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Structure and Evolution of Classical Nova Shells

A Dissertation Presented

by

Éamonn Jean Harvey BSc, MSc

to

The Graduate School

in Partial Fulfilment of the Requirements

for the Degree of

Doctor of Philosophy

at the

Centre for Astronomy

School of Physics

under the supervision of Dr. M. P. Redman

National University of Ireland Galway

February 2018
Abstract

This thesis focuses on shells ejected during classical nova events. Novae are due to thermonuclear runaway on the surface of a white dwarf in a binary system. The work herein concentrates on nova shells individually to understand and unify nova shells as a whole. This thesis aims to follow the ageing process of classical nova shells from ejection to centuries post-ejection. This research was undertaken using imaging, spectroscopy and polarimetric observations, as well as morphology, kinematic and photoionisation simulations. The three main results chapters in this thesis integrate the methods listed above to follow the ageing process of expanding nova shells. The first results chapter focuses on the shell of V5668 Sagittarii (2015) from 0 - 822 days post-discovery. A main finding from the examination was that V5668 Sagittarii displays O II rather than N III flaring around the 4640 Å region. This flaring episode has been commonly seen but misidentified in erupting slow nova systems. A symmetry discovered in the expanding nova shell of GK Persei (1901) is presented in the second results chapter. The revealed shaping of knots in the GK Persei nova shell are attributed to fast chasing dwarf nova winds. In addition, the velocity is determined for the first time of the only known apparent jet in a classical nova system. The low velocity of the apparent jet is attributed to an illuminated lobe of the fossil planetary nebula within which the GK Persei shell resides. The third results chapter includes: the discovery of two shells around known nova producing systems, a time evolution analysis of four of the better-studied classical nova shells, and the finding what could be a nested shell structure from multiple nova ejection episodes. A common axial-
symmetry between all of the studied classical nova shells is revealed throughout the thesis and concluding that through considerations of the inclination of the source towards the observer the wide variety of observed nova light curves and spectral characteristics can be reconciled.
Dissemination of Research

Refereed

  
  E. J. Harvey, M. P. Redman, M. J. Darnley, S. C. Williams, A. Berdyugin, V. E. Pirola, K. P. Fitzgerald and E. G. P. O Connor
  
  Astronomy & Astrophysics, accepted 22/11/2017

• Modelling the Structure and Kinematics of the Firework nebula: The Nature of the GK Persei Nova Shell and its Jet-like Feature
  
  E. Harvey, M.P. Redman, P. Boumis, S. Akras
  
  Astronomy & Astrophysics, Vol. 589, A64, November 2016

• A Morpho-kinematic and Spectroscopic Study of the Bipolar Nebulae: M 2-9, Mz 3, and Hen 2-104
  
  N. Clyne, S. Akras, W. Steffen, M. P. Redman, D. R. Goncalves and E. Harvey
  
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In Prep

• Prevailing Characteristics of Classical Nova Shells E. Harvey et al.
• A Deep Optical Study of the Supernova Remnant G 166.0+4.3 (VRO)  
P. Boumis et al.

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• Talk: Polarimetry of a DQ Her-like nova: V5668 Sgr (2015) E. Harvey et al. NAM UK, Hull, July 2017

• Poster: A Deep Optical Study of the Supernova Remnant G 166.0+4.3 (VRO) P. Boumis et al., Greek Astronomical Society, Crete, July 2017


• Talk: Old Nova Remnants E. Harvey & M.P. Redman, Irish National Astronomy Meeting, Queen’s University, Belfast, August 2015

• Poster: The Old Nova Shells of GK Per, Z Cam and AT Cnc E. Harvey, M.P. Redman & P. Boumis. Institute of Physics, Spring Meeting, Cork, Ireland. April 2015

• Talk: Tracing the Firework nebula E. Harvey, M.P. Redman & P. Boumis. Irish National Astronomy Meeting, Trinity College Dublin, August 2014
Departmental Seminars

