

SUPERNOVAE SURVEYS: FROM THE GROUND UP

By

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Declaration

I hereby declare that the work in this thesis is that of the candidate alone, except where indicated below or in the text of the thesis. The work was undertaken between the 1st of August, 2018 and the 1st of July, 2023 at the Australian National University (ANU), Canberra. It has not been submitted in whole or in part for any other degree at this or any other university.

Statement of Contribution

This thesis is submitted as a Thesis by Standard Format in accordance with https://policies.anu.edu.au/pp1/document/ANUP_012815.

I declare that the research presented in this thesis represents original work that I carried out during my candidature at the Australian National University, except for contributions to multi-author papers incorporated in the thesis where my contributions are specified in the *Context and Contribution* section of each main chapter.

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Abstract

Rapid cadence observations are key in developing a stronger understanding of transient astronomical events. With these observations, we stand to better understand the progenitor systems that result in supernovae, kilonovae, gravitational waves, and gamma-ray bursts. These cataclysmic events reveal key signatures in their earliest stages that need to be understood to properly reduce systematic errors with their use in modern cosmology. Modern surveys (e.g. LSST, ASAS-SN, and ZTF) provide extensive discovery pipelines that allow rapid follow-up of these events, and can provide daily discovery reports, however they are still unable to probe the physics that develops on timescales less than a day.

The first chapter of this thesis, we explore the viability of Siding Spring Observatory as an observing site for followup of LSST's upcoming discovery pipeline. Extensive weather data collected from various sources at the observatory have been analyzed to identify long-term trends in wind, humidity, temperatures, and observing conditions. While strong gusts reaching speeds exceeding 55 meters per second can occasionally occur near the mountain's summit, the majority of the mountain does not experience such high winds, and hence is unlikely to force dome closures. Cloud cover poses a challenge for astronomical observations, with approximately 46% of nights experiencing some cloud. Despite the relatively poor observing conditions for an astronomical site, SSO can still play an important role in transient follow-up, as it can observe a similar sky to LSST due to its latitude, and its longitude is unique enabling observations at times when no other observing sites can.

This analysis is then followed by a discovery paper highlighting the importance of rapid cadence observations of supernovae. SN2019com was discovered on March 31, 2019, with the last non-detection images taken on March 28, 2019. Multiple spectra obtained using the WiFeS instrument on the ANU 2.3m telescope revealed strong similarities to SN2009ip, the first recorded supernova imposter. Early photometry from the Las Campanas SWOPE telescopes indicated an early blue excess, consistent with a shock cooling event. Analysis of this excess provided measurements of SN2019com’s progenitor radius, ejecta mass, and ejecta velocity. Subsequent observations with the Hubble Space Telescope (HST) displayed a light source consistent with SN2019com’s location, providing further evidence of its similarity to SN2009ip. This kind of analysis was only possible due to a rapid transient follow-up pipeline developed through this thesis, and shows the importance of early observations in determining progenitor systems of peculiar supernovae.

Finally, work done towards developing a low-cost solution to getting UV observations of these high-energy events. The ozone layer exhibits a complex spectral absorption profile in the near-ultraviolet wavelengths, influenced by seasonal variations in solar intensity and atmospheric circulation. Overcoming this obstacle is crucial for achieving a usable signal-to-noise ratio in scientific observations. GLUV is an affordable and long-duration high-altitude balloon experiment designed to deploy a network of NUV telescopes at altitudes between 20-30 km. The GLUV Pathfinder, a spectrometer-based system, serves as a precursor to the final GLUV project, aiming to characterize the NUV sky background as a function of altitude, latitude, and seasonal phase.

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1

Introduction

1.1 Supernovae

Supernovae (SNe) are the explosive deaths of stars that rapidly brighten and fade over the course of weeks to months. As they are currently understood, there are two main classifications of SNe: Type Ia and Core-Collapse (Type Ib, Ic, II). These types can be distinguished by analysing their spectral features (see Fig 1.1). Studying supernovae has become a major component of modern astronomy. Their discovery has brought forth a wave of understanding, providing a tool allowing astronomers to peer back into the history of the universe. Together with kilonovae, they are responsible for the creation of all heavy elements in our universe through nucleosynthesis. SN Ias are used in observational cosmology to gauge distances owing to their predictable brightness properties, making them useful as a 'standard candle'.

Unfortunately, SNe are relatively rare. One event is estimated to happen per

galaxy every century. This make observing them an arduous task. It has only been in the last couple of decades where instrumentation has allowed us to view these events unfold in large quantities. Much of the knowledge of their progenitor systems and underlying physics is yet to be uncovered.

Despite their importance in modern-day cosmology, they still inherently display some systematic uncertainties due to their complex progenitors which make them less "standardisable" than required. As such, the progenitor system of supernovae must be more deeply studied in order to reduce these systematic errors. Unfortunately, predicting where and when a supernova will go off is not yet possible, and so the progenitor must be determined after the supernova is discovered. This is theoretically possible, as neutrino measurements can be made before optical counterparts are seen (e.g. SN1987A), however localising the supernova with neutrinos is not yet possible. With few exceptions, there are no images pre-explosion of these objects, making determining the progenitor a difficult task.

Fortunately, there are semi-empirical models of supernovae which can yield information about their progenitor systems. They work by modelling the amount of light emitted at different wavelengths during the shock breakout/interaction and subsequent cooling stages, in order to determine the size and mass of the progenitor. These models require high cadence data at the earliest stages of the explosion in order to accurately ascertain the progenitor properties. Getting these observations requires rapid response pipelines to be developed to get data as soon as possible after detection.

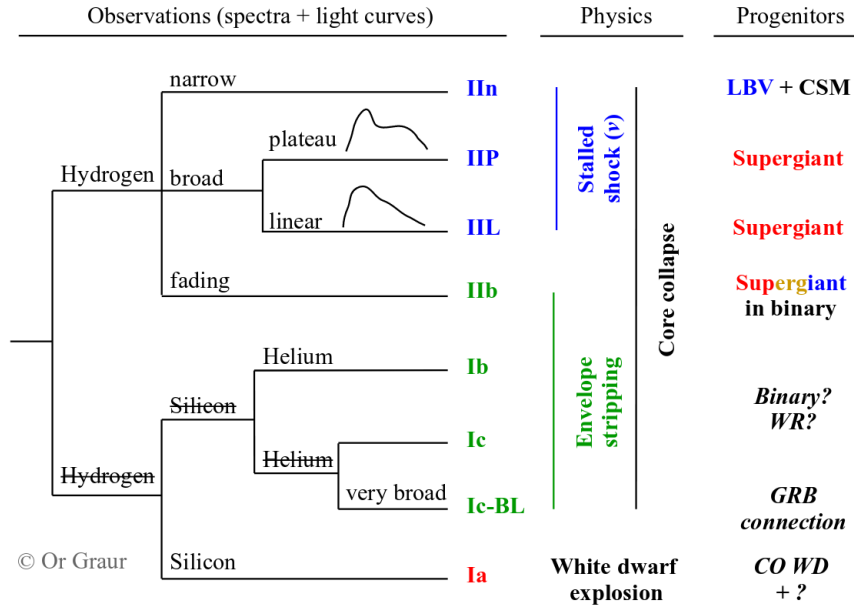


Figure 1.1: Decision tree showing what signatures lead to classification of SN types - Taken from [Graur \(2017\)](#)

1.1.1 Type Ia Supernovae (SN Ia)

SN Ia are an incredibly important tool for astronomers as they detonate at a near constant brightness, allowing them to be used as 'standard candles' ([Wood-Vasey et al. 2008](#)). These standard candles are useful as they allow measurement of distances to galaxies from our own, by comparing how bright they appear, to how bright they should be at a fixed distance from Earth. Relative distances between galaxies allow for more accurate mapping of space, and led to important discoveries such as the accelerating expansion of the universe ([Perlmutter & Schmidt 2003](#)).

Overview

SNe Ia are the most commonly discovered SNe owing to their large optical luminosity, with an energy output of 10^{43} erg/s at peak brightness. They are classified by their lack of Hydrogen or Helium spectral signatures (as shown in Fig 1.1), along with redshift adjusted Silicon, Iron, Sulfur, and Calcium which are prominent at peak brightness ([Filippenko 1997](#)). Their luminosity is derived from radioactive decay of ^{56}Ni to ^{56}Co , followed by ^{56}Co to stable ^{56}Fe (as shown in Fig 1.2). The majority of the light emitted during a SN Ia event is between the U and I bands,

making them a primarily optical phenomenon.

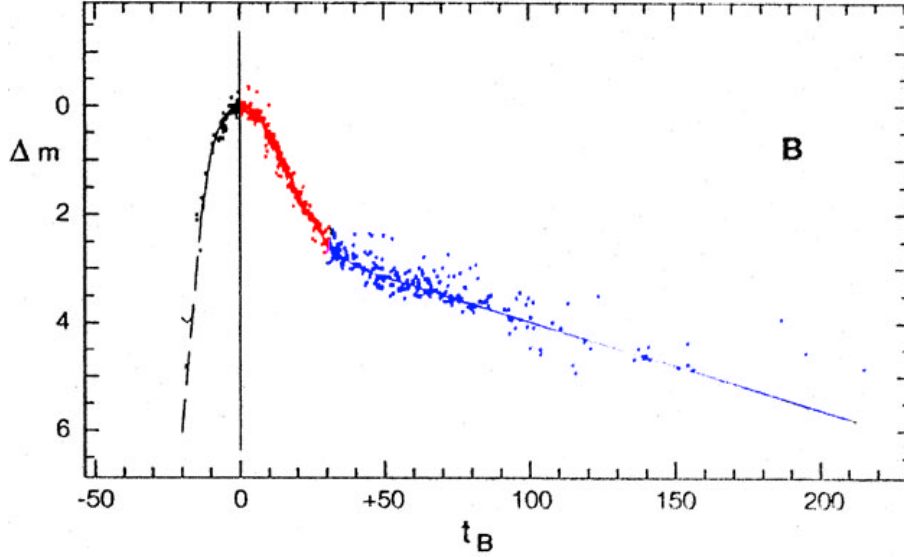


Figure 1.2: SN Ia light curve, centred around peak brightness (Cadonau 1987). Red shows light from ^{56}Ni to ^{56}Co decay, blue shows ^{56}Co to stable ^{56}Fe .

Supernova Progenitors

The lack of Hydrogen or Helium in the spectral signature of SN Ia events indicate the progenitor is not a main-sequence star, but rather a degenerate stellar core such as a white dwarf (WD). The chemical composition appears to be primarily Carbon-Oxygen (CO), as evidenced by spectral analysis of SN Ia remnants (Badenes et al. 2006). This core undergoes thermonuclear combustion once the Chandrasehkar mass has been exceeded, either by accretion of surrounding gas, stellar material, or a merger. Spectral evolution of these events indicate $0.6M_{\odot}$ of ^{56}Ni is produced by the CO burning, which would release $\approx 1.1 \times 10^{51}$ ergs. The gravitational binding energy as calculated by

$$E_{\text{binding}} = \frac{3GM^2}{5R}$$

is $\approx 0.5 \times 10^{51}$ ergs. Hence the energy released by the thermonuclear burning is enough to unbind the WD, producing SN Ia.

Once ignition has started, the highly degenerate material burns through at an

accelerating rate (Maoz et al. 2014). The actual mechanism which causes the runaway thermonuclear burning is still undetermined. It is put down to the gradual accumulation of pressure added by the accretion of material onto the WD, however this is a highly simplistic idea that does not probe the underlying physics of SN Ia detonation. This is an important issue, as SN Ia are highly important in cosmological explanations of the universe. Unknowns in their models may introduce systematic uncertainties which need to be reconciled in the future.

Single Degenerate (SD) Progenitor model

The generally accepted model for the mechanism behind SN Ia events is that they form as part of a binary system between a degenerate star and a main sequence star (van den Heuvel et al. 1992). The degenerate star is the remnant of the core of a star that has lost its outer envelope of helium and hydrogen after the Asymptotic Giant Branch (AGB) phase, and is typically a carbon-oxygen white-dwarf (WD) (Hoyle & Fowler 1960). The WD feeds off of its neighbour, gravitationally pulling in the outer layers of its atmosphere over time (called a Roche-lobe overflow). The neighbour is typically a main sequence, sub-giant, Helium, or red giant star. The WD accrues more and more material until it reaches the Chandrasekhar limit (about 1.44 solar masses), at which point the gravitational field overpowers the electron degeneracy pressure that stops it collapsing (Chandrasekhar 1931). This overwhelming gravity increases the core temperature, eventually forcing the carbon and oxygen within the star to fuse, releasing gargantuan amounts of energy in the form of a thermonuclear explosion. This energy overpowers the binding gravitational potential energy of the WD and blows it apart.

The nature of the companion is still unknown. The rate of SNe Ia is often used as a way to understand the nature of the companion. There have been many attempts to produce scenarios which would explain SN production rates, however due to the homogeneity of SN Ia events, and the wide range of possible companion stars, finding a definite answer is difficult. Instead of a main sequence star, the secondary could be any of the following.

- Subgiant ([Han & Podsiadlowski 2004](#))
- Helium star ([Tutukov & Yungelson 1996](#)) (A star that has had its Hydrogen enveloped removed gravitationally through some binary interaction).
- Red giant ([Patat et al. 2011](#)). This would sometimes encase the WD such that the radius of orbit would be smaller than the radius of the red giant. For this reason, it may be called a symbiotic companion. Alternatively, the WD simply feeds off the outer layers of the companion.

Whilst it is the current most popular opinion amongst astronomers that the SD model is most common, there are still difficulties apparent in trying to model how the WD accretes mass to beyond the Chandrasekhar limit in order to detonate. There exists a range in which the accretion rate can stably increase the mass of the WD, which changes as the WD becomes more massive. As the WD accretes Hydrogen or Helium from the secondary star, the stellar material fuses due to the immense gravity of the WD. If the accretion rate is just right, stable nuclear burning can occur on the surface ([Nomoto 1982](#)).

If the accretion rate is too high, then the accreted material will likely expand to a large volume, much like a red giant ([Iben & Tutukov 1984](#)). This would stall the accretion process, limiting the WD to a sub-Chandrasekhar mass. If the accretion rate is lower than the stable burning rate, stellar material will accumulate on the surface of the WD in a cold, degenerate layer. The problem is it could explosively ignite, releasing more energy than that required to eject the fused material off the surface ([Starrfield et al. 1972](#)).

There is a relatively small mass flow rate range in which material can accumulate onto a WD ([Maoz et al. 2014](#)). Anything that is not within this range would stifle the efficiency of mass accumulation. This could explain the rarity of SN events for any given galaxy, however this uncertainty in the progenitor system means that the method of mass accumulation for a SD WD system is still a very open question.

Double Detonation Progenitor model

In the case of a slow accretion from a Helium star donor, a cool Helium crust can form on top of the WD. This is compressed enough to become degenerate, and once it becomes sufficiently massive, the Helium can ignite explosively ([Taam 1980](#)). This detonation sends a shockwave through the WD. The resulting pressure wave can spark ignition of the Carbon and Oxygen in the WD, forcing a thermonuclear explosion.

This type of explosion would be expected to show strong signatures of Carbon and Oxygen being formed from the outer layer of Helium fusing. [Bildsten et al. \(2007\)](#) showed that a high mass accretion rate could result in this type of SN requiring less Helium than previously thought to provide the initial detonation, bringing this theory more in line with observation.

Double Degenerate (DD) Progenitor model

Another potential way for SN Ia to form is through the Double Degenerate (DD) model. In this, there is a merger between two WDs. The WDs orbit each other, losing energy through gravitational waves, and spiralling in until they eventually collide. This idea is somewhat more simplistic than the SD model, as the progenitor stars are known. It is theorised that the lower mass WD will be tidally disrupted forming an accretion disk around the more massive WD, which eventually settles onto its surface, and causes a SN explosion once the Chandrasekhar mass has been reached ([Moll et al. 2014](#)).

Since all the material involved is already Carbon or Oxygen, this model does not suffer from the same issues with mass accumulation rates as per the SD model. As they would merge rapidly, non-symmetric mass gain can occur. This difference in densities within the WD can yield different nucleosynthesis processes, and gravitational instability, compressing the WD down into a Neutron Star (NS) ([Nomoto & Iben 1985](#); [Shen et al. 2012](#)), as opposed to producing a SN Ia.

An alternative DD model is that of a direct collision between two WDs. While WDs are small compared to stars, and especially so compared to the emptiness of space, this merger could be feasible (whilst still rare) in dense stellar environments such as galactic nuclei and globular clusters. [Thompson \(2011\)](#) invoked a different model, wherein a triple star system could increase the chances of collision. A highly eccentric orbit could accelerate the rate of gravitational wave energy loss, forcing the WDs to merge sooner than if in a binary system. This tertiary system, however, is not likely to be responsible for a significant portion of SN Ia events, owing to the rarity of tertiary star systems observed.

SN Ia progenitor summary

As shown, there are many competing theories as to the progenitor system of Type Ia SNe. Each of these options are viable depending on the initial configuration of each star system. It is unfortunate that there are so many options still open for debate, given the importance of SN Ias in modern cosmology. The main consensus is that the majority of SN Ia observed originate from a SD binary system. The similarity between each SN Ia event would indicate that they mostly have similar origins.

1.1.2 Core-Collapse Supernovae (CC SNe)

Core collapse supernovae are the explosive deaths of massive stars, with mass (m) of $8M_{\odot} < m < 40M_{\odot}$. Owing to the large range of their progenitor systems, they are not useful as standard candles in the same way that SN Ia are. They exhibit large variation in their light-curves, as a study that [Pritchard et al. \(2014\)](#) highlighted. Well after they've migrated off the main sequence, massive stars experience episodic nucleosynthetic burning of elements from helium and beyond, increasing in atomic number through various fusion pathways. This burning provides support to the star, supporting it from the core outwards against the oppressive force of gravity. Fusion continues and the battle to maintain hydrostatic equilibrium (HSE) rages on, until a iron-ash core is acquired. Upon reaching iron, nuclear fusion can no longer support the star forcing a rapid deviation from HSE.

Type Ib/Ic

Type I SN are classified by the lack of Hydrogen in their spectral features. SN Ib and Ic are differentiated from Ias by their lack of ionised Silicon. Furthermore, SN Ic are differentiated from SN Ib by their lack of Helium ([Filippenko 2005](#)).

SN Ib/c explosions can have a strong radio component, thought to be caused by a dense CSM being hit by the supernova shock ([Chevalier 1982](#)). The dense CSM combined with the lack of H/He spectral lines in the supernova explosion indicates a massive star partially or fully stripped of its hydrogen and helium envelope. This envelope stripping is thought to occur through either stellar winds, or mass transfer to a companion star. Since their progenitors are some of the most massive stars that exist, Type Ib/c SN are much rarer than SN II ([Sadler & Campbell-Wilson 1997](#)). While their spectral features are different, their light curves can be quite similar to SNe Ia, causing SNe Ib/c to be a source of contamination when trying to observe SN Ia ([Homeier 2005](#)).

While SNe Ics are differentiated from Ibs by their lack of Helium, small amounts have still been seen in their explosions ([Filippenko et al. 1995](#); [Matheson et al. 2000](#)). This discovery implies the sole differentiating factor between Ibs and Ics is the abundance of Helium in the progenitor star.

Type IIP/IIl

Type II SN have Hydrogen apparent in their spectra. They come about from the gravitational collapse of a supergiant star ([Filippenko 2005](#)). Type IIs can be further classified according to their light curves and spectra into Type II_n, IIP, II_L, II_b. They are the most common type of SN, however due to their limited luminosity, they are not as frequently observed as Type Ias.

The most common type of the Type II SN is the IIP. This type of SN produces

a lightcurve that plateaus in brightness for roughly 100 days post-maxima. This plateau is powered by the shock wave of the supernova explosion. Hydrogen in the photosphere of the progenitor star undergoes recombination, allowing residual internal energy to be radiated away (Kasen & Woosley 2009; Dessart et al. 2013; Popov 1993). This recombination wave propagates outwards into the expanding ejecta, which adiabatically cools as it expands (Arnett 1982).

Red Supergiants (RSGs) are thought to be the progenitor of the IIP supernova. This is backed by analytical solutions to hydrodynamic diffusion (Arnett 1980), requiring large stars ($r \sim 10^{12}\text{m}$) to match the observed ejecta velocities determined spectroscopically (Smartt 2009). Schawinski et al. (2008) used theoretical models of UV light curves of shock breakout (described in 1.1.3) to confirm the link between RSGs and SN IIP.

SN IIP are closely linked to SN IIL, with the main difference being the more linear decay in luminosity for the IIL (Filippenko 1997), as opposed to the plateau stage of the IIP. Both exhibit rapid drops in luminosity during their nebular phases, around 100-150 days post-maxima. In general, IIL tend to be brighter initially, and experience the rapid drop sooner (Valenti et al. 2015). The distinction between IIP and IIL supernovae is still an open question, with debate ongoing around whether they are two distinct classes of SN, or rather if there is a spectrum of SN that exhibit their behaviour.

Type IIn

Type IIn SN are characterised by their narrow emission lines, particularly their Balmer series lines. The FWHM of these strongest lines (notably $\text{H}\alpha$) is on the order $v \approx 100 \text{ km s}^{-1}$ (Filippenko 1997). These lines are thought to be the result of SN ejecta colliding with the progenitor star's CSM. The SN shock ionises the unshocked CSM, which then recombines to produce the narrow emission lines (Chugai 1991).

The narrow emission lines are the distinctive feature of SN IIn, however they also exhibit broad emission lines like other SN II ($v \approx 1,000 - 10,000 \text{ km s}^{-1}$). These broader lines come from the underlying SN ejecta, as well as possible Thomson scattering of the CSM (Dessart et al. 2009).

They are very heterogeneous in nature, implying the existence of multiple progenitor systems which can create them. Some display long-lived light curves, shining for years beyond their initial explosion (Filippenko 1997; Stritzinger et al. 2012), whereas others are shorter lived and more luminous (Ofek et al. 2007). This disparity implies that there may be multiple ways to produce SN IIn (Nyholm et al. 2020).

1.1.3 Early UV signatures of supernovae

Shock breakout is the stage of a CCSN event where the first shockwave of the explosion erupts out of the surface of the progenitor star (Lovegrove et al. 2017). This shockwave has an optically thick leading edge, making it difficult to analyse. As this shockwave expands, it becomes more optically thin, allowing for the hotter underlying shock to shine through it (Waxman & Katz 2017). This initial flash is the first (photon) observation that can be seen in the event of a SN. Since the properties of the shock breakout are determined by the star's structure, it carries information about the surface gravity, radius, atomic composition and explosion energy.

The supernova shock heats the photosphere to very high temperatures, so it is best observed in the ultraviolet. In order to accurately model their progenitors, high-cadenced coverage at high-energy wavelengths (blue and higher) is required. Most ground telescopes do not cover the UV wavelengths, as the earth's atmosphere is mostly opaque at these wavelengths due to absorption from ozone at 13-25km above the surface of the Earth in the Earth's stratosphere. In order to circumvent this, one needs to place telescopes above the ozone layer to increase UV throughput. This would normally mean space telescopes which are prohibitively expensive, however a balloon-borne telescopes present a cheaper (albeit more mechanically complicated) alternative.

The initial stages of a SN event are important to analyse, as they contain clues to pin down the progenitor system which spawns them. As the SN develops from its initial stages, the photosphere remains untouched, until the shock generated by the explosion reaches the photosphere. For a CC SN, this shock-breakout stage can reveal information about the star’s pre-supernova state (Quimby et al. 2007).

The shocks take place over the course of minutes to hours after the initial detonation event. Despite this tiny window, the *Swift* (Brown et al. 2007; Bayless et al. 2015) and *Kepler* (Garnavich et al. 2016) telescopes have both been able to capture the shock breakout event of CC SN.

Owing to the difficult nature of observing SN events, there is little direct evidence to suggest that SN Ia events happen from binary star systems. The rarity of SN mean that nearly all SN events have been extragalactic. This means that they occur too far away to be able to resolve single stars. Kasen (2010) theorises that emissions should be visible when the ejecta of the SN collides with the companion star. The visible emission will depend on the alignment of the SN with the companion relative to Earth, estimated to occur 10% of the time. The emissions are predicted to be strongest in high-energy wavelengths, peaking in X-ray to UV wavelengths. When comparing Kasen’s theory to observations however, Brown finds that the emissions exist, but are redder than expected (Brown et al. 2018).

The main signatures of SN are prompt bursts of high energy photons, causing a brief blip in the observed light curve (see fig. 1.3). Kasen (2010) analytically provides an explanation for this flash, wherein the shocked ejecta collides with the companion star. The shock front travels around the star, forming a shock-cone behind it (much like a supersonic projectile flying through the air). Due to the pressure differential between the shock front and the cavity formed behind the companion star, radiation is channelled into the void, allowing it to escape the optically thick ejecta. Adiabatic expansion forces the shock front to eventually close up the cavity, after which it becomes optically thick to high energy photons again. This burst of

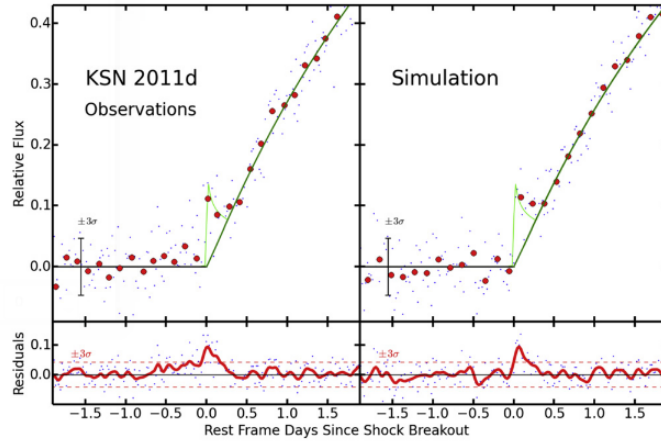


Figure 1.3: Left: Light curve showing shock breakout of KSN2011d directly from Kepler data. Right: a simulated light curve created using the statistical properties of the Kepler photometry and the best fit photospheric model (Garnavich et al. 2016). Red points are binned averages of the blue points, which represent the total dataset. The shock breakout model is drawn as green. The 'relative flux' axis shows a normalised value with peak brightness at 1.0.

high energy photons is a result of the initial burst, leading to observational clues of the progenitor system of the SN.

CCSN tend to undergo a rapid increase in brightness during the shock breakout phase, occurring just before the expansion of the ejecta . After this, the radioactive decay of the ejecta overtakes as the primary source of light (Arnett 1982). For SN Ia, at maximum light, the energy loss due to diffusion is equal to the energy input from radioactive decay of ^{56}Ni . The faster the ejecta (i.e. the speed of expansion), the quicker the diffusion time, and hence the steeper the rise in the light-curve.

The light from the expanding ejecta is not fully understood. There have been attempts to model it using strictly black-body radiation (Arnett 1982), but this poses a few problems. The radiation escaping would have to be modelled off of the temperature of the expanding photosphere, and it is very difficult to determine where the photosphere of a SN is at any given time after shock breakout. Thermal photons should be able to escape soon after the ejecta becomes transparent to high-energy wavelengths, owing to the similarity between the atomic cross-section for Compton scattering at short wavelengths, and Thomson scattering. Comparing the U,B,V light curves predicted by Arnett's black-body SN to observations (Barbon

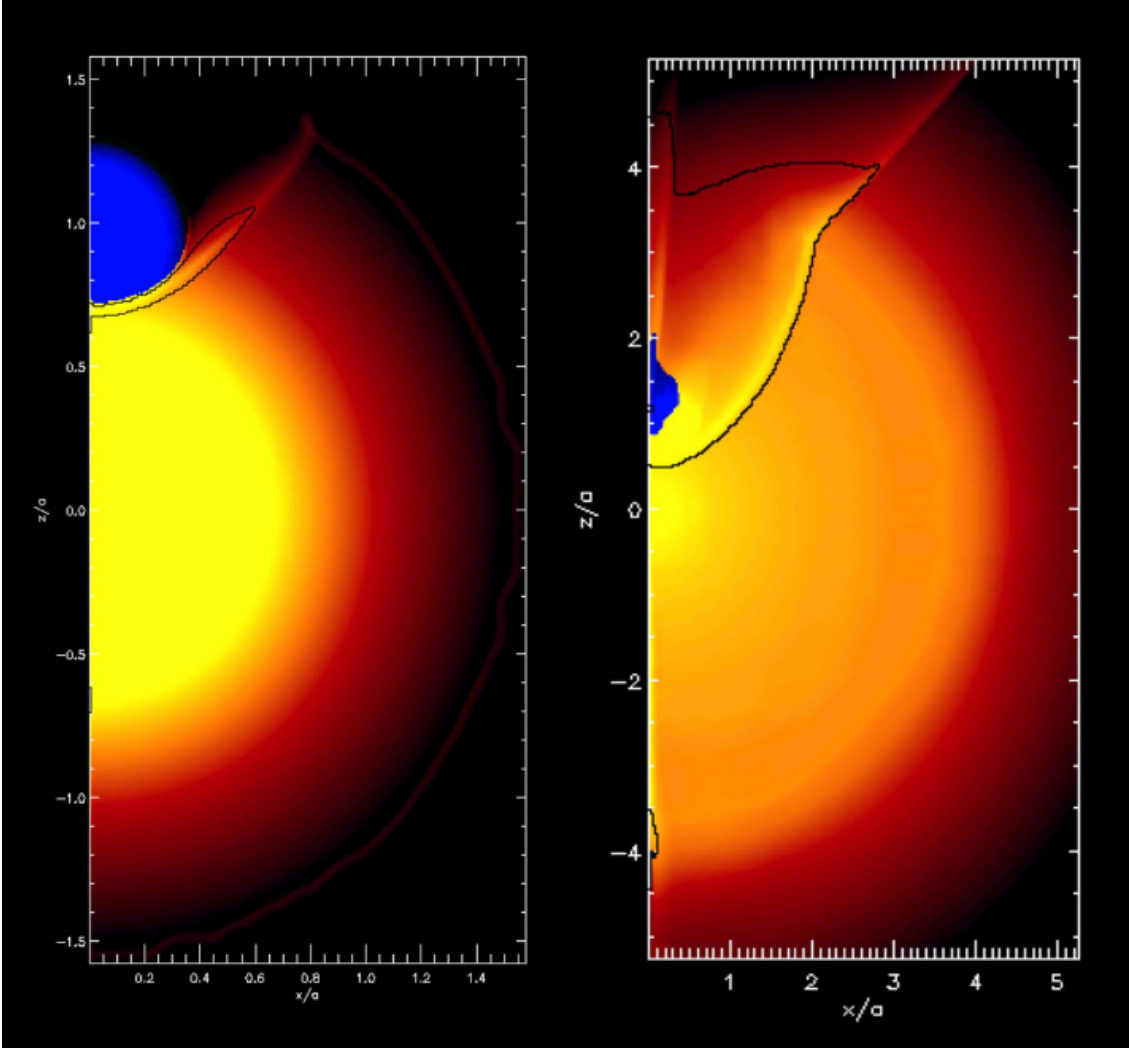


Figure 1.4: Hydrodynamic simulation of expanding ejecta (yellow-red) hitting companion star (blue). The black contour outlines the shock interaction. As can be seen on the right, there is a hot, dense wall from the shock front, with a shock cone formed behind the companion star. It is through this cavity that the UV / X-ray burst can escape from, before the shock front collapses further behind the star due to adiabatic expansion (Kasen 2010).

et al. 1973), there is close agreement initially, however the analytical solutions diverge from reality after some time. This was put down to the simplistic black-body model ignoring radiative transfer effects within the ejecta.

