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Niels Bohr Institute
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Part A Thesis

High energy space phenomena: A window to the dark universe.

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Abstract

Because of the vast expanse of the universe we live in, very little starlight reaches us from the environments furthest from us. To explore the region of space unavailable to us via direct detection, extremely energetic phenomena can be used to investigate the space between us and them, by illuminating the universe otherwise obscured. Gaining a thorough understanding of the physical processes at play in the high-energy events populating our universe is of prime importance because any signatures deviating from the intrinsic appearance of the object can be attributed to the intervening material and thus an indirect inference can be made about the dark universe. In this thesis I present some of the work I am involved with related to high-energy phenomena, specifically: Quasars (QSOs), Gamma-Ray Bursts (GRBs) and Supernovae (SNe). The work I present here consists of four projects I am involved with and the majority is still a work in progress. The work I have been doing is specifically on the *average* properties of the UV to near-infrared spectra of a selection of QSOs, the explosion environments of high-velocity ejecta core-collapse supernovae, the average optical afterglow of long-duration GRBs and the search for high-redshift, lensed SNe, including the quadruply lensed supernova, "SN Refsdal".

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1 High-energy space phenomena: A window to the dark universe.

1.1 Introduction

> *Astronomy? Impossible to understand and madness to investigate.*
>
> — **Sophocles (450 BC)**

In this Part A Thesis I will summarize some of the work I have been doing during the first two years of my PhD, while also officially enrolled in the masters programme. The work I have done is mainly divided into three subjects: QSOs, GRBs and SNe and is related to various aspects of the different subjects.

For QSOs, I have researched the average properties of a sample of bright $M_r \leq -27.5$ QSOs and created a composite spectrum for community usage. I showed an application of the composite in inferring dust content of the quasar host galaxies and additionally, I find a steeper slope of the quasar power-law continuum as compared to the traditionally assumed one, indicating an intrinsically harder continuum. This project therefore investigates both intrinsic properties of the quasar phenomena, but also allows for the conditions of the intervening material to be inferred, both in the quasar host or potential absorption systems in the line-of-sight.

For GRBs, I am involved with the X-shooter GRB collaboration and will be investigating the average properties of the GRB optical afterglows for the sample we are building. Data-collection for the sample is continuous and we have an ESO TOO-program to do ground-based follow-up of the optical afterglow from GRBs detected with *Swift*. I have developed an algorithm to normalize the afterglows, which is then used as a product of the afterglow sample, for example for absorption-line studies. Once a sufficient sample size is reached, I will lead a project to construct a composite afterglow spectrum. This afterglow composite can then be used twofold: as a cross-correlation template to determine redshift for newly discovered noisy afterglows and as a way to explore the average properties of the optical afterglows, thereby also allowing identification of potentially interesting outliers for further observations.

For SNe, I am involved in two projects. One related to the explosion environments of type Ic and Ic-BL supernovae without accompanying GRBs where we have obtained a sample of 19 supernova host galaxies observed with an IFU, allowing spatially resolved diagnostics to be calculated for the stellar progenitor population. This work is done to investigate whether the explosion environments of the two types of SNe differ and can also be used to constrain the explosion mechanisms for the different kinds of SNe. This project is in an indirect way related to an investigation of the GRB progenitor system, because fast-ejecta SNe are sometimes seen associated with GRBs and the reason why some GRBs have SNe and others don't remains a mystery. The other SN-project I am involved with is a collaboration with the Frontier Fields program, where spectroscopic follow-up of potential high-redshift supernovae are carried out using X-shooter. The scientific rationale behind this project is the increased chance of "serendipitously" discovering high-redshift SN in the Frontier Fields because of the strong gravitational lensing in the galaxy clusters targeted. If high-redshift SN are of the Ia-type this will help constrain our current cosmology where the high-redshift SNe carry the highest leverage in terms of discerning between different world-models. As part of this work I am working on the quadruply lensed supernova "SN Refsdal" where the X-shooter observations have helped constrain the SN type.

This report will present a brief status of the work that has been done in the three fields and how it relates this to my own research. Apart from the research I have been doing, I have taken 31 ECTS points distributed in the following PhD-schools and regular courses: "Coping with the challengers of a PhD + Scientific Writing", "Responsible Conduct of Research", "Introduction to University Pedagogy", "Summer Schools in Statistics and Computation for Astronomers", "Introduction to sub-mm interferometry and science with ALMA", "Advanced Methods in statistical data analysis", "Classical Astrophysical Papers". Additionally I have taught the mandatory 840 hours including the Mechanics 1 and 2 courses for which I was awarded the Jens-Martin prize for excellence in teaching.

I will conclude with an outlook of what I will be working on in the last two years of my PhD. I attach the submitted quasar paper, and the advanced draft of the "SN Refdal"-paper with this Part A Thesis.

Publications

Paper I

An X-shooter composite of bright $1 < z < 2$ quasars from UV to Infrared

Selsing, J; Fynbo, J. P. U.; Christensen, L; Krogager, J.-K.

Submitted to A&A. Recommended for publication after minor revision.