• Classical Nova Shells American Museum of Natural History, New York, 20 October 2015

• Old Stellar Shells University of Denver, 23 October 2015


• Creation and Destruction in Classical Nova Shells National University of Ireland Galway, 20 March 2017
“Cloictheach tenedh do faicsin i r-Ros Dela dia domnaigh fhele Géuirgi ria ré cuig n-uár do lá, & eoin duba diairme índ & as, & aen-en mor a medon, & teigdis fo cluim-sidhe na h-eóin becca in tan teighdis isin cloctheach. Tantacar amach co n-uargabatar in coin bai for lar in baile a n-airdi isin aér, & tar-laicset h-é síss arís, co n-erbailt fo chétóir, & tuargabatar tri brutu & di lénid a n-airde, & ro leicsit sis arís. In chaill iarom fora n-desetar na h-eonu do rochair fothaib, & in dairbre for a n-dessid in t-én mor ro bái for crith cona fhremaib a talmuin.”

Annála do Tigernach, 1054 A.D.
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*Declaration of Authorship*

- This dissertation is submitted for the degree of Doctor of Philosophy.

- This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except as specified in the text.

- Where I have consulted the published work by others, the source is attributed.

- This work has not been submitted for any other qualification.

Signed:

______________________________

Date:

______________________________
Chapter 1

Introduction

Stella Novae, or ‘new stars’, stand at the cross-roads of stellar evolution, harbouring a middle-aged Sun-like star and an old white dwarf. They are characterised by violent eruptions and are important sources of elements such as lithium. A younger companion feeds the white dwarf hydrogen-rich material until a critical pressure is reached, then a thermonuclear runaway eruption follows. The ejected nuclear processed material forms seeds for the next generation of stars. These nova events are observed regularly (∼35 occur in our galaxy per year) and develop on timescales of hours to hundreds of days. These stellar systems repeat their eruptions anywhere from every few months to millions of years.

Novae produce high-energy gamma-rays down to radio waves, with the observational ranges acting as probes for various underlying physical processes. High-cadence imaging, spectroscopy, and polarimetry are all needed in conjunction with multi-wavelength observations to better understand these sys-
tems. In this thesis I will be providing an overview of classical novae and their wider relevance by concentrating on observational as well as modelling techniques developed during the course of my studies.

1.1 Evolution of Single Stars

The Sun is traditionally used as the standard star for defining stellar properties. The Sun was born in a metal-rich environment and is most likely a third or fourth generation star. Like most stars it is primarily composed of hydrogen and this is the source of its fuel for the first major period of its lifecycle. The period of time that a Sun-like star spends burning hydrogen at its core is referred to as the main-sequence of the Hertzprung-Russell diagram (bottom-centre of Fig. 1.1). A star evolving off the main-sequence is an indication that it has exhausted its hydrogen core and now has to switch to burning helium.

Our Sun will develop a degenerate helium core and spend time on the red giant branch (marked RGB on Fig. 1.1). While on the RGB the Sun will experience a thermonuclear fusion runaway, called a “helium flash”, in its core and lifting the degeneracy. This helium flash is not to be confused by a helium flash observed later, during the asymptotic giant brach (AGB) phase of evolution, where this flash has its origins in burning of helium on the stellar surface. After the RGB phase the Sun will burn helium in its core while on the horizontal branch (HB)

If a star has an initial mass $0.5 \, M_\odot < M_* < 8 \, M_\odot$ then it will evolve onto the HB after it depletes its helium core. Regardless, stars with $< 10 \, M_\odot$ will evolve onto the AGB where they are characteristically cool and luminous. The
star is luminous due to its bloated size and the temperature is low due to the multi-shelled structure of the stellar envelope. The time characterised by the presence of a photoionised expanding shell illuminated by an emerging white dwarf (WD) following the AGB branch stage of stellar evolution, is known as the planetary nebula (PN) phase (Paczynski, 1971). These lower mass stars will spend their final stage of evolution as a carbon-oxygen (CO) WD.

