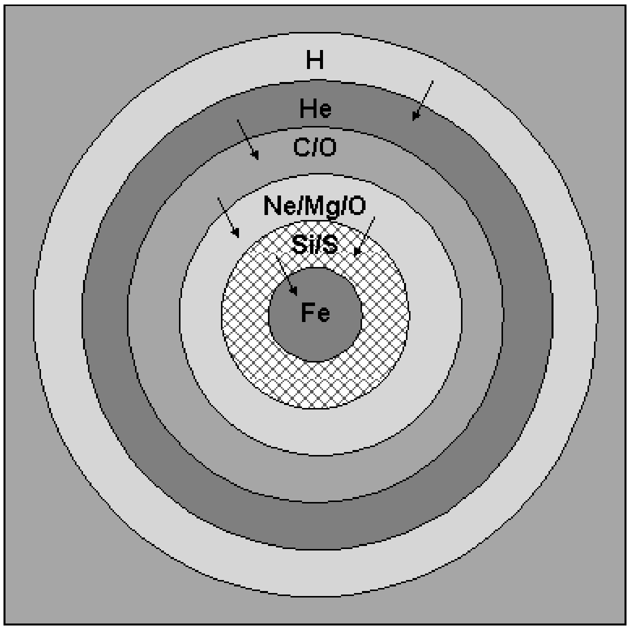

Figure 2.1: At the late stages of a massive star's life, the inner parts have an onion-like structure with heavier and heavier elements closer to the center.

are needed to fuse even heavier elements, because the interior has to be squeezed to very high temperature and pressure by the gravity to allow fusion of heavier elements. As the electric forces between the positively charged nuclei try to keep them apart, high pressure and temperature are needed to get them close enough for the strong nuclear force to make them fuse. Massive stars can do this. As the central fuel is exhausted the core shrinks and heats up until it can ignite the ashes, and still heavier elements can be fused. In this way the fusion proceeds via neon, magnesium, silicon, sulphur and finally to iron.

The star has now an onion-like structure (Fig. 2.1): an iron core is surrounded by a shell of silicon burning and more layers of lighter and lighter elements follow all the way out to the original hydrogen atmosphere. Now, this is how the elements are produced! Fusion not only keeps the star hot enough to prevent gravitational implosion. Fusion not only keeps the star shining. Fusion actually makes the heavy elements in the universe. Hydrogen and helium, the two lightest elements, were created in the early universe, during the first three minutes following the Big Bang. Nearly all other elements have been produced by fusion in stars. This can take place calmly within the deep interiors of evolving stars (hydrostatic nucleosynthesis) or fiercely in the supernova explosions themselves (explosive nucleosynthesis). For us, a carbon-based life-form breathing oxygen, the nucleosynthesis is certainly an interesting aspect of the life of massive stars, as are the supernova explosions that expel the freshly synthesized material into the interstellar medium, where it can be recycled to form new stars and planets.

The most efficient stage of fusion is the very first step, from hydrogen to helium. Fusing heavier elements is increasingly less efficient as the mass deficit (ΔM) gets smaller. Considering also the fact that hydrogen is by far the most common element in the universe, we are not surprised to see most stars in the long lived hydrogen burning stage. At late burning stages, from carbon burning and onward, the major part of the released energy comes out as neutrinos. These particles easily escape right through the star, and thus do not contribute to the internal pressure. The time-scales for advanced nuclear burning are short. As an example, a 25 $M_\odot$ star model predicts the following time scales (Weaver & Woosley 1980a): hydrogen burning $\sim$ 7 million years, helium burning $\sim 500,000$ years, carbon burning $\sim$ 600 years, neon burning $\sim$ 1 year, oxygen burning $\sim$ 6 months, and silicon burning $\sim$ 1 day.

Thus the nuclear burning proceeds at a more and more violent pace, but little is seen on the surface of the star. It takes time for the light produced in the center of the star to diffuse all the way to the surface. For the sun, the light we see escaping from the surface was actually produced in its center about a million years ago. Therefore, the short timescales involved for the late fusion stages in the central regions make them invisible to the surface of the star. The changes inside the star simply have no time to affect the observable appearance of the star until the explosion itself reveals what has been going on. Therefore, unless future astronomer can learn to detect and decipher the neutrino signals from evolved stars, we will never be able to predict when a supernova explosion will occur. For there comes an end. Stars do not live forever. Iron (^{56}Fe) is the most stable nucleus, so fusion of ^{56}Fe to heavier nuclei will not release more energy. When the stellar core is made up of iron-group elements, there is no way to keep up the internal pressure. Gravity always wins in the end.

2.2 Why do they explode?

The end is near. With a fully developed iron core the dying star cannot maintain the internal pressure to prevent a catastrophic gravitational collapse. At this point the central core of ~ 1.5 $M_\odot$ is only about 1000 km in radius and has a temperature of a few billion degrees.

The pressure supporting the very dense core from gravitational collapse at this time is not the normal heat pressure anymore, but is dominated by the laws of quantum mechanics. The electrons in a relativistic, partially degenerate electron gas cannot be squeezed together more tightly than this. But this pressure can only support a core mass smaller than a certain critical value, the Chandrasekhar mass. Outside the core, there is still fusion going on. In the shell just above the iron core, silicon is fused to iron. This supplies the core with more material until it becomes heavier than the Chandrasekhar mass. Moreover, at these high temperatures ^{56}Fe is photodisintegrated, broken apart by energetic gamma-rays. Dismounting this heavy nucleus drains energy from the core, just as fusing it together released energy. Simultaneously, the protons in the core capture electrons and transform to neutrons. This decreases the electron gas pressure, and triggers the collapse.

The core collapses rapidly (in less than a second) until it reaches truly enormous densities exceeding that of nuclear matter ($\gtrsim 10^{14}$ g cm^{-3}). At this phase the matter is supposed to "stiffen" as nuclear forces between the neutrons come to play. The infalling material "bounces" as it hits the stiff core and thus the collapse is halted. A shock wave is built up and starts to propagate out from the core. We are left with a newly formed compact neutron star in the center, and a shock wave on its way outward, while the very outer parts of the star are still unaware of the drama taking place in the center.

For the last decades, it has been a major problem for supernova researchers to understand how this bounce at supra-nuclear densities is actually turned into an explosion of the entire star. Computer models did not succeed very well in making the (model) star explode. In most models the shock has simply been to weak to lift off the stellar envelope at the observed 10,000 km s^{-1}. This is because the shock loses energy due to photodisintegration of ^{56}Fe, as well as to escaping neutrinos, on its way to the surface. Generally, the initial shock stalls long before it reaches the stellar surface. In this case, all the matter falls back toward the center and accretes onto the neutron star. Again, there is a limit to how massive a neutron star can be. The pressure support is a complicated mix between quantum mechanical pressure and nuclear forces. The exact maximum mass of a neutron star is unknown, but is probably no larger than 2 – 3 M$_\odot$. If the infalling matter makes the mass of the neutron star exceed this limit, it will implode into a black hole. No supernova explosion would result.

But supernovae do explode. Instead of this prompt explosion mechanism, the most popular model today is a delayed explosion. This involves the copious amounts of neutrinos created in the collapse. Although these particles interact very weakly with matter, there are so many of them that even a feeble interaction (~ 1 % of the energy) could revive and amplify the shock to set off the explosion. Models involving neutrino heating have indeed succeeded in exploding model stars (Herant et al. 1994), although the details of neutrino interactions at these high temperatures and densities are not particularly well understood.