Paper II

Spectroscopic classification and confirmation of the first multiply imaged supernova

P. L. Kelly, G. Brammer, **J. Selsing**, S. A. Rodney, J. Hjorth, R. J. Foley, L Christensen, and et al.

Advanced draft

Paper III

Spectrophotometric analysis of GRB afterglow extinction curves with X-shooter

J. Japelj, S. Covino, A. Gomboc, S. D. Vergani, P. Goldoni, **J. Selsing**, Z. Cano, V. D'Elia, H. Flores, J. P. U. Fynbo, F. Hammer, J. Hjorth, P. Jakobsson, L. Kaper, D. Kopač, T. Krühler, A. Melandri, S. Piranomonte, R. Sánchez-Ramírez, G. Tagliaferri, N. R. Tanvir, A. de Ugarte Postigo, D. Watson, R. A. M. J. Wijers

Japelj et al. (2015)

Paper IV

GRB hosts through cosmic time - VLT/X-shooter emission-line spectroscopy of 96 GRB-selected galaxies at 0.1 < z < 3.6

T. Krühler, D. Malesani, J. P. U. Fynbo, O. E. Hartoog, J. Hjorth, P. Jakobsson, D. A. Perley, A. Rossi, P. Schady, S. Schulze, N. R. Tanvir, S. D. Vergani, K. Wiersema, P. M. J. Afonso, J. Bolmer, Z. Cano, S. Covino, V. D'Elia, A. de Ugarte Postigo, R. Filgas, M. Friis, J. F. Graham, J. Greiner, P. Goldoni, A. Gomboc, F. Hammer, J. Japelj, D. A. Kann, L. Kaper, S. Klose, A. J. Levan, G. Leloudas, B. Milvang-Jensen, A. Nicuesa Guelbenzu, E. Palazzi, E. Pian, S. Piranomonte, R. Sanchez-Ramirez, S. Savaglio, **J. Selsing**, G. Tagliaferri, P. M. Vreeswijk, D. J. Watson, D. Xu

Krühler et al. (2015)

1.2 Quasars: Cosmic Lighthouses

The word quasar is derived from quasi-stellar radio source which is what quasars were initially detected as: point-like radio sources without an optical counterpart. When the first optical counterpart was discovered it indeed resembled a blue star, but spectroscopic follow-up revealed a confusing pattern with very broad emission lines superposed on a blue continuum. When the lines were matched to the correct atomic species, a cosmological origin was established which posed a problem for the mechanisms powering the source because the extreme energies inferred. The Eddington limit is the maximal luminosity a gravitationally bound object of a given mass can have without radiation pressure tearing the object apart and at the luminosities inferred from the cosmological origin of the quasars and the observed brightness's the required masses of the sources were extremely high. Quasars also exhibits a large degree of variability in the observed flux on differing time-scales in the order of weeks and years with shorter time-scale variability is superposed on longer variability periods. The short timescale variability observed require a relatively small emitting regions, which poses a problem for a potential stellar origin of the emission and gives merit to the idea of a black hole powering the emission. One of the first quasars discovered, 3C 273, is estimated to have a mass of $\sim 900 \times 10^6 M_\odot$ (Peterson et al., 2004) determined using a technique called reverberation mapping in which the time-delay between the continuum emission and line emission is used to infer the radius of the emitting region. From the radius of the emitting region and the velocity of the emitting material, an estimate of the gravitational mass can be made. The mass inferred for 3C 273 far exceeds the maximal possible mass a star can have before it would immediately collapse to a back hole (Belczynski et al., 2010).

The optical-to-ultraviolet emission mechanism of quasars is by now quite well understood (Elvis et al., 1994). A supermassive black hole at the center of a galaxy is surrounded by a hot accretion disc, which emits a featureless thermal continuum (Shakura and Sunyaev, 1973; Pereyra et al., 2006). The central continuum photoionizes a region of hot clouds, and further out, cold clouds which gives rise to lines with both broad and narrow components (Elvis, 2001). Varying conditions in the clouds ensure that each ionic species have optimal conditions to produce line emission (Baldwin et al., 1995). Despite the apparent different conditions in which the emission arises, the overall shape of most quasar spectra looks similar (Dietrich et al., 2002). The remarkable uniformity of the average spectral properties across luminosity and redshift indicate very similar underlying physical mechanisms which can be understood in terms of Eigenvector 1 (Boroson and Green, 1992; Francis et al., 1992) where the Eddington ratio drives the relative strength of the lines and orientation effects influences the observed kinematics of the lines (Shen and Ho, 2014) accounting for the majority of the inter-quasar variation. This means that the accretion rate and the mass of the black hole largely determine the spectral appearance of a given quasar. Quasars are a part of a more general class of objects called Active Galactic Nuclei (AGN) and the classification of a given type is in part believed to be viewing effects (Elvis, 2001).

The average quasar spectrum of the sample presented in Paper I is shown in Fig. 1.1 where the position of the most prominent emission lines has been marked. The purple dashed line is a power-law fit to the spectral regions deemed free of contaminating emission lines and it can be seen that a pure power-law relatively well describes the continuum, which is also the shape that is predicted from Pereyra et al. (2006).