It is only within the last decade or so that we have been able to obtain good data on the earliest stages of SN Ia shocks. The Sloan Digital Sky Survey (SDSS), Supernova Legacy Survey (SNLS), and Kepler missions have shed light onto what high-cadence astronomy can provide us with (e.g. Garnavich et al. 2016; Rest et al.

2018), providing constraints on the early light curves of SN Ia. High cadence astronomy is needed to find young SN, to determine the progenitor systems that produce these events. One such example of a young SN is 2011fe, found in M101 less than a day after detonation (Bloom et al. 2012). Whilst this was a major event in the astronomical community, more high cadence data is required in order to refine what we have learnt from it.

1.2 Ultraviolet Astronomy

Atmospheric opacity can interfere with the effectiveness of ground measurements of light at the, particularly outside the optical spectrum. The elemental composition of the atmosphere can interact with incoming light in multiple ways. For example, high energy light (UV, X-rays, Gamma rays) can ionise molecules easily, or cause chemical reactions to occur. Lower energy light (e.g. IR) can deposit energy into the vibrational modes of molecules. These interactions cause the atmosphere to absorb or scatter the light, making it opaque to these wavelengths. Despite this, there are some 'windows' that appear in the spectrum through which light can penetrate.

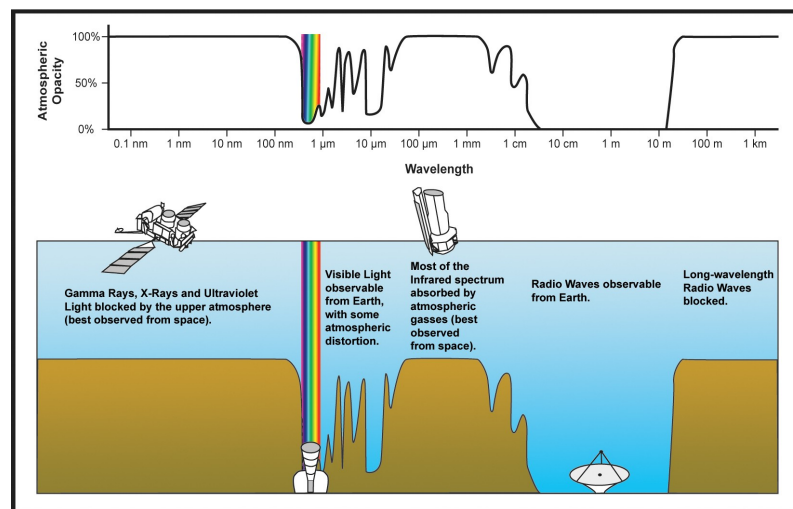


Figure 1.5: Opacity of the atmosphere seen as a function of wavelength. As can be seen, the Earth's atmosphere is mostly opaque, with light being able to penetrate in the optical, some IR, and some radio wavelengths. The optical region is denoted by the rainbow spectrum. Credit: Wikimedia (public domain).

Due to this optical window, ground telescopes primarily focus on optical observations. The Earth's atmosphere absorbs a significant portion of UV light, making it challenging for ground-based telescopes to capture clear and precise UV images. Scientific frames taken in this regime would have almost zero throughput, even on typically clear nights. This atmospheric opacity restricts the availability of high-quality UV data and limits the potential scientific discoveries that could be made in this wavelength range. As a result, UV observations are typically carried out using space-based telescopes, such as the Hubble Space Telescope, which can bypass the atmospheric interference and provide unobstructed views of celestial objects in the UV spectrum. While ground telescopes excel in capturing optical light, the UV range remains largely inaccessible to them due to the absorption properties of our atmosphere. Approximately 50% of the near-ultraviolet regime (320 – 400nm) is blocked by the ozone layer, with that percentage increasing to nearly 100% when looking at higher energy UV (100 – 280nm) light.

1.2.1 Galaxy Evolution Explorer

The Galaxy Evolution Explorer (GALEX) was a pioneering mission in the field of ultraviolet astronomy. Its primary objective was to survey the entire sky in the UV range, capturing images and spectra of celestial objects with unprecedented sensitivity (Bianchi & GALEX Team 1999). GALEX operated for over a decade, providing valuable insights into various aspects of galaxy evolution, stellar populations, and the interstellar medium.

One of the key goals of GALEX was to study the formation and evolution of galaxies. By observing galaxies in the UV range, GALEX was able to trace the young, hot stars that emit copious amounts of UV radiation. This enabled astronomers to investigate the rate of star formation and understand how it varies across different types of galaxies (Salim et al. 2005). GALEX also contributed to our understanding of galaxy mergers, interactions between galaxies, and the processes that shape their morphology (Yoshida et al. 2008).

In addition to galaxy studies, GALEX surveyed the UV emission from nearby stars, providing valuable data on stellar evolution and stellar populations in our own Milky Way galaxy and beyond (Kalirai et al. 2007). GALEX also contributed to the study of active galactic nuclei (AGNs) by observing the UV emission from supermassive black holes at the centers of galaxies (Ciotti & Ostriker 2007). This helped shed light on the mechanisms that power these energetic phenomena.

The mission's data archive has been a valuable resource for astronomers worldwide, facilitating a wide range of research projects even after the mission ended in 2013. The breadth of knowledge that the GALEX was able to unlock by observing the UV universe, revealing phenomena that were previously hidden or poorly understood in other wavelength ranges.

1.2.2 Cosmic Origins Spectrograph

The Cosmic Origins Spectrograph (COS) has played a pivotal role in advancing the field of ultraviolet (UV) astronomy. Installed on the Hubble Space Telescope (HST) during the final servicing mission in 2009 (Green et al. 2012), COS has greatly enhanced our understanding of various astrophysical phenomena by enabling high-resolution UV spectroscopy.

One of the key contributions of COS is its ability to study the intergalactic medium (IGM) and its impact on galaxy evolution (Werk et al. 2014). By observing the absorption features in the UV spectra of distant quasars, COS has allowed astronomers to probe the properties of intervening gas clouds (Beckett et al. 2023). These observations have shed light on the distribution, composition, and ionization state of the IGM, revealing the intricate web of gas that permeates the universe. Understanding the IGM is crucial for unraveling the processes involved in galaxy formation, as it serves as the reservoir from which galaxies accrete gas to fuel star formation.

COS has been utilised to determine progenitor systems of peculiar supernovae,

with it aiding in the characterisation of SN IIn as Type II supernovae that explode within a dense halo of circumstellar material (Fransson et al. 2014). It has also been used to study the effects of supernova outflows, and prove the utility of UV spectroscopy for tracing warm gas in starburst-driven outflows (Wood et al. 2015) when compared to more typical analysis of the $H\alpha$ spectral line.

Additionally, COS has made substantial contributions to the field of exoplanet research. By observing the UV spectra of exoplanet transits, COS has facilitated the study of their atmospheres, and mass-loss processes (Fossati et al. 2018). The high-resolution UV spectroscopy offered by COS has allowed astronomers to analyze the abundances of elements in these solar systems, providing insights into their evolutionary stages and chemical enrichment.

GALEX and COS have made a profound impact on astronomy by providing tools through which to explore the UV universe. These telescopes were both very costly missions due to the challenges associated with their operation in space. Bringing the cost of UV astronomy down is vital for increasing accessibility for research groups worldwide, enabling the next generation of astronomers to explore this incredibly fruitful field.

1.2.3 Spectroscopy

Spectroscopy plays a vital role in supernova observations, offering valuable insights into the physical processes and properties of these cosmic explosions. It is a tool that provides information about the composition, velocity, and temperature of the supernova ejecta. Spectral analysis also enables the classification of supernova types; in particular separating SN Ia from CCSN, which is much harder to do photometrically. CCSNe on the other hand are much more similar, and may require photometry to distinguish properly (in particular SNe IIP and IIL, which are distinct only through their light curves). Spectroscopy also helps trace the elemental evolution of a supernova over time, providing crucial data for modeling the explosion and its aftermath.

Ultimately, spectroscopic observations of supernovae provide a wealth of information that deepens our understanding of stellar evolution, nucleosynthesis processes, and the dynamics of supernova explosions.

Spectroscopy allows us to probe elemental signatures of intermediate mass elements (e.g. Carbon, Oxygen, Silicon) at peak brightness easily (Mandel et al. 2011). Early spectral analysis was performed on SN2011fe (Hsiao et al. 2013); one of the first, well studied young SN events. This study provided insights as to the time scale of differing nucleosynthetic events occurring within a SN explosion. For example, in this study, they note that C(I) emissions can act as a tracer for unprocessed material, allowing for the transition between deflagration and detonation to be followed in pseudo-real time.

Spectroscopic follow up of young SN events have been focused on providing short wavelength light analysis, due to the initial UV burst (Kasen 2010) being an interesting topic to analyse. Doppler redshifting and shock cooling can bring this initial burst down to optical wavelengths, enabling most ground telescopes with spectrographs to observe them at later epochs. This is not a reliable source of shock detections however, as the redshift required to bring shock breakout into the optical regime necessitates the source being much further away.

1.3 Rapid cadence surveys

For the vast majority of astronomical history, astronomers have been limited to what was visible with the naked eye. This meant that the limiting factor has been the brightness of the object that they wanted to observe. Over the last century, cameras have been developed which allow for extremely faint objects to be seen by allowing the receiver to collect light for long periods of time. Unfortunately, this means that any transient object observed cannot be accurately modelled, as the time aspect of these events has been blurred by the long exposure times. For example, taking a week long exposure would limit your time resolution to week long intervals. This

is not useful when trying to observe the early stages of a SN event, which evolves throughout the course of a week. It is only within the last decade that technology has allowed us to capture dim objects in short exposures, which is the exactly what transient objects require to observe.

This type of technology is still limited by the same principle: longer exposures allow for dimmer objects to be seen. However, with the development of Charge-Coupled Devices (CCDs), highly precise and sensitive instruments have been created that can see the local universe (with redshift $z < 0.1$) with amazingly short cadences. Currently, these CCDs are capable of capturing short exposures with high signal-to-noise, making the limiting factor for SN shock observations more a logistical automation problem.

With the recent boom in computing power, large scale, rapid cadence surveys are becoming more accessible than ever. This presents a powerful tool for time domain astronomy. The large scale surveys such as ASAS-SN (2014-present) ([Kochanek et al. 2017](#)) and ZTF (2018-present) ([Bellm et al. 2019](#)) are increasing transient discoveries at an exponential rate.

ZTF alone has doubled the number of discovered transient objects since its introduction in late 2017, and hence leading to a doubling of the number of supernovae discovered too. The Vera C. Rubin Observatory (VCRO) is expected to increase this by a factor of 10-100 ([Jones et al. 2016](#)).

Multi-messenger astronomy is also a recent development, with the discovery of gravitational waves (GWs) in 2016 ([Abbott et al. 2017](#)). The merger events detected are incredibly energetic. Neutron star mergers emit in the optical regime in addition to the GWs. This has been observed as a blue event, quickly shifting to red. Most analysis techniques developed to date have been focused on the light component, and so rapid followup of these events is required in order to probe the underlying physics while the gravitational waves are still observable.

Supernova shock physics requires higher cadence at the earliest stages of detonation. The shock breakout stage of supernovae occurs on the timescale of minutes, not days. Large scale surveys are unable to provide this rapid cadence. There is a need for dedicated followup instruments to capture photometry at these timescales to aid in more accurately modelling supernovae and their progenitors.

Analysis of supernova shock lightcurves is limited by the availability of data of these events. Fortuitously, there is overlap with the exoplanet hunters, with missions such as Kepler (and K2) and TESS providing photometry at a high enough cadence to see these events. Unfortunately, these surveys observed at optical and NIR wavelengths. Despite this, shock breakout has been observed using these instruments ([Garnavich et al. 2016](#); [Armstrong et al. 2021](#)).

1.3.1 Kepler & K2

The original Kepler mission was designed to discover exoplanets orbiting nearby stars. This was accomplished by using high cadence photometry to measure the light coming from a particular source repeatedly, and trying to find any dips in brightness that may occur over the course of each campaign. Due to these design parameters, Kepler also turned out to be a great tool for finding young SNe.

Kepler’s second mission (K2) provided photometry for a range of scientific goals. One of these goals was to provide high-cadence data for helping determine the progenitor systems of Type Ia SN. As previously mentioned, high cadence data might be able to elucidate the nature of the binary companion.

Data from K2 provided the first look at the shock breakout profile of a SN IIP event ([Garnavich et al. 2016](#)). For the first time, shock breakout theories were testable. The results they found were consistent with predictions made by Nakar and Sari ([Nakar & Sari 2010](#)) for a red supergiant progenitor. Unfortunately, the rise time to the peak flux of the shock breakout is less than the exposure time for K2, so shock breakout was not resolved.

1.4 Early detection and follow-up

Tracking the early evolution of supernovae is important as it is the early stages that provide insight into the progenitor that became a SN. Current models of the cooling curve after shock breakout (e.g. [Piro 2015](#); [Waxman & Katz 2017](#)) derive progenitor mass, radius, time of explosion, and ejecta velocities from photometry. Unfortunately, these properties are highly degenerate, making them hard to extract.

Higher cadence observations of the shock breakout stage (and subsequent shock cooling) constrain these values which helps to categorise the progenitor star. Time of explosion is the easiest parameter to lock down with higher cadence photometry, as it can be constrained by the last non-detection. High cadence lightcurves of shock cooling are immensely helpful in constraining this parameter space to determine likely progenitor stars of SN (e.g. [Garnavich et al. 2016](#); [Armstrong et al. 2021](#)).

Spectra also provide an alternative means to determine ejecta velocity. By measuring the full-width half-max (FWHM) of spectral lines, the ejecta velocity can be determined. This in turn can be used to verify the shock breakout model's efficacy.

1.4.1 VCRO and LSST

The Vera C. Rubin Observatory (VCRO) houses the Simonyi Survey Telescope (SST), commonly referred to as the Large Synoptic Survey Telescope (LSST), and is built on the Cerro Pachón ridge near La Sarena, Chile ([Ivezic et al. 2019](#)). SST is a 8.4m class telescope with a field of view of 3.5 degrees, covering 9.6 square degrees, with a 3.2 gigapixel sensor. Still under commissioning, it is expected to get first light in 2023. The telescope's primary goal is to conduct a 10-year survey (the the Legacy Survey of Space and Time) of the entire visible southern sky, producing an unprecedented, deep, and high-resolution dataset of astronomical objects and events. Its comprehensive survey will enable the discovery and monitoring of

a vast array of dynamic phenomena, including supernovae, gamma-ray bursts, tidal disruption events, and more.

Furthermore, LSST’s enormous datasets, estimated to be on the order of 35 TB per night (Ivezić et al. 2019), will enable population studies and statistical analyses of transients, shedding light on their rates, properties, and distributions across cosmic timescales. The unprecedented volume of data will facilitate the discovery of rare and elusive events, unveiling new classes of transients and opening avenues for breakthrough discoveries (Lupton 1993). LSST’s data-driven approach, coupled with machine learning and advanced data analysis techniques, will enable the identification and characterization of transient events with enhanced efficiency and accuracy.

LSST is expected to put out several million alerts per night, which can then be followed up by observations from other observatories (Ridgway et al. 2014). This enormous number accounts for all sources that have changed brightness or position significantly since the last exposure. There are multiple data product streams that LSST will produce, the fastest of which will produce transient alerts within 60 seconds of the image readout. This will provide alerts that telescopes within Chile can follow up on. Depending on location and timing of the SN discovery, other telescope sites will then be able to follow-up. Early-time spectra of transient objects are highly sought after, particularly for SN as their earliest stages are where the most scientifically fruitful observations can be made.

1.4.2 Siding Spring Observatory

The similar latitudes of Siding Spring Observatory (SSO) and VCRO result in them seeing the same night sky, just at different times of the day (see Fig 1.6). As VCRO comes out of night, SSO will start its night, allowing for continuous coverage of the night’s sky for follow-up observations of interesting transients. This continuous coverage is particularly important for analysing the shock breakout and shock

cooling epochs of a SN, as they evolve quite quickly. Automation of the ANU 2.3-metre telescope (2m3) at SSO is underway, which will allow for much more efficient Target of Opportunity (ToO) triggers for interesting supernovae that are discovered.



Figure 1.6: World map showing location of Siding Spring Observatory (left marker) and La Serena (right marker).

The 2.3-metre is equipped with the Wide Field Spectrograph (WiFeS) ([Dopita et al. 2010](#)). WiFeS contains an Integral Field Unit capable of observing $38'' \times 25''$ sections of sky with $1'' \times 1''$ resolution spaxels. Its broad wavelength coverage makes it ideal for optical follow-up of transient objects. Since the shock cooling phase of supernovae is an optical phenomenon that develops over a few days, WiFeS is a perfect tool to capture the spectral evolution of the earliest stages of a supernova.

The automation of 2m3 requires the implementation of a weather monitoring system to safely operate. Unifying the weather station for all telescopes at SSO would provide great cost savings, however the effect of localised weather patterns on the mountain are unknown. In order to maximise the accuracy of a universal weather monitoring system, an appropriate location on the mountain must be found. [Goodwin et al. \(2013\)](#) and [Wood et al. \(1995\)](#) have measured seeing and photometric fractions in the past, however they represent the site as a whole, losing the minutia of localised weather characteristics.

Observatory sites are typically characterised by their seeing, turbulence profile, cloud fraction, and other weather phenomena that may force dome closures (e.g. Lombardi et al. 2009; Ehgamberdiev et al. 2000; Plauchu-Frayn et al. 2020; Radu et al. 2012). SSO has had seeing and turbulence characterised, however cloud and humidity are not well described. These are important parameters to know when designing astronomical surveys as they directly impact how long a given telescope can be on-sky. SSO is a humid site, and experiences dome closures due to humidity at a higher rate than other observing sites.

1.5 Summary

Modern day cosmology faces limitations stemming from various factors, including uncertainties surrounding the progenitors of supernovae. Type Ia supernovae serve as crucial cosmological distance indicators, but the precise nature of their progenitor systems remains an active area of research. Resolving the uncertainties associated with progenitors is essential for improving the accuracy of cosmological distance measurements and refining our understanding of the universe’s expansion.

To gain insights into the early stages of supernova explosions, specifically the phenomenon known as shock breakout, a comprehensive observational approach is required. Supernovae are unpredictable and rare events, making it challenging to capture the earliest stages. Large coverage and rapid cadence photometry, involving frequent and precise measurements of a supernova’s brightness over time, are essential for maximizing the chances of detecting and characterizing shock breakout events. This approach allows astronomers to track the rapid evolution of the initial burst of intense radiation associated with shock breakout.

The importance of UV coverage in capturing the earliest stages of shock breakout cannot be overstated. During shock breakout, the most significant component of radiation is in the ultraviolet (UV) range. The shockwave from the exploding star reaches the surface and breaks through, leading to an intense release of UV

photons. UV observations play a critical role in directly probing the high-energy processes and properties of the shockwave, the outer layers of the progenitor star, and the explosion dynamics. By capturing the UV component of shock breakout, astronomers gain valuable insights into the mechanisms driving the explosion and the physical characteristics of the progenitor star’s surface.

Global collaboration in the transient astronomy community is essential for aiding the upcoming deployment of the Large Synoptic Survey Telescope (LSST). Complementary observations and follow-up campaigns conducted by researchers worldwide further enhance the scientific potential of LSST’s wide field of view. By working together, the transient astronomy community can maximize the discovery and characterization of transient events, unraveling their astrophysical significance and advancing our understanding of the dynamic nature of the universe.

1.6 Thesis outline

This thesis aims to demonstrate the importance of high-energy time-domain astronomy by using rapid follow-up of interesting supernovae to ascertain progenitor properties. A discovery paper is presented to highlight the data handling processes involved in transient astronomy (in particular the rapid turnaround needed), which in turn is used to justify the analysis performed in the latter sections.

It also aims to assist in developing a rapid-response system for similar endeavors in the future. With LSST about to go on-sky, and the ANU 2.3m telescope being recently automated, it is prime time to develop a transient processing pipeline for Siding Spring Observatory. A complete site survey of SSO has not been completed prior to this work, and the work done in Chapter 3 presents evidence of high variability across the site; information has then been used in the 2.3m automation project. From this work, SN observation efficacy rates can be calculated more accurately for survey designers.

Finally, this thesis also works towards developing a dedicated instrument for early detection of high-energy objects. Balloon borne instrumentation has been trialed in the past, however these have generally focused on X-ray (e.g. Polarised Gamma-ray Observer: PoGOLite) and microwave (e.g. the Millimeter Anisotropy eXperiment IMaging Array: MAXIMA) events. While SN shock breakout can be observed at X-Ray wavelengths, the photon flux becomes so low at such regimes such that the size of the detectors needed prohibits balloon borne instrumentation being developed due to weight and financial limitations. UV instrumentation hits a middle ground where the detectors are still accessible cheaply, and UV flux from SN events is easily detectable.

The work in this thesis ties these elements together by working through the practical difficulties present in developing SN surveys, discussing the limitations of ground-based SN follow-up, and developing tools to help mitigate these limitations.

1.6.1 Overview of chapters

Chapter 2: 2019com

This chapter presents an analysis of a SN IIn, highlighting the importance of rapid follow-up of interesting supernovae. The spectra of SN IIn vary significantly from each other, making comparison between them difficult as their progenitors are not well understood. Spectral comparison is used to confirm one of the supernovae captured throughout this thesis (2019com) bears a strikingly similar spectrum to 2009ip, the so called "supernova imposter". There are only a handful of these objects that have been discovered, and the work performed here provides great context for what the progenitors of these objects actually are. Through an application of [Sapir & Waxman \(2017\)](#)'s model of shock breakout, we determine a likely mass and radius range of the progenitor, providing evidence of the progenitor star's class.

Chapter 3: Siding Spring Observatory observing conditions

In order to get a handle on the viability of an observation site for rapid transient follow-up, a site survey must be conducted. Siding Spring Observatory (SSO) is Australia's premier optical observing site, home to many telescopes including the ANU 2.3m telescope (hereforth 2m3). 2m3 is currently being upgraded to be fully automated, which would aid in the follow-up of transient objects discovered by the VCRO when it goes online in late 2022. SSO's latitude ensures a large overlap in observable area with VCRO, and its longitude ensures that it would be the first site able to observe VCRO's fields after the data has been reduced. Chapter 2 details the importance of early observations in the field of supernova modelling, reinforcing the importance of SSO as a site for transient followup.

Chapter 4: GLUV Pathfinder

One of the limitations of shock breakout analysis is the unavailability of high energy light from the earth's surface. Ground telescopes are not able to effectively observe in higher energy regimes than optical light due to the opacity of the atmosphere. GLUV presents a low cost solution to this problem. Before it can be commissioned, a pathfinder mission is necessary in order to determine the opacity of the atmosphere to UV light at the altitudes that GLUV will fly. This is a significant unknown that will drive the final design of the GLUV telescope. GLUV Pathfinder is a spectrograph statically mounted to the Google Loon platform that will measure the backgroud UV from scattered light in the Earth's atmosphere, measuring a realistic effective brightness from which the final telescope's limiting magnitude can be calculated and compensated for.

2

SN2019com: Potential supernova imposter

Context and Contribution

This chapter includes the work done setting up a young supernova follow up survey using the ANU 2.3m telescope, located at Siding Spring Observatory. Section 2.1 describes the pipeline set up by me, using the PyWiFeS reduction pipeline ([Childress et al. 2014](#)). Section 2.2 is an in-prep paper by Harrison J. Abbot, Brad E. Tucker, Chris Lidman, Patrick Armstrong, Cesar Rojas-Bravo, and Thimo Timmermans. My contribution was the entire paper, with suggestions on direction from my supervisors Brad and Chris. Patrick helped to get the code running for the progenitor analysis, Cesar performed zero point corrections on the SWOPE photometry that ultimately was not used, and Thimo assisted in follow-up observations.

2.1 Young supernova follow-up pipeline

Shock breakout is a very shortlived event that can only be captured serendipitously, requiring a telescope to be pointed and exposing at the supernova’s location at its earliest stages. The subsequent shock cooling phase is a much longer lived phenomenon, and can occur over a time period on the order of days. This is still a relatively short lived event, and so an automated triggering pipeline was created to allow us to observe these events. This pipeline triggered Target-of-Opportunity (ToO) observations on the ANU 2.3m telescope located at Siding Spring Observatory. A flowchart of the process is shown in Figure 2.3.

The first stage of the pipeline was a broker system, pulling from daily alerts from the Transient Name Server (TNS) ([Gal-Yam 2021](#)). This system scraped new young supernova candidates as they came in using the TNS API. The potential targets were then filtered based off of multiple criteria.

It was discovered early on that some research groups were much more reliable than others at providing valid supernova candidates. GAIA ([Gaia Collaboration et al. 2016](#)), for example, pushed out a large volume of potential transient sources, however they were non-discriminant in transient detection and most alerts were not supernovae. As such, the first filter applied was to limit the alerts to those from dedicated supernova surveys, e.g. ZTF ([Bellm et al. 2019](#)), ASAS-SN ([Kochanek et al. 2017](#)), ATLAS ([Tonry et al. 2018](#)), Pan-Starrs1 ([Chambers et al. 2016](#)).

The second stage of the pipeline was to determine the age of the supernova. This is done by comparing the time of first detection to the last non-detection. Sources with a gap greater than 3 days between these times were filtered out, as the survey being conducted relied on observing supernovae at their earliest stages, and shock cooling is unlikely to be observable beyond this time frame.

The third limiting factor was the discovery brightness of the supernova candidate. While supernovae rise significantly in apparent magnitude over the course of a few weeks, shock breakout and shock cooling aren’t necessarily observable at this

brightness, especially when limited to using optical filters. As such, the discovery magnitude was a more appropriate gauge of whether the supernova candidate would be visible or not.

ToO observations on the ANU 2.3m were limited to 1 hour per night by the observing policy. After allowing for calibration frames to be taken with the requested filters and gratings available to WiFeS (the instrument used for our observations) (Dopita et al. 2004), only 45 minutes of on-sky time was available. This meant that the limiting magnitude was realistically $m_{AB} \approx 20$ on a clear night. As described in section 3, this only occurs 35% of the time, and so a more realistic limiting magnitude was $m_{AB} \approx 18$.

The final pre-processing stage was to limit by the on-sky position. This limited the search to only those candidates that were observable at Siding Spring Observatory. The initial goal was to take spectral observations of targets that lie within the field of view that the TESS satellite (Ricker et al. 2015) was also observing, as the high cadence photometry that provided would theoretically be able to observe the shock-breakout stage, despite its near-infrared filter. This requirement was then relaxed after TESS pointed north, as the area of overlap between SSO’s available sky, and TESS’s observations, was reduced to almost zero.

By the end of this stage, the potential candidates was whittled down from roughly 200 to approximately 1 alert per week. At this point, a manual review was performed in order to determine if the candidate was worth following. This was a judgement call, trying to make the most of the ToO observing allowance of 20 hours per quarter. The ANU 2.3m was also not automated, and so the judgement call also had to factor in the willingness of the observing astronomer to give up their observing time to observe our targets for us.