![Stellar Evolution Diagram](image)

Figure 1.1: Stellar evolution of a Sun-like star in a colour-magnitude diagram. Adapted from public talk given by the late Dr. Olivier Chesneau at the College de France, Paris, 9 February 2011.

For stars with mass $> 8 \, \text{M}_\odot$, after the horizontal branch they will burn non-degenerate carbon in a similar manner to hydrogen and helium until it is exhausted. Stars with initial mass $> 8 \, \text{M}_\odot$ will become oxygen-neon-magnesium (ONeMg) WDs, if an ONeMg WD attains $1.44 \, \text{M}_\odot$ it will become a neutron
star following a core-collapse supernova. Elements as heavy as iron are used as nuclear fuel in this manner for stars $> 11 \, M_\odot$. If a CO WD reaches a mass of $1.44 \, M_\odot$ it will explode as a Type Ia Supernova (SNIa).

In modern astrophysics, it is understood that WDs are supported by electron degeneracy pressure and neutron stars are supported by neutron degeneracy pressure. Without these degeneracy pressures, the stars would collapse under gravitational pressure. Since we are concerned only with WDs in the present context, the focus in this thesis will be on electron degeneracy.

WDs are supported by the pressure exerted from electrons composing a fermion gas ruled by Pauli’s Exclusion Principle. According to the Pauli Exclusion Principle no two fermions may access the same half-integer spin orbital simultaneously. This phenomenon creates a pressure due to the large accumulated momentum of the electrons, as Heisenbergs Uncertainty Principle states.

The Chandrasekhar limit is the theoretical mass limit of a WD and is estimated to be $M_{\text{Ch}} = 1.44 \, M_\odot$ (Nauenberg, 1972). If this limit is exceeded, the stellar object can no longer be considered a WD. As stated earlier, a CO WD will end as a SNIa if $M_{\text{Ch}}$ is exceeded, whereas an ONeMg WD will collapse into a neutron star (Nomoto and Kondo, 1991). The Chandrasekhar limit has proven to be one of the most singularly important parameters of modern astrophysics as it predicts a specific mass at which all SNIa are generated. Since the limit informs astronomers of the intrinsic luminosity of the object, the distance to the object can be reliably derived. Hence, if a SNIa is observed within a certain galaxy, the distance to that galaxy can be estimated using information derivable in consideration of the Chandrasekhar limit. These events are known as the most reliable distance indicators in the Universe, although
distance determination via parallax methods is more reliable for nearby ob-
jects.

There have long been attempts to standardise the eruption characteristics of classical novae so that they could be used as distance indicators. This has proven difficult after initial efforts, i.e. della Valle and Livio (1995), have been more recently brought into doubt, mostly by Kasliwal (2011). The debate is discussed in more detail later in Section 1.5.2.

1.2 Double Stars

As ancient supernova blast waves sweep the interstellar medium into swirling wisps, it is quite common for stars to form in binaries, 20% to 80% of all stars depending on spectral their type, e.g. Raghavan et al. (2010). A binary system can be formed through a tidal capture process as well, when two stars become bound after coming into close proximity (Press and Teukolsky, 1977). It is also possible to have more than two stars formed together. A complication in the understanding of stellar evolution is that stars in a binary system will share material through accretion and winds. This sharing process essentially contaminates both stars and they influence one another. The rate of influence varies from system to system as it depends on the mass ratio, metallicity, proximity and evolutionary state relative to one another.

Double (or binary) stars are commonly categorised by their mass, proximity and whether or not they are interacting, see Fig. 1.2.
Figure 1.2: Graphic showing equipotentials of the four states in which a binary may exist. The first and second Lagrangian points are marked L1 and L2 in each of the panels. Material falls onto the accretor via the L1 point. Credit: Vik Dhillon, retrieved from http://www.vikdhillon.staff.shef.ac.uk/seminars/lives_of_binary_stars/masstrans.html on 10 August 2017.