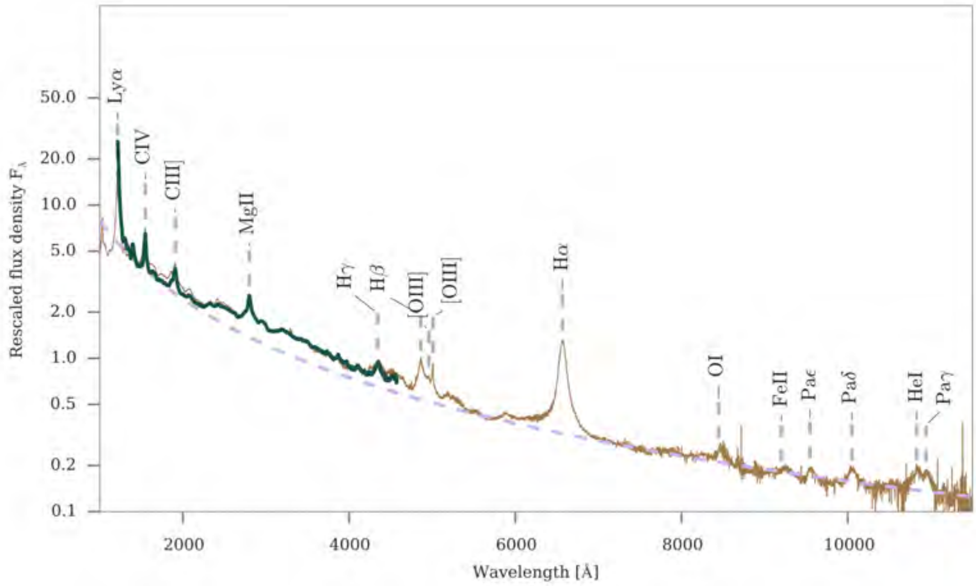

Fig. 1.1: Quasar composite spectrum from Paper I. The brown line is the average quasar spectrum where several of the prominent lines have been marked. The purple dashed line is a power-law fit to the regions free of contaminating emission and the dark green line is an average spectrum constructed for all SDSS spectra fulfilling the selection criteria imposed on the sample observed with X-shooter.

Even though the general principles behind the quasar phenomena seems to be relatively well understood, important details remains unknown especially in terms of understanding the total contribution of the quasar feedback in regulating star formation in galaxies (Di Matteo et al., 2005), how the first quasar became so massive so rapidly after the creating of the universe (Wu et al., 2015), how the co-evolution of the quasars and their host galaxies works (Ferrarese and Merritt, 2000), what role quasars played in reionization (Hopkins et al., 2007) and what shape the intrinsic optical/ultraviolet (UV) spectral energy distribution has (Krawczyk et al., 2015). The quasar contribution to reionization depends on the quasar luminosity function (QLF), which in turn depends on the assumed slope of the quasar SED. The QLF is the integrated luminosity of all quasars as a function of redshift and when calculating it, a representative quasar SED model is required. The quasar optical SED is usually is modeled by a power-law where the slope of the quasar continuum is determined from the average slope of large samples of quasars (Vanden Berk et al., 2001; Richards et al., 2006; Shen et al., 2011; Lusso et al., 2015) where regions free of emission lines is determined "by-hand". It is very efficient to build large samples of quasars from SDSS (Pâris et al., 2014), but the relatively modest wavelength coverage of the instrument install at Apache Point Observatory (Gunn et al., 2006) makes it difficult to uniquely determine a representative slope. Work has been done to extend the average quasar spectrum to longer wavelengths using other instruments (Glikman et al., 2006), but a well-defined sample of quasars with spectra covering the entire range from ultra-violet to near infrared has not been compiled. The work I have carried out in Paper I seeks to address specifically this point by observing 7 extremely bright, $M_r \leq -27.5$, quasars which will therefore contain negligible amounts of host galaxy contamination. Additionally the composite spectrum I have generated can be used to infer the dust content of the quasar host galaxy and potential intervening absorption systems, specifically Damped Lyman Alpha (DLA) systems. DLAs are defined as having hydrogen column densities higher than $N_{\rm HI} > 2 \times 10^{20} cm^{-2}$, determined from the equivalent width of the hydrogen absorption lines or absorption line profile fitting. This class of objects are believed to be self-shielding systems of gas that contain a significant fraction of the neutral hydrogen at redshift $z \sim 5$ (Storrie-Lombardi and Wolfe, 2000). Since these objects are to a large degree observed in absorption, our understanding of these object depend heavily on our knowledge of the illuminating object. An example of inferring the dust properties and amount is presented in Krogager et al. (2015), where artificially reddening a composite quasar spectrum is used to fit for the amount of dust under some assumed extinction law. The quasar composite used in that work consists of the template by Vanden Berk et al. (2001) stitched together with the one by Glikman et al. (2006) to produce a quasar composite covering the range of wavelength investigated. Paper I presents a single template that covers the entire region from UV to infrared for a homogeneous selection and the composite template presents a useful contribution to various areas for the astronomy community.. The paper, template and all the code used to generate the composite is made publicly available at `https://github.com/jselsing/QuasarComposite` as a way to encourage open source science.

1.3 Gamma-Ray Bursts: Flashes in the Dark

The existence of GRBs was serendipitously discovered by the VELA satellites, launched to detect potential detonations of nuclear bombs in space and could not have been discovered by earth-based telescopes due to the inability of gamma-rays to penetrate earths atmosphere. Short flashes of gamma-rays were detected for which a terrestrial origin could be excluded and a new celestial phenomena had been discovered. Significant advances has been made, especially through the rapid, space-based follow-up carried out with BATSE (Harmon et al., 2004) establishing the cosmological origin of GRBs though the isotropic distribution of bursts (Meegan et al., 1992), BeppoSAX (Boella et al., 1997) to identify the first X-ray counterpart (Costa et al., 1997) for which an optical afterglow was also found and the *Swift*-satellite (Gehrels et al., 2004) finding afterglows for ground based follow-up, using all available wavelengths.