There is still a possibility that a black hole will form in the case of a successful supernova explosion. After the neutron star has formed, and after the shock has started to move outward, there might still be matter falling back onto the neutron star (Woosley & Weaver 1995). This fall-back might again provide enough matter to trigger the collapse of the neutron star. In such a case, we will have a normal supernova explosion accompanied by the formation of a black hole.

Given the uncertainties in the explosion mechanism some researchers take a more pragmatic approach. In their models, they artificially trigger the explosion with a given energy. Given a progenitor model, they can then explore the nucleosynthesis and dynamics of the explosion. Their results can in turn be used in spectral synthesis codes which produce supernova light curves and spectra that ultimately are to be compared to observations.

Unknown parameters in such a pragmatic approach are the total energy of the explosion and the position of the mass-cut. The total energy can be constrained by the observed velocities in supernovae. To get 5 M$_\odot$ of matter moving at 10,000 km s^{-1} requires an energy of a few foe (1 foe = 10^{51} ergs = 10^{44} Joule, the typical energy of a supernova). The mass-cut divides (in mass coordinates) the matter that is ejected from the matter that will form the compact object. This quantity can be constrained observationally by determining the mass of ejected iron-peak elements in the explosion. In this sense, observations give important clues to the explosion mechanism of supernovae.

2.3 Why do supernovae shine?

As the shock breaks out of the stellar surface the star can brighten as much as 100,000 times. A "new star" is shining on the sky. The supernova stays bright for weeks as the thermal energy from the explosion diffuses out through the gas. The shape of the early light curve of the supernova is mainly determined by the energy of the explosion and by the progenitor's radius and mass. But as the supernova expands it rapidly cools, and thus gets fainter. If this was the full story in the life of a supernova, it would fade from visibility after only a few months. There are, however, more effects at play at late times. The supernova may be lit up by radioactivity, by circumstellar interaction or perhaps by pulsar powering.

2.3.1 The late time emission from core collapse supernovae

In the explosion itself, large amounts of the iron-peak element ^{56}Ni (nickel-56) are produced. This nucleus is radioactive and quickly decays to radioactive ^{56}Co (cobalt-56), with a half life time of 6 days. ^{56}Co further decays to stable ^{56}Fe (iron-56) with a half life of 77 days. It is the latter decay, $^{56}\mathrm{Co}\rightarrow^{56}\mathrm{Fe}$, that keeps the supernova shining after a few months. In the decay, energetic gamma-rays (and positrons) are released in the interior of the supernova ejecta. The gamma-rays are scattered by electrons in the expanding gas, and are down-graded in energy. This energy is eventually radiated as optical light (e.g., Kozma 1996). The resulting (bolometric) light curve will have the supernova brightness drop by 50% each 77 day period. As the ejecta expand, some gamma-rays will eventually be able to escape directly. The explosion of SN 1987A provided ample evidence for this process. Not only did the late light curve follow the characteristic decay time of ^{56}Co (Kozma & Fransson 1992), but space-borne observations also detected the gamma-rays themselves (Matz et al. 1988). That core collapse supernova light curves fade with the cobalt decay time scale at late phases was anticipated theoretically (Colgate & McKee 1969; Weaver & Woosley 1980b) and has been observed also for several other supernovae (Barbon, Cappellaro, & Turatto 1984; Turatto et al. 1990; Patat et al. 1994). This actually makes it possible to determine the amount of ^{56}Ni ejected from a supernova. We simply have to measure the absolute luminosity at late phases, if it is clear that radioactive decay dominates the emission. For SN 1987A the measured amount was 0.072 ± 0.018 $M_\odot$ (Suntzeff & Bouchet 1990), and values close to that number have been found also for a few other supernovae, for example: SN 1990E ($0.073^{+0.018}_{-0.051}$ $M_\odot$, Schmidt et al. 1993), and SN 1992H (~ 0.075 $M_\odot$, Clocchiatti et al. 1996). Similar values were obtained for SN 1979C and SN 1980K (Fransson & Chevalier 1989). Why all these supernovae happened to eject 0.07 $M_\odot$ is not well understood.

One supernova, SN 1991G showed evidence for a smaller amount of ejected ^{56}Ni, ($0.024^{+0.018}_{-0.010}$ $M_{\odot}$, Blanton et al. 1995), and below we will see that there are more cases like that (Papers I and VI).

Observing ^{56}Ni represents direct evidence of supernova nucleosynthesis. Determining the ejected mass of ^{56}Ni is also an important probe of the explosion mechanism itself. As nickel is formed in the very center of the exploding star, observing the ejected amount constrains the mass-cut. It can be used to investigate how much matter falls back after the initial launch of the shock wave.

Later on, when most of the ^{56}Co have decayed, more long-lived radioactive species take over the powering. After about 1000 days the decay of ^{57}Co becomes important, and even later ($\gtrsim$ 2000 days), the supernova is lit up by $^{44}\mathrm{Ti}\rightarrow^{44}\mathrm{Sc}\rightarrow^{44}\mathrm{Ca}$. The produced ^{44}Ti (titanium-44) decays to ^{44}Sc (scandium-44) with a half life time of 60 years. ^{44}Sc then quickly decays to stable ^{44}Ca (calcium-44) in only 4 hours. In fact, the only radioactively powered supernova which we have been able to follow to such late phases is SN 1987A, as is reported in Paper III. Gamma-rays from the decay of ^{44}Ti have also been seen from the supernova remnant Cas A (Iyudin et al. 1994), the remnant of a supernova that exploded in our galaxy only about 300 years ago, although it seems that it was not recognized by contemporary astronomers.

Another possible source of excitation for the supernova might be circumstellar interaction. At late stages, a massive star loses large amounts of mass through stellar winds. This material surrounds the progenitor star when it eventually explodes as a supernova. When the supernova ejecta, typically thrown out at velocities of 10,000 km s^{-1}, hit the circumstellar material (CSM), energy is released (Chevalier & Fransson 1994). This energy can keep the supernova shining for many years. It offers the possibility to investigate both the supernova ejecta, and the old progenitor stellar wind. Two examples are SN 1979C and SN 1988Z, both still shining in the optical (Turatto et al. 1993b; Fesen & Matonick 1993; Fesen et al. 1999).

Lastly, I will briefly mention pulsar powering of supernovae at late phases. Neutron stars (pulsars) are believed to form in supernovae. If these pulsars are active from birth, they may also contribute to the energy budget of the supernova. An observational signature would be emission lines that broaden with time (Chevalier & Fransson 1992). No evidence for this phenomena has, however, been found to date. In particular, for the well studied SN 1987A, the pulsar, if present, must be contributing much less to its environment than the pulsar in the Crab nebula.

Most supernovae discovered are too faint to be observed for more than a few weeks. The brighter (closer) ones can be followed for a few years, while some of the supernovae interacting with their CSM can shine for decades. There is, however, even older evidence for supernova explosions, the supernova remnants. I have already mentioned the Crab nebula, the remnant of the SN 1054 explosion. The ejected material of the exploded star is still shining brightly after 945 years. This supernova remnant is powered by the Crab pulsar in the middle of the nebula. More common among supernova remnants is that they are lit up by the interaction of the fast ejecta with the circumstellar or interstellar medium.