1.2.1 Cataclysmic Variables

Cataclysmic variable stars are exciting examples of binary star systems as their interactions lead to observable phenomena that include eruptions and flashes due to various physical processes at play. How any two bodies interact is best
viewed in the context of a system developed by French mathematician Joseph-Louis Lagrange (Lagrange, 1772). The Lagrangian system consists of a set of five points, known as Lagrangian points, commonly referred to as gravitational null points. The points are known by their nomenclature: L1, L2, L3, L4 and L5.

In order to understand accretion in nova systems, it is best to focus on the L1 point (marked on all panels in Fig. 1.2) as matter spills onto the WD star through here. In the semi-detached binary scenario, the companion star has filled its Roche lobe, known as Roche lobe overflow as illustrated in Fig. 1.2. A Roche lobe is the volume of space surrounding a stellar body that encapsulates the star’s minimum equipotential surface. After a star has expanded to fill its Roche lobe, material may leave through the L1 point and become gravitationally bound to its companion and the transfer material gradually loses kinetic energy and spirals onto the surface of the companion star. In this case, the spiralling of material from the donor star onto the companion star is known as an accretion disk. The accretion stream from the companion impacts the accretion disk at a preferred point, known as the “hot spot”. If the accreting star is magnetic, then the magnetic field will likely feed the material onto the star’s surface through its magnetic poles.

1.3 Novae

The focus of the work herein is on classical nova systems and their expanding shells. Classical novae are a distinct class of stellar system, however some related objects exist, which are distinguished below. All of the objects/events
in this section exist at the cross-roads of evolution regarding some of the most intensely studied stellar phenomena in astronomy, i.e. between PN and SNIa stages of evolution. Classical, recurrent and dwarf novae all occur within cataclysmic variable systems containing a WD and a companion. Classical novae are thermonuclear runaway (i.e. TNR, see Section 1.5) events within tight stellar binary systems, on the surface of a WD with a main sequence stellar companion, from which it accretes, simultaneously pre-PN and post-PN, see Section 1.1. Classical, recurrent novae and PNe all share morphological characteristics and are possible SNIa progenitor systems.

**Recurrent Novae**

Recurrent novae (RNe) share the same eruption mechanism as classical novae but are generally weaker (4-9 magnitudes in the V band) and repeat every 1-100 years (Warner, 1995). Many may appear to have lower amplitudes as they commonly contain a red giant companion that would raise the observed quiescent brightness of the system. It is believed that all classical novae are recurrent, but on longer timescales (∼ 10^3 to a few × 10^5 years). Classical and RN eruptions result from fusion and detonation of accreted hydrogen and/or helium on the surface of a WD (Warner, 1995; Woudt et al., 2009).

Unlike classical novae, RNe have typical inter-eruption timescales on the order of decades. There are about ten identified RN systems in the Milky Way, although several others are identified in extragalactic systems such as M31 and the Large Magellanic Cloud (Bode, 2011; Patterson et al., 2013; Shafter et al., 2014; Darnley et al., 2016). They are the most likely progenitor systems of SNIa from the nova group since the higher mass the WD the more frequent
its nova eruptions are (Hillman et al., 2016; Kato and Hachisu, 2012; Yaron et al., 2005; Townsley and Bildsten, 2005).

**Dwarf Novae**

Dwarf novae, exhibited by GK Persei and other classical nova systems as well, result from an instability in the accretion disk surrounding the WD star. This instability is caused by a disturbance in the magnetic field of the WD, a change in viscosity of the accretion disk, or clumpy accretion leading to a brightening of 2 - 6 magnitudes (Osaki, 1996). These events accelerate winds to the order of $1 - 6 \times 10^3$ km s$^{-1}$ (Cordova and Mason, 1982; Mauche and Raymond, 1987; Kafka and Honeycutt, 2004), generally faster than classical nova winds. The relative speed of the outflows between dwarf and classical novae is important as dwarf novae have been observed in several classical nova systems. If a faster wind chases an expanding classical nova shell then its effect must be taken into consideration, this phenomenon is discussed in Section 5.3.1 of this thesis. Dwarf novae are also important in terms of accretion disk physics as the majority of the emission is from the disk during their rise and fall (Osaki, 1996).