The GRB phenomena consists of mainly two observable phases. A prompt phase of emission radiating up to a total of 10^{55}ergs if the energy emitted is isotropic, which is comparable to the entire universe (Kumar and Zhang, 2014) for the duration of the burst and an afterglow phase which is believed to be associated with the burst ejecta interacting with the circumburst material. The prompt phase can last 1^{-3} - 1^{3} s with a clear bimodality in the total sample of burst durations observed pointing to two distinct populations of objects also supported by the differing hardness ratio of the two types, with the short type typically having a higher fluxes at shorter wavelengths. These two population are classified as short GRBs if the duration is less than 2 seconds and long GRBs if the duration is longer than 2 seconds.

The central engine for the bursts is still an open question, but the association of long GRBs with supernova of type Ic-BL points to a massive stellar origin (Woosley and Bloom, 2006; Hjorth, 2013). The association of a weaker "kilo nova" with the short GRBs is seen a sign for merger-driven explosion mechanism (Tanvir et al., 2013) for those types of explosions. Several models exist to explain both types of burst, with the collapsar-model being favored for the long GRB and the merger of two neutron stars is favored for the short GRB. A common idea for both explosion mechanisms is to explain the amount of energy released as accretion of matter onto a black hole, which, as for the quasar emission mechanism, can carry a very high yield in terms of energy. For the long GRBs, the core of a massive, rapidly rotating star collapses when the iron core exceeds the Chandrasekhar limit, forming a black hole. Through conservation of angular momentum an accretion disc is formed, which via strong magnetic fields launches a jet that can break out of the stellar photosphere (Woosley and Heger, 2006). The differing velocities of the ejected material cause shocks inside the outflowing material, which emit inverse Compton-scattered synchrotron-radiation, bright in gamma-rays. When the swept-up material reaches the circumburst medium additional shocks causes the optical afterglow to be emitted. A typical cartoon for this kind of explosion mechanism is shown in Fig. 1.2.

Because the explosion mechanism itself is hidden from sight inside the exploding star, direct detection of the collapse is extremely difficult if not impossible. The prompt emission is in many cases too short for detailed investigation so an informative way to learn about the GRB explosion mechanism is to investigate the afterglow, which is visible for longer periods of time, allowing for ground based follow-up. Because the afterglow is a featureless power-law continuum in the optical (Paradijs et al., 2000), just as with the quasar continuum, it can be used to infer the properties of the intervening material, both in the host galaxy and in potential DLA systems. Since the

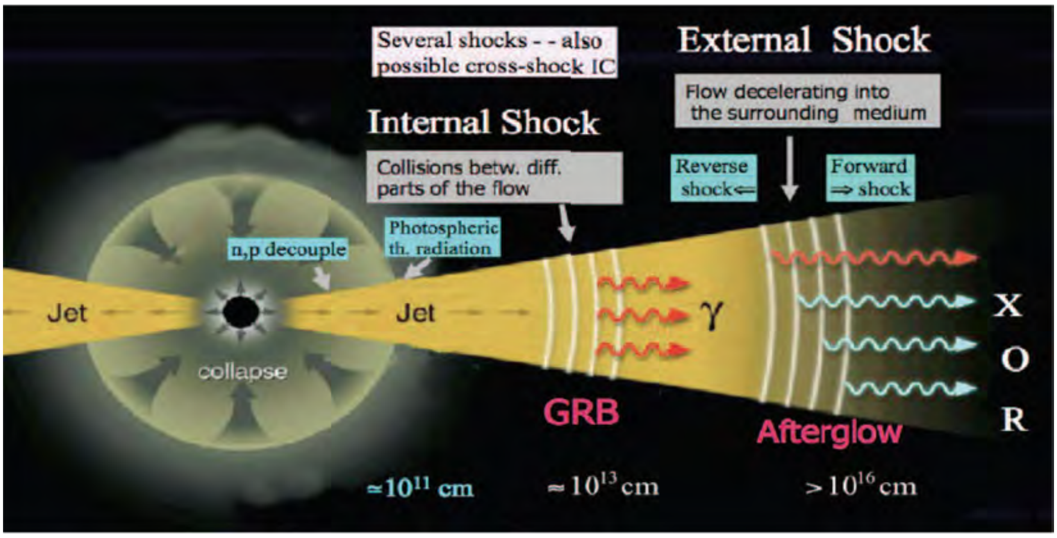

Fig. 1.2: Schematic view of the emission mechanisms in the traditional fireball model. Schematic taken from Meszaros and Rees (2014).

sight-lines selected by GRB afterglow are different than the ones selected by quasars, they provide an independent view of otherwise unobservable galaxies. Since the quasars are always positioned in the center of the host galaxies and the long GRBs are shown to trace the stellar light (Fruchter et al., 2006; Anderson et al., 2015), this potentially could make a difference in the picture drawn by using the two types of phenomena. Additionally, since GRBs are visible to such extreme redshifts (8.2 and 8.1, Tanvir et al., 2009; Salvaterra et al., 2009), they provide a unique probe to trace star formation at the earliest times.

