CHAPTER 1

CONCLUSIONS AND FUTURE WORK

On the one hand there remain many unknowns about the explosions and progenitors of Type Ia supernovae (henceforth SNe Ia). On the other hand, there are many question that have been answered. The community has the unified believe that the SN Ia phenomenon is caused by the explosive burning in degenerate carbon and oxygen material. This suggests with a high probability a CO-WD - a remnant of a $0.5\,M_{\odot}$to $8\,M_{\odot}$star. Traditionally there have been two assumptions, first that a CO-WD will accrete from a main-sequence to redgiant companion - known as the single degenerate scenario (SD-scenario), second that this growth will end at the Chandrasekhar mass ($M_{\mathrm{Chan}} = 1.38\,M_{\odot}$; Chandrasekhar, 1931) sort and the CO-WD will explode in a SN Ia.

Recent work by many authors (e.g. Bianco et al., 2011; Hayden et al., 2010; Maoz & Badenes, 2010) has started to suggest that at least one of these assumptions - the SD-Scenario - is unlikely or complete impossible for the bulk of SNe Ia. These authors often suggest the merger of two white dwarfs - known as the double degenerate scenario (DD-scenario) - as the favoured scenario. Furthermore, reaching $1.38\,M_{\odot}$ is one of the difficulties, especially in the SD-Scenario, which led some authors to speculate on a lower explosion mass of $1 - 1.2\,M_{\odot}$(e.g. Sim et al., 2010).

This thesis is trying to address both the question of the progenitor as well as the explosion mass. The SD-Scenario predicts that post-explosion the companion star of a SN Ia is - although depending on the evolutionary state prior to the explosion more or less perturbed - visible post-explosion. In this thesis we have tried to find the this companion star, but up till now to no avail. Secondly to address, among other questions, the progenitor mass we have started to automate the fitting of SN Ia. This technique has been applied successfully to a handful of supernovae (Mazzali et al., 2007), but is currently only possible manually. The problem of automation is technically very challenging and we have currently completed two milestones - the ability to calculate many solutions in a cloud-like environment and the implementation of GAs as the optimization algorithm of choice.

This thesis has contributed important pieces of the puzzle that is the SN Ia phenomenon, but the question remains: How and why do these objects explode?

1.1. Single or Double Degenerate?

The initial idea for this thesis was simple: High resolution spectroscopy and high precision astrometry of close and young SN Ia remnants should reveal the suggested donor star. At this time the only viable scenario was the SD-Scenario. The DD-Scenarios was almost unanimously believed to lead to accretion induced collapse (AIC) and not SNe Ia. The first project (Chapter **??** on page ??) was to confirm Tycho-G as the progenitor of SN 1572 and then move on and find the progenitors in both SN1006 and SN1604.

The observations however started to show a completely different picture. The very unusual kinematics claimed for Tycho-G by Ruiz-Lapuente et al. (2004), was only slightly unusual. The Besançon model suggested the unusual velocity to be very usual if Tycho-G was placed at a distance that would make it compatible with a background interloper (see Section **??** on page ??). This suggests that kinematics are not a conclusive evidence but only suggestive and motivated us to find a more tangible feature.

The SD-Scenario in most cases suggests Roche Lobe Overflow (RLOF) as the mass transfer. A consequence of this mass transfer mode is tidal coupling of the donor star's rotation to the orbital rotation. This tidal coupling also implies that the rotation of the donor post-explosion is coupled to its escape velocity (see Section **??** on page ?? and Figure **??** on page ??). Most low-mass stars (spectral type later than F) rotate much less than the predicted rotational velocity of a donor post-explosion - a serendipitous coincidence. Our work in Chapter **??** on page ?? suggested that Tycho-G does not have an unusually high rotation. Follow-up work with improved data (see Chapter **??**) established this low rotation not only for Tycho-G but also for five other stars close the the center of SN 1572. This find is not entirely without caveats and the rotation might vanish post-explosion when the star puffs-up. In addition, the observable is not the rotation but the projected rotation ($v \sin i$), however if $\sin i$ would approach zero we would expect the star to have a high proper motion in the plane of the sky. None of our candidates show such a trait (see Figure **??** on page ??). We have, howeverm found one star that exhibts very high rotation (consistent with the predictions for a donor star). However this star (Tycho-B) is a hot A-star where high rotation is not unexpected. In addition, we found Tycho-B to have a very low spatial velocity. As the escape velocity and the rotational velocity are coupled we would expect a high spatial velocity for such a high rotation. Finally, we have calculated a distance from measurements of the surface gravity and temperature, which suggests Tycho-B to be a foreground star. We conclude that observations of the stars in SN 1572 is consistent with SN 1572 having had no donor star.