If the candidate passed this stage, then an alert was raised on the telescope’s control software to alert the observer of a new supernova candidate that a ToO was being triggered on. An automated message was generated to provide instructions to

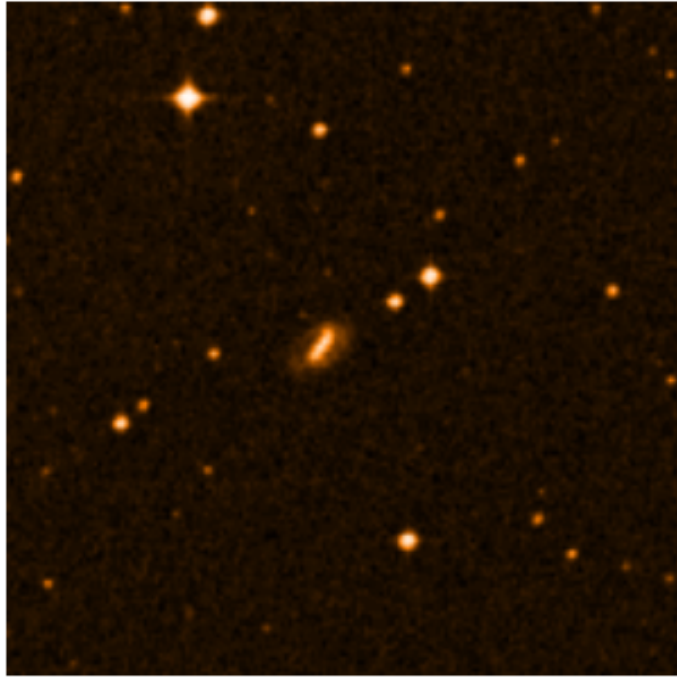


Figure 2.1: Example finding chart of SN2021ymn, pulled from DSS servers (York et al. 2000). This is an archival image so the SN is not present, and can be expected to be seen as an extra source in the centre of the image.

the observing astronomer, including the position on sky, callibrations required, and length of exposures. The pipeline generated a finding chart from DSS (York et al. 2000) imagery, with the same field-of-view as the 2.3m’s finder, to help the observer locate it without having to manually look one up (see Figure 2.1). Finally, the pipeline generated an elevation chart with the supernova’s position (see Figure 2.2), to help the astronomer decide on a schedule of observations for the night including our target.

During the day following observations, the relevant observations were loaded onto a local directory to be run through the PyWiFeS pipeline. A manual review of the frames was performed to separate out the ToO observations from the rest of the scheduled observer’s frames, and then the data was reduced into a final datacube that could then be analysed to see if the candidate was a young supernova. This was again a manual review process, looking for tell-tale features such as a strong bias towards blue wavelengths, and a high enough signal-to-noise ratio to warrant repeat observations.

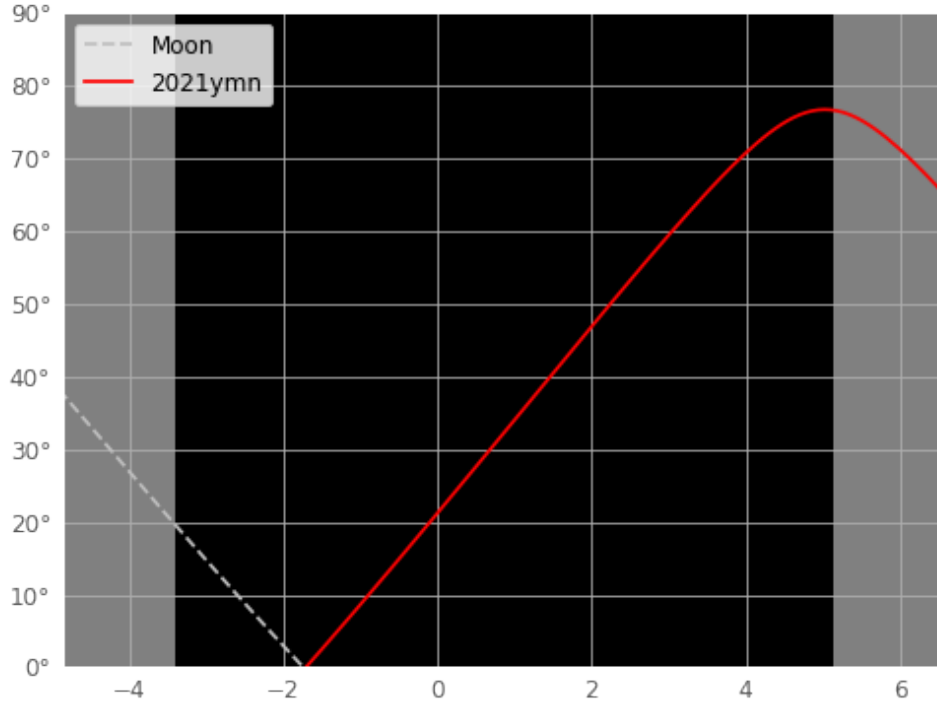


Figure 2.2: Example altitude chart generated for SN2021ymn when it was visible. Grey zones indicate twilight, where as black shows dark hours. The x-axis is hours from midnight, and the y-axis is the target’s altitude in the sky.

If the candidate fit these criteria, further ToO observations were triggered daily for the next 5 days in order to record the evolution of the supernova during these early stages. This also then triggered ToO photometry observations with telescopes available to our working group, notably SWOPE ([Brown et al. 2013](#)). An example of the results of this pipeline is described in Section 2.2.

The pipeline has since been used to follow up young supernova candidates for other programs, e.g. the Dark Energy Bedrock All Sky Supernovae DeBASS (DeBASS). It has also been used to spectroscopically confirm young supernova candidates that are then published as ATel’s e.g. ([Lidman et al. 2021a,b,c](#)), allowing other groups to follow up on the interesting candidates as they see fit. Finally, it has also been utilised to produce early spectra of other interesting transient objects that have been written into their own single-object papers (e.g. [Nicholl et al. 2020](#)).

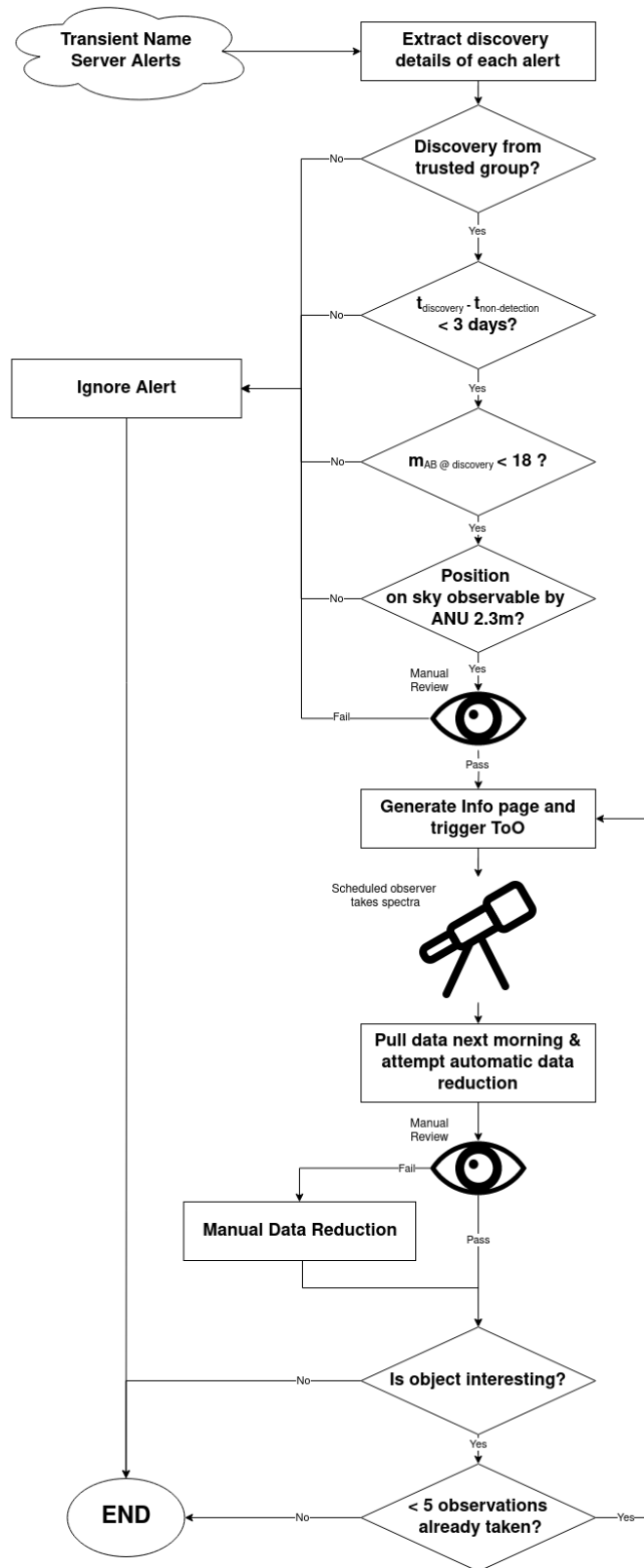


Figure 2.3: Decision and process flowchart of the supernova alert pipeline developed. Manual stages included are a review of the reduced alert list, observation of the object, and a post-reduction review.

Over the course of the 2.5 years that the pipeline was active, 137 SN alerts made it to the first manual selection process. Of these, 43 were deemed appropriate for follow-up. Many of the rejections were due no host-galaxy being visible in the vicinity of the discovery, meaning that they were likely false detections. The other biggest filter affecting the efficacy of this program was the number of observers for each supernova. The quality of the reduced spectra was unfortunately highly dependant on the experience of the observer, which in turn affected the number of follow-up observations ToOs were triggered on as the second manual review was a quality check. The ANU 2.3m telescope has since been automated, so this should not be a problem in the future and a high rate of successful ToOs can be expected with future continuation of this program.

Out of the 43 good initial ToO observations, 28 showed evidence of a blue excess in the reduced spectra; a tell-tale sign of a young supernova. Follow-up observations were triggered on these 28, up to 5 times over the week following the first observation. Due to the high fraction of cloudy nights at SSO (described in Chapter 3), only 2 supernovae had a full suite of observations. Relaxing this metric, 26 were able to be observed multiple times providing multi-epoch spectra of young supernovae.

2.2 SN2019com: Shock cooling in a 2009ip-like supernova

Abstract

We present the early evolution of SN2019com, a young peculiar Type IIn supernova (SN). Initially discovered by the All-Sky Automated Survey for Supernovae (ASAS-SN), SN2019com was observed at a distance of $\approx 54Mpc$ in IC 4712 on 2019-03-31 UTC, with the last non-detection images on 2019-03-28 UTC. Using WiFeS on the ANU 2.3m telescope, we obtained multiple spectra of SN2019com, which showed strong spectral similarities to SN2009ip; the first recorded Supernova Imposter. Early photometry from the Las Campanas SWOPE telescopes showed an

early blue excess, consistent with a shock cooling event. Fitting this excess, we measure a progenitor radius of SN2019com ($122.8^{+11.0}_{-8.2} R_{\odot}$), ejecta mass ($2.57^{+0.56}_{-0.65} M_{\odot}$), and ejecta velocity ($9520^{+340}_{-212} \text{km s}^{-1}$). Late time images with HST show a light source consistent with the location of 2019com, providing further evidence that this is an 09ip-like supernova.

2.2.1 Introduction

Core collapse supernovae (CCSNe) are the explosive deaths of massive stars, $M > 8M_{\odot}$ (Woosley & Weaver 1995; Sukhbold et al. 2016). These objects display a wide variety of spectral and photometric features, implying the existence of multiple progenitor scenarios that lead to their explosions.

As the core collapses, a shock is formed and travels outwards. As the shock reaches the outer edge of the star, the optical depth of the plasma ahead of the shock decreases (Waxman & Katz 2017). Once it becomes thin enough, a bright X-ray / UV flash escapes, lasting on the order of seconds or minutes, and is known as shock breakout. This is the first visible sign of a supernova explosion occurring. The energised envelope then undergoes a shock cooling phase which releases UV / optical light on a time scale of days. If there was sufficient circumstellar material (CSM) surrounding the star, the shock breakout can be delayed and extended.

As the shock front moves radially outwards, it undergoes adiabatic expansion and cools. This process of shock cooling can be seen as a reducing blue excess in early time light curves of the supernova (SN). Encoded in the early evolution of the supernova light curve is the structure of the progenitor at the time of the explosion.

It is difficult to determine SN progenitors as surveys rarely have the depth to have useful pre-explosion imaging. Given the scarcity of SNe, it is uncommon to them appear in a nearby galaxy. Only the nearest galaxies have their individual stars resolvable by telescopes like HST and large ground telescopes with adaptive optics systems. Direct detection of SN progenitors has been utilised to determine

the progenitor of nearby SNe, but this has only been possible in a handful of cases, for example SN2009ip (Smith et al. 2016).

An easier method for determining SN progenitors is by getting early detection and follow-up of the shock breakout and cooling. Progenitor systems of CCSN have been determined (e.g. (Arcavi et al. 2017; Garnavich et al. 2016; Bersten et al. 2012)) by applying semi-empirical shock breakout models developed by Nakar & Piro (2014), Sapir & Waxman (2017) and Rabinak & Waxman (2011). Nakar & Piro (2014) presents a shock cooling model that successfully described the progenitor of SN2011dh (Arcavi et al. 2011) as a compact core with an extended, low-mass envelope, which was confirmed with archival HST imaging (Maund et al. 2011) showing it to be a yellow supergiant. This result conflicted with the Rabinak & Waxman (2011) model, which models SN lightcurves from red supergiant (RSG) and blue supergiant (BSG) progenitors.

One subclass of CCSN, the type IIn supernova (SN IIn), shows signs of interaction with its surrounding circumstellar material (CSM) through their narrow spectral features (notably $H\alpha$ with a line FWHM on the order $\mathcal{O}(10) - \mathcal{O}(1000)$ km s⁻¹ (Schlegel 1990; Filippenko 1997)). These velocities are lower than the photosphere of the ejecta ($\mathcal{O}(10,000)$ km s⁻¹), and arise from the heating of a dense CSM via shock heating (Chugai 1991; Chugai & Danziger 1994; Aretxaga et al. 1999). Filippenko (1997) indicates that their existence can be the result of a Luminous Blue Variable (LBV) progenitor, which pumps large volumes of material into the progenitor’s surroundings which subsequently gets shocked by the SN.

If the SN progenitor is embedded in a massive dust envelope then Nakar & Piro (2014) predicts that no shock cooling could be observed at red wavelengths. Since IIn are surrounded by CSM at time of detonation, they should not show evidence of shock cooling in redder (gri+) passbands. The supernova discussed in this paper (SN2019com) follows this trend, only showing signs of shock cooling in u’ and b’.

Within the family of SNe IIn, there is a further subclass dubbed ‘09ip-like’.

SN2009ip is a peculiar SN IIn, and was eventually determined to be the first supernova imposter found (Smith et al. 2010). Supernova imposters are defined to be stars that undergo large outbursts comparable in brightness to SN explosions, continue to live on as a star beyond this event. SN2009ip underwent several large outbursts in the final stages of its life - in 2009, 2010, and early 2012, before undergoing its final, believed detonation late 2012 (Mauerhan et al. 2013). Owing to the peculiar nature of this event, long term spectroscopic and photometric follow-up were undertaken to find clues as to its progenitor system (Pastorello et al. 2013; Fraser et al. 2015; Graham et al. 2017). Unfortunately, SN2009ip was discovered far outside its host galaxy, and so determining the nature of its progenitor's birth environment has been speculative to date (Smith et al. 2016).

SN2009ip has been extensively analysed to try and determine its progenitor system (Mauerhan et al. 2013; Fraser et al. 2013; Ofek et al. 2013; Smith et al. 2013; Margutti et al. 2014; Smith et al. 2014; Graham et al. 2014). Smith et al. (2014) showed that the progenitor is consistent with a blue supergiant, with Mauerhan et al. (2014) showing it occurred within an asymmetric CSM. Continuous monitoring by Fraser et al. (2015) showed no evidence of further detonations, with light dominated from CSM interaction after the secondary peak in the SN light-curve. While SN2009ip was confirmed as a SN IIn (Szalai et al. 2019), some sources Smith et al. (2016) hint at the possibility of a Pair Instability SN (PISN) event.

Woosley et al. (2007) proposed PISNe as a SN mechanism, characterised by high ejecta masses with low ($< 5000 \text{ km s}^{-1}$) expansion velocities. They are theorised to be low metallicity, massive stars ($M > 100 M_{\odot}$) undergoing a process in which gamma rays (produced by the hot stellar interior) are transformed into electron-positron pairs, which reduces the internal outward thermal pressure and as the star begins to collapse, which can produce localised thermonuclear runaway, leading to large mass-loss events prior to the final core-collapse. These eruptions can be related to LBV outbursts seen in supernovae such as SN2009ip (Smith et al. 2016), and iPTF14hls (Howell 2019).

In this paper, we analyse the early lightcurve of SN 2019com by fitting the BSG model of Waxman et al. to the light curve to constrain the parameters of the progenitor. Early time spectra is used to confirm the results of this fitting method by calculating ejecta velocities from the spread of spectral lines. The progenitor parameters determined are then compared to SN2009ip to show their similarities and differences. We also have late time followup with the Hubble Space Telescope (HST) showing the possible existence of remnant star, adding information to the progenitor.

2.2.2 Observations

Discovery and Follow-up

SN2019com was discovered on 2019 March 31.29 (MJD = 58573.29) at RA: 18:31:06.926, DEC: -71:41:32.68 (J2000) by ASAS-SN (ASASSN-19hv). It was reported to have an apparent magnitude of $m = 16.7$ (Brimacombe & Stanek 2019) with the g-Sloan filter on the ASAS-SN “Bohdan Paczyński” unit in Cerro Tololo Inter-American Observatory (CTIO) in Chile (Kochanek et al. 2017; Shappee et al. 2014).

SN2019com was noted as being young, with the last non-detection having a limiting magnitude of $m = 17.7$ at MJD = 58572 on the discovery telescope. A Target of Opportunity (ToO) was triggered on the ANU 2.3m telescope Wide Field integral Spectrograph (WiFeS), located at Siding Spring Observatory (SSO). The first observation was taken at 2019 April 1.72 (MJD = 58574.72). Observations were made with the R3000 and B3000 gratings with spectral coverage of 3200Å to 9800Å at a resolving power of $\frac{\lambda}{\Delta\lambda} \sim 3000$.

Distance

The measured redshift of SN2019com, using the $H\alpha$ line, is $z = 0.0124 \pm 0.0009$. This matches the known redshift of IC 4712 (under the name ESO 071- G 014), with $z = 0.012799$ (Mathewson & Ford 1996).

A radial distance from the centre of IC 4712 was also calculated, for local environment analysis using IFU spectroscopy. Using the angular size of IC 4712 from the 2MASS catalogue [Skrutskie et al. \(2006\)](#), and measuring the angular distance between the core and SN2019com (Figure 2.5), we calculate a projected distance of 1.75 kpc.

Photometry

Follow-up photometry was triggered on the Las Campanas Observatory 1-m Swope telescope in Chile. Several epochs were obtained on Swope in the uBgVri bands [Stritzinger et al. \(2011\)](#), SN2019com from MJD = 58578 - 58636 (Figure 2.4).

The supernova was detected young as it was still rising in luminosity for the first 15 days of observation. Furthermore, the tail end of a luminous excess in the u-band can be seen, suggesting that the tail end of shock break out was observed. This is discussed further in Section 2.2.3.

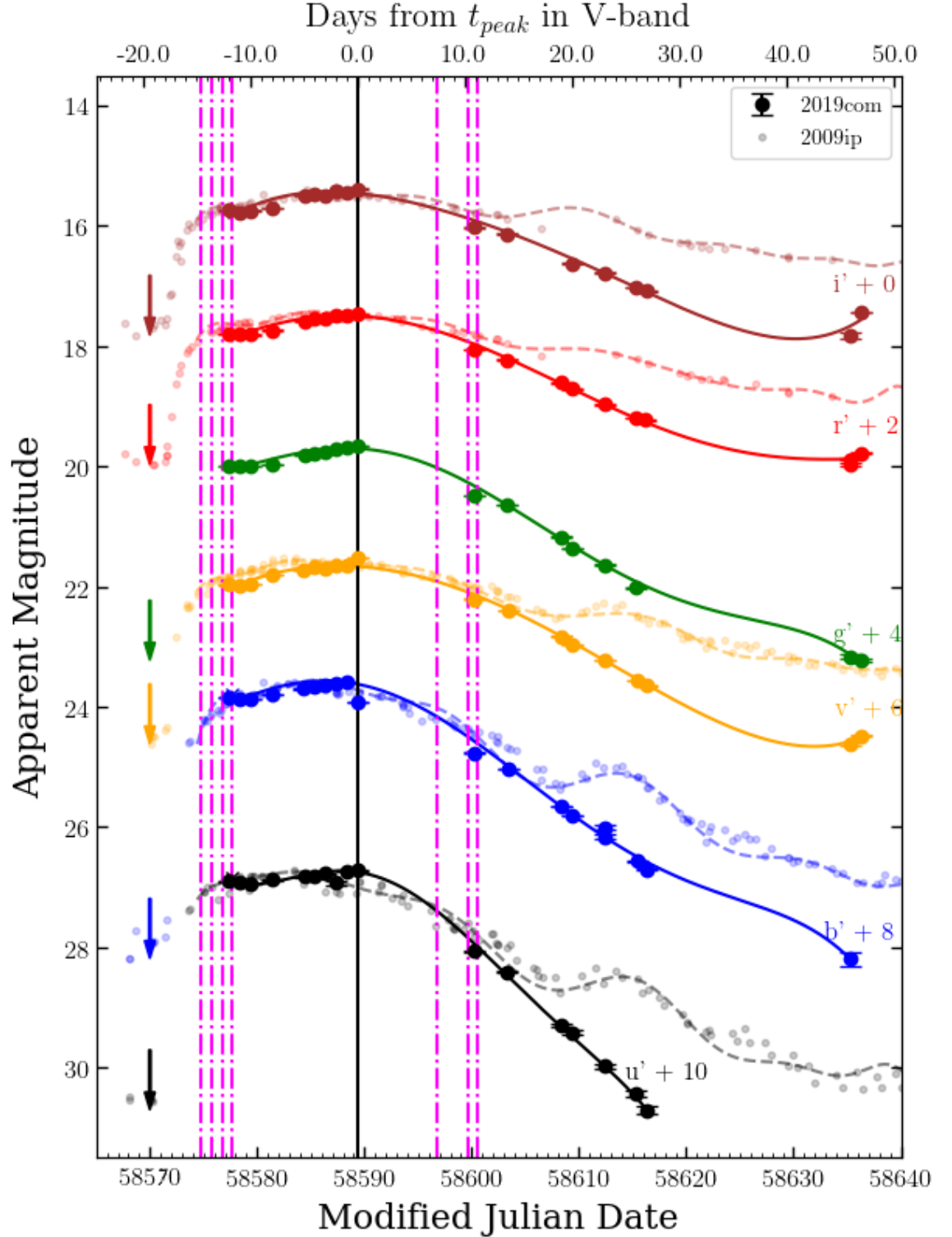


Figure 2.4: SWOPE Light curves of SN2019com compared to the final outburst of SN2009ip, seen in 2012. Time to reach max brightness is approximately 19 days for both, and the first 14 days post-max is similar. After this, the second bump in the SN2009ip light curve differentiates the two. The secondary maximum is attributed to the ejecta hitting the previous outburst’s material.

Spectroscopy

WiFeS is an integral field spectrograph, with a $25'' \times 38''$ field of view (see Figure 2.5). Datacubes were produced using the PyWiFeS pipeline (Childress et al. 2014), designed specifically for reducing WiFeS data. Bias subtraction, interpolation over bad pixels in the WiFeS CCD, and cosmic ray rejection are initially performed to clean the data. Wavelength calibration is done with comparison to a CuAr arc lamp, and flat fielding with a quartz lamp, and twilight sky observations. Flux calibration was done using spectra of the standard stars HD55496, HD111721, and HD161770, as done previously with AWSNAP Childress et al. (2016).

The first spectrum showed a strong, blue, continuum, indicative of a young Type II SN (Figures 2.6 and 2.8). Prominent, narrow Balmer lines were also seen, indicating a type IIn. Spectra were run using SNID (reference Blondin and Tonry) likewise providing several matches to type IIn spectra.

10 spectra of SN2019com were taken over three separate epochs. These relate to the initial discovery ($t = t_{max} - 11$ days), the declining light curve ($t = t_{max} + 10$ days), and post-SN ($t = t_{max} + 150$ days).

Spectra from the spaxels including SN2019com were averaged (shown in Figure 2.5), and an equivalent region on the opposite side of IC 4712 was averaged and subtracted, to remove host contamination. This is necessary as the pixel scale of WiFeS was not sufficient to extract the flux of the SN2019com without significant host contamination. Sky subtraction was performed in a similar manner, using a region far from the host galaxy centre (see Fig. 2.5).

Late time spectroscopy using the ANU 2.3m telescope was captured to verify the accuracy of the subtraction technique used. The frames were captured 1.5 years after the original images, and no supernova was present in the image. The spaxels where the SN was originally located were subtracted from the original spectra, and no distinct differences were found. Even though spectra from opposite sides of a galaxy can be noticeably different, it is suspected that the poor resolution of the

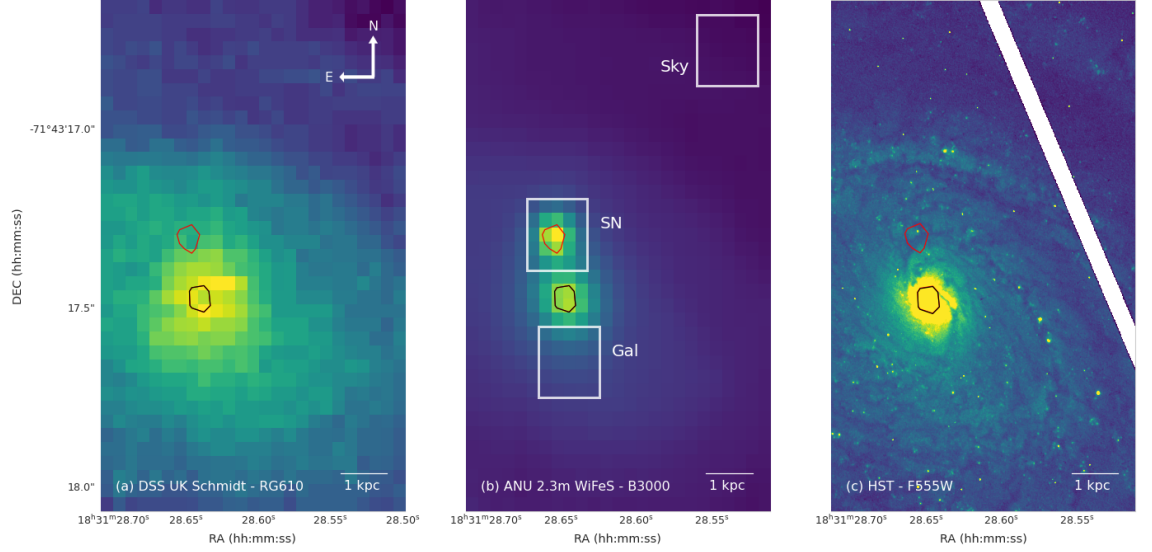


Figure 2.5: **(a)** Archival view of IC 4712 from SDSS [York et al. \(2000\)](#). The black contour shows the galaxy centre, and red contour the location of SN2019com . **(b)** Collapsed spaxels from WiFeS datacube, taken with the R3000 grating, with each pixel showing an average flux density over the $5300 - 9800 \text{ \AA}$ wavelength range. Each pixel equates to $262 \times 262 \text{ pc}$ at IC 4712 's distance. White boxes show spaxel selection for the supernova, as well as galaxy and sky subtraction. **(c)** Late-time HST image of IC 4712 . Bright point source still visible in same location as SN2019com , consistent in brightness with 2009ip between outbursts.

spaxels in the WiFeS image averaged out a large enough area that these differences were smoothed out. This confirmed that the original subtracted spectra were valid, and not skewed by the location of the subtracted region being different. In the end, the original corrected spectra were used to minimise error introduced in using data from different nights.

To account for angular velocity about the centre of IC 4712 , both regions were converted into their rest frame separately. In order to test this method, two opposite regions were selected from late time ($t > 150$ days) spectroscopy and subtracted, which resulted in a flat SED, meaning there was little bias in the selection region; i.e. the local environment of SN2019com is similar to the environment at a common radius around the centre of IC 4712 .

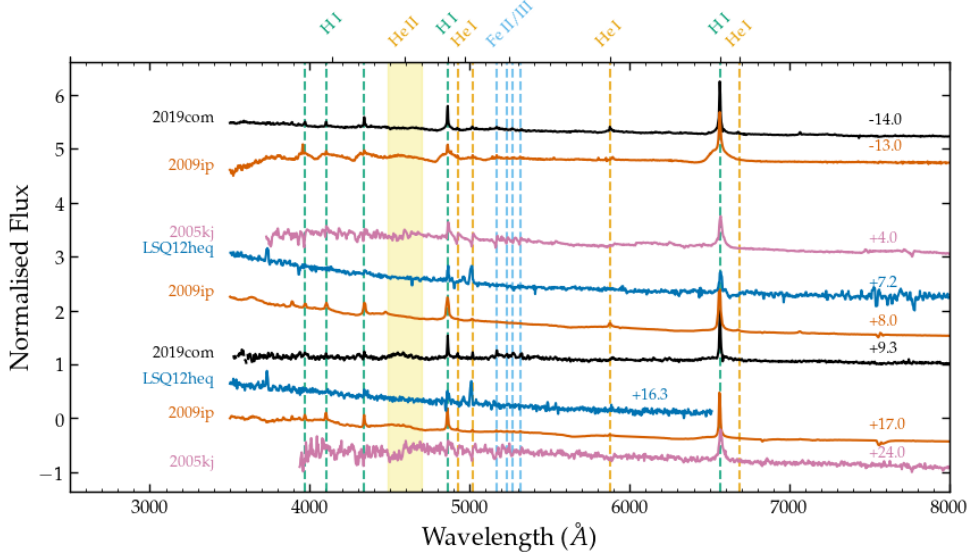


Figure 2.6: Comparison of 2019com, SN2009ip, 2005kj and LSQ12heq. The He I lines in 2019com and 2009ip are weaker than other IIn candidates for a single transition (or multiplet), and a broad He II ($\lambda = 4686\text{\AA}$) bump can be seen emerging at late times.