A ground-based follow-up program has been undertaken using X-shooter, in which all *Swift*-bursts with galactic $A_V \leq 0.5$ and an XRT position within 10 minutes are followed up, if possible. This program has led to a lot of papers, investigating single bursts (e.g. Sparre et al., 2011; D'Elia et al., 2014; Krühler et al., 2013; Xu et al., 2013; de Ugarte Postigo et al., 2014; Schulze et al., 2014; Japelj et al., 2015; Hartoog et al., 2015, to mention some) which include GRBs with identified associated SNe, short GRBs and detections of molecular hydrogen. In Paper III (Japelj et al., 2015) we investigate the shape of the extinction curves in the host galaxies, at the position of the GRBs, for a sample of extincted afterglows. An example of an extincted afterglow is shown in Fig. 1.3 where the spectrum is shown in black and the continuum level estimation shown in red. From the normalized spectrum the neutral hydrogen column density can be estimated and from the modeling the afterglow SED the preferred extinction law can be inferred. For the sample of eight bursts we investigated here, there seemed to be a preference for SMC-like dust towards the GRB sightlines.

Additionally, for some of the triggers we have executed, only emission from the GRB host galaxy is visible. The study of the host galaxies of GRBs in emission is an indirect way of investigating whether GRBs prefer unusual environments

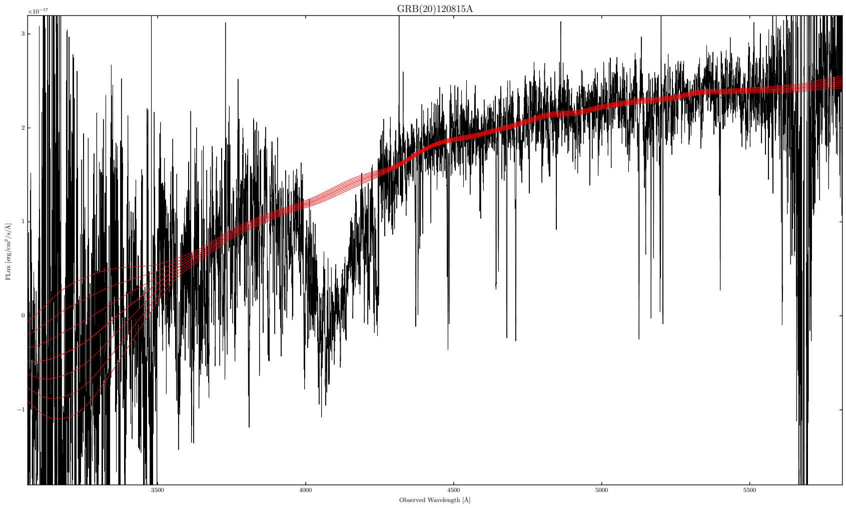

Fig. 1.3: Extincted afterglow spectrum of GRB 120815A in black. The broad absorption feature at 4100 Å is from Lyman α absorption in the host indicating a redshift of $z \sim 2.35$. A multitude of narrow absorption lines are visible in the spectrum belonging to various ionic species of elements. The thick red line is the continuum level, as determined from the normalization algorithm developed, the narrow red lines are the 1, 2, 3 σ lines indicating the uncertainty in the continuum placement. The continuum-level algorithm I developed will be presented in a future paper.

and if the GRBs trace star formation. For a sample of 96 host galaxies, we have investigated in paper IV (Krühler et al., 2015) whether there is a preference for GRBs to occur in metal-poor hosts as is expected from the theoretical explosion models (Woosley, 1993). If this is the case, this would mean that GRBs cannot be used as a representative proxy for star formation at high redshift and would have a bias towards low metallicity environments. What we showed in paper IV is that there is indeed a preference for low metallicity host, but only at low redshift which is attributed to the metallicity evolution of the universe where conversely at redshift $z \sim 3$ most of the star formation in the universe takes place in $Z_{\odot} \leq 0.5$ galaxies and thus the bias of GRB host towards lower metallicities disappears.

1.4 Supernovae: The fiery deaths of massive stars and their environments.

Supernovae are a special class of celestial phenomena related to the death of heavy stars and has been known since *De stella nova*, published by Tycho Brahe in 1573. Broadly speaking, there exists two kinds of SN explosions: thermonuclear and core-collapse. A thermonuclear SNe, called type Ia SN, begins with a carbon-oxygen white dwarf gravitationally sustained by electron degeneracy pressure. The explosion is started by a potential binary companion transferring mass via Roche-lobe overflow, which cause the white dwarf to exceed the Chandrasekhar mass where carbon starts to fuse. Because the star is gravitationally sustained by degeneracy pressure, the star is isothermal and when the critical fusion temperature is reached, the entire star undergoes runaway thermonuclear explosion. In the other type of SNe, called SN type II or core-collapse SN, a stellar iron core that exceeds the Chandrasekhar limit undergoes collapse. The Chandrasekhar limit is the maximal mass a gravitationally bound object, supported by electron degeneracy pressure, can have. As the density increase during the collapse, electrons will start being captured by protons and this speeds up the process by reduction of the electron degeneracy pressure and the gas pressure. Depending on the initial properties of the collapsing star, different scenarios can occur where in some cases a compact remnant is left behind, either a neutron star or a black hole. The energy from the core-collapse is converted into kinetic energy of the outer layers, which then decays radioactively, powering the SN. GRBs and different kinds of core-collapse SN, are linked to the deaths of massive stars. However, neither the progenitor system nor the production conditions that lead to each kind of explosion in a massive stripped star are well understood. The different kinds of SNe are determined by the initial mass and metallicity of the stellar progenitor, as well as by the metallicity-dependent mass loss in the stellar winds at the end phase of their evolution and the interaction with a sufficiently close companion star. The rotation of the stellar progenitor may also be another factor that determines the type of SN explosion. Type Ic SNe are explosions from the most heavily stripped massive stars that have been removed of both their H and He layers. Long duration gamma-ray bursts (GRBs) may be the most extreme cases of stellar explosions, and a few cases have been associated with broad-lined Type Ic SN (Woosley and Bloom, 2006) which is a sub-class of SNe which resembles type Ic SNe, but has extremely broad lines, indicative of high-velocity ejecta. Other long GRBs surprisingly lacked the distinct SN signatures (Fynbo et al., 2006). The connection between long-duration GRBs and broad-lined SNe Ic (SNe Ic-BL/hypernovae) and the existence of SNe Ic-BL without observed GRBs raises the question of what distinguishes a GRB progenitor from that of an ordinary SN Ic-BL without a GRB. This question may be answered by observing the stellar progenitors, which give rise to the various types of SN explosions. However, searches for SN progenitors of type Ibc in images taken before the explosions have failed, because the galaxies are distant and individual stars are difficult to distinguish (Maund et al., 2005). Progenitors of a few type II SNe has been detected in pre-explosion images Van Dyk et al., 2012 and confirms the massive progenitor scenarios suggested by the models.