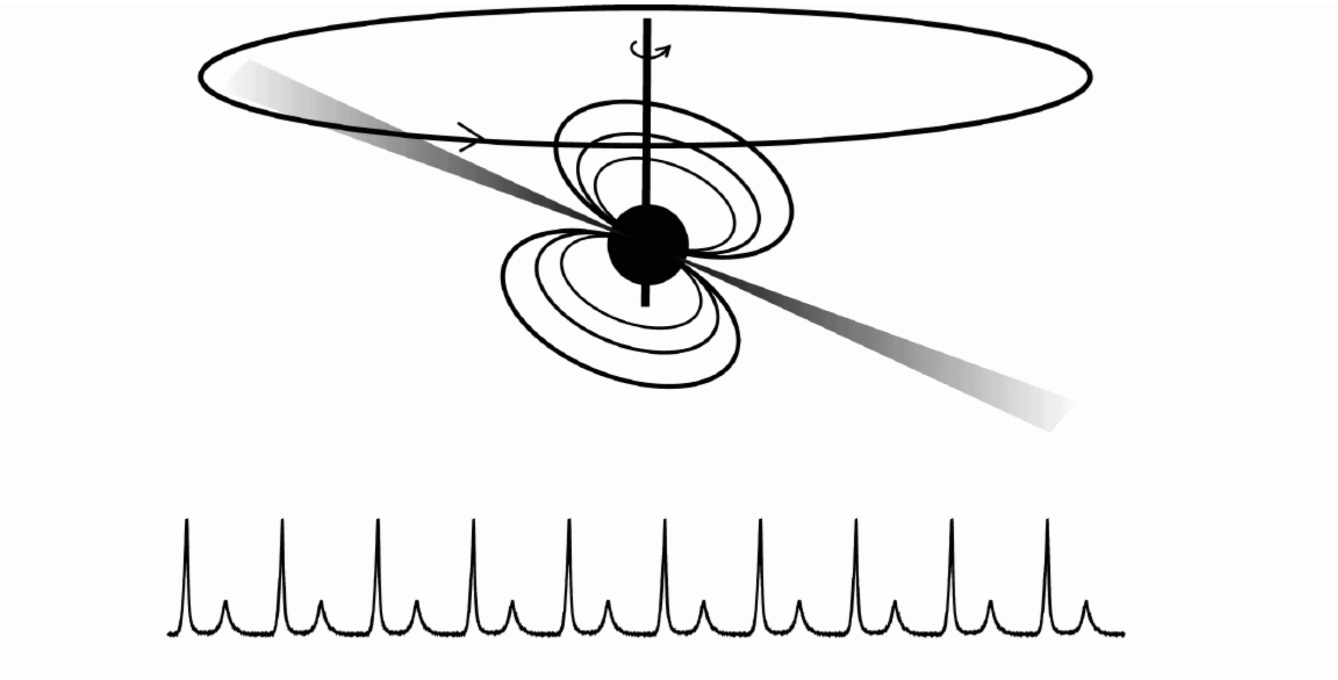

Figure 2.2: The lighthouse model of pulsar emission. The neutron star quickly rotates and shines a beam of radiation along the direction of the magnetic poles. Below are the actual pulses from the Crab pulsar, observed in the far-UV with the Hubble Space Telescope (Paper IV). Graphics: BEM

2.4 The compact objects; Neutron stars and Black holes

In the collapse of the stellar core, matter is compressed to enormous densities. The electrons are "squeezed into" the protons to form a large ball of densely packed neutrons. This neutron star is like a 10 kilometer large atomic nucleus. At a density of $\gtrsim 10^{14}$ g cm^{-3}, a single teaspoonful of this material would weigh about 3 billion tons, as much as an ordinary mountain. Quantum mechanical effects will determine the properties of the interior, and trying to understand these objects forces us to stretch the physics far outside of the realms we meet in the laboratories on earth. Observationally, neutron stars were first identified as pulsars. These are the beacons of the universe. Pulsars carry superstrong magnetic fields and drag them along as they quickly rotate around their axis. Flashes of radio emission are sent toward the observer for every rotation of the neutron star. The result is a periodic, pulsating signal (Fig. 2.2).

The rotation is indeed very fast, the Crab pulsar rotates almost 30 times every second (actually 29.857275 times, see Paper IV). The period is also exceedingly stable; the pulsars are very accurate clocks. The slow-down rate of the Crab pulsar measured in Paper IV shows that it takes more than 75,000 years before the pulsar clock runs slow by a mere second. It was in fact the fast rotation of the Crab pulsar, and its stable period, that paved the way for the interpretation of pulsars being magnetized, rotating neutron stars (Gold 1968). More than 1000 radio pulsars are known today, but only five pulsars are known to pulsate also in the optical. Among them are the Crab pulsar in the Crab nebula, the Vela pulsar, and the pulsar in the supernova remnant SNR 0540-69.3. These associations of pulsars with supernova remnants also represent evidence for the theoretical picture of neutron star formation in supernovae. The detailed mechanism for the emission from pulsars is not clearly understood; the physics of relativistically moving particles in a strong electromagnetic field is far from trivial. Many models, however, seem to agree that the same mechanism must be responsible for the emission from the infrared up to the gamma-ray region (e.g., Lyne & Graham-Smith 1998), as the pulse profile is very similar in these energy bands.

As mentioned previously, a neutron star cannot be heavier than 2 – 3 $M_{\odot}$. The quantum mechanical pressure that supports the star can simply not match the gravitational forces if the neutron star mass exceeds this limit. If the mass grows larger than the limiting mass nothing can prevent the star from collapsing into a black hole. A black hole is a rather bizarre astrophysical object. All that remains is basically the gravitational field of the collapsed stellar core, but (at least mathematically) all the matter has been squeezed into a nothingness called a singularity. By definition, black holes do not emit light by themselves, but can be detected and studied by their interaction with outside matter. While black holes were mainly studied as a strange mathematical consequence of general relativity some 50 years ago, today most astronomers regard them as an astrophysical reality.

2.5 How do we observe them - and what can we learn

Much of my research is based on observations of supernovae at late phases with ground based telescopes. As the weather in Sweden is not optimal for astronomical observations, these have been conducted abroad. On the northern hemisphere I have used the 2.56m Nordic Optical Telescope (NOT) on the top of the volcano island La Palma, Spain. In the southern hemisphere I have used the European Southern Observatory (ESO) telescopes in the Andean mountains on La Silla (3.6m, 2.2m, NTT) and Paranal (Very Large Telescope (VLT)), Chile. These telescopes are all situated at about 2600 meters above sea level at remote sites, ideal for astronomical observations. The observations include photometry, to get the light curves, as well as low dispersion spectroscopy for more detailed physical information, such as chemical compositions, expansion velocities, temperatures, and densities. The light is registered on a modern electronic detector, a Charge-Coupled-Device (CCD) which is very efficient in collecting every single particle of light (photon) gathered by the telescope. The electronic format is also well suited for further computer processing. Reducing and analyzing the data is the major part of an observing astronomer's job.

Figure 2.3: It's black and It looks like a hole. I'd say it's a black hole. (Copyright 1999 by Sidney Harris.)

A few supernovae per 100 years are expected to explode in an average galaxy. Today, due to large automatic supernova searches, many new supernovae are discovered each year. While 27, 13 and 34 supernovae were seen in the years 1968, 1978 and 1988, respectively, in 1998, 160 supernovae were discovered. In fact, of the $\sim$ 1600 supernovae seen during the 20th century, more than 50% were discovered the last decade. The major part of these are too far away to be studied in detail, and most supernova observations are limited to early times when the supernova is bright. To observe supernovae at late times requires large telescopes but can be well worth the effort. Only at late times are the supernovae transparent enough to reveal the products of the massive star's nucleosynthesis. Also the late spectra of the optically thin supernova are often easier to interpret than spectra at early phases. Late time light curves can reveal the presence of freshly synthesized radioactive material, and only at late times can we hope to see any signs of the centrally formed compact objects.