2.2.3 Analysis

Ejecta Velocity

The $H\alpha$ line of SN2019com was extracted, revealing a multi-Gaussian emission profile. This is typical of SN IIn, the result of the ejecta hitting a dense CSM, providing a reverse-shock [Filippenko \(1997\)](#); [Schlegel \(1990\)](#). Each spectrum was de-redshifted using the host redshift, and then into velocity-space centred at $H\alpha$ in order to measure the full-width half-max (FWHM). The FWHM of each Gaussian was calculated using the SciPy’s `curve_fit` routine, and is tabulated below in Table 2.1. A continuum offset was also included in order to extract the spectral profile of $H\alpha$, independent of the underlying black-body emission. This offset was approximated as constant across the width of $H\alpha$ within the $\pm 2000\text{km s}^{-1}$ range analysed, and so would not affect the FWHM. The brightness of the forward shock was highly contaminated by the background continuum, and so large errors were inherent in the FWHM values. Final values for the FWHM of each Gaussian are in line with typical SN IIn ejecta, with the forward shock on the order of 10000km s^{-1} , and reverse shock on the order of 100km s^{-1} .

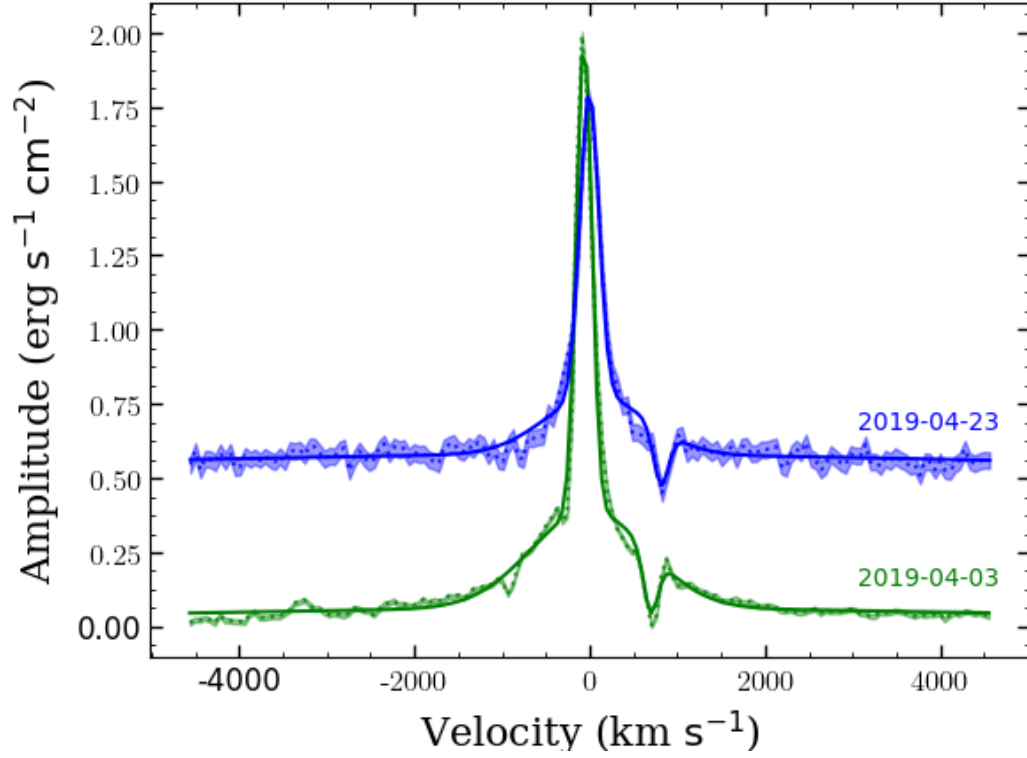


Figure 2.7: 2019com spectrum zoomed in around the $H\alpha$ line, showing the observed line compared to the fit provided by SciPy’s `curve_fit` routine, with FWHM values determined outlined in Table 2.1. The absorption feature to the right of the peak was fit separately. The solid lines show the fit, with dotted lines showing the real data, and shaded region showing the measured error in the observed data.

	Pre-Max	Post-Max
Forward Shock		
Amplitude	0.04 ± 0.01	0.06 ± 0.02
FWHM	9360 ± 5420	9320 ± 3490
Reverse Shock		
Amplitude	0.91 ± 0.02	1.06 ± 0.01
FWHM	207 ± 4	220 ± 4
Unknown Shock		
Amplitude	0.19 ± 0.01	0.24 ± 0.01
FWHM	1650 ± 90	1640 ± 70
Continuum Offset		
Amplitude	0.022 ± 0.011	0.11 ± 0.02

Table 2.1: Fit values for each Gaussian from the $H\alpha$ spectral line profile. Amplitudes are in units of $10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ and FWHM are in units of km s^{-1} . The large errors in the forward shock stem from difficulty subtracting the broad emission profile from the continuum offset.

Early excess and shock cooling

Prompt follow-up photometry of SN2019com allowed us to capture the SN four days after last non-detection. Our first three u' and B' points show a negative gradient before increasing for the next 9 days to reach max. In Fig. 2.8), we compare this early photometry to SN2009ip, highlighting a clear blue excess, visible in the u' -V and B-V plots. In the redder r' -V, this excess is not apparent, which is indicative it is the result of capturing the tail-end of shock cooling event. Shock cooling can last roughly 10 days from the initial explosion [Armstrong et al. \(2021\)](#), matching the estimated time of explosion denoted by the arrows in figure 2.4.

The B-V plot shows a stronger excess than the u' -V plot due to the reddening inherent as shock cooling progresses. By the time the SWOPE photometry was captured, most of the UV excess had already passed. Following this logic, the R-V plot should show an excess at later times. This is not apparent as the underlying SN lightcurve overpowers the shock LC by the time the blue excess ends, as can be seen by the peak of the LC occuring at the time of the 4th SWOPE datapoint.

The spectra taken of SN2019com show He I lines, but lack C I and O I lines. This indicates a He dominated envelope around SN2019com, confirmed by a broad He II lump appearing post peak luminosity. (see Figure 2.6). This feature is found in carbon sequence Wolf-Rayet stars, indicative of the potential progenitor.

We model the early excess using a Monte Carlo method to try to measure the progenitor. We use the models of [Rabinak & Waxman \(2011\)](#) with the properties of a BSG, chosen due to the link between IIn and LBV's. For our initial conditions, we use a mass range of $(50 - 500M_{\odot})$ and radius $(10 - 250R_{\odot})$ consistent with other LBV's in literature ([Machado et al. 2002](#); [Stahl et al. 2001](#); [Najarro et al. 2009](#)), an ejecta velocity $(5000 - 15000 \text{ km s}^{-1})$ consistent with the broad Gaussian profile of H_{α} 2.1, along with t_0 (MJD 58570) as determined from ASAS-SN Sky Patrol archival photometry ([Kochanek et al. 2017](#)).

Results of the fitting, and confidence in the fits, are show in figure 2.9. SNIIPy

([Armstrong et al. 2021](#)) struggled to determine a time of detonation. As such, the value of $t_{off} = -7.34^{+0.27}_{-0.25}$ days is highly influenced by the priors used (where t_{off} is the time between the first LC datapoint and the estimated time of detonation). We find a radius of $122.8^{+11.0}_{-8.2} R_{\odot}$, and ejecta velocity of $9520^{+340}_{-211} \text{km s}^{-1}$, agreeing with the measured ejecta velocity of 9200km s^{-1} from the $\text{H}\alpha$'s FWHM. The ejecta mass was poorly constrained, at $2.57^{+0.56}_{-0.65} M_{\odot}$.

The ejecta mass and progenitor radius are highly degenerate with each other, but remain insensitive to the detonation time and ejecta velocity. Conversely, detonation time and ejecta velocity are highly degenerate with each other, but not ejecta mass or progenitor radius. The detonation time can be constrained to within ± 0.5 days from archival data on ASAS-SN's Sky Patrol [Kochanek et al. \(2017\)](#); [Shappee et al. \(2014\)](#). Ejecta velocity was constrained using the FWHM of the $\text{H}\alpha$ line using the WiFeS spectra.

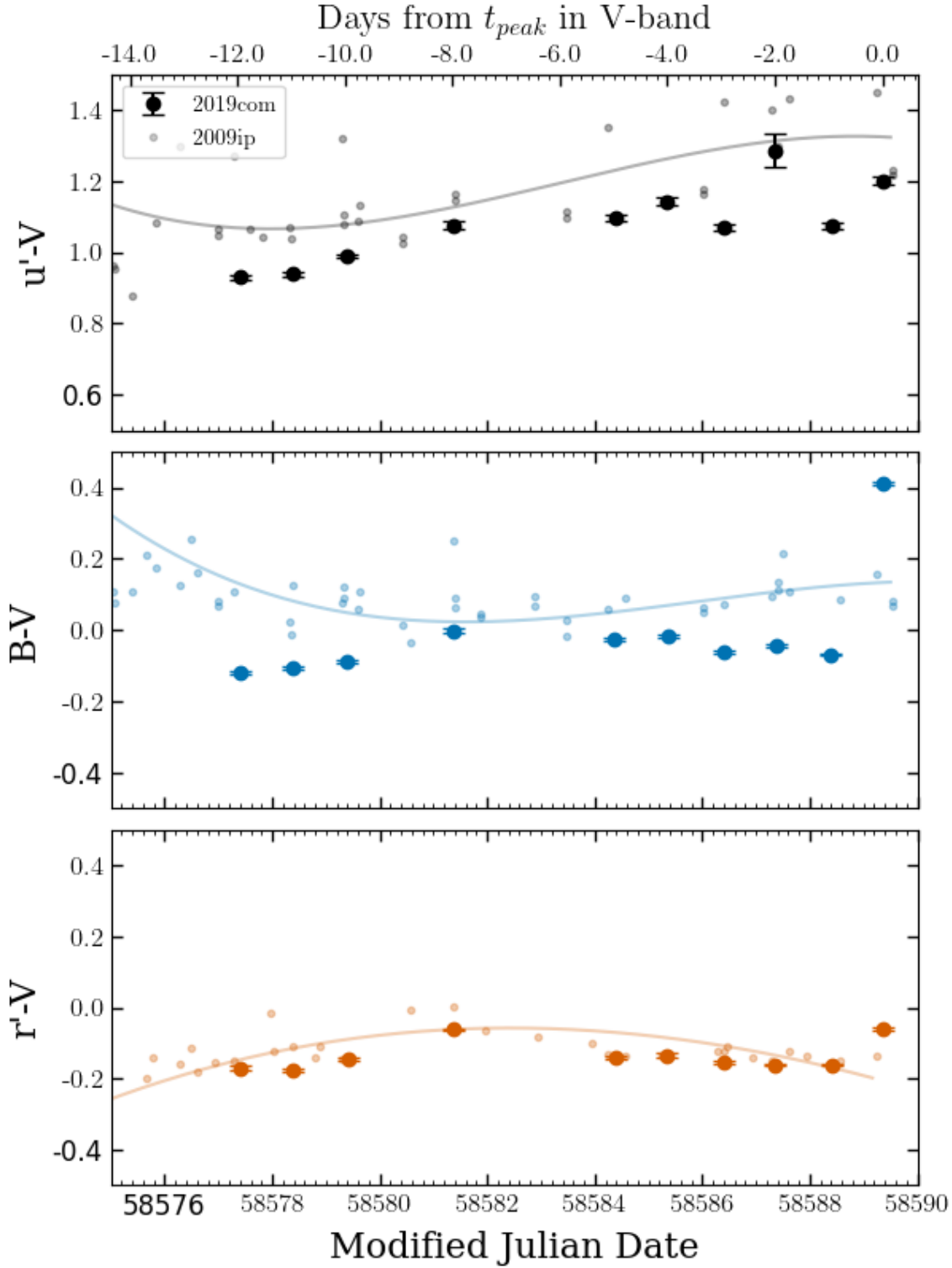


Figure 2.8: Colour evolution comparison between SN2009ip and SN2019com . A cubic fit to SN2009ip’s lightcurves are shown as the lines. A clear 0.4 mag blue excess for SN2019com can be seen at early times, as well as near peak. This is more prominent in $B-V$ vs $u'-V$ due to late-stage shock cooling being redder than the initial outburst.

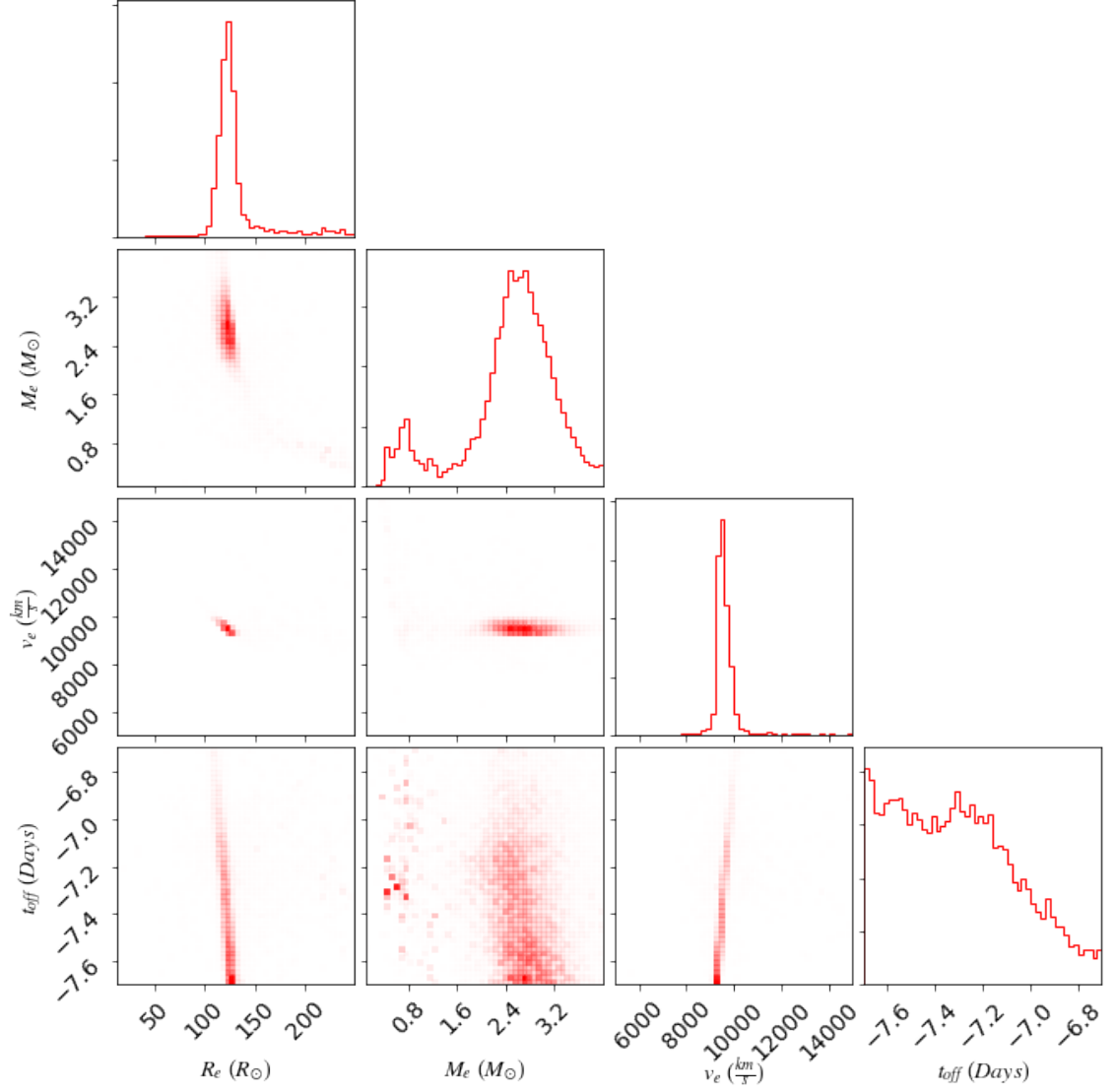


Figure 2.9: Corner plot showing fits obtained from MCMC. R_e is the progenitor radius, M_e is the ejected mass, v_e is the ejecta velocity, and t_{off} is the time between the first SWOPE datapoint and the estimated time of detonation as determined by SNIIPy. Time of initial detonation is poorly constrained, however is known to within ± 0.5 days from ASAS-SN’s daily cadence photometry.

Previous Outbursts

Since the spectra of SN2019com shows similarities to SN2009ip, ASAS-SN and the Catalina Sky Survey’s archival light curves were analysed in order to see if there were any prior outbursts. Neither of these surveys show anything that would indicate prior activity in the vicinity of SN2019com . This is most likely due to the limiting magnitude of these surveys, combined with the distance and extinction present for SN2019com .

Late-time HST Followup

Late time followup of SN2019com was captured with the Hubble Space Telescope (HST) on 2021-03-01; 2 years post explosion. In these images, there is still a clearly visible bright spot where SN2019com exploded. Figure 2.5 shows a combined image from the F555W and F814W filters. The majority of the light is contributed from the F555W filter, indicating that the source peaks in the blue. This is confirmed by absolute magnitude calculations which reveal that the object sits at $M_{F555W} = -10.08$, and $M_{F814W} = -9.26$, or a $V - I$ colour (equivalent to $M_{F555W} - M_{F814W}$) of 0.82 mag.

The being measured in the HST image is the sole bright source located in the SN contour of Figure 2.5. The contour was created by calculating a contour of equal flux around the brightest spaxel in the 2.3m datacube. The points along the polygon defining the contour were selected by interpolating values between the centres of each spaxel between which the contour would fall. This provided a relatively smooth contour which has been copied over to all three images in Figure 2.5. The SDSS, 2.3m, and HST images were aligned by casting them all into the same coordinate reference system (J2000). Further confirmation of alignment can be seen in the shape and scale of the galactic arms which are visible in all 3 images. Confirmation using individual stars as reference points cannot be performed due to the limited resolution of the 2.3m spaxels. The brightest spaxel within the red contour of the Fig 2.5b lies in the top-right corner, as does the brightest source in Fig 2.5c. This would imply that the light source in the late time HST image could be the same source

as the 2.3m image. The source still being visible in the HST image is unexpected, and implies that SN2019com may have survived the outburst that led to its initial detection.

Massey et al. (2006) determined $V - R$ and $R - I$ for 19 nearby LBV's. Calculating from this sample, LBV's have a $V - I$ ranging between 1.24 and 0.18, with an expected range of $0.55 \pm 0.07\text{mag}$. While bluer than most LBV's, SN2019com's post-explosion brightness is still feasible.

2.2.4 Discussion

The discovery of SN2019com is important since there are some conclusions to be drawn about the progenitor system, a feat not possible for SN2009ip due to its remote environment (Smith et al. 2016). For the first time, we have the observed shock cooling in a Type IIn SN, which also happens to be 09ip-like. Both have similar spectral features, both indicate a massive star progenitor, and both had a similar rise light curve rise time. SN2009ip was shown to have multiple outbursts before exploding as a SN, whereas SN2019com which appears to have survived its initial outburst that led to its discovery in 2019, as can be seen in the HST imagery. Despite this, there are still clear differences between the 2019com and 2009ip, which indicate that similar progenitors can lead to different explosion characteristics.

Classification

In order to classify SN2019com, various classification routines such as SNID (Blondin & Tonry 2007), DASH (Muthukrishna et al. 2019b) and RAPID (Muthukrishna et al. 2019a). All of these are template based classifiers, with SNID and DASH being spectroscopic, and RAPID being photometric. Both DASH and RAPID are machine learning based algorithms, whereas SNID uses an analytical cross-correlation function to determine similarity. The results that each of these gave were inconsistent with each other, hinting at the peculiar nature of SN2019com.

Each observation with WiFeS was run with SNID and DASH. SNID provided

consistent results across the first epoch ($t < t_{max}$), with both SN IIP and IIL classifications being found with high likelihoods ($> 90\%$). The main difference between IIP and IIL SN appear in their light curve, with IIP having an extended plateau whereas IIL have a linear decline post-max. Spectrographically, SNe IIP and SNe IIL are very similar. Since SNID is a spectroscopic classifier, this confusion between the two at early times can be seen as a consistent result. At later times however ($t > t_{max}$), this classification turns to a SN Ia-CSM ($> 80\%$) or a 87a-like SN II. This confusion may have risen due to the similar circumstellar environments of Ia-CSM and IIn, with both having a dense CSM, affecting the emission seen. The magnitude of SN2019com came in at $M \sim -17.4$ at peak brightness, which is somewhat inline with what is expected of a regular SN. However, mass estimates of SN2019com (described later) hint at the possibility of a super-luminous supernova (SLSN) occurring, which could be occluded to the observed brightness by a dense CSM.

DASH was unable to find a consistent fit for SN2019com within its templates across each observation day. Both the red and blue spectra of WiFeS were analysed, along with a combined spectrum to span the whole $3500\text{\AA} - 9500\text{\AA}$ range. The first day's combined spectrum is matched to the IIn SN1998S, with a predicted $t = t_{max} - [10, 14]$ days at a 99.99% match. This date range is consistent with the time of t_{max} as seen in the ASAS-SN light curve. Taking each spectrum separately however yields a Ia-CSM (99%) at $t = t_{max} + [6, 10]$ days on the blue side, and a IIn at $t = t_{max} \pm 2$ days on the red. Beyond this, the spectral classifications include IIP, IIL, and Ic-broad, each with varying date ranges that do not line up with first detection.

SN2009ip was also run through these classifiers as a means of comparison with SN2019com. Since it had a much higher cadence dataset, data was limited to the same epochs at which SN2019com had data for a fair comparison of performance. SN2009ip faired similarly to SN2019com through the classifiers, with SNID and DASH both providing conflicting results of PISN, SNIa-CSM, and Ic-broad popping up as classifications, however the date range was much better defined from DASH with it accurately determining the date of initial outburst.

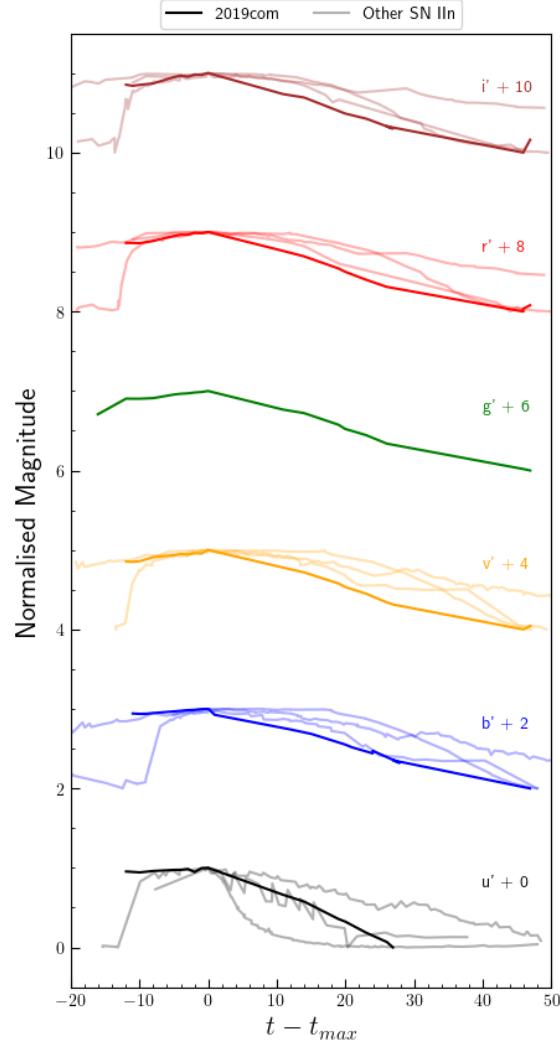


Figure 2.10: Comparison of 2019com’s normalised lightcurve to other SNe IIn. The comparison SNe include SN1987a, SN2009ip, and SN2010al. SNe IIn lightcurves can be very dissimilar, particularly at bluer wavelengths. Late-time HST photometry of SN2019com is not included as it cannot be directly compared to other SN due to differing filters.

Analysing the SWOPE LC rise with RAPID ($t < t_{max}$, SN2019com was given the classification of AGN at 56% probability. AGN can be ruled out using the spectra taken with WiFeS. In the date range $t_{max} - 12 < t < t_{max} + 22$ days, a Pair Instability SN (PISN) classification was given at 70% probability, and finally including photometry from $t > t_{max} + 35$ days yields a classification of a Superluminous SN (SLSN) at 70% probability. SLSN can be disregarded as the SN only reached $M_{AB} \approx -17$ at peak. These date ranges were chosen as these were the times This differs from the classification given from the ASAS-SN light curve which yields a 91bg-like SN Ia at a 48% probability. The wildly varying predictions would indicate

that SN2019com is uncommon, and RAPID cannot be relied upon to provide an accurate classification.

Light curves prove to be inadequate for determining the type of SNe IIn, as they can vary significantly, particularly at bluer wavelengths. A comparison of various SNe IIn is shown in Figure 2.10. This lack of consistency is likely the cause for the poor performance of RAPID. The dense CSM that surrounds IIn progenitors significantly affects the LC of these objects, as their brightness is highly dependant on the opacity of the CSM.

The multi Gaussian profile of the $H\alpha$ line (see Section 2.2.3) is a feature unique to CSM interacting SN. This feature stems from the formation of two shocks (Tsunaka et al. 2019) as the SN shock heats the surrounding CSM. This feature narrows the range of possible progenitors to Ia-CSM or IIn. Silverman et al. (2016) shows similarity between the Ia-CSM and IIn spectra, with Balmer lines with FWHM $\sim 2000 \text{ km s}^{-1}$ present in both, however Ia-CSM typically show no He lines; something that was present in SN2019com .

Finally, we compared a sample of IIn spectra to SN2019com . Data for each SN was pulled from the Open Supernova Catalogue (Guillochon et al. 2017). Data was restricted to SN that had spectra obtained 10 days before t_{max} , so as to be consistent with SN2019com 's early spectra. The closest match found was SN2009ip, with prominent Balmer and He I lines present at similar ratios at similar epochs. The IIn classification of 2009ip is consistent with the narrow emission lines seen in SN2019com as well as the relative intensity of emission lines as compared to $H\alpha$. One thing to note however is the evolution of SN2019com appears to be faster than that of SN2009ip, as spectra taken at $t_{max} + 20$ days for SN2019com is a closer match to the spectra at $t_{max} + 30$ days for SN2009ip. A SN IIn classification also fits the multi-gaussian line profile of $H\alpha$, as interaction with the surrounding CSM produces a reverse shock as the ejecta expands outwards.

The lack of consistency amongst all the SN classifiers is an indication to the

peculiar nature of SN2019com . Owing to the strong presence of Hydrogen emission lines in SN2019com 's spectra, SNID's classification of 91bg-like can be ruled out. The RAPID classification of PISN is consistent with the mass range found by fitting the Waxman BSG model to the shock cooling curve. PISN are still a theoretical construct, however, and have not been confirmed through observation prior to this, and so the use of a template based classifier to give this classification was deemed unreliable. Both DASH and SNID do not include SN2009ip as a template in their databases, hence the inability to find it as a similar SN. That in addition to the variability inherent in the IIn subclass explains the inconsistency in classifications these routines provided. Running SN2009ip's lightcurve and spectra thorough SNID and DASH provide similarly inconsistent results.

Light Curve

A date of last non-detection was procured from ASAS-SN ([Kochanek et al. 2017](#)). This was matched to the date of last non-detection of SN2009ip, and from this we see a similar rise time in both SN (see Fig 2.4). The initial decay of the light curve is also similar, however SN2009ip showed a clear secondary maximum in its light curve approximately 23 days after t_{max} .

The existence of a secondary maximum in a light curve could be attributed to the initial shock breakout peak preceding the typical SN maximum, however this is not the case for SN2009ip, which is evident from the time scales of these events. Shock breakout and cooling occurs over the first few days of eruption, whereas the first peak of SN2009ip occurs 15 days past the last non-detection date. This was used to confirm the existence of an ejected outer layer typical of an LBV ([Graham et al. 2014](#)). By using the time between peaks and the forward shock velocity, the outburst's radius was determined, which matched the radius calculated from its prior outburst event. Hence we can conclude that it is the first peak of SN2009ip, not the second, that is comparable to the SN peak that SN2019com shows in its SWOPE light curve. SN2019com shows no such secondary peak, and so we can conclude that there were no prior outburst events in the lead up to going SN. This is confirmed

via archival LC data from ASAS-SN (Kochanek et al. 2017) and Catalina (Drake et al. 2009).

By contrast, SN2019com appears to have a maximum in the u' band before photometry was triggered on it. This combined with t_0 , as determined via our shock cooling analysis (Section 2.2.4) and the ASASSN non-detection indicates that this is potentially the shock cooling curve.