An indirect method to distinguish between the different progenitor scenarios is to explore the environments at the locations of the SN and GRBs to look for systematic trends (Levesque, 2014). SN Ic-BL without observed GRBs lie in systematically more metal rich environments than SNe with GRBs (Modjaz et al., 2008; Graham and Fruchter, 2013). Integral field data of the host of GRB 980425/SN 1998bw show that the location of the SN (a Type Ic-BL) is close to a very metal poor region, but that the metallicity variations in HII regions in the dwarf galaxy host are otherwise minor (Christensen et al., 2008). In comparison, Type Ic sites are shown to be relative metal rich. Recently the abundances at the sites of different kinds of core collapse SNe have been determined and shows that SNe Type Ic lie in systematically more metal rich environments than other types of core collapse explosions (Modjaz et al., 2011; Leloudas et al., 2011; Kuncarayakti et al., 2013; Kelly and Kirshner, 2012). In contrast Anderson et al. (2010) argue that metallicity is not the dominant parameter for the SN type. The metallicity difference may have a physical origin, as a higher metallicity may give rise to stronger line-driven winds that remove the outer H and He layers of the star Vink and Koter, 2005, a necessary condition for a Type Ic SNe. This argument does not explain the lower abundances at the sites of SNe Ic-BL as well as at GRB regions, since GRB progenitors are expected to be metal poor (Woosley, 1993), unless the GRB-SN progenitors underwent a peculiar evolutionary phase marked by chemical homogeneous mixing. A possible solution to this dilemma is a massive binary progenitor system, rather than a metallicity effect.

Using integrated central oxygen abundance of the host galaxy as a proxy for the SN site (Prieto et al., 2008; Kelly and Kirshner, 2012), adopting the luminosity-metallicity relation for SDSS galaxies (Tremonti et al., 2004), gives systematically larger abundances than those measured in the SNe regions (Modjaz et al., 2011). This offset is not surprising since galaxies targeted for SNe searches are more luminous and massive and consequently have higher abundances and they can have abundance gradients in their disks (Sanders et al., 2012). To understand SN progenitors it is important to establish the systematic effects, which arise from the oxygen abundance determinations, when only an integrated spectrum can be obtained (e.g. low-luminosity or distant, unresolved galaxies), as well as the implications of metallicity gradients in large massive galaxies.

To try and answer the question about what determines the type of SN Ic exploding, we have taken data for 19 SN Ic and Ic-BL hosts using the IFU installed at VLT/VIMOS which gives spatially resolved spectra allowing diagnostics to be determined locally which for the redshift of the host corresponds to the physical sizes of the molecular clouds hosting the stellar progenitor population. We show in Fig. 1.4 a mosaic of the Hα emission determined from the VIMOS data superposed on the SDSS images of the host which we can translate into a star formation rate. Additionally using stellar population modeling, we can constrain the progenitor age and thereby the mass that will help discerning between the different types of progenitor stars.

For the metallicities determined locally we reproduce the trend seen earlier that Ic-BL prefer lower metallicity environments as compared to normal Ic, which we show in Fig. 1.5. This is still preliminary very work and the values might chance slightly. A thing to note is that the 1-σ intervals around the mean values are consistent