The second remnant to be scrutinized was SN 1006 (see Chapter **??**). Using the FLAMES instrument on the Very Large Telescope (VLT) we obtained spectra of stars around the center to a limiting magnitude of $V < 19$. Our primary set were stars with $V < 17.5$, resulting in $L(V) > 0.5 L_\odot(V)$ at the distance of the remnant. The models predict a remaining donor star with much higher luminosity ($10\text{–}100 L_\odot$ Marietta et al., 2000). We again find no stars to have unusual rotation or spatial velocity. Consistent with the find in SN 1572 - no identifiable donor star.

If they exist finding donor stars seems much harder than we initially thought. The results in both SN 1572 and SN 1006 are consistent, although there exist some weak candidates in SN 1572.

Finally, for SN 1572 we have found one star that thus far has eluded spectroscopic scrutiny. This star (Tycho-A2 by our nomenclature) has an unusual proper motion (see Figure **??** on page ??) and is located very close to the X-ray center of SN1572. This makes it a prime candidate. Unfortunately it hides 0.4″away from the 4 magnitudes brighter Tycho-A (see Figure 1.1), which makes it impossible to obtain ground-based optical spectroscopy, but offers the possibility for challenging infrared observations aided by adaptive-optics. We are currently running a GNIRS campaign to obtain the fundamental stellar parameters, radial velocity and rotation.

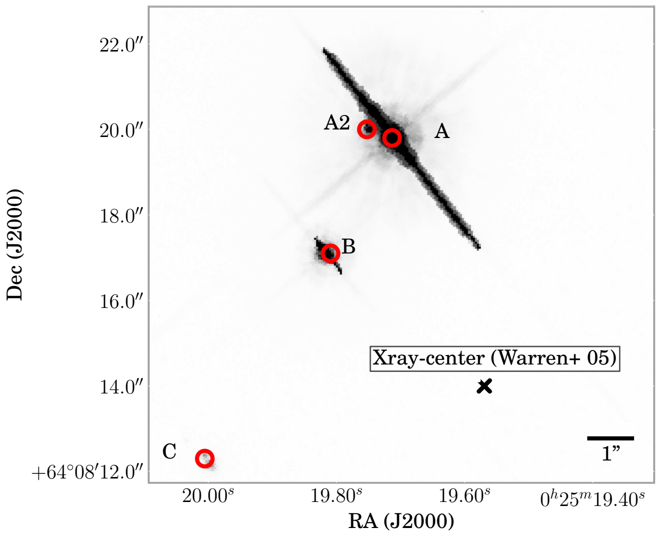

Figure 1.1 Overview of inner region of the remnant of SN1572. All labelled stars except Star-A2 have existing high-resolution spectra. Tycho-A2 is located very close to Tycho-A (0.6″). Spectroscopy can only be obtained with adaptive optics in the infrared.

In the case of SN 1006 we have analyzed our prime candidate list, but still have the less promising candidates to analyze ($L < 0.5\,L_{\odot}$). We have identified a path to extract information despite their subpar S/N ratio, but have not applied this yet.

The bottom line, however, for both SN1572 and SN1006 seems to be: No bright progenitors. There are as always caveats, but we do think that with current theoretical knowledge and current instrumentation it is not worthwhile to scrutinize the candidate stars in both remnants further. One could however think about photometrically deep observations of these remnants and look for a hot white dwarf suggested by some new models (Fink et al., 2010).

1.2. The curious case of Kepler

The last of the well-known remnants and the most distant one (**?**, estimates a distance of ≥ 6 kpc) is SN 1604 - also known as Kepler's supernova. The morphology of this remnant is not as clean and spherical as the one of SN 1006 and SN 1572 (see Figure 1.2). For a long time SN 1604 was believed to be a Type Ib supernova (henceforth SN Ib), but prominent iron emission in X-ray spectra (Reynolds et al., 2007) suggests this event to be a SN Ia (Hughes et al., 1995). In addition, SN 1604 shows an abundance in nitrogen which is unusual for a SN Ia. In addition, Blair et al. (1991) and Sollerman et al. (2003) suggest that the remnant itself possesses a very high systemic velocity of $\approx 250\,\mathrm{km\,s^{-1}}$. A recent study by Chiotellis et al. (2011) suggests that a SD-Scenario with an AGB star as a donor would explain all of the observed peculiarities. In addition, Chiotellis et al. (2011) make the prediction that this star should be visible and very bright post-explosion.