Detection of a shock cooling excess in a SN IIn is an unexpected result. It is generally thought that the dense CSM surrounding the SN would block a lot of the light from the initial burst, only allowing light to emerge through at later times closer to t_{max} . In the case of SN2009ip, shock cooling was caught thanks to rapid follow up (Margutti et al. 2014), and was seen at a significantly lower luminosity than the SN peak ($|M_{SB} - M_{SN}| = 3.57$). SN2019com on the other hand showed signs of a u' and b' excess close to the SN peak luminosity ($|M_{SB} - M_{SN}| < 1$).

SN2009ip-like SNe undergo an imposter phase prior to detonation, with likely non-terminal explosions occurring months to years prior to final detonation. SN2009ip's early outbursts were fainter than its final detonation, and was likely visible due to its close proximity, and lack of extinction from its host galaxy due to its remote location. Unlike other SN2009ip-like events such as SN2005gl and SN2016bdu (Pastorello et al. 2018), SN2019com shows no sign of prior outburst in archival data in recent years, as determined by looking at ASAS-SN Sky Patrol data dating back to 2014, and Catalina Sky Survey data dating back to 2005. The detection limits of these surveys was likely a limiting factor in seeing prior outbursts of SN2019com, along with host galaxy extinction. It is possible that SN2019com's 2019 outburst was the first sign of the progenitor being a SN imposter, as the HST imagery shows the direct detection of a surviving object coincident with the SN2019com's position. This is discussed further in the **HST Followup** section of the discussion.

Shock Fitting

The Python package used to model the progenitor (hereforth **SNIIPy**) was developed by [Armstrong et al. \(2021\)](#). **SNIIPy** is a Markov Chain Monte Carlo (MCMC) algorithm which uses Bayesian statistics in order to sample a probability distribution provided by an underlying model. A continuous random variable is sampled along the probability distribution, which can then be used to integrate over that variable, providing an estimate for the most likely value of that parameter given some constraints. With **SNIIPy**, the early time photometry was fit with semi-analytical models in order to provide a simple estimate of some physical parameters of the progenitor star, including the radius, ejecta mass, shock velocity, and explosion time. There are two models used in the fitting, the P15 model provided by [Piro \(2015\)](#), and the SW17 model provided by [Sapir & Waxman \(2017\)](#). The P15 model does not make any explicit assumption about the density profile of the progenitor, instead assuming that the extended mass is lower than the core mass, and that the mass is concentrated around the outer radius of the envelope. In contrast, the SW17 model assumes a polytropic density profile. The SW17 model is an extension of earlier work by [Rabinak & Waxman \(2011\)](#) (RW11) by calibrating RW11’s model to agree with numerical simulations.

Both the P15 and SW17 models provide a relationship between the time and luminosity of the first peak, and the radius and mass of the progenitor. These models were used by [Arcavi et al. \(2017\)](#)’s SN2016gkg paper in order to fit the early time photometry of SN2016gkg. They recast these models into luminosity functions which depend on the radius, ejecta mass, and shock velocity. It is these recasted functions which are used to fit SN2019com. More details can be found in Section 3.2 and 3.3 of [Armstrong et al. \(2021\)](#).

Early time photometry of SN2019com shows a clear u' and B excess not visible in the redder bands (see Figure 2.8). This is typical of early time shock cooling, as the shock breakout emits most at higher energy wavelengths. The shock develops into optical wavelengths as it cools, as seen in [Garnavich et al. \(2016\)](#), however the

effect is less pronounced. SN2019com's excess was processed by SNIIPy to determine progenitor constraints.

SNIIPy was constrained with priors determined by external sources. The date of shock breakout was constrained within a day by using the last non-detection of SN2019com from the ASAS-SN light curve. Ejecta velocity was loosely constrained by gaussian priors estimating the FWHM of the underlying SN $H\alpha$ emission line, with $5000\text{kms}^{-1} < v_{ej} < 15000\text{kms}^{-1}$, relating to the forward shock of a IIn. Ejecta mass and progenitor radius were given a large range of $0.1M_{\odot} < M_{*} < 5M_{\odot}$ and $10R_{\odot} < R_{*} < 250R_{\odot}$ in order to assure that the MCMC walkers were able to find fits freely without indicating a non-physical object.

The P15 model returned values that lined up better with the spectroscopically determined ejecta velocity, and time of detonation. From this model, SN2019com has a radius of $122.8^{+11.0}_{-8.2}R_{\odot}$, ejected mass $2.57^{+0.56}_{-0.65}M_{\odot}$, and ejecta velocity $9520^{+340}_{-212}\text{km s}^{-1}$.

The SW17 model returned conflicting values, but with much larger errors, with progenitor radius $454^{+236}_{-264}R_{\odot}$, progenitor mass $17.9^{+77.2}_{-4.8}M_{\odot}$, ejecta velocity $5644^{+3492}_{-494}\text{km s}^{-1}$ and detonation time $6.93^{+0.23}_{-0.24}$.

SN IIn are difficult to model through analysis of their light curves, as the dense CSM inherent in their progenitors significantly affect the luminosity over time. The CSM also broadens the velocity range of the SN shock fronts as layers of gas at differing densities respond to the outward shocks. This can be seen in the poor performance of the SW17 model, particularly when calculating the progenitor radius and ejecta velocity. The estimates for $R_{\odot}$ are large to the point of being non-physical, and are only saved by the large error range. The extremely large radius is likely an estimate that includes the CSM as part of the photosphere. Further details on the limitations of SNIIPy are detailed in [Armstrong et al. \(2021\)](#).

Spectra

Type IIn supernovae are characterised by their (relatively) narrow emission lines. This broad definition results in a huge variety of IIn spectra. In figure 2.6, some comparable reference IIn spectrum have been plotted against SN2019com and SN2009ip. In this, it is clear that there is a lot of variance in the He lines. Most notable is the development of a broad He II emission region in both SN2019com and SN2009ip at later epochs, as well as a P-Cygni profile seen in SN2005kj, and strong emission from LSQ12heq for He I, both not seen in SN2019com or SN2009ip.

The early time spectra of SN2019com is similar to other IIn SNe, with prominent, narrow H I lines and a blue continuum offset due to black body emission. Towards the later epochs ($t_{max} + 18$ days), broad metal lines emission lines start appearing, notably Fe II multiplets. Simultaneously, the He I lines fade. This evolution occurs at a faster rate than other SN2009ip-like IIn's, see Fig 2.6. SN2019com displays evidence of these lines forming approximately 10 days before SN2009ip at a similar epoch. [Pastorello et al. \(2018\)](#) shows a series of SN2009ip-like IIn's which have some variability in the epochs at which similar spectral features develop, so it is expected that SN2019com would also show some variability here.

The profile of the $H\alpha$ line shows a multi-gaussian fit, which is indicative of the forward and reverse shocks that IIn typically display. The velocities derived from the FWHM of these gaussians were determined using Python's SciPy package, and are listed in Table 2.1. The contribution of the continuum offset was approximated to be constant across the width of $H\alpha$. Oddly, SN2019com cannot be modelled well by a double gaussian, as the best fit obtained with SciPy's `curve_fit` routine produced a χ^2_ν 80. Adding a third gaussian to the fit produces a χ^2_ν 6. While this is still not perfect, it is clear that the introduction of a third gaussian produces a much better fit. The velocity of this third gaussian is slower than a typical SN explosion, yet faster than the reverse shock of a typical IIn. Details are tabulated in Table 2.1. A possible explanation for this would be an early eruption moments before detonation. This would follow the LBV progenitor narrative, however shows a difference from prior SN2009ip-like IIn in which outbursts occurred months to

years before final detonation.

HST Followup

Direct detection of a surviving object is still the only way to classify a SN imposter as their spectral features are not unique from SN IIn. This is in part due to the diversity of IIn spectra, stemming from their many possible progenitor channels. The late time images from HST confirm the existence of an object consistent with the location of SN2019com. This object has an absolute magnitude of around $M = -10$ with HST's F555W filter. This is similar to SN2009ip's pre-explosion magnitude, which was also at $M = -10$ with HST's similar F606W filter. This is a key piece of evidence that shows that SN2019com is 2009ip-like in nature.

SN2019com was seen to explode at an absolute magnitude of $M = -17.4$, brighter than 2009ip's outbursts and consistent with most SNe IIn (Stritzinger et al. 2012). SN2019com shows a linear decay rate of 0.06mag/day in the 30 days post-max in the V-band. This is consistent with 1999el-like (Di Carlo et al. 2002) and 1998s-like (Kiewe et al. 2012) events. It is also similar to 2009ip which decayed at a rate of 0.054mag/day in the days between peak brightness and the secondary bump in the lightcurve.

It is evident from the difference in brightness between filters that the remnant is blue, which aligns it with the progenitor of 2009ip, which was classified as a Luminous Blue Variable (LBV). These stars are known to produce massive outbursts which can be mistaken as a supernova (as was the case for 2009ip), however there are no known LBV that produce outbursts as bright as SN2019com and still exist as a remnant.

One possibility to consider is that the object in the HST imagery is a star forming region as opposed to the remnant of SN2019com. Alternatively, it is possible that the remaining source is a bright companion star to SN2019com's progenitor that was not destroyed in the outburst. If SN2019com is an LBV, then it would

be expected to be found in a star-forming region due to their short-lived nature, and there is a real possibility that it had a massive companion. WiFeS was used to follow up with spectroscopy, but its sensitivity and resolution did not allow for direct measurement of the object.

2.2.5 Conclusion

SN2019com shows many similarities to the supernova imposter SN2009ip spectroscopically. It is not unique in this regard, as other SN such as SN2010md, SN2015bh, SN2016bdu also have similar spectroscopic properties around peak. SN2019com is significant as we have captured its shock cooling phase with time series spectroscopy and photometry, allowing us to determine the progenitor star's mass and radius. SN2019com has a radius of $122.8^{+11.0}_{-8.2} R_{\odot}$, ejected mass $2.57^{+0.56}_{-0.65} M_{\odot}$, and ejecta velocity $9520^{+340}_{-212} \text{km s}^{-1}$ as determined by the P15 model. The SW17 model returned conflicting values, but with much larger errors, with progenitor radius $454^{+236}_{-264} R_{\odot}$, progenitor mass $17.9^{+77.2}_{-4.8} M_{\odot}$, ejecta velocity $5644^{+3492}_{-494} \text{km s}^{-1}$ and detonation time $6.93^{+0.23}_{-0.24}$. The ejecta velocity as determined by the FWHM and $\text{H}\alpha$ in the early time spectra agree better with the P15 model. Using these values, we can see that SN2019com's progenitor is similar to other SN IIn, which have been linked to LBV progenitors.

There is no evidence in archival light curves that SN2019com was an LBV, as there were no prior seen luminous outbursts. Furthermore, the lack of a secondary peak in its light curve would indicate that there were no clumps of CSM nearby SN2019com as it detonated, further showing its disconnect from an LBV progenitor.

There is still clearly a remnant object at the position of SN2019com that can be seen in the HST imagery. The absolute magnitude shows the remnant sits at $M_{F555W} = -10.08$, and $M_{F814W} = -9.26$; very similar values to SN2009ip between outbursts. This also shows that the star is blue, lending credence to the LBV progenitor.

This work highlights the utility of shock cooling analysis for determining progenitor constraints, and the need for high cadence surveys at shorter wavelengths in the future.

Acknowledgements

H.J. Abbot is supported by the Australian Government Research Training Program (AGRTP) Scholarship. The Digitized Sky Survey was produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions. Data was taken with the ANU 2.3m telescope, located in Siding Spring Observatory on the traditional land of the Kamilaroi/Gamilaroi people in Coonabarabran, NSW, Australia.

3

Siding Spring Observatory Site Survey

Context and Contribution

This chapter was published as [Archival Weather Conditions at Siding Spring Observatory](#), by Harrison J. Abbot, Josephine Munro, Tony Travouillon, Christopher Lidman and Brad E. Tucker, PASP, 133, 1027. This work is presented here exactly as in the publication. My contribution was the majority of the wind, humidity and temperature data analysis, as well as the determination of cloud cover on site, with the rest covered by Josephine Munro. I wrote the majority of the paper, with Josephine writing 3.6, and with inputs and suggestions from Tony, Chris and Brad.

Abstract

Weather conditions are a key factor in deciding where to build telescope facilities. They are also a critical factor when planning and designing large surveys. Siding Spring Observatory, located in Northern New South Wales, Australia, has been a national hub for optical astronomy for decades. Weather data have been gathered from multiple sources on site and analysed to show long term trends in wind, humidity, temperatures, and observing conditions on site. A gradual decrease in humidity was observed due to the recent drought, a trend that is expected to continue into the future. Downtime due to high humidity occurs most in winter, with 17.5% of observing time sitting above 90%. Wind direction and speeds are highly variable across the mountain. Predominant winds are NNW in summer (Dec-Feb), and S in winter (Jun-Aug). Strong gusts in excess of 55ms^{-1} can rarely be experienced near the apex of the mountain, however the majority of the mountain does not experience this, and the median wind speed is 3.4ms^{-1} . Temperatures are consistent across the mountain, with a median of 14.1°C . Diurnal temperature variations are largest in summer, at 11°C . 46% of nights are cloudy, with a further 9% - 29% having poor viewing conditions depending on wavelength range.

3.1 Introduction

The weather conditions at an observatory have a large impact on its scientific productivity. It is therefore extremely valuable for astronomers and technical staff to understand them. From its conception, a new telescope or instrument uses weather statistics to determine several key requirements. For example, a dome must survive extreme wind events and be adequately designed to properly flush the telescope's thermal footprint. From an operation standpoint, understanding thermal gradients also helps to specify the active cooling necessary to thermalise the telescope before the start of operation. Site statistics are also important to determine whether the site is adequate to carry out specific science goals. Before even going into seeing requirements, some surveys require a minimum fraction of suitable observing conditions to successfully carry out their objective.

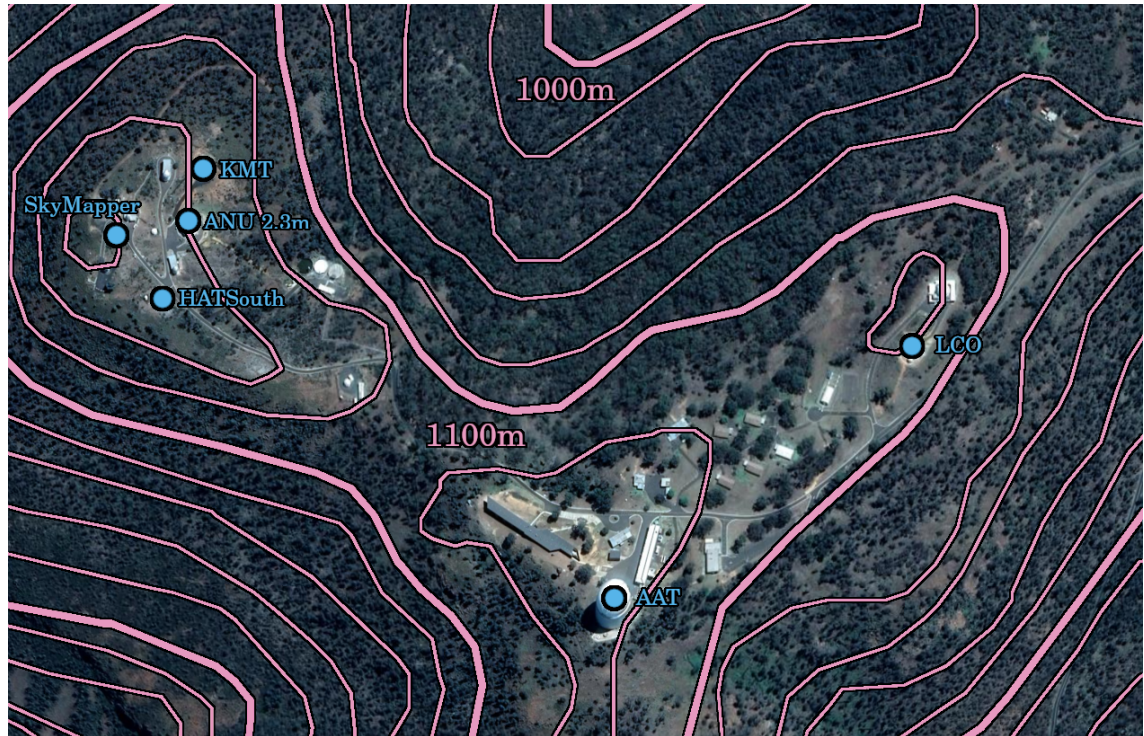


Figure 3.1: Top down view of site, with contours pulled from Geoscience Australia ([Minty et al. 2009](#)). The highest peak lies at 1165m, nearby the SkyMapper telescope. The telescope sites included in this study are labelled. Weather station locations are located nearby, but not necessarily under the blue dots.

Recent site studies have been driven by new generations of telescopes and technologies like the ELT ¹, the advance of adaptive optics which required a more thorough characterisation of sites turbulence parameters, and finally by the development of new sites on the Antarctic continent. This new wealth of data has helped many new telescope projects find suitable locations. It is important to note that many of these telescopes actually have modest requirements. Large arrays of small telescopes are now very popular to study fast transient events or even tracking low-earth orbit objects, valuing longitudinal coverage matched with good weather.

Siding Spring Observatory (SSO) is located on Mount Woorut, near Coonabarabran, Australia (31.273 S, 149.062 E). The site is roughly 1120m above sea level (see Fig 3.1), with its peak at 1165m. Average seeing on site is approximately 1.2" ([Goodwin et al. \(2013\)](#)), although many telescopes report worse seeing largely

¹Extremely Large Telescope, Chile

as the result of dome and mirror seeing. The mountain can be split into two main regions: the western ridge, home to most of the telescopes, including ANU 2.3m (2m3), HATSouth (HAT, [Bakos et al. \(2013\)](#)), the Korea Microlensing Telescope (KMT, [Kim et al. \(2016\)](#)) and SkyMapper (SM, [Keller et al. \(2007\)](#)), and the eastern ridge which include the Anglo-Australian telescope (AAT) and the Last Cumbres Observatory (LCO, [Brown et al. \(2013\)](#)). The western ridge is elevated roughly 20m above the eastern ridge, as can be seen in Figure 3.1.

SSO is not only Australia’s premier optical and infrared site, but also has no competition at that longitude, and so a good understanding of its weather conditions is vital. Opened in 1964, SSO was prized for its dark skies and isolation from artificial lighting. Atmospheric statistics were not widely evaluated for astronomical sites at this time. As relocation to another site with better statistics would have been prohibitively expensive, weather statistics at SSO have not been aptly studied and astronomers have relied on anecdotal experience. For the site to be properly exploited scientifically, it is important to understand not only its weather characteristics but also temporal trends and local features. This work is part of a broader plan to better characterise the weather conditions at the observatory. An analysis of the main weather parameters will be presented in this paper. This study will focus on the major weather parameters: humidity, cloud cover, temperature, wind speed and wind direction.

3.2 Instrument Data

A variety of meteorological instruments are present on site, as each telescope has its own weather station. These instruments include the [Campbell Scientific HMP45](#)², [Campbell Scientific Windsonic1-L](#)³, [Gill Instruments Metpack Pro](#)⁴, and [Vaisala](#)

²<https://www.campbellsci.ca/hmp45c-1>

³<https://www.campbellsci.com/windsonic1>

⁴<http://www.gillinstruments.com/products/anemometer/metpak-pro-weather-station.html>

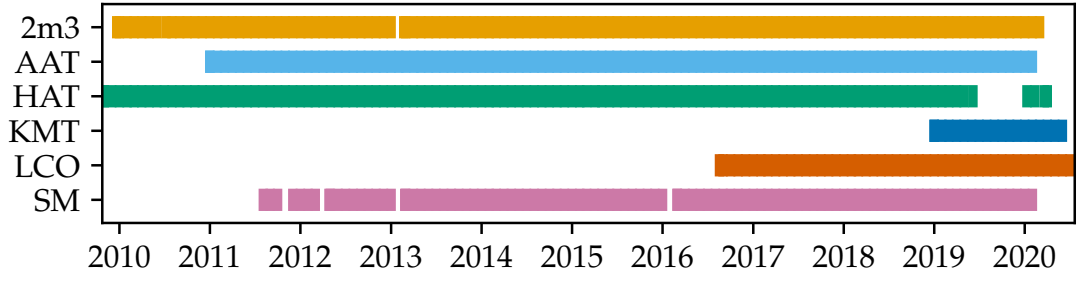


Figure 3.2: Range of data available for each telescope, after pre-processing. Details can be found in section 3.2

WXT510⁵. A summary of each instrument used in this analysis is presented in Table 3.1.

	Vaisala WXT510	Gill Instruments Metpak Pro	Campbell Scientific HMP45C-L	Campbell Scientific Windsonic1-L	Weathertronics Module 1220, Module 1240
	HAT, KMT, SM	AAT	LCO, 2m3	LCO	2m3
Wind Speed					
Range (ms^{-1})	0 $\rightarrow$ 60	0 $\rightarrow$ 60	-	0 $\rightarrow$ 60	0 $\rightarrow$ 90 *
Accuracy (ms^{-1})	± 0.3 (@<15 ms^{-1}) $\pm 2\%$ (@ $\geq 15\text{ms}^{-1}$)	$\pm 2\%$ (@12 ms^{-1})	-	$\pm 2\%$ (@12 ms^{-1})	$\pm 5\%$ (@12 ms^{-1})
Wind Direction					
Accuracy ($^{\circ}$)	± 2	± 3 (@12 ms^{-1})	-	± 3	± 3
Resolution ($^{\circ}$)	1	1	-	1	-
Temperature					
Accuracy ($^{\circ}\text{C}$)	± 0.3 (@20 $^{\circ}\text{C}$)	± 0.1	± 0.2 (@20 $^{\circ}\text{C}$)	-	-
Resolution ($^{\circ}\text{C}$)	0.1	0.1	-	-	-
Relative Humidity					
Accuracy (%)	$\pm 3\%$ (@<90%) $\pm 5\%$ (@ $\geq 90\%$)	$\pm 0.8\%$ (@23 $^{\circ}\text{C}$)	$\pm 2\%$ (@<90%) $\pm 3\%$ (@ $\geq 90\%$)	-	-
Resolution (%)	0.1%	0.1%	-	-	-
Precipitation					
Collecting Area (cm^2)	60	-	-	-	-
Accuracy (%)	5	-	-	-	-
Resolution (mm)	0.01	-	-	-	-

Table 3.1: Summary of specifications for each weather station used. More details can be found at the manufacturer websites, listed in the footnotes.

The data obtained for wind, humidity and temperature have differing cadence across each telescope, ranging from 30s with HAT, to 15min with LCO (barring any downtime). This difference should not have a significant effect on the results however, as even at the longest cadence (15 mins), this still results in over 35000 data points over a year long period. A larger difference is to be found with the length of the datasets used. Figure 3.2 shows the lengths of the datasets used for

⁵https://www.vaisala.com/sites/default/files/documents/WXT510_User_Guide_in_English.pdf

each telescope analysed.

Both LCO and KMT have significantly shorter datasets than the others, meaning that general trends in weather patterns cannot reliably be ascertained from them. Despite this, there does not appear to be a significant difference between the median and quartile ranges obtained from these telescopes compared to the others (see Table 3.5), indicating that the data obtained over the last few years was not abnormal compared to the last decade.

To remove instrumental errors and artifacts, various methods were applied. For temperature and humidity, a 2 sigma cutoff was used to remove erroneous data points, such as those recorded during the early 2013 bushfires. Given the large volume of data, the values presented below are largely representative of real-world extremes. Wind was treated differently, as extremes in wind speed affect construction windows for telescope domes, and can also affect observations. To remove systematics in wind data, histograms of wind speed were generated. Any outliers that did not fit a smooth Weibull distribution were discarded, as these were most likely sensor errors.

3.3 Wind

Wind speed and direction are both important factors that affect the day-to-day operations at SSO. Observatories have upper limits to wind speeds they can operate in and the combination of speed and direction will influence the amount of thermal flushing and wind shake that telescopes will experience. This section will concentrate on the global and local wind patterns visible in the data, as well as point out sources of systematic error in the datasets.

The western ridge of the mountain has been the most popular site to build domes to date, as it is the highest point on the mountain and is mostly clear of trees. Multiple sensors have been used from this side of the mountain, and reveal a generally

consistent, yet somewhat localised wind pattern. The wind across the mountain has a median speed of 3.4ms^{-1} , and a mean of 3.9ms^{-1} . Gusts appear to be strongest near the ridge of the mountain, with SM experiencing winds in excess of 55ms^{-1} , however this is atypical of the rest of the mountain. The peak gust speed averaged across each site is 40ms^{-1} . The most shielded sites (HAT and KMT) experienced wind speeds around half of those in more open areas, with a median wind speed of only 2.1ms^{-1} .

The horseshoe shape of Mt. Woorut has a significant effect on the wind patterns that each site experiences. This is particularly evident during summer, when strong NW winds blow across the mountain, but only affects the west face and mid-to-east ridge, as the west face creates a wake that protects the western ridge (detailed in 3.3.2). Furthermore, the trees on the mountain dampen the southerly winds for the western ridge. This is particularly evident in HAT's wind data, due to the fact that it is the closest to the treeline.

This shielding from the west face of the mountain also affects the wind speeds that each sensor reads, however this is not the only source of obstruction. The wind sensors for AAT, HAT, LCO and SM are all obstructed in some direction by their respective domes. AAT is blocked from the east, HAT is blocked from all but the east, LCO is blocked from NE and SW, and SM is blocked from the south. These were all seen as dead zones when plotting wind roses, and hence are not shown in this paper. This results in the wind speed values from these telescopes (as seen in Figure 3.4) to be skewed lower than is realistic. Furthermore, due to the short-term dataset at KMT, only the 2m3 appears to have reliable data for wind. Nevertheless, general directional trends can be seen across the mountain, after taking into account the location of each weather station relative to their respective domes.

3.3.1 Speed

Wind speed appears to be highly variable across the mountain, with HAT and KMT showing half the average wind speed of SM and 2m3, despite their close proximity

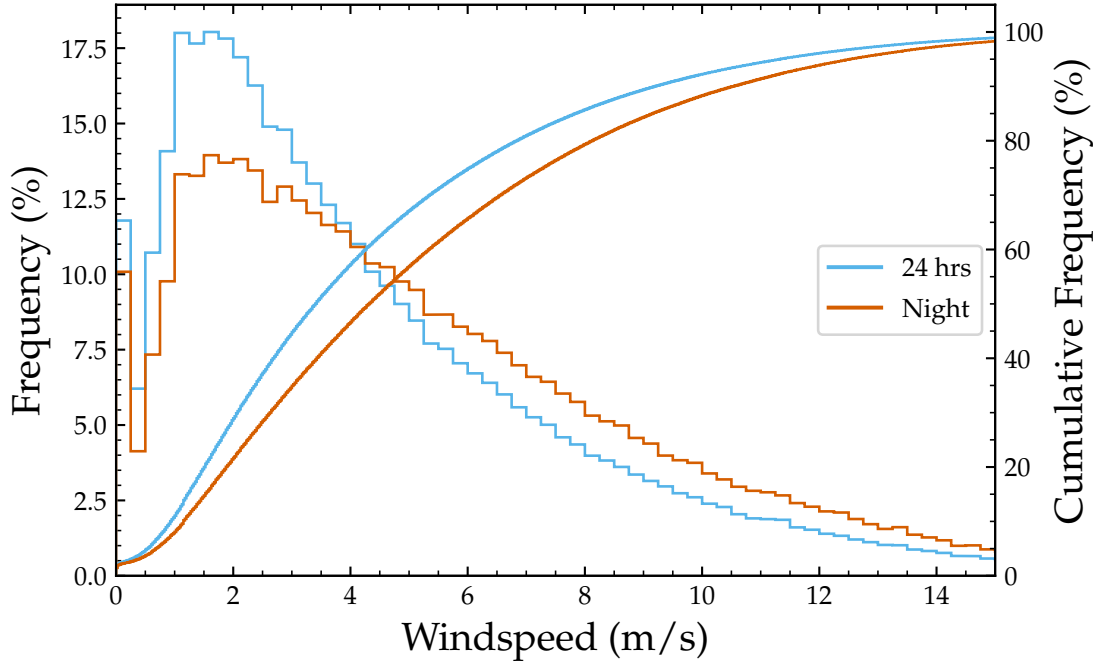


Figure 3.3: Wind speed distribution showing a direct comparison between night hours (non-inclusive of twilight) versus a whole 24 hour period at 2m3.

on the mountain. This is most likely due to their proximity to the treeline on the mountain, causing a dead zone for air currents. Furthermore, HAT is located in a small basin, protecting it from gusts. This effect means that HAT experiences primarily easterly winds, in contrast to the rest of the mountain.

LCO, HAT and KMT all display lower variance in wind speeds, with their inter-quartile ranges being 2.4ms^{-1} , 2.4ms^{-1} , and 2.5ms^{-1} respectively. In comparison, the average inter-quartile range over all telescopes was 3.2ms^{-1} , or 4.0ms^{-1} if excluding these telescopes. This is expected as these are the most shielded sites, and hence do not follow the general wind trends across the mountain. Another explanation for this is that the other telescopes (2m3, AAT and SM) are all much closer to the steeper terrain, unobstructed by other telescopes or the mountain ridge in the directions where wind is most prominent.