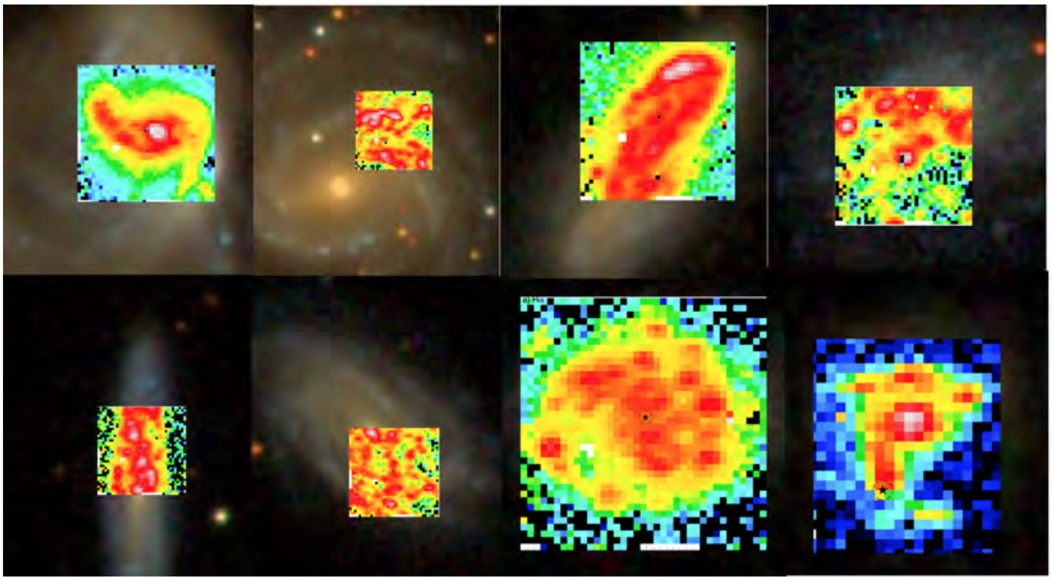

Fig. 1.4: A mosaic showing 8 of the targeted SN Ic and Ic -BL host galaxies with the Hα flux determined from the VIMOS observation superposed on the SDSS postage stamps. This is part of our sample, investigating the local properties of helium-poor SNe.

within the errors, therefore pointing to a non-significant difference in the types of environments preferred.

An additional project we have been working on is the detection and follow-up of magnified SNe in the Frontier Fields. Over the past decade, the deep HST Treasury surveys (GOODS, CANDELS, CLASH) have enabled "free" SN searches, which have collectively accumulated scores of SN detections that reach to uniquely high redshifts (Riess et al., 2007; Rodney et al., 2014; Graur et al., 2014) in clusters of galaxies selected for observations over large periods of time with relatively high cadence.

The ongoing Hubble Frontier Fields program now provides a powerful new tool for the discovery of particularly high-z SNe. Gravitational lensing in the prime fields can magnify fluxes significantly, making it possible to detect distant background events. The Hubble Frontier Field survey thus provides the first opportunity to discover SNe at $2 < z < 3$, building up a small but important "New Frontier" sample. Because Type Ia SNe are standardizable candles as a consequence of the similar ejected Ni^{56}-masses, we can use lensed SNe Ia to directly measure the true lensing magnification μ and confront the predictions from existing lens models (e.g. Riehm et al., 2011; Li et al., 2012; Patel et al., 2014). Our sample of lensed SNe Ia is already proving to be a very valuable tool for testing galaxy cluster dark matter models (Rodney et al., 2015), which will be particularly valuable for the study of z > 8 galaxies magnified by these clusters (e.g. Zheng et al., 2012).

The unique combination of deep imaging, strong lensing, and rapid cadence in the HFF program has also provided two very exciting discoveries of multiply-imaged transients. In January and August of 2014, we observed two short transient events in separate images of the same strongly lensed galaxy, measured to be at z=1.005 with

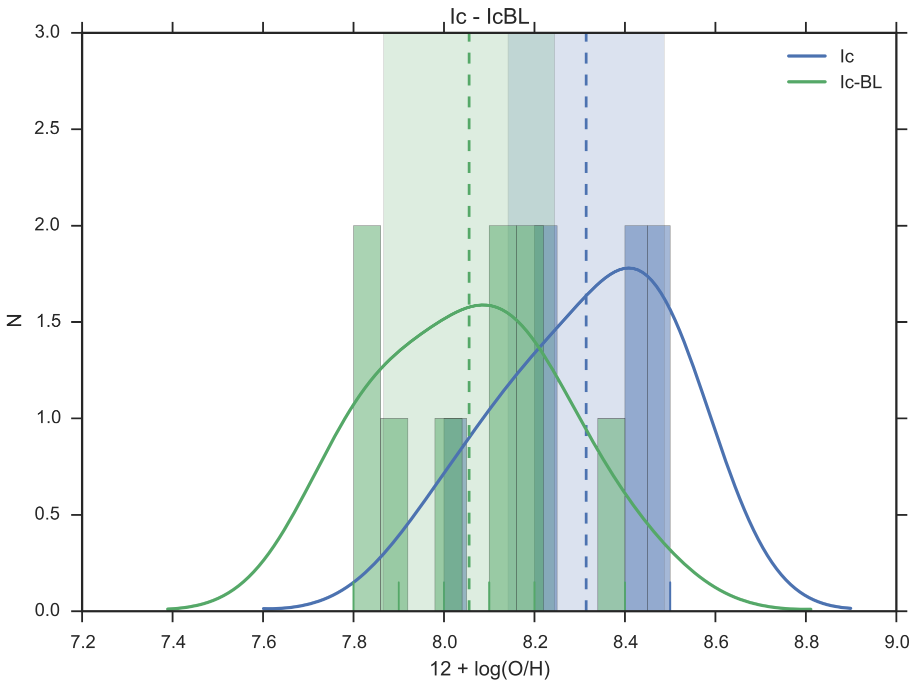

Fig. 1.5: Number of SNe as a function of metallicity. The green colors represent the metallicity if SN Ic-BL and the blue represent the metallicity of SN Ic. A marginal evidence for a preference for lower-metallicity environments is shown.