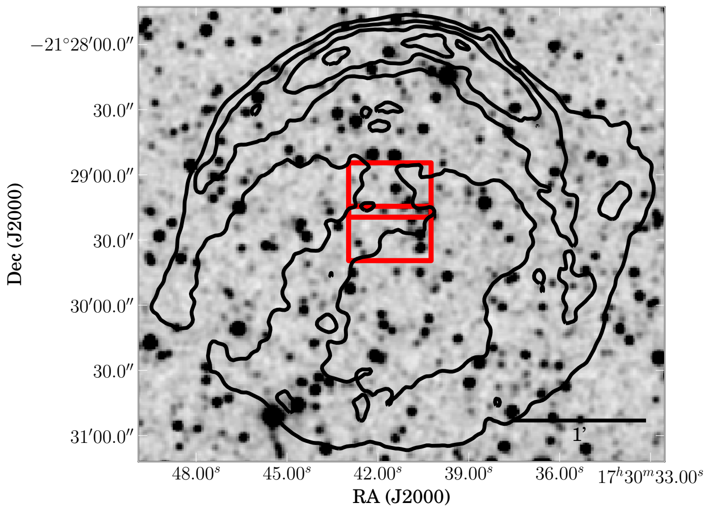

Figure 1.2 VLA contours of Kepler's remnant (SN1604) overlayed on a 2MASS image. The red rectangle show the overlapping north and south field of our WiFeS observing campaign.

We have obtained data with the WiFeS integral field spectrograph. The field of view for this instrument is rectangular with dimensions of $25'' \times 38''$. We have two overlapping fields that cover all stars at a projected velocity of $1300\,\mathrm{km\,s^{-1}}$(assuming a distance of 6 kpc) (see Figure 1.2). Extracting stellar spectra from our poor seeing data ($> 1.5''$) is technically challenging and we have not invested much time in this project.

A very recent study (Williams et al., 2011) has suggested that a fourth SN Ia remnant has features that suggest a SD-Scenario. This remnant - RCW 86 - shows large amounts of iron in the X-ray spectrum and no central neutron star has been found which suggests a SN Ia event. A distance of 2.5 kpc places it between SN 1006 and SN 1572 a territory that we are very familiar with. We plan to observe this remnant, like SN 1006with FLAMES in the coming semester.

1.3. Divide et impera

Maybe finding the progenitors of SNe Ia is too difficult using our current techniques. It might be much easier to employ the successful "Divide et Impera" - "Divide and Conquer" strategy. We believe it might be sensible to divide the question of the progenitor into accretion method and the mass of the CO-WD at the time of explosion. For the accretion method in the SD-Scenario tests seem to frequently fail (e.g. no donor in remnants, not enough SSS) and for the DD-Scenario there are no strong testable predictions yet. We believe a different path - namely understanding the explosion mechanism (delayed detonation or pure detonation) and CO-WD mass at explosion might be the best way forward. In terms of explosion mass there are currently two favoured scenarios. First the explosion of the CO-WD close to M_{Chan} ($1.38\,M_{\odot}$). As shown in Chapter **??** on page ??, however, the burning of a $1.38\,M_{\odot}$CO-WD only produces the right abundance pattern when introducing a (slightly contrived) delayed detonation. When exploding a $1\,M_{\odot}$CO-WD this problem does not exist, a detonation of such a star produces the right optical photospheric spectrum (Sim et al., 2010). The main problem with these sub-Chandrasekhar mass explosions is that there exists no caveat free theory for the ignition yet - however some suggestions exist (e.g. Sim et al., 2010). We believe that fitting many SN Ia spectra in the photospheric phase might yield the answer to the explosion mechanism and might yield subsequently a mass estimate. We are currently exploring this option with Dalek code. Another key to find the explosion mass of any given SN Ia might be the abundance of stable iron in nebular spectra. Theory predicts more iron for the M_{Chan} case and less for the sub-Chandrasekhar mass scenario.