At very late phases, most of the supernova emission will emerge in the infrared part of the spectrum. Space observatories are needed to access this wavelength range. This thesis involves a study of SN 1987A with the Infrared Space Observatory (ISO), and also a study of the Crab nebula and its pulsar in the far-ultraviolet using the Hubble Space Telescope (HST). The space-borne observations are necessary to get a comprehensive, coherent picture of these objects, where most of the interesting physics show up in the wavelength windows hidden from the ground.

In the future, large telescopes in space and on the ground will allow us to study supernovae in even greater detail and for even longer times. As we probe deeper into space, a larger sample is also available. Much remains to be understood.

It can be worth emphasizing that although the theoretical models give a very persuasive and detailed picture of element formation in supernovae, more observational evidence is needed to confirm this view. It has actually proved to be rather difficult to acquire abundances from supernova spectra. This is mainly due to the fact that supernovae are far from being homogeneous (McCray 1996). The low temperatures of the ejecta at late phases further complicates this task. Therefore, rather elaborate modeling is required to determine abundances in supernovae (Kozma & Fransson 1998a,1998b). More evidence for nucleosynthesis in supernovae comes from observations of supernova remnants. Oxygen-rich supernova remnants, as Cas A and N132D, show filaments which seem to be made up by elements expected from unmixed debris from an exploded massive star (Chevalier & Kirshner 1979; Blair, Raymond, & Long 1994; Hughes et al. 1999).

Likewise, there are many theoretical reasons to believe that neutron stars and black holes are indeed formed in supernova explosions. Associations like the pulsar in the Crab nebula argue in favor of this, but there is still no hard observational evidence for the formation of these compact objects in a supernova. Following supernovae to very late phases might eventually allow us to actually observe these exotic objects form.

Lately, the connection between (some) supernovae and (some) gamma ray bursts (GRB) have been suggested by the occurrence of SN 1998bw at the same time and location as GRB 980524 (Galama et al. 1998; Patat et al. 2000 (Paper VIII)). This very interesting connection certainly requires further studies. There are many questions left for the supernovae to answer.

Chapter 3

The thesis

In this section I will discuss some of the areas of research I have been involved in during my PhD-studies. I want to put the four papers that build up this thesis in context and also discuss some of their implications. For details, the reader is referred to the publications themselves.

3.1 A bright supernova fades away (Paper I)

On July 29, 1994 a bright supernova was discovered in the galaxy NGC 4041 in the constellation Ursa Major (Cortini & Villi 1994). About two weeks after discovery it reached its maximum brightness of $V \sim 13.3$. This is bright enough to be seen with an amateur telescope. The supernova was quickly classified as a Type II supernova (Bragaglia, Munari & Barbon 1994), the explosion of a massive star. Early spectroscopy showed narrow emission lines which further called for a classification as a supernova Type IIn (Filippenko & Barth 1994; Cumming, Lundqvist, & Meikle 1994).

At Stockholm Observatory, Robert Cumming, Peter Lundqvist and myself had some interest in Type IIn supernovae, which we believed to show evidence for interaction with the progenitor's stellar wind. We decided to take a closer look at SN 1994W, to see if it could tell us something about the Type IIn phenomenon. It turned out to tell us something completely different.

Robert Cumming quickly contacted the Isaac Newton group of telescopes on La Palma in the Canarian Islands, to get service observations for this supernova. In this way, we obtained spectroscopy from the William Herschel and the Isaac Newton telescopes. Photometry on four epochs were collected using the Jacobus Kapteyn Telescope. The spectroscopy was reduced by Robert Cumming and showed the evolution of the narrow emission lines seen in this supernova. In Paper I, we suggest that these lines were formed in a thin, circumstellar high-density shell close to the supernova. This analysis was mainly done by Peter Lundqvist. The most interesting feature of SN 1994W was, however, not the narrow lines, as we had first expected. Instead, the photometry revealed a very unusual explosion.

The photometry from the service observations were followed up with our own observations at the Nordic Optical Telescope on La Palma. In total, we obtained photometry of SN 1994W from 125 days to 197 days past the explosion. In late 1995 an IAU information bulletin on variable stars caught our attention. In this, Tsvetkov (1995) reported on an unprecedented brightness decline at late stages for SN 1994W. We realized that this was a very interesting supernova indeed. In fact, together with Bruno Leibundgut, Jason Spyromilio, Claes Fransson and others, I was already involved in a search for supernovae with this kind of behavior, using the ESO La Silla telescopes (see §3.2). I immediately started to work on our photometry.

It is far from trivial to measure the brightness of a faint point source positioned on a complex background, such as a galaxy. Normal aperture photometry, which simply adds all the flux inside a given aperture and subtracts the background just outside it, is known to be inadequate for these situations (e.g., Turatto et al. 1993a, see also Paper II). The best way is therefore some kind of point spread function (PSF) subtraction. The image of a star on the CCD has a certain shape, the PSF, depending on the instrument and the atmosphere. Determining the PSF of well exposed stars outside the galaxy, and fitting this to the supernova should minimize the errors. Although many software packages for photometry in crowded fields exist today (e.g., DAOPHOT, DOPHOT, ROMAFOT), none of them is optimized to the circumstances experienced in supernova research. In particular, it is of importance to be able to fit the background component simultaneously with the supernova PSF. Luckily, I knew that a new software package was developed for this task at Lund Observatory. Stefan Spännare had just presented the POLYFIT software in his Licentiate thesis (Spännare 1997). I spent some days at Spännare's residence in Lund to get acquainted with the software, and then used it for our images of SN 1994W. This allowed us to fit a PSF to the supernova and simultaneously fit the background slope. The analysis confirmed that SN 1994W had faded in an unprecedented manner. After the plateau stage, during which this supernova was among the most luminous supernovae ever, it got 25 times fainter in merely 12 days. The distance to NGC 4041 is well known, so this meant that SN 1994W became substantially less luminous than other supernovae at these late phases. At 197 days past explosion, SN 1994W was 27 times fainter than the well studied SN 1987A at the same epoch. As the late time emission is supposed to come mainly from the radioactive decay of ^{56}Co $\rightarrow$ ^{56}Fe, we concluded that SN 1994W must have ejected very little ^{56}Ni (the parent nucleus of ^{56}Co) in the explosion.

The slope of the light curve after $\sim$ 120 days was also very steep for SN 1994W, it decayed faster than the half life time of ^{56}Co. In Paper I, we discuss the possible reasons for this; dust formation might dim the supernova at later times or circumstellar interaction might enhance it in the early phases. In either case the amount of ejected ^{56}Ni is very low, $\lesssim$ 0.015 $M_{\odot}$. This was in fact the lowest amount of ejected ^{56}Ni ever measured for a supernova.

3.1.1 Evidence for Black hole formation?

We know that ^{56}Ni is synthesized in the very center of the exploding star. The amount of ejected ^{56}Ni thus tells us something about the explosion mechanism itself. In Paper I we argue from the observed shape of the early light curve that the progenitor was a very massive star. Such stars are expected to produce significant amounts of ^{56}Ni, so the low mass of ejected ^{56}Ni observed in SN 1994W is an indication that much of the produced nickel fell back onto the central object after the launch of the shock. If enough mass falls back, the neutron star will collapse to a black hole. In fact, theoretical predictions for the formation of a black hole in a supernova explosion suggests that the main observational characteristic for such a phenomenon is a supernova with a light curve that quickly plummets to very low luminosities (Woosley & Timmes 1996). This is exactly what we see in SN 1994W. The light curve of SN 1994W might actually be consistent with a supernova where all the synthesized ^{56}Ni fell back into a black hole. The late time emission could then come from the residual thermal energy diffusing out from the mantle (Weaver & Woosley 1980a), or possibly also from some circumstellar interaction. We might see, for the first time, the formation of a black hole in a supernova explosion.