X-shooter. Collectively nicknamed "Spock", both of these events are too faint to be a normal SN and too bright to be a stellar flare. The light curves are also faster than expected from a He shell explosion on a white dwarf (a ".Ia" event Bildsten et al., 2007), and fainter than any of the "fast optical transients" yet seen in wide-field ground-based surveys (e.g. Kasliwal et al., 2010; Poznanski et al., 2010; Vinkó et al., 2014). Lens models (and Occam's razor) suggest that these two events are most likely spatially coincident on the source plane. If the two events were also coincident in time, then this could be an example of an extremely rare neutron star collision (a "kilonova" Tanvir et al., 2013; Barnes and Kasen, 2013). If not, these may be two separate outbursts from an extremely bright nova with a remarkably fast recurrence timescale of $\sim$1 year. This would be a unique nova, as it would have a recurrence timescale on par with the most extreme examples known (Tang et al., 2014) and would also be at least an order of magnitude more luminous than a typical nova. In November of 2014 we discovered another exciting transient, this time with four distinct sources appearing almost simultaneously in a strongly lensed spiral galaxy at $z = 1.5$. Dubbed "SN Refsdal," this is the first ever example of a strongly lensed SN with multiple resolved images (Kelly et al., 2014, Figure 3). The Einstein Cross configuration is generated by a galaxy-scale lens, but the SN host galaxy is also multiply imaged by the cluster, so we expect to see SN Refsdal return elsewhere in the cluster field in 1–5 years (Oguri, 2015; Sharon and Johnson, 2015). Measurements of the relative magnifications and time delays among these multiple images will soon deliver an unprecedented suite of powerful new mass model constraints and the reappearance of "SN Refsdal" in the future will be a crucial test for these mass models.

With the X-shooter observations we have obtained of "SN Refsdal" in paper II, we see a clear detection of a broad Hα at a redshift consistent with the host galaxy, which we show in Fig. 1.6. By matching templates to the spectrum of "SN Refsdal" we confirm that the best matching existing SN spectra is similar to that of the peculiar type II SN, SN 1987A.

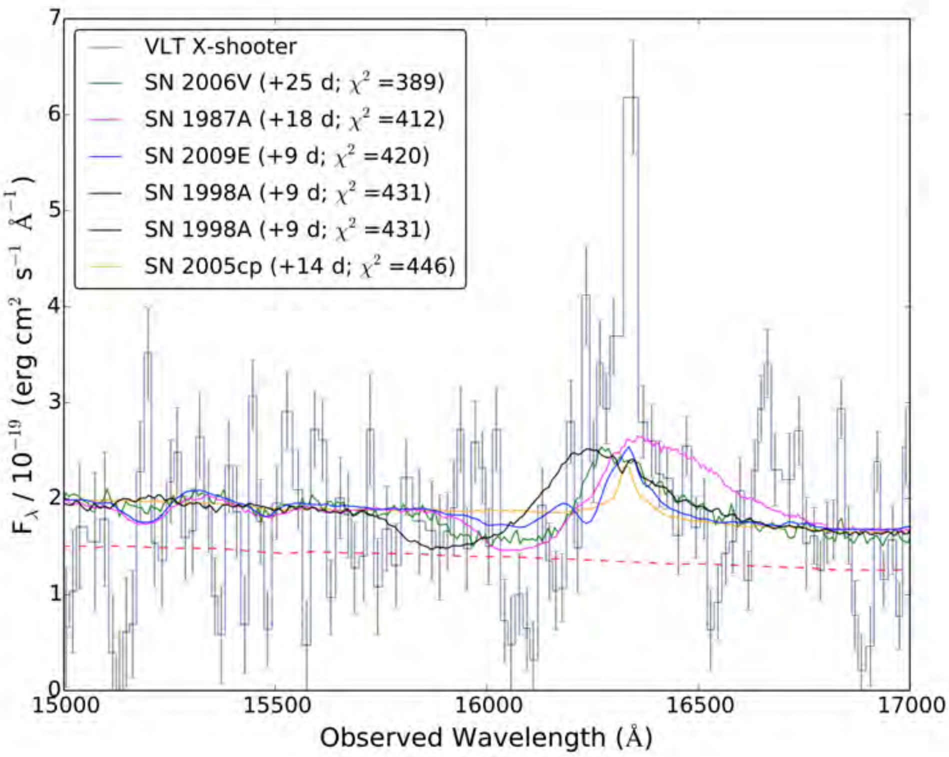

Fig. 1.6: X-shooter spectrum of the quadruply lensed SN, Refsdal. The broad feature at 16300 Å is Hα-emission from the SN explosion. Over plotted are the best fit templates.

1.5 Future work

Having just started my scientific change of environment at UCSC, I will work with Enrico Ramirez-Ruiz on a project related to the explosions of SNe, specifically how the polarization of the elements synthesized in the explosion depends on the regions in which they are deposited. Additionally I will work on a project with Jason Xavier Prochaska related to my work on quasars. The "SN Refsdal" classification-paper is nearing progressing and during my stay in California, I will visit Patrick Kelly at Berkeley to collaborate on finishing it. My VIMOS project is quite progressed and I have begun drafting a paper, which I hope to finish within the next year. Additional work is needed for the population fitting and this will likely require a great deal of time to do. As the X-shooter afterglow sample continues to grow, I will normalize the spectra as they are delivered and when I return from my exchange, produce the X-shooter afterglow composite for which I will write a paper, similar to the quasar paper.

I have finished all of my mandatory duties in teaching and courses, so I can devout the entire last two years of my PhD studies on doing research, which I look forward to.

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