Wind speeds are higher during the summer along the western ridge of the mountain, as seen in Figure 3.4, with median speeds 1.8ms^{-1} , 0.8ms^{-1} faster than the

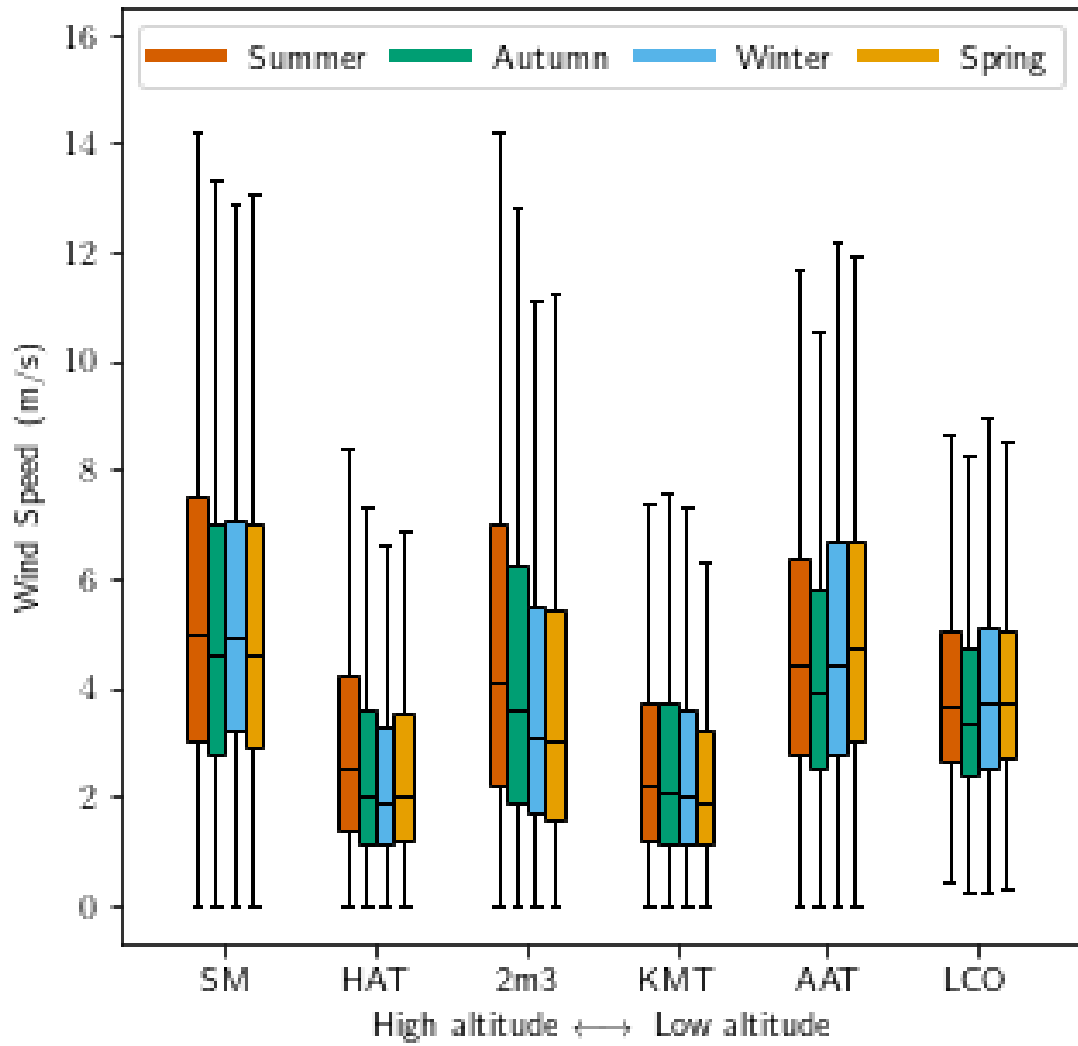


Figure 3.4: Seasonal wind speed range for each site analysed, across all hours of the day.

yearly median for 2m3 and SM respectively. KMT and HAT experience little to no change in seasonal wind speeds due to the obscured sensors. This trend is not apparent for the eastern ridge.

Night brings upon higher wind speeds, as can be seen in Figure 3.3. The histograms shown in this figure follow a Weibull distribution, typical of unobstructed wind speed measurements. Figure 3.3 shows that the median wind speed at the 2m3 at night is 4.2ms^{-1} , 0.9ms^{-1} higher than the 24-hr median. The average difference in median wind speeds across site is 2.0ms^{-1} , however this is skewed by the obstructed telescopes providing lower readings and hence less variation.

Gusts are capable of reaching in excess of 20ms^{-1} on the mountain, however this is so infrequent that these data points were considered outliers when creating Figure 3.4. The rate of dome closures due to wind speed is negligible. Even winds in the $10\text{--}15\text{ms}^{-1}$ range are infrequent, only making up 2.5% of recorded wind speeds, as seen in Figure 3.5. Peculiarly, even though summer has higher median wind speeds, and a larger inter-quartile range, it appears to be the winter months that experience the higher fraction of $<10\text{ms}^{-1}$ wind speeds, implying that while summer is generally windier, winter experiences a higher fraction of sudden gusts. Despite this, the strongest gusts occur in autumn. April showed the largest fraction of gusts stronger than 28ms^{-1} . These extreme cases only accounted for 0.0006% of the recorded wind speeds.

The western ridge of SSO experienced the strongest gusts, likely due to the steep land wicking up any easterly winds. SM detected the highest gust speed at over 55ms^{-1} . Analysis of the distribution of windspeeds do not reveal any obvious systematic errors inherent in the data; the dataset follows a smooth Weibull distribution with no obvious anomalies.

3.3.2 Direction

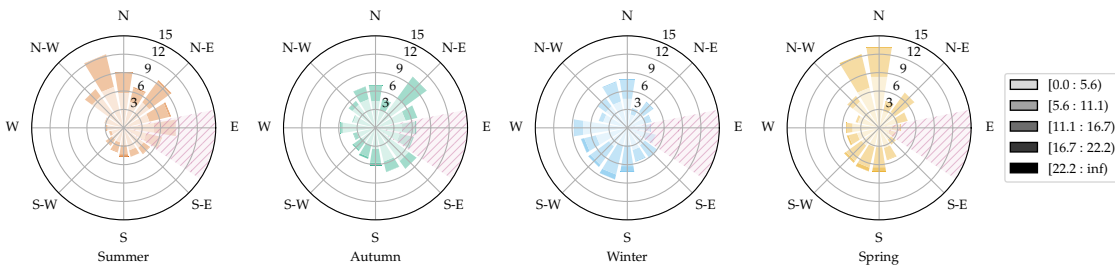


Figure 3.5: Windroses for the AAT, separated into different seasons. Speeds listed are in ms^{-1} . The circles denoted 3, 6, 9, 12, 15 are percentiles. The weather station is obscured from wind by the dome at approximately 100° bearing. A rough area affected by this is shown as the pink, hatched area.

The geometry of the mountain plays a significant effect on the directionality at each telescope location. Wind direction across the western half of site appears to be dominated by south-easterly winds. This trend is likely caused by the strong

updrafts along the west ridge of the mountain brought in by northerly and westerly winds hitting the western face and wicking air from the eastern side of the mountain. This is evidenced by the fact that AAT, LCO and SM show a stronger westerly component to their wind distributions. SM shows northerly and westerly winds as the sensor is above the altitude of the ridge line and also to the north of the dome, whereas AAT and LCO show this as they are far from the wake of the ridge.

The prevailing wind direction across site is variable dependant on location, particularly on the west half of the mountain. Here we see strong easterly and southerly winds dominate. There does not appear to be much directional dependency with the time of year for these telescopes, indicating that the geometry of the mountain plays a larger effect on local winds than global trends.

The prevailing direction is seasonal as measured by AAT. AAT's wind sensor is partially obstructed by the telescope's dome, located approximately 100m away at a bearing of 100° . As such, winds coming from the E and ESE are under reported.

Summer brings around strong SE and SSE winds across KMT and 2m3. At SM, E and ENE winds are dominant. HAT is dominated by E winds, however this is always the case regardless of season. AAT also shows signs of increased wind from the E and ENE. Stronger winds are seen during summer at LCO, however directionality is independant. The sharp directionality of HAT and LCO's windroses are indicative of major obstructions nearby the sensor. This is backed by the fact that the directions they detect the strongest are distinctly dissimilar to the other sites.

Given the large variations in wind direction across site, any differences that wind could bring in (e.g. temperatures, humidity) should present themselves in the data. This is discussed more in in section 3.4 and section 3.5, but there do not seem to be any relation between wind direction and these parameters. As such, we can conclude that any telescope site chosen on SSO will experience similar temperature and humidity trends as the rest of the mountain.

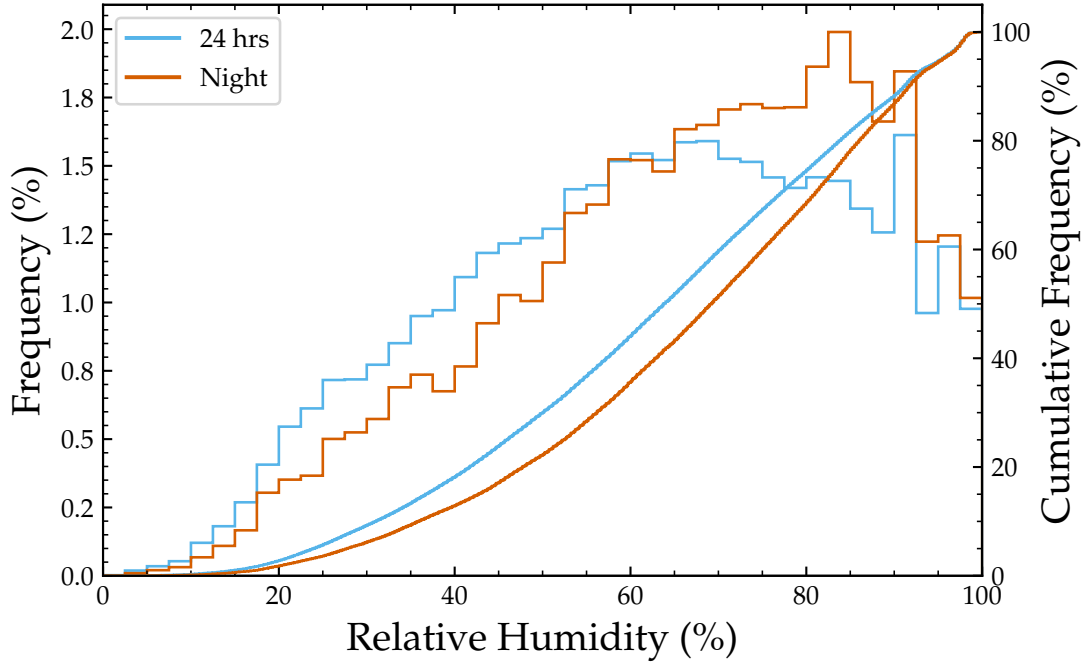


Figure 3.6: Humidity distribution showing a direct comparison between night hours (non-inclusive of twilight) versus a whole 24 hour period at AAT.

3.4 Humidity

Relative humidity is an important factor for the safe operation of each telescope. Depending on the design, different relative humidity limits are set to avoid formation of dew of the telescopes optics and structure. In this section, we present the distributions of relative humidity that each telescope experiences, as a means to discuss a source of downtime when designing surveys.

The average median humidity across site was 60.3%, very close to the mean humidity at 59.4%. The largest differences from these values are seen in the KMT and LCO data, which can be explained by the fact that the datasets have a smaller range, weighted towards more recent years. As can be seen in Figure 3.8, there is a decreasing trend logged over the past decade, most visible from the depth of each minima. Adding a linear fit to daily median humidity reveals a decrease of 6.5% over the decade, which can be attributed to the recent drought that inland Australia experienced.

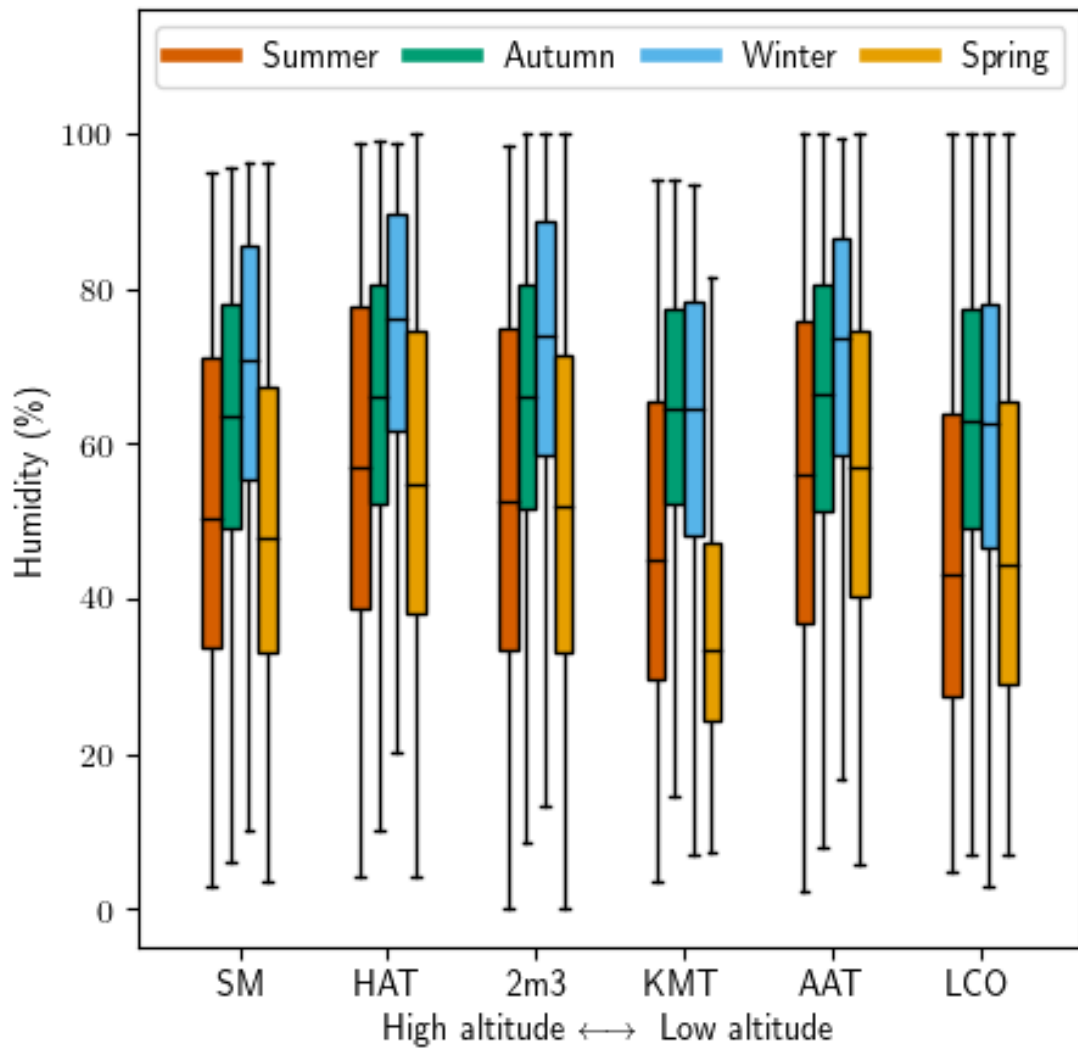


Figure 3.7: Seasonal humidity ranges for each site analysed, across all hours of the day

There are clear trends within the humidity over the seasons, as one would expect. All weather stations show the summer and spring months as being the driest (see Figure 3.7) with median relative humidity sitting between 50 – 60%. Winter is the most humid time of year, with median humidity sitting between 65 – 75% across site. This time of higher humidity correlates with the lower fraction of clear time evident in the winter months in Figure 3.12.

A spike was seen within the 90-100% range in the humidity histograms for most telescopes. This is most likely due to water accumulating on the sensors (e.g. from rain), and taking time to evaporate away. The winter months show a massive increase in this sensor over-saturation, with a three-fold increase compared to summer.

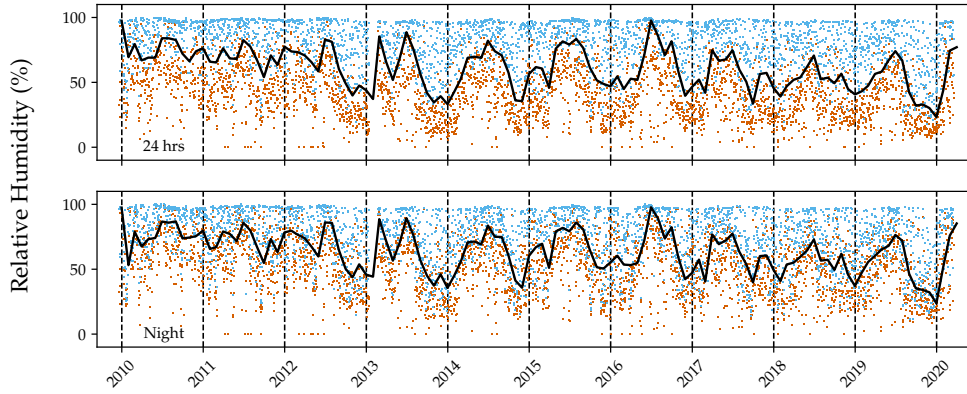


Figure 3.8: Time series of the relative humidity at the 2m3. Red points are daily binned minimums, blue are daily binned maximums, and the black line follows monthly binned medians.

A clear downwards trend can be seen, a result of the recent drought in this region of Australia.

This correlates to increased cloud coverage, seen in Figure 3.12. It also falls in line with Figure 3.7, which shows higher quartile ranges for humidity in winter compared to other months.

As the temperature lowers, relative humidity increases due to a decreasing water content that the air can support. This effect is seen in Figure 3.6, as the lower temperatures of night skew the distributions to higher relative humidity, despite similar air water content. A commonly used relative humidity threshold at SSO is 90%, above which it is recommended the domes are closed to avoid damage to the telescopes. This occurs 7.8%, 10.4%, 17.5%, and 7.3% of the time for summer, autumn, winter and spring nights respectively.

3.5 Temperature

Temperatures at SSO appear to be largely homogeneous across site. Figure 3.10 shows no major variations across site, with the exception of KMT's quartile range of summer temperatures being larger than the others. This is possibly due to the shorter dataset available for KMT (see Figure 3.2).

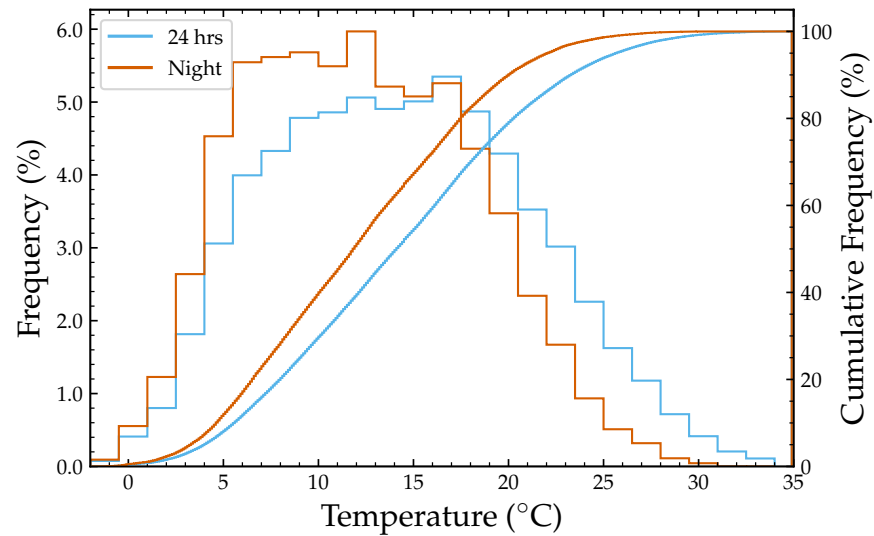


Figure 3.9: Temperature distribution showing a direct comparison between night hours (non-inclusive of twilight) versus a whole 24 hour period at AAT.

Overall, temperatures have been relatively consistent over the past decade. Diurnal temperature variations are highest during summer and spring, however these don't exceed the seasonal variations. The median temperature across site is 14.1°C with temperature variations of 6.9°C throughout the day. Nights experience less temperature variations, with an average of 4.8°C difference, not inclusive of twilight hours. The minimum temperature reached was -2.4°C , and the highest (after removing erroneous points from the 2013 bushfires) was 36.6°C across the mountain. Summer temperatures average 20.5°C , and winters average 7.2°C . Summer has the highest diurnal temperature variations, with an average 11.0°C variance throughout the day. Winter has the smallest, with 6.2°C variation.

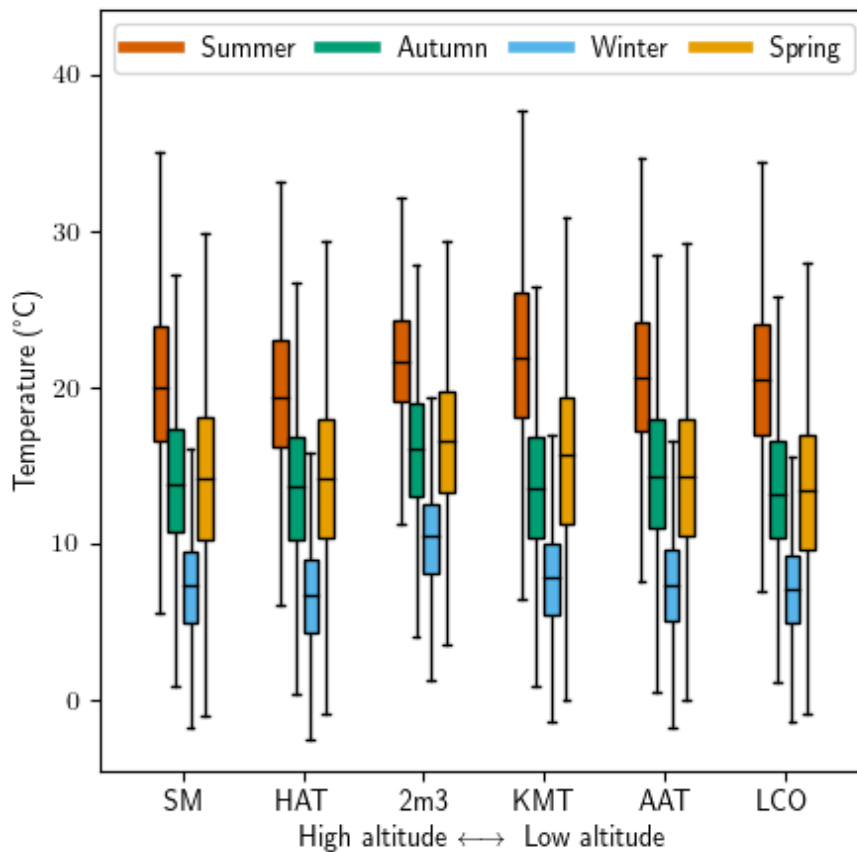


Figure 3.10: Seasonal temperature ranges for each site analysed, across all hours of the day

3.5.1 Temperature Locality

2m3 and KMT both show higher median summer temperatures than the others (22.2°C and 21.9°C respectively, versus 20.8°C as the average median temperature across site). A correlation that was noted is that both are located on the eastern face of the western ridge of the mountain, meaning they are more exposed to updrafts from the nearby valley located ENE from the telescopes.

2m3 experiences higher wind speeds than KMT, and also experiences the majority of winds from the same direction (SE). This means that any effect on temperature that the wind may have would be more extreme at 2m3 as opposed to KMT. If this were the case, the higher temperatures would indicate that warmer air blows in from the valley (ENE), or cooler air blows from the SW (which would not affect the 2m3 or KMT due to their shielded locations on the mountain). The wind roses for the 2m3 and KMT both show stronger SSE winds during the summer, which suggests

that the temperatures are not being affected by the wind direction.

2m3's higher temperature does not just appear during summer, but throughout the year. This is indicative of a systematic error, stemming from the location of the temperature sensors which are located within the dome. As such, the 2m3 data for temperature is only accurate when the dome is open, and has been omitted from Table 3.2, Table 3.3 and Table 3.4.

A more likely explanation for the higher temperatures at KMT is the short dataset, as only 1.5 summer seasons are accounted for. The other seasons are roughly the same as the other medians, indicating that the higher temperature is not the result of a systematic error.

3.5.2 Temperature Changes

The 2m3 recorded temperatures internal to the dome, and hence was excluded from the detailed diurnal temperature analysis. Data from January 2013 was removed from temperature analysis as there was an anomalous spike at all telescopes, due to the bushfires that passed over SSO on January 13th. Most telescopes weren't seriously damaged from this event, and were up and running relatively quickly after the fires passed.

	$\Delta\tilde{T}_{24hrs}(^{\circ}C)$				
	Summer	Autumn	Winter	Spring	All
AAT	$10.4^{+3.5}_{-5.7}$	$7.3^{+3.7}_{-4.2}$	$6.0^{+3.5}_{-3.3}$	$8.9^{+3.8}_{-4.5}$	$8.0^{+4.8}_{-4.7}$
HAT	$11.3^{+4.2}_{-5.6}$	$7.9^{+4.4}_{-3.7}$	$6.4^{+3.8}_{-3.4}$	$9.7^{+5.0}_{-3.5}$	$8.7^{+5.7}_{-4.5}$
KMT	$11.7^{+4.8}_{-5.9}$	$7.7^{+5.2}_{-3.7}$	$7.0^{+3.6}_{-3.6}$	$10.1^{+8.1}_{-2.9}$	$8.8^{+7.0}_{-4.2}$
LCO	$9.8^{+3.9}_{-4.5}$	$6.8^{+4.3}_{-3.4}$	$5.5^{+3.6}_{-2.5}$	$7.5^{+5.2}_{-3.5}$	$7.3^{+5.5}_{-3.7}$
SM	$11.7^{+4.2}_{-6.6}$	$7.9^{+4.2}_{-4.5}$	$6.1^{+3.9}_{-3.2}$	$9.9^{+4.4}_{-4.9}$	$8.6^{+5.9}_{-4.9}$

Table 3.2: Median temperature variations across a 24 hours period (midnight to midnight) at each site. Range given by the 5th and 95th percentiles.

$$\Delta\tilde{T}_{night}({}^{\circ}C)$$

	Summer	Autumn	Winter	Spring	All
AAT	4.7 ^{+3.8} _{-2.9}	3.7 ^{+3.4} _{-2.3}	3.0 ^{+3.9} _{-1.8}	4.6 ^{+4.0} _{-2.8}	4.0^{+4.1}_{-2.5}
HAT	6.4 ^{+4.8} _{-3.2}	5.6 ^{+3.8} _{-2.6}	5.2 ^{+3.3} _{-2.7}	6.4 ^{+4.4} _{-2.8}	5.9^{+4.4}_{-2.8}
KMT	9.8 ^{+4.7} _{-5.2}	7.4 ^{+4.6} _{-3.9}	6.8 ^{+3.8} _{-3.7}	9.2 ^{+8.2} _{-3.1}	8.2^{+5.8}_{-4.1}
LCO	7.5 ^{+3.4} _{-3.8}	6.3 ^{+4.2} _{-3.5}	5.2 ^{+3.8} _{-2.7}	6.2 ^{+5.8} _{-3.1}	6.4^{+4.4}_{-3.3}
SM	5.3 ^{+4.0} _{-3.2}	3.8 ^{+3.7} _{-2.5}	3.2 ^{+3.6} _{-1.8}	5.1 ^{+4.4} _{-3.1}	4.3^{+4.5}_{-2.6}

Table 3.3: Median temperature variations across the nights (evening twilight to morning twilight) at each site. Range given by the 5th and 95th percentiles.

$$\tilde{T}_{24hrs}({}^{\circ}C)$$

	Summer	Autumn	Winter	Spring	All
AAT	20.6	14.3	7.3	14.3	14.2
HAT	19.4	13.6	6.7	14.1	13.4
KMT	21.9	13.5	7.8	15.7	14.5
LCO	20.5	13.1	7.1	13.3	13.0
SM	20.0	13.8	7.3	14.1	13.2

Table 3.4: Median temperatures across SSO per season. Values are obtained by averaging the median temperature of each day in the season, across all years of each site’s recorded dataset.

Each site at SSO appears to have relatively stable diurnal temperature variations. Table 3.2 shows typical changes in temperature throughout each 24 hour period, starting and ending at midnight. The typical temperature range is between 8-10°C, with higher ranges during summer than the other seasons. This correlates with the lower relative humidity that summer brings along, as can be seen in Figure 3.7. Lower humidity generally results in higher temperature variations, as the air has less thermal capacity.

Night hours are a subset of total hours of the day, and so the temperature ranges should be smaller than those over a 24 hour period. This can be seen in Table 3.3

which shows median night temperature ranges are lower than median 24-hr temperatures as would be expected. Despite showing roughly half the ΔT 's, the 5th and 95th percentile of ΔT 's are only marginally decreased compared to the 24-hr ΔT 's.