I have also participated in the study of another supernova, SN 1997D (Turatto et al. 1998 (Paper VI)). Also this supernova ejected very low amounts of ^{56}Ni, no more than 0.002 $M_\odot$. It was modeled as the explosion of a 26 $M_\odot$ star. Again, such a star is expected to produce significant amounts of nickel, so the measured low amount indicates that fall-back has been important also for this supernova. The high progenitor mass of SN 1997D has, however, recently been disputed by Chugai & Utrobin (2000), who modeled this supernova as a low energy explosion of a 8 – 10 $M_\odot$ progenitor. Such a star would not create much ^{56}Ni at all, and fall-back would not be needed to account for the observed low amount of nickel.

To summarize, SN 1994W and SN 1997D have the hitherto lowest measured amounts of ejected ^{56}Ni. If nothing else, this shows that core collapse supernovae eject different amounts of ^{56}Ni, which is important to know to trace where the iron in the galaxy comes from. If these supernovae originated from massive progenitors, which originally ejected substantial amounts of ^{56}Ni, then some material must have fallen back onto the neutron stars after the explosion. Depending on the initial mass of the neutron star, the amount of fall-back, and on the maximum mass allowed for a neutron star (i.e., the equation of state of the dense matter), this may have triggered a collapse to a black hole. We can not, of course, prove that this happened for SN 1994W or SN 1997D, but the observations are at least consistent with this possibility. Further studies of supernovae at late phases are needed to establish whether black hole formation in supernovae indeed occurs.

3.2 The late time emission from a Type Ib supernova (Paper II)

Several different mechanisms can be at work to keep supernovae shining at late phases. Radioactivity, circumstellar interaction or possibly pulsar powering would all show characteristic signatures in the late time photometry and spectroscopy of the supernovae. On the theoretical side, a lot of work has been done at Stockholm Observatory to model the emission from core collapse supernovae at late times (Kozma & Fransson 1998a,1998b, see also Fransson & Chevalier 1989; Chevalier & Fransson 1994; Fransson 1994; Houck & Fransson 1996).

Observationally, however, rather few core collapse supernovae have been followed to late times. Therefore, an observational monitoring program using the ESO La Silla telescopes was initiated, to follow core collapse supernovae to late phases. Jason Spyromilio and Bruno Leibundgut at ESO were the two main drivers behind this project, and they also conducted the first observing runs. Later on, I took the main responsibility for writing proposals, observing and reducing the data. I conducted five observing runs on La Silla for this project and during a six-month studentship at ESO headquarters in Garching, 1997 – 1998, I worked on the data for one of the supernovae from this sample, SN 1996N.

SN 1996N was discovered on March 12 in the galaxy NGC 1398, 70 million light years away (Williams & Martin 1996). We followed the supernova from Chile until 337 days past explosion. From an early spectrum we could classify it to be a Type Ib supernova, with no sign of hydrogen in its spectrum. Later spectra, reduced by Bruno Leibundgut, were consistent with this, displaying the usual strong emission lines of intermediate mass elements, such as oxygen and calcium (see Fig. 1.3). Again, much effort was directed to get accurate photometry of the supernova. An additional complication with the observations utilizing focal reducers (EFOSC-like instruments), is that the PSF is not uniform over the field. We used two complementary methods to acquire the magnitudes of the supernova: PSF-fitting using DOPHOT (Schechter, Mateo, & Saha 1993), and a template subtraction method using frames of the galaxy taken after the supernova had faded from visibility. The light curve turned out to be rather steep (~ 1.75 magnitudes per 100 days); the luminosity dropped faster than the decay rate of ^{56}Co (0.98 mag/100 d). We interpreted this as due to leakage of gamma-rays. As the progenitor was depleted of its massive hydrogen envelope, all the gamma-rays from the radioactive decay were not trapped in the ejecta. With the continuing expansion, more and more of the gamma-rays could escape and the optical light curve thus fell below the light curve expected for full trapping.

We further noted the similarity of the spectra of SN 1996N to those of the Type IIb SN 1993J. This triggered us to speculate about the origin of the spectral feature seen redward of [O I] $\lambda\lambda$ 6300,6364 (see Fig. 5 in Paper II). It was attributed to Hα in SN 1993J, and the same identification in SN 1996N would make up the first evidence of hydrogen in a Type Ib supernova. Such a finding would strengthen the belief that Type II and Type Ib/c supernovae are related, and differ only in the degree of depletion of the hydrogen envelope (e.g., Filippenko 1997).

Finally, we noticed that many of the emission lines in SN 1996N were blueshifted by about 1000 km s^{-1} with respect to the parent galaxy. This was seen also in SN 1993J where a number of possible explanations were offered by various authors: optical depth effects (Wang & Hu 1994), line blending (Houck & Fransson 1996) and asymmetries in the supernova (Spyromilio 1994). Another possible scenario is dust formation, as was seen in SN 1987A (Lucy et al. 1989). In Paper II, we discuss all these scenarios without finding any really satisfying solution. Large scale asymmetries in supernovae have been proposed to be responsible for the high space velocities observed for pulsars. Such asymmetries might also account for the measured early polarization of Type II supernovae (Wang et al. 1996), and are often mentioned in GRB-supernova models. This may also be the explanation for the observed blueshifts in SN 1996N.

More core collapse supernovae have to be followed to late times to judge whether the blueshifts of the emission lines is a common phenomenon. If an asymmetric explosion is in fact the explanation, redshifts would be as common. To date, the sample of hydrogen deficient core collapse supernovae observed to late phases is very small. SN 1996N is indeed one of the best studied objects and is therefore useful for comparisons. This was, for example, seen in the paper on SN 1998bw by Patat et al. (2000 (Paper VIII)).

3.3 Mass of ^{44}Ti in SN 1987A (Paper III)

SN 1987A in the Large Magellanic Cloud was discovered on 23 February 1987. It was the brightest supernova in modern times and allowed astronomers to make much more detailed observations of a supernova than ever before. In particular, it was possible to observe the emission from a very wide wavelength range, and to very late phases. At Stockholm Observatory, Cecilia Kozma, together with Claes Fransson, has developed a detailed spectral synthesis code for the emission from the ejecta of this supernova (Kozma 1996; Kozma & Fransson 1998a,1998b). At very late times ($\gtrsim$ 2000 days), the radioactive decay of ^{44}Ti$\rightarrow^{44}$Sc $\rightarrow^{44}$Ca dominates the emission from the supernova (Woosley, Hartmann, & Pinto 1989; Kozma & Fransson 1998a). The half life of radioactive ^{44}Ti is 60 years (Ahmad et al. 1998; Görres et al. 1998). ^{44}Sc, in turn, quickly decays to ^{44}Ca. Most of the emission at these stages emerges in the far-infrared region (Kozma 1999), in particular in the emission line of Fe II at 26 μm (1μm = 10^{-4} cm). SN 1987A is the only supernova for which one has been able to follow the radioactive decay input to these late phases, and thus gather information about the released amount of titanium. [Fe II] 26 μm is not observable from the ground, as the infrared emission cannot penetrate the earth's atmosphere. However, it was accessible to the Infrared Space Observatory (ISO) which observed the infrared universe from 1995 to 1998. The ISO satellite carried a rather small mirror, which made it insensitive to distant supernovae. SN 1987A was the only supernova one could expect to detect with ISO. Here, I will discuss the observations with the Short Wavelength Spectrograph (SWS), which operated in the wavelength regime 2.38 – 45.2 μm and thus covered the Fe II line at 26 μm. Several groups made several attempts to detect [Fe II] 26 μm with SWS. However, no emission from the supernova was ever seen.