1.4. The Dalek Code

We have presented two major milestone of the automatic fitting process of SNe Ia (see Chapter **??** on page ??). For the actual synthesis of the spectra we have chosen the 'Mazzali and Lucy Monte Carlo' code (MLMC) code as it strikes the right balance between speed and accurate representation of the spectra for this task. In a first step we have wrapped the MLMC and enabled it to access a cloud-like computing environment (heterogeneous computing environment). This makes it very easy to test different optimization algorithms in a speedy and efficient manner. As the parameter space for SN Ia fitting is extremely complex and large, the automation is a technically challenging and ambitious project. We have however shown that GAs are able to solve this problem. The initial speedy advancement has now been hampered due to our lack of knowledge in GAs - a vast field in numerical optimization. We have added two GA experts to our team, which consisted only of radiative transfer experts and observers. Currently we are finetuning the algorithm with our newfound skillbase and will soon try to fit many SN Ia spectra. Similar to Mazzali et al. (2007), we hope to explore the explosion parameter space but with many more datapoints. A trend in such a dataset might then again give insights into the unanswered progenitor question.

1.5. Trouble in Paradise

During the work of this thesis the field of SN Ia research has changed significantly. When we started the donor star search there seemed little doubt in the community about the SD-Scenario. Over the recent years the SD-Scenario, however has been seriously shaken and there has been some newfound support for the DD-Scenario. The renaissance of theDD-Scenario is often based on the fact that this scenario does not provide as strong predictions as the SD-Scenario. This contention has reinvigorated the field of SN Ia progenitors and makes it a challenging and intriguing area to work in.

New transient and all sky surveys will soon start drowning us in a deluge of data. Currently the astronomical community is ill equipped to deal with such large amounts of data. This is not suprising as most astronomers are experts in physics and not data processing. This problem is not unique to astronomy, more and more fields are gathering much more data than is ever processable by individuals. We believe this is a great opportunity to start cross-disciplinary research. The fundamentals of science (e.g. pattern recognition) are definitley not unique to individual areas. New areas of science like eScience are trying to provide techniques and tools for scientists irregardless of the field.

We have tried to conduct cross-disciplinary research in automatically fitting SNe Ia spectra. Stephan Hachinger (the expert in manual fitting amd radiative transfer) and me initially have tried using the methods that were taught to us during our undergraduate years in physics (e.g. Newton-Raphson). These methods are still useful for very simple problems, however do not scale to today's highly non-linear problems with many correlated variables. Sam Inverso, a computer scientist working in the area of neuro-science, joined us first and helped us do our first baby-steps in GAs. His help has advanced the Dalek code to its present state. In the last half year two new members have joined the team, whose research is in numerical optimization. They are very interested in applying their techniques to 'real world' problems, which are scarce in the optimization community.

This thesis definitley shows: Multidisciplinary research is not only a buzzword, but can advance individual fields of science much faster than they could advance in isolation.

GLOSSARY

$M_{\mathbf{Chan}}$ Chandrasekhar mass (1.38 $M_{\odot}$; see Chandrasekhar (1931)). 1, 5

AGB asymptotic giant branch. 4

AIC Accretion Induced Collapse. 2

CO-WD Carbon/Oxygen White Dwarf. 1, 4, 5

Dalek code Automatic SN Ia spectrum fitting code. 5, 6

DD-Scenario double degenerate scenario (merging of two white dwarfs). 1, 2, 4, 5

donor donor. 2, 4

FLAMES FLAMES. 2, 4

GA genetic algorithm. 1, 5, 6

GNIRS Gemini Near InfraRed Spectrograph. 3

main-sequence main-sequence. 1

MLMC Mazzali and Lucy SN Ia spectrum synthesis code. 5

RCW 86 RCW86. 4

redgiant redgiant. 1

RLOF Roche Lobe Overflow (see **?** for a more detailed description). 2

SD-Scenario single degenerate scenario (single white dwarf accreting from non-degenerate companion). 1, 2, 4, 5

SN Ia Type Ia supernova. 1–6

SN Ib Type Ib supernova. 3

SSS supersoft X-ray source. 4

VLT Very Large Telescope located in Chile. 2

WiFeS Wide Field Spectrograph. 4

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