		2m3	AAT	HAT	KMT	LCO	SM	Average
Wind Speed (ms^{-1})								
(P_0)	Min	0.0	0.0	0.0	0.0	0.3	0.0	0.0
(P_{25})		1.8	2.8	1.2	1.1	2.6	3.0	2.1
(P_{50})	Median	3.4	4.4	2.1	2.1	3.6	4.8	3.4
(P_{75})		6.1	6.4	3.6	3.6	5.0	7.1	5.3
(P_{100})	Max	44.5	49.2	22.1	17.3	36.5	68.3	39.7
	Mean	4.4	4.8	2.7	2.7	3.4	5.3	3.9
Temperature ($^{\circ}\text{C}$)								
(P_0)	Min	-2.1	-2.0	-2.6	-2.6	-2.9	-2.3	-2.4
(P_{25})		11.9	9.1	8.5	9.5	8.5	8.4	9.3
(P_{50})	Median	16.3	14.2	13.4	14.5	13.0	13.2	14.1
(P_{75})		20.7	19.2	18.2	19.9	18.3	18.3	19.1
(P_{100})	Max	33.1	36.1	39.1	37.7	34.8	38.9	36.6
	Mean	16.3	14.4	13.6	15.0	13.6	13.6	14.4
Humidity (%)								
(P_0)	Min	0.0	0.0	3.9	3.1	1.8	2.9	1.9
(P_{25})		42.9	46.0	46.9	36.3	35.7	41.4	41.5
(P_{50})	Median	62.6	63.9	64.6	55.7	55.0	59.8	60.3
(P_{75})		80.4	80.4	81.9	72.7	72.7	77.5	77.6
(P_{100})	Max	100.0	100.0	100.0	94.0	100.0	96.3	98.4
	Mean	61.3	62.4	63.6	54.8	54.9	59.2	59.4

Table 3.5: Wind speed, temperature and humidity for each telescope, broken down into quartile ranges.

3.6 Cloud cover

The amount of clear sky is directly correlated to the scientific output capacity of the telescope. Typically the better a site is, the more clear sky time it has.

Better telescope sites are also drier; with lower rainfall totals and low humidity. This has a two-fold effect, it limits the amount of time the dome is closed due to rain and lowering the dew point.

It is simple to evaluate the cloudy fraction at a site; using HAT-South's Boltwood Cloud Sensor II, which uses an IR thermopile to monitor the difference between sky and ambient temperature. However, discerning between thin cirrus cloud (non-photometric) and no cloud (photometric) is more difficult. Two converging methods using a calculated zero point were used. The fraction of cloudy time, where cumulus clouds are present, was determined using SM weather data, where an IR thermopile is used to sample a patch of sky with approximately 80° in diameter field of view. Without cloud the sensor reads the sky-ambient temperature as quite cold, around -30°C . Conversely, if low and warm cumulus clouds are present the sky-ambient temperature reads higher; around -10°C . The cloudy fraction was 46%. This method is blind to upper level clouds, such as cirrus, which will greatly impact the quality of observation. So another method was needed to determine the photometric percentage time. Two separate methods were devised; one providing an over estimate, and the other an under estimate.

Estimated zero-points (ZP) from SM observations were used to determine the cloudiness of the sky throughout the night. They were first corrected by using extinction coefficients calculated from SM Data Release 3 and the known airmass from each observation (3.1). The corrected ZP's were binned into fortnights, from which a 90th percentile value was calculated. This was defined as a photometric ZP value for the fortnight. From here, a magnitude drop-off of 0.5 mag was used to define a non-photometric night (3.2). Any ZP values that were brighter than this were labelled as non-photometric, and taking this as a ratio of total observations provides the non-photometric fraction (3.3).

$$ZP_{corr} = ZP_{raw} + K_f \times AM_{raw} \quad (3.1)$$

$$ZP_{cloudy} = ZP_{90\%} - 0.5 \quad (3.2)$$

$$CF = \frac{n_{cloudy}}{n_{obs}} \times 100\% \quad (3.3)$$

Fortnightly bins were used in order to have a long enough baseline to capture clear nights in a majority of cases, while also being short enough to minimise any trends from dust accumulation on the mirror. For this method, the non-photometric fraction at SSO for the past decade sits at 19.8%. This value is based off the g-band filter.

With the second method, a histogram of the corrected ZPs for the g-band filter was constructed, this histogram has a Gaussian shape. The percentage of data below a magnitude cutoff of the peak of the Gaussian minus 0.5 gave this method's estimate of the non-photometric fraction. For this method, the non-photometric fraction is 13%.

Cloud coverage at SSO is more prevalent during the summer months, photometric fraction dropping to around 30% during winter; compared to around 45% for summer months. Fig 3.12 shows the cloudy, non-photometric and photometric fractions on a monthly basis.

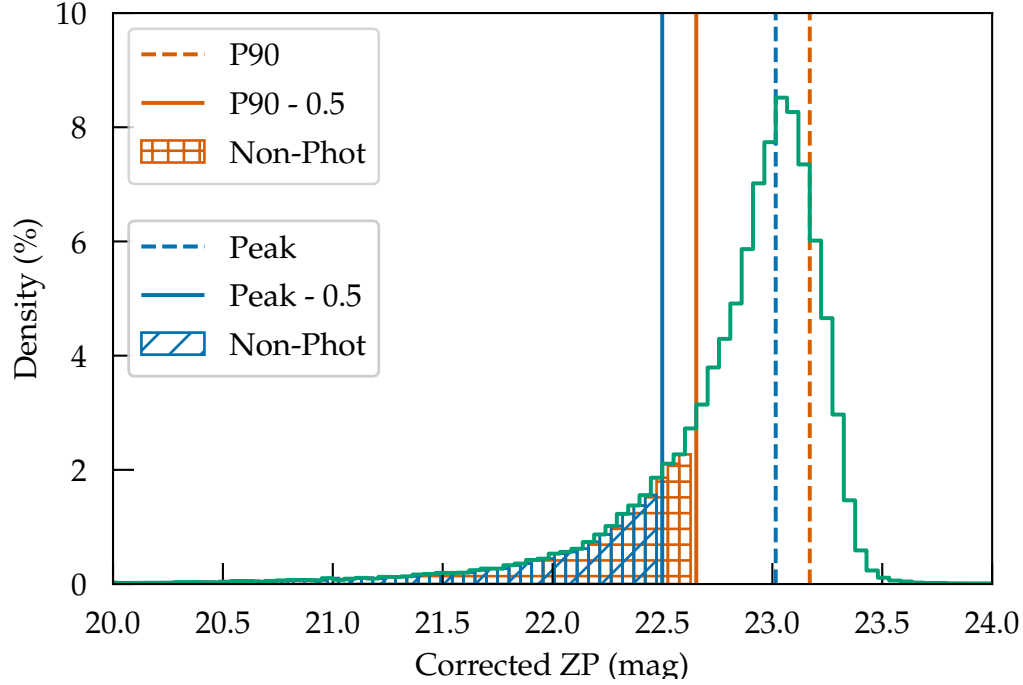


Figure 3.11: Graphic representation of the cloudy fraction calculations. The green line is a histogram of the zero points after they have been corrected for airmass. P90 is the 90th percentile.

Filter	λ_{ave} (Å)	Cloudy	NP ₉₀	P ₉₀
u	3500	46%	29%	25%
v	3800	46%	24%	30%
g	5100	46%	20%	34%
r	6200	46%	14%	40%
i	7700	46%	12%	42%
z	9200	46%	9%	45%

Table 3.6: Cloudy and observable fraction in each SM filter calculated from estimated zero points in SM Data Release 3. NP is non-photometric, and P is photometric.

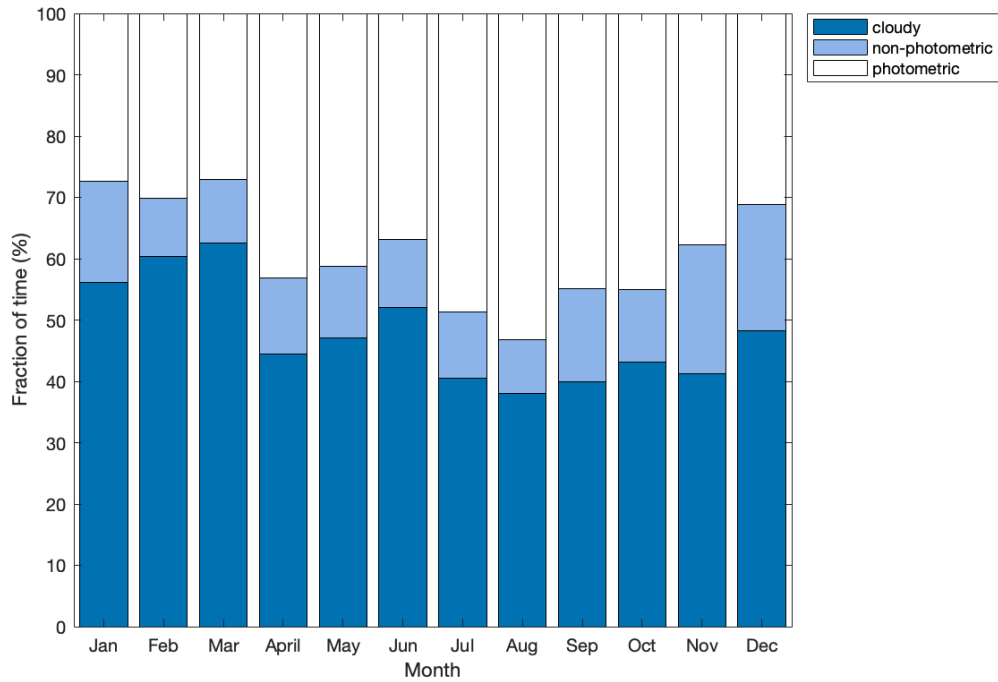


Figure 3.12: Monthly averages of cloudy, non-photometric and photometric fraction.

3.6.1 Precipitation

The precipitation data was taken from the HAT-South weather station. The average annual precipitation for SSO is 606mm. The monthly precipitation average is shown in Table 3.7. The majority of precipitation occurs in summer, the least occurs in the winter months. The autumn months are more variable; with March having highest rainfall and April having the lowest.

A break down of the hours in a day, Fig 3.13, shows that rainfall during summer preferentially occurs in the early afternoon. The rainfall in summer and autumn mainly contribute to the afternoon spike; whereas spring and winter rain is much more evenly distributed throughout the 24 hour period.

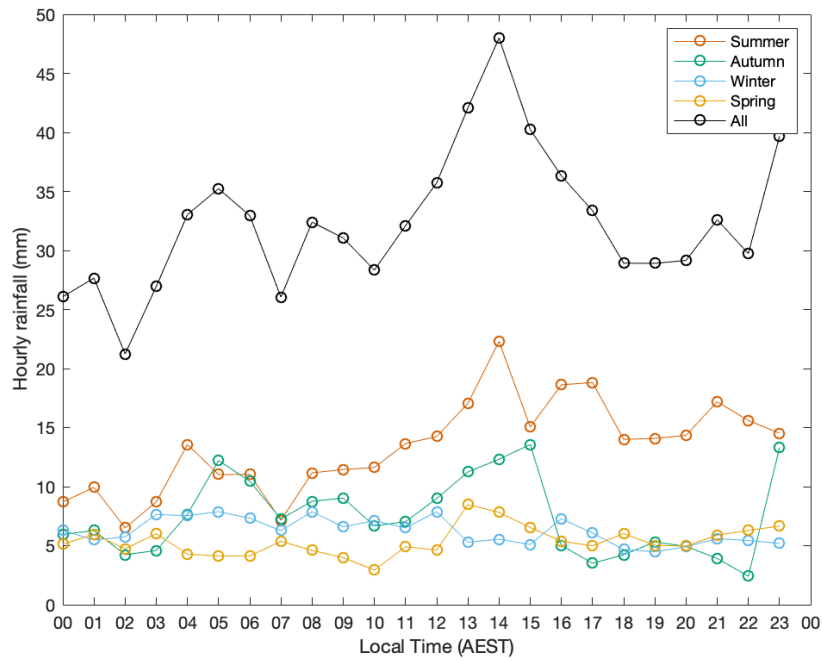


Figure 3.13: Hourly precipitation.

Monthly precipitation (mm)

	Min	25th Percentile	Median	75th Percentile	Max
January	1.8	26.7	82.4	108.5	149.0
February	4.9	28.5	43.9	143.3	205.5
March	20.2	52.6	94.1	123.7	180.7
April	1.3	9.2	18.7	41.3	76.8
May	7.0	39.3	74.1	80.4	89.2
June	12.5	22.6	34.4	85.5	150.1
July	1.1	4.8	47.3	70.0	124.8
August	6.9	16.6	38.8	69.2	109.3
September	3.1	18.8	44.7	103.5	241.5
October	7.7	14.7	51.1	93.3	137.8
November	16.8	34.0	50.1	89.1	270.3
December	17.9	37.6	76.8	115.6	235.8
Monthly Average	8.4	25.5	54.7	93.6	164.2

Table 3.7: Statistics for monthly precipitation

3.7 Conclusion

In this paper, we analyse up to a decade of weather conditions across multiple weather stations at Siding Spring Observatory in Coonabarabran, Australia. The data analysed included wind (sustained and gust) speed and direction, relative humidity, air temperature, cloudy time and photometric time, and precipitation. This data was split into day and night, as well as seasons, in order to aid in future development of telescopes at SSO by advising on the best time to build, as well as helping future survey designers to account for projected rates of weather downtime. A summary of numerical results is shown in Table 3.5.

The main conclusions from this study are as follows:

- The median wind speed across site is 3.4ms^{-1} throughout the day, with nights showing an average 0.6ms^{-1} increase. This cannot be taken as an estimate of the wind speeds at arbitrary points on the mountain, as the wind speeds across site are highly localised, with some sites getting winds half the strength of others due to obstructions by the treeline or large domes. Summer is the windiest season, however winter brings upon the strongest gusts. Autumn has the lowest median wind speeds out of all seasons.
- Wind direction is also highly localised, however trends do appear across seasons. The most predominant wind direction in spring and summer comes from NNW (337.5°), and in winter it is S (180°). Telescopes along the eastern side of the western ridge experience similar winds all year round, coming from the SE (135°). Telescope domes provide a significant source of shielding, especially in the case of the AAT owing to the size of the dome. There are no significant changes in direction between day and night.
- Relative humidity shows seasonal trends. The driest seasons are summer and spring, with winter having the highest humidity. This correlates with the diurnal temperature variations being much higher in summer/spring compared to the winter months. Median humidity values across site sit at 60.2% during

daytime, and 61.2% at night. Relative humidity exceeds 90% during 7.8%, 10.4%, 17.5% and 7.3% of the time in summer, autumn, winter and spring respectively. There appears to be a general downwards trend in relative humidity over the decade, at a rate of 6.5% per decade. This can be attributed to the ongoing droughts across inland Australia. A result of this is a higher fraction of clear nights at recent times. Relative humidity appears to be relatively consistent across the whole mountain at any given time.

- Temperature also shows seasonal trends, as is expected. The hottest months are in summer, with a median temperature of 20.8°C. The coldest months are in winter, with a median temperature of 7.8°C. Summer also has much larger diurnal temperature ranges than other months, with a variation of 11.0°C versus 6.2°C as seen during winter. The diurnal variations show lower temperatures and mildly lower variability at night time. There does not appear to be any obvious trend in temperature over the last decade, nor at different location on the mountain.
- Photometric fraction is estimated between 30% and 40% within optical bands. This fraction increases with longer wavelengths, with the highest fraction of 45% seen in the z band, and the lowest at 25% in the u band.
- The yearly average for rainfall is 606mm. Monthly precipitation averages show more rainfall during the summer months than the winter months. During summer, rainfall is more likely to occur in the afternoon and evening.

Since temperature and humidity stayed relatively constant across the mountain, a centralised weather station can be used effectively at SSO to monitor these statistics. Wind direction and speed are highly localised, and so sensors should be located nearby the domes for accurate measurements.

To assess SSO's viability as an observing site for future telescopes, we present a comparison to other sites around the world. This includes the National Astronomical Observatory in Mexico ([Plauchu-Frayn et al. 2020](#)), Maidanak in Uzbekistan

(Ehgamberdiev et al. 2000), La Silla Observatory in Chile (Sarazin 1997), Roque de los Muchachos Observatory in the Canary Islands (Radu et al. 2012), Paranal Observatory in Chile (Sarazin 1997; Lombardi et al. 2009), and Mauna Kea observatories (Bely 1987).

As shown in Table 3.8, SSO experiences poorer photometric fraction than other sites worldwide. This is partially due to the lack of standardisation in methodology for defining a photometric fraction, but is primarily affected by poor weather on site. It also experiences the highest relative humidity by a large margin, caused by the significantly lower altitude the observatory is located at (1165m for SSO compared to 2390-4200m for the rest). The temperatures at SSO are warmer than most sites, which can also be attributed to the lower altitude. Too few datapoints were found to say anything conclusive about the monthly precipitation compared to other sites.

Site	SSO	San Pedro Martir (Plauchu-Frayn et al. 2020)	Maidanak (Ehgamberdiev et al. 2000)	La Silla (Sarazin 1997)	La Palma (Radu et al. 2012)	Paranal (Lombardi et al. 2009)	Mauna Kea (Bely 1987)
Wind Speed (ms^{-1})	3.4	5.8	2.1	1.5	~ 6.0	2.2	5.7
Temperature ($^{\circ}\text{C}$)	14.1	8.7	3.6	-	~ 9.0	12.8	~ 2 (night)
Humidity (%)	60.3	28.5	-	37	~ 33.5	14.5	13 (midnight)
Photometric Fraction (%)	30-40	-	58	59	-	78	81
Annual Precipitation (mm)	606	313	-	-	-	-	-

Table 3.8: Summary of weather statistics from multiple observatories, taking the long term average of the monthly median values. Exceptions to this are written in text in the table. Values with a leading tilde ($\sim$) are values read from plots, and not explicitly stated in text.

3.8 Acknowledgements

The authors would like to acknowledge the Wayilwan and Kamilaroi people, Traditional Custodians of the land on which Siding Spring Observatory is located. We would also like to acknowledge the Ngunnawal and Ngambri people, Traditional Custodians of the land on which Mount Stromlo is located, and where most of the research for this paper was done. We pay our respects to their Elders past and present, and extend that respect to Aboriginal and Torres Strait Islander peoples there today.

The authors would like to thank the operators of the telescopes on SSO for providing their archival meteorological data and first hand expertise. In particular, Steven Lee and Ashley Anderson with the AAT, Gaspar Bakos and Zoltan Csubry with HAT, Dong Jin Kim and Chung Uk Lee with KMT, Mark Willis with LCO, Chris Onken and Chris Wolf with SM, Ian Price and Jon Nielson with the 2m3, and Ian Adams for SSO overall.

We would also like to thank Chris Onken and Chris Wolf for their contribution of the SSO extinction coefficients derived from Skymapper Data Release 3 that were provided before it went public.

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4

GLUV Pathfinder

Context and Contribution

This section includes the work from multiple papers. Section 4.2 was published as **GLUV Pathfinder: setting up for rapid cadence UV monitoring of the transient universe**, by Harrison J. Abbot, Joice Mathew, Ryan Ridden-Harper, Brad E. Tucker, Eduardo Trifoni, Robert Sharp, James Gilbert, Nirmal Kaipachery and Mikhael Sayat, SPIE Proceedings, 11444, 114446. This work is presented here exactly as in the publication. My contribution was the majority of the text and efficacy rates, with plots by Nirmal Kaipachery and Mikhael Sayat, and inputs and suggestions from Brad Tucker and Rob Sharp.

Section 4.3 is based on my contribution to the design of GLUV Pathfinder, which specifically was the the mechanical and thermal design of the payload, which included power and weight budgeting, CAD modelling, as well as the manufacturing

of the housing and platform mounts. This section also includes some extra information summarised from [GLUV pathfinder mission](#)’, by Nirmal Kaipachery, Joice Mathew, James Gilbert, Rob Sharp, Harrison Abbot, Ryan Ridden-Harper, and Brad Tucker, SPIE Proceedings, 11203, 112030. This extra information is a summary of the survey strategy used by the onboard equipment which my contributions were designed to support.

4.1.1 is a summary of design specifications sourced from [Ridden-Harper et al. \(2017\)](#) and [Sharp et al. \(2016\)](#), and was the basis for the requirements for the GLUV pathfinder mission.

4.1 Science case

The development of dedicated NUV instrumentation is highly important for supernovae and kilonovae astronomy, as these higher energy wavelengths reveal their initial detonation conditions. By analysing the light curve of the shock breakout and subsequent shock cooling of a supernova, the progenitor’s radius, mass and ejecta velocity can all be determined. This can have profound effects on modern day cosmology, which relies heavily on Type Ia supernovae for distance measurement. A direct detection of the progenitor of Type Ia supernovae has yet to be discovered, although it is known that there are multiple types of progenitors for these events. Kilonovae are the result of violent black hole and neutron star mergers, and result in bright flashes of UV and higher wavelength light. Hence, high energy follow-up surveys must be conducted in order to test the underpinning physics that is now possible due to the discovery of gravitational waves (GW). GW’s have brought forth the advent of multi-messenger astronomy, and are crucial for testing the limits of general relativity in a way previously not possible. Properties like the travel speed of GW’s cannot be known until compared with a known quantity, such as the speed of light. It then becomes imperative that high cadence instrumentation is developed to look in these higher photon energy regimes.

GLUV is an answer to this, and is expected to capture the initial shocks of supernovae at a rate of 10+ per year of operation. GLUV is an affordable, long duration high altitude balloon experiment being developed for the early-time detection of supernova shock-breakout at NUV wavelengths (specifically 200nm to 450nm) from within the ozone layer. The ozone layer has a complex spectral absorption profile at near-ultraviolet (NUV) wavelengths. It is dependant on seasonal effects due to solar intensity, as well as atmospheric circulation of the ozone layer. Getting above this then becomes imperative for getting a usable signal-to-noise ratio (SNR) for scientific observations. It is known that the NUV sky background noise level drops off significantly when above the ozone layer, however the noise profile from within the ozone layer has yet to be mapped ([Waller & Stecher 1998](#)). GLUV Pathfinder is a spectrometer based system to identify the sky background in the NUV, measuring this as a function of altitude, latitude, and seasonal phase in the regimes that the final GLUV project will experience.

4.1.1 GLUV Specifications & Requirements

Preliminary designs for the final GLUV instrument include a 30cm diameter primary mirror, capable of providing 5 arcsecond resolution within a 7 deg^2 area of sky, with a limiting magnitude of $m_{uv}(AB) \approx 22$ after exposures of 10 minutes ([Ridden-Harper et al. 2017](#)). Background sky glow imposes a limit on the recoverable signal, and is approximated to contribute to background noise by $m_{uv}(AB) \approx 24 \text{ mag arcsec}^{-2}$ at 350nm ([Waller & Stecher 1998](#)). Furthermore, atmospheric opacity at UV wavelengths must be overcome. GLUV will fly close to the ozone layer, meaning that the atmosphere will absorb a significant amount of the light before it reaches the instrument. There are no good measurements of the absorption profile of UV within the ozone layer, so a conservative estimate of 40% throughout has been estimated to drive the design. This, however, provides a significant problem for the final design, and it is imperative that this becomes a data-driven number before GLUV is finalised. This is the main driver behind the GLUV pathfinder mission, detailed in section 4.2.

GLUV’s primary goal is to serve as both a transient discovery and a transient follow-up instrument. Since GLUV is designed to be a low-cost solution to UV surveys, it would be feasible to launch a network of survey balloons in order to increase the rate of transient detections (Ridden-Harper et al. 2017). A constellation of GLUV’s could perform surveys as either targeted follow-up of discovered transients, or as a blind survey instrument waiting for serendipitous transient events. While one GLUV is a small instrument that would take 10+ minute exposures to reach the $m_{uv}(AB) \approx 22\text{mag arcsec}^{-2}$ goal in a 7 deg^2 field, a constellation of 10 GLUV’s could feasibly cover $0.08\text{deg}^2\text{s}^{-1}$; more than 10% that of LSST’s rate, while at a significantly lower cost. In this sense, GLUV could feasibly recover a large number of transients triggered by LSST alerts. Alternatively, if performing a blind survey, a trade-off between cadence and sky coverage must be made. Preliminary calculations show that survey area would provide more utility than higher cadence when optimising for transient discovery rates. With these design specifications, a constellation of 10 GLUV instruments can expect to see on the order of 10 GW events per year, and track them at daily cadence rates.

4.2 GLUV Pathfinder

Abstract

The ozone layer has a complex spectral absorption profile at NUV wavelengths. It is dependent on seasonal effects due to solar intensity, as well as atmospheric circulation of the ozone layer. Getting above this then becomes imperative for getting a usable SNR for scientific observations. GLUV is an affordable, long duration, high altitude balloon experiment which will fly a network of NUV telescopes at altitudes of 20-30 km. GLUV Pathfinder is a spectrometer based system to identify the sky background in the NUV, measuring this as a function of altitude, latitude, and seasonal phase in the regimes that the final GLUV project will experience. The development of dedicated NUV instrumentation is highly important for supernovae astronomy, as these higher energy wavelengths reveal their initial detonation conditions. GLUV is expected to capture the initial shocks of these events at a rate of 10+

per year of operation, well in excess of the few instances that have been seen to date.

4.2.1 Introduction

GLUV is a project aiming to develop a low-cost solution to observe widespread coverage of the sky in ultraviolet (UV) wavelengths. It is aimed at providing a high cadence UV survey for rapid followup of transient objects such as supernovae and gravitational wave sources. Identifying tracers of the progenitor systems of these objects can be found at higher energy wavelengths, and are most prominent at the earliest times in their evolution.

Ground coverage of UV bands are not feasible due to the ozone layer absorbing most of the UV light before it can reach the ground. Deployment of UV instrumentation is stifled as a result, despite it being vitally important for high-energy astrophysics. In its final form, GLUV will be a network of high-altitude, balloon based telescopes flying at altitudes of roughly 20-30km, within the ozone layer.

Atmospheric UV transmission is known to be a function of altitude, latitude and season ([Hassinen et al. 2016](#)). GLUV Pathfinder aims to tightly constrain the UV sky background and atmospheric transmission at the planned flight altitudes. It will do this by measuring the background counts of the sky using an off-the-shelf mini spectrograph, and comparing this directly to a synthetic solar spectrum. A second mission is also planned to test the suitability of this platform for imaging and photometric purposes.

4.2.2 Science Cases & Requirements

Supernova Shock Breakout

The primary use case for GLUV is aimed at getting rapid spectrographic observations of supernova shock breakout. This initial stage of a supernova's explosion is

critically important for determining the progenitor system which produced the supernova. The shock breakout's strength is proportional to the radius, mass, ejecta velocity and time since detonation ([Waxman & Katz 2017](#); [Piro et al. 2010](#)). It is most prominent in higher energy wavelengths, normally inaccessible from ground based telescopes due to atmospheric absorption.

There are many paths a star system can take to produce a supernova. The most commonly found type of supernova is the Type Ia (SN Ia), which are crucial to our understanding of cosmology as they have a very predictable relation between their light-curve width and absolute magnitude. They are extremely luminous events, able to outshine their host galaxy's core. By virtue of these properties, they can be used as standardisable candles to accurately measure distances in the distant universe. This technique was used in proving the accelerating expansion of the universe, a discovery which won the 2011 Nobel Prize in physics. These observations proved the presence of a cosmological constant in Einstein's model of the universe; General Relativity.

Whilst this discovery was monumental in impact, there still remain large error margins between observed and theoretical expansion rates. The main cause for this is a systematic error, stemming from an imprecise knowledge of the progenitors of SN Ia. The explosions of SN Ia are commonly attributed to a white dwarf (the dense core of a star remaining after running out of fusible material) accreting material from a companion main-sequence type star. Alternative explanations come from mergers of two white dwarfs, however this would occur at much lower rates than what is observed. Once a white dwarf reaches a mass limit (the Chandrasekhar mass), a runaway thermonuclear explosion starts and is seen as the SN Ia. This process should leave some indication as to what the companion star was in the initial stages of the shock propagation, in particular when the explosion collides with the companion ([Kasen 2010](#)). This shock interaction can be used to find the size of the companion, but depends on many factors such as the separation distance and viewing angle. Finding evidence of this shock interaction would constrain progenitor systems further, aiding in developing a more complete cosmological theory. To do

this consistently, it is necessary to develop high cadence UV surveys.

Core collapse supernova (CCSN) make up the rest of the supernovae discovered. These occur when a massive star ($>8 M_{\odot}$) cannot produce enough heat energy in its core to support the overwhelming gravity of its outer layers (Woosley & Weaver 1995; Sukhbold et al. 2016). As the star collapses inwards from its own gravity, the pressure experienced by the core increases until the heavier elements can be fused, producing more energy. This explosion sends a shockwave out, but is trapped by the outer layers falling inwards. This process continually happens up until the outer layers become optically thin, at which point the energy can be released and becomes the shock breakout (Waxman & Katz 2017). CCSN are the most spectroscopically diverse type of supernovae, which hints at the existence of a large range of progenitor systems. There have been many rare and peculiar CCSNe discovered to date with unknown progenitor systems (e.g. Mauerhan et al. 2013; Miller et al. 2020), hence the need for a UV survey to utilise the existing shock breakout models effectively.

Modern surveys have dramatically increased the number of supernova candidates discovered, with surveys such as ASAS-SN, ATLAS, and ALeRCE providing daily cadence photometry for early detections. Despite this, the daily cadence is not enough to capture the earliest shock phases of SN explosions. The timescale of the initial shock breakout is on the order of minutes, with an extended shock cooling phase that lasts days. The first evidence of shock breakout was found with Kepler, which provided 30 min cadence on its photometry. With this, theoretical models were proven to work in determining the progenitor system of a CCSN (Garnavich et al. 2016). This early detection emphasises the need for larger, high-energy photon surveys to limit the systematic errors in supernova cosmology.

4.2.3 Payload Overview

GLUV Pathfinder's primary goal is to determine the atmospheric UV transmission profile across a typical GLUV flight. Atmospheric ozone concentration decreases with altitude and latitude (Sharp et al. 2016), so it is preferential to fly at high

altitudes close to the Earth's poles.