Dwarf novae are observed to brighten repeatedly with recurrence timescales from days to decades (Warner, 1995). A main difference between dwarf novae and classical novae is that the change in luminosity during the event is lower for dwarf novae due to their detonation mechanism. For dwarf novae the instability in the accretion disk (Payne-Gaposchkin and Helena, 1964) leads to the expulsion of large amounts of gravitational potential energy. Dwarf novae can be responsible for shaping knots in classical nova shells, as was
shown in Harvey et al. (2016).

1.4 Classical Nova System Overview

A classical nova is a subtype of cataclysmic variable (see Section 1.2.1) and is due to TNR on the surface of a WD. The TNR (Section 1.3) is a result of accumulated matter accreted from a binary companion, generally a main-sequence or an evolved red giant star. Once a critical pressure is reached at the base of the accreted envelope, TNR occurs on the surface of the degenerate WD, leading to a rise and fall in brightness of around 6 - 20 magnitudes (V band) over a range of a few days to months (Warner, 1995). The WD exists in a close binary system with the companion being a Sun-like main sequence star, or a later G or K type star (Warner, 1995). The shell is ejected, at velocities ranging from $\sim 5 \times 10^2$ to a few $\times 10^3$ km s$^{-1}$ (Bode and Evans, 2008). Before ejection, mixing occurs between the accreted envelope and the WD core through convection, leading to a heavy-element enrichment of the roughly solar composition envelope (Casanova et al., 2011a). The envelope once expelled forms what is known as the expanding shell surrounding the inner binary system.

All classical novae are believed to reoccur, however only those observed to reoccur are called RNe and, due in part to selection effects, do so on human timescales. There are a number of RN candidates within the classical nova sample, however they remain to be confirmed (Pagnotta and Schaefer, 2014). The more frequent a nova’s recurrence, the closer it gets to the Chandrasekhar limit (Yaron et al., 2005). All classical novae are thought to eject shells of gas,
although there are few (∼ 40) known nova shells, see Fig. 1.3.

Figure 1.3: Images of classical nova shells as compiled in Bode and Evans (2008), those with light green boxes were studied in this thesis. The shell of material is expelled following TNR of the surface of the WD.

Multiple nova shells were observed surrounding the RN system of T Pyxidis (Chesneau et al., 2011) and multiple shells surrounding RS Ophiuchi were replicated using hydrodynamic modelling, although not yet observed (Mohamed et al., 2013; Booth et al., 2016). In simulations the multiple interacting ejections are shown to form cavities, spirals, arcs shells and equatorial outflows. When the models are inclination corrected, the results bare remarkable similarities to observed nova shell structure.

Detailed observations of nova shells allow for estimates of the total mass and abundances of the heavy elements ejected during nova events, as is explored in Helton et al. (2011). Knowledge of abundances in the expanding nova
shell provides constraints on the mechanism and efficiency of dredge-up from
the underlying WD. This is achieved through photoionisation modelling of the
ejected shells during their nebular stage of evolution. A full understanding
of this process would greatly improve inputs into models of the nuclear re-
actions that follow the TNR. As noted by Ederoclite (2006) and previously
by others (e.g. Ringwald et al. (1994) and references therein) observations of
old novae are often neglected after their eruption light curves have reached
quiescence. Nova shells give insight into dust production, clumping and inter-
stellar medium dispersal mechanisms, and thus they should be understood at
all evolutionary phases.