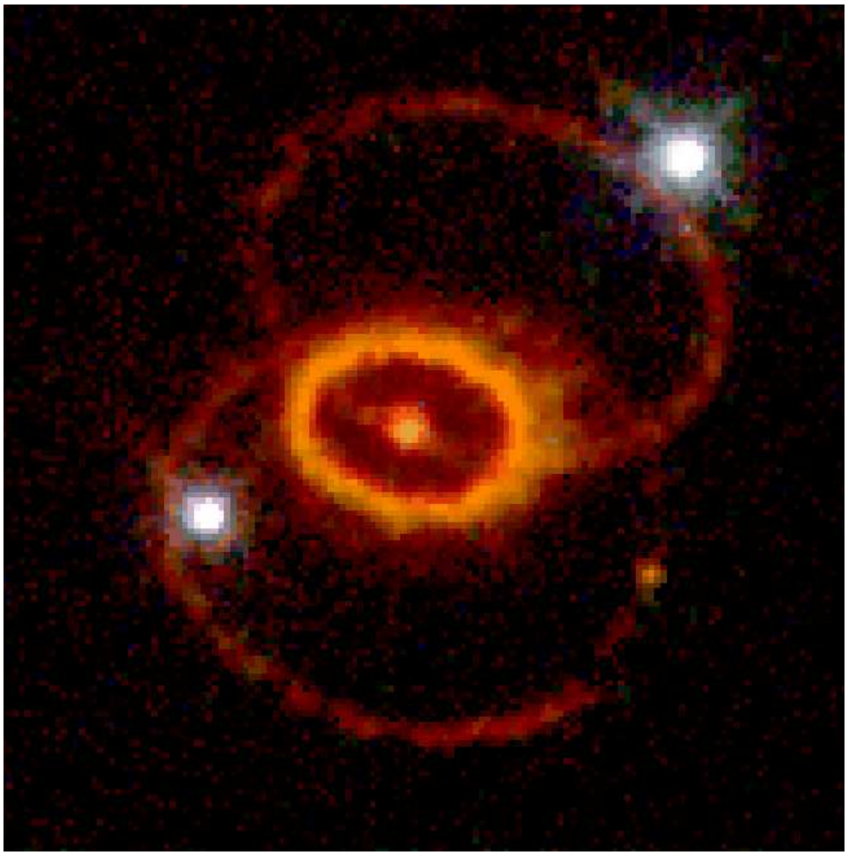

Figure 3.1: SN 1987A in the Large Magellanic Cloud. This image was taken with HST and primarily shows the rings outside the supernova. These were produced by stellar winds from the progenitor star prior to the explosion. The supernova ejecta is the blob in the middle of the innermost ring. Courtesy of NASA.

The dog that barks in the night

Sometimes, however, even a non-detection can be a useful result. As our models predicted that most of the ^{44}Ti excited emission should emerge in the observed region, we could use the non-detection to constrain the amount of ejected ^{44}Ti from the supernova. Peter Lundqvist made an effort to assemble the SWS data of SN 1987A that were dispersed between different research groups. Thereafter, we wanted to push down the upper limit on the emission from [Fe II] 26 μm as low as possible. In September 1998, I spent a week at the ISO Spectrometer Data Centre at Max Planck Institute für extraterrestrische Physik in Garching, Germany, to carefully reduce the data. This meant interactively going through all the individual steps of the data reduction pipeline. Particular care was given to the dark corrections.

The best observation was found to be the one conducted on February 4, 1998, 3999 days after the supernova exploded. In these data, we could verify that no emission was seen at 26 μm down to a very low flux level (1.4 Jy). Using the detailed time-dependent ionization models of Cecilia Kozma, we could use this upper limit to show that no more than 1.5×10^{-4} $M_\odot$ of ^{44}Ti were ejected from SN 1987A. This upper limit encapsulates our estimates of errors in distance, atomic data, and simplifications in the model such as instantaneous positron trapping and homogeneity. Our upper limit on the amount of ejected ^{44}Ti is not far from the values predicted in supernova models (Thielemann, Nomoto, & Hashimoto 1996; Timmes et al. 1996). As ^{44}Ti is created in the innermost regions of the star, such estimates are useful to constrain the various explosion mechanism assumptions used in theoretical nucleosynthesis models. For example, more asymmetric models with more entropy should produce a larger fraction of ^{44}Ti/^{56}Ni (Nagataki et al. 1998). Within the framework of these models, it should thus be possible to constrain the degree of asymmetry in the core of SN 1987A.

3.4 The optical/UV emission from the Crab pulsar (Paper IV)

As the outer parts of the star are violently expelled in the supernova explosion, the core collapses to a neutron star. For the most massive progenitors, fall-back onto the neutron star might force it to collapse to a black hole, as we discussed above for SN 1994W. Most supernovae should, however, leave a neutron star after the explosion. The most famous example, and one of the most studied objects in the sky, is the Crab pulsar in the Crab nebula, the remnant of SN 1054. Already in 1995 we applied for observing time on the Hubble Space Telescope (HST) to investigate the Crab pulsar in the far-ultraviolet wavelength regime. The emission in the far-UV cannot penetrate the earth atmosphere (thanks to the ozone layer), and thus an orbiting telescope was required for this observation. Our proposal was accepted and scheduled for the Faint Object Spectrograph (FOS) onboard the Hubble telescope. However, in February 1997, just before our scheduled observations, the astronaut crew on the space shuttle Discovery replaced FOS with the new Space Telescope Imaging Spectrograph (STIS). We had to rewrite the technical details for the new instrument and wait to be scheduled again. When we finally were approved time on STIS, scheduled for April 1998, it was noticed that the new near-infrared NICMOS instrument was leaking. This camera operated at very low temperatures, and as the cooling nitrogen was evaporating, the lifetime of the instrument was severely shortened. The HST observing time was rescheduled to use NICMOS as long as possible. Again, our Crab observations were postponed. In January 1999, NICMOS ran out of nitrogen, and STIS observations could start again. We finally got our observations on January 22, 1999.

In retrospect, the observations we achieved with STIS were much better than we could ever have gotten with the FOS. This is because STIS is a two-dimensional spectrograph which enabled an accurate background subtraction of the nebula, as well as observations of the nebula itself. In the far-UV (1140 – 1720 Å), the detector is a cesium iodide photocathode Multi-Anode Microchannel Array (MAMA), which offers a time-tag capability. This made it possible to resolve the emission from the pulsar also in time. In fact, reducing and analyzing these rather complex data benefits from some knowledge of the instrument and the data reduction pipelines. I spent six weeks at Goddard Space Flight Center, Maryland, USA in the early spring 1999, to work with the data. There I could interact with people in the STIS team, and in particular working with Don Lindler on the time-tag data was very valuable.

Our study provided the first spectrum of the Crab pulsar (in fact of any pulsar) in the far-ultraviolet regime. Together with our previous near-UV data (Gull et al. 1998 (Paper VII)) and new optical data obtained on Christmas Eve 1998 at the NOT, this provided us with the best spectrum ever obtained of a pulsar in the UV/optical regime. It must be emphasized that very few pulsars can actually be seen in the optical (e.g., Lundqvist et al. 1999 (Paper V)). In paper IV we showed that the intrinsic pulsar spectrum could be well fitted by a power law, $F_\nu \propto \nu^\alpha$, as has been proposed by various models. The best power law fit had a slope of $\alpha = 0.11$. We could also determine the amount of extinction toward the Crab nebula ($E(B-V) = 0.52$), and show that the properties of the dust are probably not very different in this direction, something that had previously been claimed. Moreover, the time-tagging capabilities of the instrument allowed us to determine the pulse period and the shape of the pulse profile in the far-UV (Fig. 2.2). The pulsar was found to rotate 29.857275 times every second, and the pulse profile in the far-UV was very similar to that previously found in the near-UV, although the primary pulse profile in the far-UV was measured to be marginally narrower than that in the near-UV (5%, 2σ).