Off-the-shelf components have been used in the development of the design, details on the electronic specifications are detailed by [Kaipachery et al. \(2020\)](#). The major components include an inertial measurement unit (IMU), GPS, a spectrometer, power supply unit, a Raspberry Pi (RPi) and temperature, humidity and pressure sensors (see Figure 4.1).

For the spectrograph, an Avantes Avaspec mini spectrograph was chosen. It has a wavelength range of 186-450nm, and will be fed by a single mode fibre pointing 45° from zenith if ignoring any rotation of the platform when in flight. A synthetic solar spectrum has been recorded by the spectrograph (see Figure 4.2). This will be used to calibrate the atmospheric spectra obtained during flight, from which a UV transmission profile can be constructed.

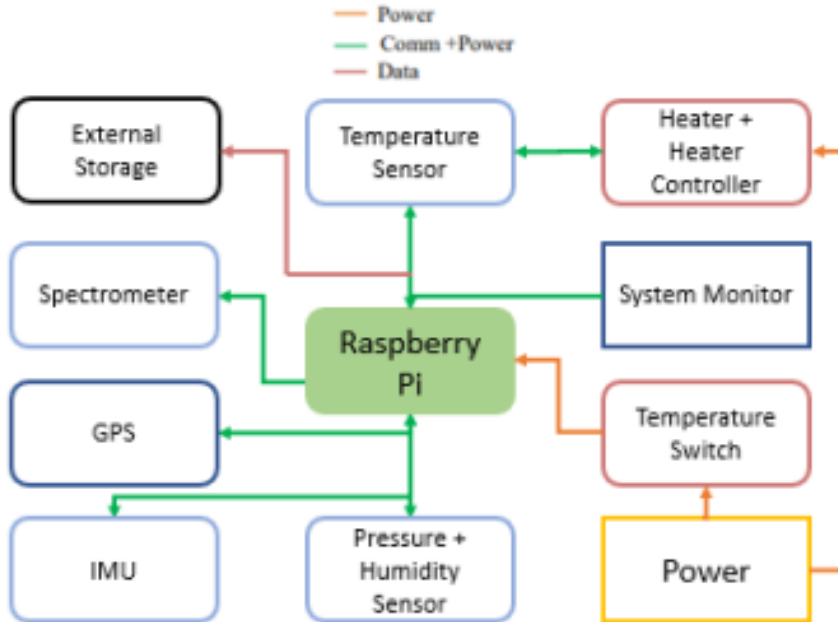


Figure 4.1: System diagram of GLUV Pathfinder showing internal connections and connection types.

Since the GLUV Pathfinder mission will be in-flight and unreachable for an extended period of time (~ 100 days), systems are put in place in order to ensure

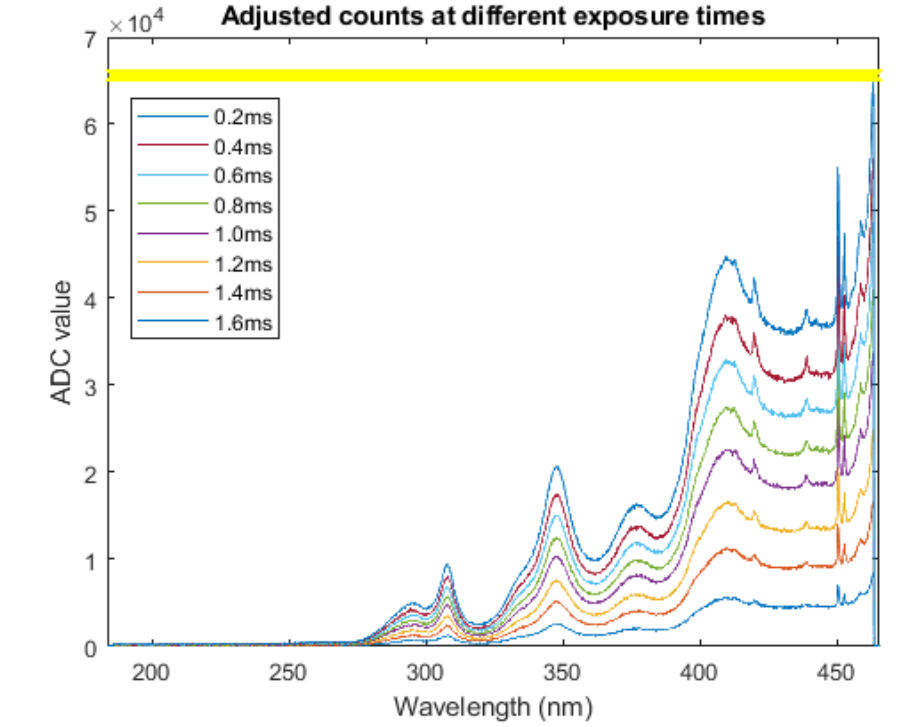


Figure 4.2: Reference solar spectrum from a synthetic source. This spectrum was taken with the optical system aboard GLUV Pathfinder, so can be directly compared to the atmospheric transmission recorded in-flight.

continuous operation of the spectrograph throughout the whole duration. The sensors used for this monitoring include a GPS, IMU, temperature probes, humidity sensor and pressure sensor. Transcievers were considered to provide procedural data-checkpoints to avoid total data-loss in the case of an unsuccessful mission, however this idea was disbanded due to power, weight, and financial constraints. The GPS is connected to the RPi via serial, while the rest are connected through I2C. The RPi logs all the data recorded from these modules into an SD card. The information recorded is tabulated in Table 4.1.

A watchdog timer circuit is used to ensure the continual operation of GLUV Pathfinder over the course of its ~ 100 day mission. A data dump will be completed every 10 minutes, with the watchdog circuit resetting the system if unresponsive for 14 minutes. Each of the subsystems in GLUV Pathfinder is parallelised so that in the event of a failure, each of the unaffected systems can still function and provide data. One case where this is highly useful is the loss of GPS signal. Depending on

availability of satellites, the GPS module can take several minutes to establish itself upon restarting. Parallelising the systems allows the rest of the payload to function as normal without the GPS being active.

Table 4.1: Summary of sensors onboard GLUV Pathfinder, their function, and units they measure in.

Sensor	Data
GPS	Latitude ($^{\circ}$), Longitude ($^{\circ}$), Altitude (km), UTC Time (YYYY/MM/DD hh:mm:ss)
IMU	Roll ($^{\circ}$), Pitch ($^{\circ}$), Yaw ($^{\circ}$)
Humidity	Humidity (%)
Pressure	Pressure (Pa)
Temperature	Temperature ($^{\circ}$ C)
UV Transmission	Counts (n/ms integration)

GLUV Pathfinder will not be actively controlled, so the pointing of the system is entirely dependant on the stability of the balloon platform. The payload will be held below the balloon by a long tether, meaning that any wind will significantly affect the pointing of the spectrograph. Initial measurements show that the rotation about zenith has the highest variability. An inertial measurement unit (IMU) will be used to record attitude information of the payload, and will be used to provide quality checks for the final dataset.

The temperatures within GLUV Pathfinder are measured by seven digital temperature sensors which are placed by each of the critical components. An average temperature is calculated across the system to determine if the payload is operating

within a safe temperature range. To regulate the heat, there are nine heating elements spread across the platform. These are attached to an aluminium backplate which acts as a heat spreader to ensure all components are heated uniformly. This system is especially important for the function of the spectrograph, which is only rated to work within a 10°C to 60°C temperature range.

The system will be shut off when not within this specified temperature range to avoid damage to the electronics. This is required as the temperatures at the flying altitude can range between 0° C to -60° C. As such, the heating system is vital for the operation of this mission. The functionality of this thermal kill-switch has been tested independently from the rest of the payload, with full system testing (including thermal and pressure testing) to be completed in early 2021.

The heating circuitry is controlled by a relay operated by the RPi, but is also able to operate independently. This is required if the system loses power for an extended period of time, and needs to be heated up before starting the main electronics. A problem arises in a situation where the RPi does not restart after losing power, but the heating circuitry still receives power. This would cause the payload to be heated indefinitely, potentially causing damage to the structure and circuitry. To fix this issue, a 60°C thermal switch was wired in series with the heating elements. This switch automatically cuts power if temperatures rise above this limit, and only reinstates power after it cools to 40°C. Therefore, in the event the RPi does not turn on, the GLUV Box temperature is limited to between 40°C and 60°C.

4.2.4 Summary & Future Work

GLUV provides a novel solution for time domain astronomy at UV wavelengths, at a fraction of the cost of a cubesat constellation. It has the potential to provide breakthroughs in our understanding of supernovae, gravitational wave counterparts, and many other transient and variable astronomical objects. Key tests are required before system development can begin.

Currently a GLUV pathfinder spectrograph, developed at the ANU, is nearing test flight. This system will tightly constrain both the sky background and atmospheric transmission expected at the planned flight altitudes. This will provide critical information for the system design of GLUV. The subsystems involved with GLUV Pathfinder have been built and are awaiting final thermal and vacuum testing prior to launch. After this, a ~ 100 day test flight will be performed to ensure the robustness of the electrical design, as well as record data on the transmission of UV light through the atmosphere at 20-30km altitude. This will be used to calculate a sky background count value, from which expected transient discovery rates can be determined for the final GLUV mission.

4.2.5 Acknowledgements

In the spirit of reconciliation, the authors acknowledge the Traditional Custodians of country throughout Australia and their connections to land, sea and community. We pay our respect to their elders past and present and extend that respect to all Aboriginal and Torres Strait Islander peoples today.

H.J.A. was funded by the Australian Government Research Training Program (AGRTP).

4.3 GLUV Pathfinder Design

4.3.1 Power Delivery

The platform available was able to provide power from two main electrical buses; one at 40-50V and one at 24V. This voltage needed to be stepped down in order to safely power the Raspberry Pi and spectrograph, both of which required 5V DC to operate. Through this, a continuous 15W of power was available to keep our instruments within operational specifications. The majority of this power was utilised for heating the payload to safe operating temperatures. Power distribution

was controlled by thermal switches, which prioritised the heating circuit above data collection. Once the payload reached safe operating temperatures, the Raspberry Pi would be turned on, which in turn started logging the outputs of all the sensors including the Avaspec Spectrograph.

A more detailed analysis of the electrical components of GLUV Pathfinder and their purpose are detailed in section 4.2.3.

4.3.2 Thermal Design

GLUV pathfinder is designed to operate within the ozone layer, at altitudes between 10-20km above the sea level. At altitude, the expected atmospheric temperature outside of the housing would reach -110°C , which poses an extreme risk to the delicate electrical components inside.

The thermal design of GLUV pathfinder revolved both the science requirements of the final GLUV instrument, as well as design specifications of the off-the-shelf components used. The AvaSpec-Mini2048CL Spectrograph and Raspberry Pi 3B+ were the two main components that had to be designed around, with the minimum operating temperatures allowable being 0°C for proper operation of the spectrograph. The Raspberry Pi also had a minimum operation temperature of 0°C , but only for operation of the LAN connection, which was not needed when in flight, and otherwise was rated to withstand -40°C . As such, the temperature sensors were placed closest to the spectrograph to ensure it maintained its minimum operating temperature.

The electrical components were insulated from the outside by expanded polystyrene (EPS) packing foam, mounted inside an aluminium casing. The insulative properties of a material are measured by its 'R-value'. Polystyrene is one of the most cost-effective forms of insulation, with a high R-value of 1.44 cm^{-1} . The aluminium case also provides some insulation, although it has a much weaker R-value at 0.15 cm^{-1} .

Thermal losses through the optical fibre are assumed to be negligible compared to heat loss through the aluminium housing. The fibre itself is insulated, and glass is a good insulator, being used as insulation material for industrial applications such as within blast furnaces. As such, heat loss from this source is not considered in the thermal design of GLUV Pathfinder.

The amount of insulation required was then an optimisation problem based off the following formula. In this equation, R is the R-value per cm, t is the thickness in cm, T_2 is the ambient outside air temperature, T_1 is the internal payload temperature, $\dot{Q}$ is the rate of heat loss, and A is the surface area through which the heat transfer occurs.

$$R * t = \frac{T_2 - T_1}{\dot{Q} * A}$$

With this in mind, the final dimensions settled on for GLUV pathfinder was a rectangular square prism measuring 37.5cm $\times$ 37.5cm $\times$ 20cm, with the insulation thickness measuring in at 7.5cm per face. These dimensions allowed for 15W of heat loss when experiencing a temperature delta of 120 °C, enabling the electronics to keep functioning at the expected minimum temperatures with a 10°C of buffer.

Each component was mounted to a sheet of aluminium, which acted as both a rigid mounting plate, as well as a heat spreader to more evenly bring the payload up to operating temperatures. The exterior dimensions limited this to a 22.5cm $\times$ 22.5cm plate, providing just enough space to mount each component. To this, 9 resistors were attached with conductive thermal paste at the interface, providing the rest of the components with up to 13.5 W of heating power. The size of the insulation in relation to the payload can be seen in Figure 4.3

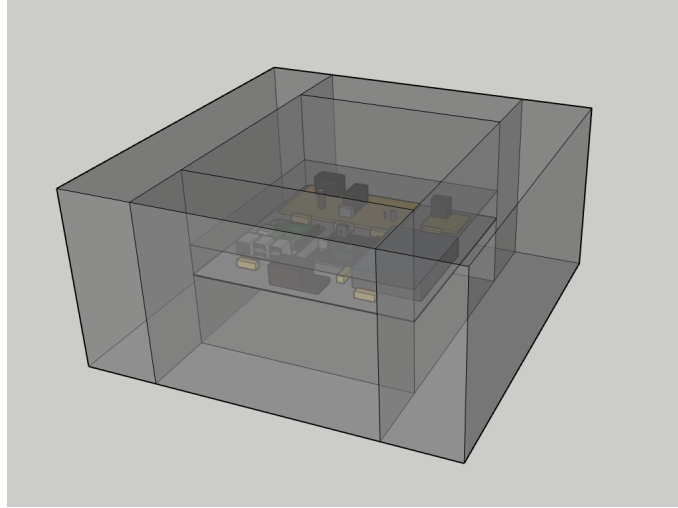


Figure 4.3: CAD Model of GLUV Pathfinder with insulation. Insulation is EPS, represented by the transparent material to be able to see the size of the payload in context.

4.3.3 Mechanical Design

Beyond the power limitations, the weight limit was capped at 5kg for the payload. Minimising the weight also increased the projected flight time, which we were trying to maximise to gather as much data as possible per flight. To ensure that this limitation was met, an appropriate material choice had to be made for the housing, as it was likely to be the primary contributor to the final weight. The dimensions of the final product already had a lower limit set by the thermal design, and so the final surface area the housing had to cover was calculated to be $2 \times 0.375^2 + 4 \times 0.375 \times 0.2 = 0.44\text{m}^2$. Aluminium sheet at 1mm thickness was chosen due to its specific tensile strength, cost effectiveness, and workability. These sheets were used for each side, and were held together with rivets placed evenly along 10×10 mm aluminium L-bar along each side. This brought the housing’s weight to approximately 1.2kg, keeping the payload well below the limit. The final weight of the payload came in to approximately 2.2kg.

Buffeting from wind gusts posed the largest mechanical risk to the entire design while in flight. The balloon had a stabilised platform to which the payload would be mounted, limiting the effects of gusts along rotational axes. Due to the thin atmosphere at altitude, the amount of lateral force imparted on the payload would be minimal, and so protecting the payload was a simple matter of latching down

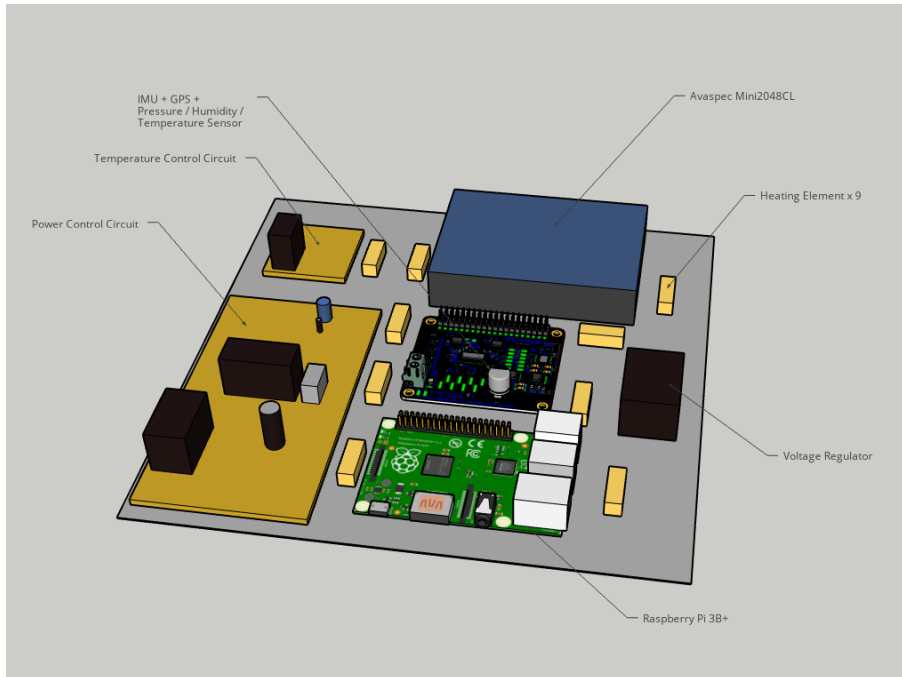


Figure 4.4: Labelled CAD Model of the payload of GLUV Pathfinder. Cables are not included in the model for visibility purposes.

the payload's access panel.

The roughest stage of the flight would be the landing. The balloon platform was designed to fall slowly to the ground, however the biggest forces would come from lateral movement as the payload touches down, potentially digging into the ground and being dragged around by the still airborne balloon. The payload had to be able to preserve the delicate optical fibre and spectrograph safely through this stage for safe re-use on subsequent flights. Fortunately, the foam used for thermal insulation is also a very common packing material used for safe shipping of commercial items. Ensuring the safety of the payload then was simply a matter of limiting the range of movement available within the payload bay. Adhesives were used to attach the insulation to the housing, however could not be used on the mounting plate, as that would remove the ability to perform maintenance on the payload without destroying some of the insulation through sheering. In the end, the mounting plate was friction fit within the payload bay, with additional packing foam pressure fit around components with inherent structural integrity (namely the spectrograph, voltage regulator, and Raspberry Pi) to use them as load bearing structures to avoid any excess movement. Pull tabs were designed to extract the payload from the housing, as with the

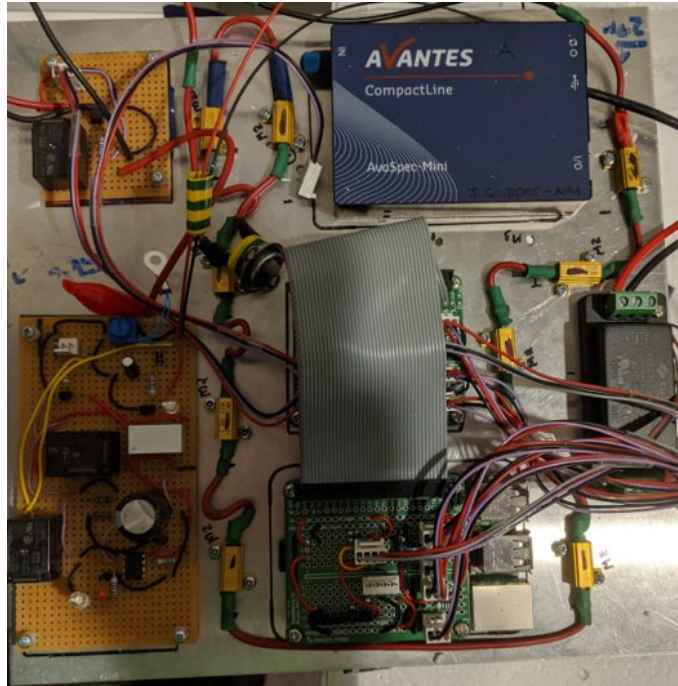


Figure 4.5: Image of the real payload, wired up as described in Figure 4.1. The payload’s multiple temperature sensors are hanging off the right side of the image, as they would have further cluttered the visible wiring.

insulation in place, performing maintenance in-situ was nearly impossible.

4.3.4 Operation procedure

GLUV Pathfinder was not designed to be actively controlled, with the intention instead being to record continuously, and sync the data collected through the spectrograph with the onboard telemetry recording the altitude and attitude. From this, the background light can be mapped retroactively to the instrument’s attitude and altitude, which would be affected by gusts when in flight. Over the duration of the 100 day flight plan, this would accumulate enough data at different headings to be able to model a function of UV opacity versus altitude.

The instrument collects light through a single-mode fibre linking the payload bay to the exterior of the housing. This was fixed at a 45 degree angle from the horizon in order to assure the spectrograph was not pointing at the balloon carrying the payload. The exposure time of the spectrograph was dynamically set, with each exposure’s duration being calculated off of the number of saturated pixels in

the previous frame. If no pixels were saturated, the exposure time would increase until a threshold of 10% was reached, and conversely it would reduce if too many were saturated. The saturated pixels would be located in the optical parts of the spectrum (due to atmospheric extinction of UV light), and so this relatively high percentage would not affect the science readings.

4.3.5 Complications

The development of GLUV Pathfinder faced significant setbacks in its build and deployment due to the stringent lockdown measures implemented in Australia amidst the COVID-19 pandemic. Restricted access to the workshop meant that non-essential workers, and particularly students, had limited opportunities to work on-site, slowing down construction and hindering the deployment process. The deployment of the project was also hampered by travel restrictions, limiting the mobility of personnel required for deployment on the balloon's platform. The uncertainty surrounding the duration and severity of the lockdowns further contributed to financial challenges and decision-making delays. Sadly, due to unfortunate timing, GLUV Pathfinder was never able to get off the ground.

5

Conclusion

This thesis explored the utility of rapid cadence astronomy by highlighting their importance in determining supernova progenitors. It also delved into the development of automated systems to aid in the discovery and classification of young transients, which helps to focus the search within more targeted surveys. I summarise the project conclusions in the following paragraphs, and finally will discuss future work this thesis leads towards.

5.1 Summary of Paper 1: Shock Breakout in 2019com

Shock breakout was likely detected in SN2019com; a Type IIn supernovae, bearing a close spectroscopic resemblance to the supernova imposter 2009ip. This transient was followed up photometrically by SWOPE, and spectroscopically by WiFeS, for the first 2 weeks following its discovery. In this, we see a slight blue excess in the first

photometric datapoints, indicative of shock breakout. Photometry was analysed using Sapir & Waxman (2017)’s shock breakout model of BSGs, using a MCMC fitter developed by Armstrong et al. (2021). Priors were supplied by spectroscopic analysis, measuring the FWHM of the $H\alpha$ line to constrain ejecta velocity, and discovery date to constrain the age. From the results of the Piro shock breakout model, we can deduce that SN2019com may have started as a massive blue star, with a progenitor radius of $122.8^{+11.0}_{-8.2} R_{\odot}$. The ejecta has a mass of $2.57^{+0.56}_{-0.65} M_{\odot}$, and velocity of $9520^{+340}_{-212} \text{km s}^{-1}$. Late time imagery was taken with HST, in which we can see that there is clearly a remaining light source 1.5 years after the initial explosion. These factors combined lead to the conclusion that SN2019com is likely a supernova imposter that may have survived the explosion which garnered its discovery, much like 2009ip.

5.2 Summary of paper 2: SSO Site Survey

A site survey was conducted for Siding Spring Observatory, in which the weather characteristics of the last decade were analysed. This was done to provide insight for future telescope development on site, determining the best locations to put weather monitoring equipment. In this, we find that SSO is a wet observing site, with common reasons for dome closure being cloud cover prohibiting observing roughly $\frac{1}{3}$ of the time, as well as humidity being very high a significant portion of the clear time. Strong winds on site are not a common reason for dome closure, however there are points on the mountain (particularly at the apex of the western peak) where wind is particularly strong that would prohibit dome usage. Wind speed is very variable across site, meaning each telescope should be fitted with wind sensors. Humidity and temperatures (and hence dew point) are very stable across the mountain, and so a common weather monitoring system can be used by many telescopes safely for these variables.

5.3 Summary of paper 3: GLUV Pathfinder

GLUV presents itself as a novel, cheap solution to set up a UV transient monitoring and follow-up system. Its primary science goal is to measure the early development of UV emission of supernovae and other high-energy transients; a feat not possible by ground telescopes due to the ozone layer's UV opacity. A pathfinder mission has been started, in which a test instrument has been built. The pathfinder flight is a proof-of-concept mission, in which the UV transmissivity of the atmosphere at an altitude range of 20-30km will be measured. This will be done to help development of the optics of the final instrument. A spectral energy distribution of the Sun's light will be captured, and compared to a synthetic solar spectrum measured at ANU through the same optical system.

5.4 Future Work

In the process of setting up the pipeline for rapid transient analysis, over 100 samples of young supernova spectra were collected. Out of these, only a single set has been thoroughly analyzed (SN2019com), meaning that the majority of observations remains underutilised, awaiting scrutiny and analysis for the discovery of more intriguing supernovae in the collected data set. These objects would then be published as their own single-object papers.

The ToO pipeline set up is currently in use for the Dark Energy Bedrock All Sky Supernovae (DEBASS) survey. This survey aims to follow up on 500+ low redshift supernova in the coming years, with the Dark Energy Camera (DECAM) providing photometry to further enhance the dataset. This survey is currently underway, and is regularly providing classification of young supernovae. Future work aims at providing a clean dataset of spectroscopically confirmed SN Ia, replacing the historic low-redshift supernovae samples that have caused many issues for scientists in the Dark Energy Survey. These old sample sets suffer from calibration uncertainties, limiting their usefulness. DEBASS in turn will help to measure the dark energy content of the universe to unprecedented precision.

Very recently, the ANU 2.3m telescope has been automated. This represents a significant leap forward in astronomical observation capabilities, particularly in the context of the upcoming LSST alerts. The ANU 2.3m telescope has now become a highly efficient and responsive instrument for transient follow-up observations. This automation enables efficient scheduling and prioritisation of targets throughout the night, maximizing observing time. With the LSST expected to discover a vast number of transients and events across the night sky, and SSO's unique longitude allowing for rapid cadence follow-up of alerts in the southern sky, the scientific output of the ANU 2.3m is set to skyrocket. In order to enable seamless coordination with the LSST, ensuring that transient phenomena are promptly characterized, a broker systems needs to be set up to listen to the LSST alerts, and prioritise them based off of scientific significance. A significant portion of this pipelining has already been set up (as detailed in Section 2.1), but with the sheer number of alerts expected of LSST, the still existing manual processes (notably the review of the final target list) should be programatically automated. A further step that could be taken is automated classification of the tracked objects, with the hopes that peculiar supernova can be flagged and subsequent follow-up observations can be made, turning them into topics for more single-object papers, and potentially a survey paper after a large enough sample has been collected.

The ANU 2.3m's automation also allows for automation of the reduction pipeline, as a recorded list of targets, standard stars, and callibrations would all be taken in a standard format, as opposed to the human created observing logs that existed prior. This removes the need for most of the still existing manual processes in the transient follow-up pipeline. Furthermore, the automation drastically increases the observing efficiency of the telescope, enabling a significant increase in the number of ToO's that can be triggered per quarter. Automation of the reduction pipeline would turn the ANU 2.3m telescope into a transient classification powerhouse, boosting its prominence in the scientific community.

Due to the impact of the COVID-19 pandemic, the GLUV project was delayed,

preventing its completion within the timeframe of my PhD. Travel restrictions ended up stopping GLUV Pathfinder from going on its maiden voyage, and the availability of the balloon platform became much more limited. Once GLUV Pathfinder can perform its first flight, the data it captures will need to be processed in order to create a model for atmospheric extinction of UV at altitude. This process would have to occur multiple times throughout the year, and at multiple locations, in order to build a comprehensive model that accounts for seasonal and geographic variations. This model can then be used to drive the final design of GLUV, which will then be built to be able to observe the optical component for the initial target of 10 gravitational wave sources per year. Additionally, GLUV will likely provide high cadence UV photometry of the shock breakout, shock interaction, and/or shock cooling of supernovae, which would serve as the basis of a slew of highly impactful papers upon reduction and analysis.

5.5 Summary

Telescope site survey papers are crucial for successful supernova follow-up observations. Supernovae are rare and unpredictable events that require quick and accurate observations to capture critical information about their properties and evolution. A telescope's location plays a crucial role in obtaining high-quality data, as it determines the atmospheric conditions, light pollution, and accessibility to the target. The site survey helps astronomers select the best possible location for a transient followup telescope, which maximizes the chances of detecting supernovae and obtaining high-quality observations. Additionally, a well-placed telescope can provide long-term monitoring of the supernova, capturing its evolution over time.

This was exemplified by the discovery of SN2019com, a rare IIn supernova, which has ties to the peculiar supernova 2009ip. Rapid followup allowed us to record the spectral evolution of this object, partially capturing the shock cooling lightcurve, enabling a measurement of the progenitor star's physical properties.

Telescope site survey papers are essential for optimizing the observing conditions and ensuring successful supernova follow-up observations, which are critical for advancing our understanding of these explosive cosmic events. The site survey paper presented in this thesis highlights SSO's viability as a follow-up telescope for transients discovered with LSST.

Finally, work was done to develop a novel, transient follow-up telescope for UV observations. This project aims to supplement ground-based observations with an observing regime not otherwise visible to them. Together with the automated ANU 2.3m telescope, they will provide wide-band coverage of SN events, providing stronger constraints on supernova progenitors from shock physics.

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