3.4.1 The missing mass of the Crab nebula

One of the major reasons to do the HST observations mentioned above was to search for the "missing mass" of the Crab nebula. Based on the observed chemical composition, as well as on the presence of the neutron star, the mass of the progenitor was probably initially in the range 8 – 13 $M_\odot$ (Nomoto 1985). However, the observed mass of the filaments is less, 4.2 $\pm$ 1.8 $M_\odot$ (Fesen, Shull, & Hurford 1997). Moreover, the velocities of the observed filaments are on the order of 1400 km s^{-1}, which is also low for a supernova remnant. The total kinetic energy of this explosion is thus at least ten times lower than the canonical value measured for other supernovae (10^{51} ergs). Either SN 1054 was a very unusual supernova, or there is in fact an outer shell of fast moving matter still to be detected around the visible nebula. The outer shell hypothesis was put forward by Chevalier (1977) and many attempts have been made to detect this hypothetical shell ever since, but with no success (Fesen et al. 1997). This might, however, be due to the very low circumstellar densities around the Crab. If the missing mass has nothing to interact with, it will be difficult to detect in radio emission, where most studies have been conducted.

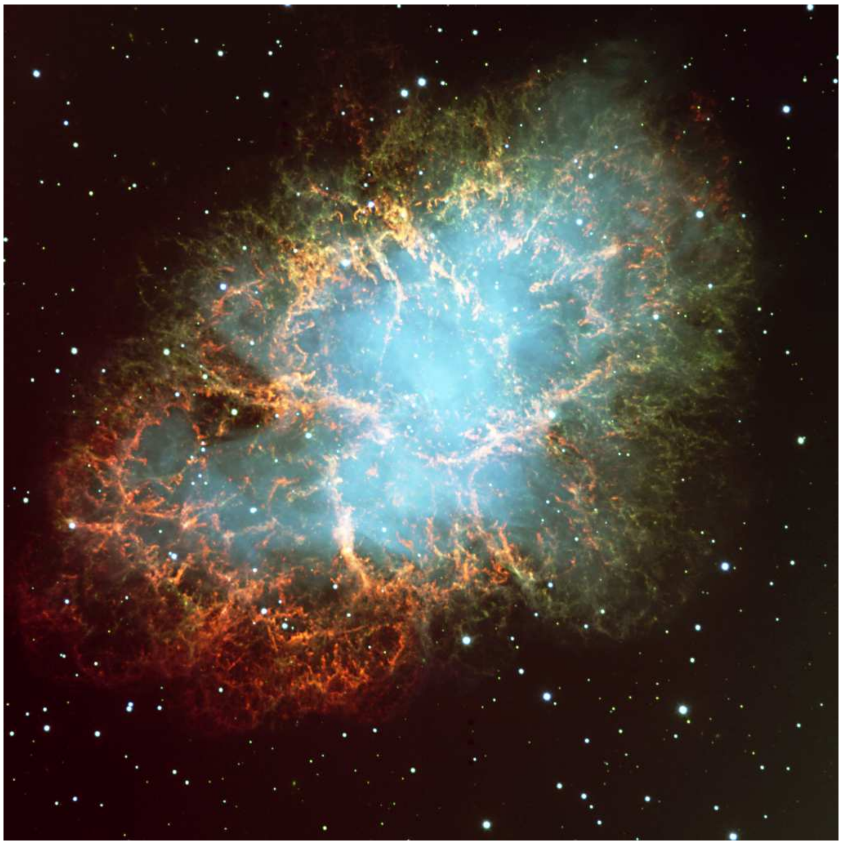

Figure 3.2: The Crab nebula. This image was taken at the VLT during FORS2 commissioning. Courtesy of ESO.

Lundqvist, Fransson, & Chevalier (1986) proposed that the best way to search for the shell might be in the far-UV, by detecting absorption in C IV λ 1550. The pulsar would be an ideal background source for this study. So, 22 years after the prediction of the outer shell by Chevalier (1977), and 13 years after the suggestion by Lundqvist et al. (1986) to search in the UV, we were able to point the HST toward the Crab pulsar. The broad absorption line of C IV λ 1550 was indeed detected in our spectrum.

With the awarded six orbits of observing time, the signal-to-noise of the detected C IV λ 1550 absorption line is not brilliant (Fig. 10, Paper IV), but we do see a broad, blueshifted absorption line that extends out to $\sim$ 2500 km s^{-1}. This is certainly faster than the velocity of the bright filaments that cruise at $\sim$ 1400 km s^{-1} (Davidson & Fesen 1985). In fact, together with the observations of Clark et al. (1983), this represents the highest velocity ever measured in the Crab, and shows that there is indeed fast material outside the visible boundary of the nebula. This could be interpreted as evidence for the long sought outer shell.

To estimate how much mass and energy such a shell contains, Peter Lundqvist made a simple spherically symmetric toy model of the shell. From the observed line profile, a lower limit to the mass of the shell was found to be ~ 0.3 $M_\odot$, with an accompanying kinetic energy of $\sim 1.5 \times 10^{49}$ ergs. We cannot, however, exclude that the outer shell hides as much as 10^{51} ergs, since the high velocity material could well be hidden in the noise of our C IV λ 1550 line. Moreover, more detailed photoionization models are required to explore how much of the carbon that resides in C IV. The old models of Lundqvist et al. (1986) seem to indicate that the line profile is produced in material distributed with a rather steep density profile.

In summary, we were indeed able to confirm the presence of high-velocity material outside the visible boundary of the Crab nebula. This material carries some of the missing mass and energy of the SN 1054 explosion, and in that sense it supports the view of an outer shell. This study could, however, neither confirm nor reject that the Crab nebula is the remnant of a normal (10^{51} ergs) supernova explosion. In this respect, the nature of the SN 1054 event remains unknown.

Publications not included in this thesis

V. P. Lundqvist, **J. Sollerman**, A. Ray, B. Leibundgut, & F. Sutaria, *Deep optical observations at the position of PSR1706-44 with the VLT-UT1*, A&A, 343, L15 (1999)

VI. M. Turatto, P.A. Mazzali, T.R. Young, K. Nomoto, K. Iwamoto, S. Benetti, E. Cappellaro, J.I. Danziger, D.F. De Mella, M.M. Phillips, N.B. Suntzeff, A. Clocchiatti, A. Piemonte, B. Leibundgut, R. Covarrubias, J. Maza, & **J. Sollerman**, *The Peculiar Type II Supernova 1997D: A Case for a Very Low 56Ni Mass*, ApJ, 498, L129 (1998)

VII. T.R. Gull, D.J. Lindler, M.D. Crenshaw, J.F. Dolan, S.J. Hulbert, S.B. Kraemer, P. Lundqvist, K.C. Sahu, **J. Sollerman**, G, Sonneborn, & B.E. Woodgate, *Space Telescope Imaging Spectrograph Near-Ultraviolet Time-tagged Spectra of the Crab Pulsar*, ApJ, 495, L51 (1998)

VIII F. Patat, E. Cappellaro, J. Danziger, P. Mazzali, **J. Sollerman**, T. Augusteijn, J. Brewer, V. Doublier, J. F. Gonzalez, O. Hainaut, C. Lidman, B. Leibundgut, K. Nomoto, J. Spyromilio, L. Ricci, M. Turatto, J. Walsh, T. J. Galama, J. Van Paradijs, C. Kouveliouto, P. M. Vreeswijk, F. Frontera, N. Masetti, E. Palazzi, & E. Pian, *The metamorphosis of SN 1998bw*, submitted to A&A

På svenska (In Swedish)

Denna avhandling handlar om supernovor, det explosiva slutet för en massiv stjärna. En massiv stjärna lever hårt och dör ung, åtminstone med astronomiska mått mätt. Medan vår sol kan skina lugnt i 10 miljarder år kommer en 25 gånger tyngre stjärna att tömma sitt bränslelager 1000 gånger snabbare. Stjärnan utvinner sin energi genom fusion, sammanslagning av lättare grundämnen till tyngre grundämnen. När den omvandlat allt väte, det lättaste och ymnigast förekommande ämnet, till helium hettas stjärnans centrum upp tills det blir tillräckligt hett för att omvandla heliumet till kol. På det viset fortsätter stjärnan att bilda tyngre och tyngre grundämnen. Det är på detta sätt som alla tyngre grundämnen skapats; både syret vi andas och kolet i våra celler har en gång bildats inne i en massiv stjärna. Då stjärnan bildat järn i sitt inre betyder det slutet för dess skinande tillvaro. Järn är nämligen den stabilaste av alla atomkärnor och ytterligare fusion genererar ingen energi för stjärnan att stråla ut. Då trycket i stjärnans centrum hastigt sjunker är katastrofen ett faktum, tyngdkraften pressar blixtsnabbt samman dess centrum till en oerhört tät kärna. Då den överliggande materien störtar in i denna kärna studsar den hastigt tillbaka. Kollapsen vänds till en explosion där hela stjärnan, utom dess kompakta kärna, trasas sönder och slungas ut med hastigheter av 10.000 kilometer i sekunden. Vi observerar denna explosion som en stjärna som flammar upp på himlavalvet, en supernova (Figur 1.1).

Min forskning om supernovor rör deras senare stadier. I stjärnans centrum skapas under explosionen stora mängder nickel-56. Det är ett radioaktivt ämne som kvickt sönderfaller till kobolt-56 som i sin tur faller sönder till stabilt järn. Det är energin från det radioaktiva sönderfallet som får supernovan att lysa vid sena stadier, d.v.s efter några månader. Jag har observerat supernovor med stora optiska teleskop på Kanarieöarna och i Chile. Dessa observationer kan bland annat bestämma hur mycket radioaktivt nickel som kastas ut vid en supernovaexplosion.

För supernova (SN) 1994W fann vi en anmärkningsvärt liten mängd nickel, den minsta man någonsin påträffat hos en supernova. Eftersom vi tror att det var en mycket massiv stjärna som exploderade, och sådana stjärnor producerar en hel del nickel, så tyder detta på att en del av det nickel som skapats fallit tillbaka mot neutronstjärnan, den kompakta kärna som explosionen lämnade kvar. Eftersom neutronstjärnor inte kan bli hur massiva som helst kan man spekulera i huruvida materien som faller tillbaka kan få neutronstjärnan att kollapsa till ett svart hål. För en något utförligare diskussion i ämnet, hänvisar jag till min artikel “Ett svart hål blir till”, Forskning & Framsteg 1/99.

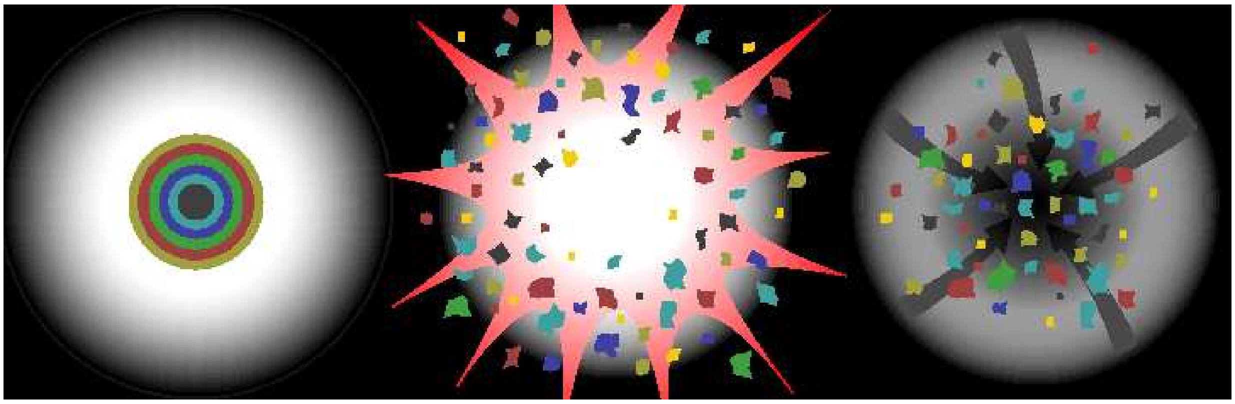

Figure 3.3: Konstnärlig bild av en supernovaexplosion och bildandet av ett svart hål. Bilden är från min artikel "Ett svart hål blir till", Forskning och Framsteg 1/99, grafik: Gunnar Kaj

I avhandlingen presenterar jag också en studie av SN 1996N. Detta var en explosion av en stjärna som förlorat sitt massiva vätehölje. Den falnade därför mycket snabbt, eftersom den inte kunde absorbera all energi från det radioaktiva sönderfallet. Vi fann även att spektrallinjerna i denna supernova verkade komma från materia som rör sig emot oss med en hastighet av ungefär 1000 kilometer i sekunden. Det kan tyda på att explosionen i fråga inte var fullständigt symmetrisk.

SN 1987A flammade upp på den södra stjärnhimlen i februari 1987. Det var den ljusstarkaste supernovan sedan 1604, och har därför studerats i detalj av supernovaforskarna. Vi har använt satelliten ISO för att studera den infraröda strålningen från denna supernova vid mycket sena tidpunkter (4000 dagar). Vi såg just ingenting. Med hjälp av detaljerade datormodeller av SN 1987A kunde vi ur denna icke-detektion härleda att supernovan måste ha producerat ganska lite radioaktivt titan.

Slutligen har vi använt rymdteleskopet Hubble för att studera Krabbnebulosan och dess pulsar. Nebulosan är resterna av en supernova som observerades år 1054. Den var synlig för blotta ögat på ljusa dan i 23 dagar, och i nästan två år om natten, enligt de historiska källorna. Krabbnebulosan är ett av de mest studerade objekten på stjärnhimlen (Figur 3.2). Den rymmer dock fortfarande många olösta frågor. Ett exempel är att Krabbnebulosan verkar innehålla mindre materia och expandera långsammare än man förväntar sig av en supernovaexplosion. Man har därför spekulerat i, och sökt efter, ett yttre skal som kan innehålla den "försvunna" massan och energin. Genom att med Hubbleteleskopet studera en absorptionlinje i det ultravioletta våglängdsområdet lyckades vi detektera materia utanför den synliga nebulosan. Detta stödjer hypotesen om ett osynligt skal runt

Krabbnebulosan, även om våra observationer inte slutgiltligt kunde avgöra frågan om nebulosans "försvunna" massa. Dessa observationer gav även värdefull information om Krabbpulsaren. Denna neutronstjärna roterar oerhört snabbt och sänder ut strålning i en smal kon, ungefär som en fyr (Figur 2.2). Den periodiska pulsen har studerats i nästan alla våglängdsområden, och vi har nu också lagt till den ultravioletta biten. Vårt spektrum av Krabbpulsaren, från rymdteleskopet Hubble och det Nordiska Optiska Teleskopet, är sannolikt det bästa spektrum som någonsin presenterats av en pulsar i detta våglängdsområde.

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