The shorter time-scale on which novae take place poses an observational
advantage over the evolutionary time-scale for planetary nebulae (PNe) (Ches-
neau and Banerjee, 2012). Currently, PNe are being observed more; increased
observations should allow for an improved definition of the correlation between
the orbital parameters of the central binary system and the morphological pa-
rameters of their host PNe. PNe and classical novae are closely related; novae
have been observed within old PNe, examples of which are GK Per (Shara
et al., 2012b) and V458 Vul (Wesson et al., 2008a).

The properties typically observed of novae include the peak luminosity,
the rate of decline, and the character of the post-eruption spectrum (Bode
and Evans, 2008). Novae emit across a large range of wavelengths, from ra-
dio (Ribeiro et al., 2014) up to gamma (Fermi-LAT-Collaboration, 2014) and
some are said to resemble miniature supernovae (Takei et al., 2015). In addi-
tion, they are probable candidates of SNIa progenitor systems (Hillman et al.,
2016; Kato and Hachisu, 2012). Classical novae are the third most energetic
eruptions in the Universe after gamma-ray bursts and supernovae (José, 2012).

Light from a quiescent classical nova system is due to three components. Firstly, the WD contributes mainly in the ultraviolet; the secondary star contributes in the red and infrared, whilst the optical range is dominated by the accretion disk (Ederoclite, 2006). Material transferred through Roche lobe overflow falls onto the accretion disk surrounding the WD star. The shape of the accretion disk is determined by the strength of the WD’s magnetic field, i.e. if the WD is strongly magnetic it will accrete via its polars whereas a WD with a weak magnetic field will accrete via a thin disk. An example is the WD belonging to the GK Persei system, explored in Chapter 5 of this thesis, that has a magnetic field strength of 1-10 megagauss Watson et al., 1985. Once a critical pressure is reached at the core-envelope interface, deflagration spreads through the accreted envelope, followed by detonation and TNR. The WD mass varies from a lower limit of about $M_{\text{WD}} > 0.4 \, M_\odot$, derived from the core mass-luminosity relation found in Paczynski (1971), up to the Chandrasekhar limit (Bode and Evans, 2008).

Estimates of the effective temperature of the photosphere provide the time when ionisation conditions for different molecules are reached (Kelly et al., 2014). It is possible to define the temperature through a spectral energy distribution, e.g. Evans et al. (2014b). Constraining mass, temperature and abundances for any observed nova allows for estimations of the ionisation structure. These physical constraints are estimated using a photoionisation codes such as CLOUDY, described in Section 3.1.2.

It has been shown in recent years that there is a preference for the larger WD masses in novae to be associated with a younger Milky Way disk popula-
tion. The Milky Way disk nova population eject smaller amounts of previously accreted matter at higher velocities in comparison to novae from older stellar populations (Shafter, 2013; Shafter et al., 2014).

Stages in a classical nova eruption can be summarised, following the outline presented in Evans (2001):

1. A ‘fireball’ phase, when ejecta are optically thick.
2. A free-free phase, during this phase the ejecta thin out.
3. A dust-formation phase, not applicable to all novae.
4. A nebular phase.
5. A ‘coronal’ phase, in which coronal lines, such as [Ca iv], [Al v], [Ne vi], are prominent, \(\sim 15\%\) of novae display this phase.

### 1.4.1 Classical Nova disambiguation

Several nomenclature schemes have been developed for classical novae, often leading to overlapping interpretations of nova type. For simplification, ‘novae’ mentioned herein strictly refer to classical novae. Names given to types of novae include CO, ONeMg, Fe II, Fe IIb, He/N, fast and slow. The latter two come from the photometric evolution of the nova’s light curve characterised by its ‘speed class.’ The speed class is determined by the time in days taken for a nova to decrease in brightness by 2 \((t_2)\) or 3 \((t_3)\) magnitudes.

The speed class of a nova is related to its ejection velocity and peak absolute magnitude. The maximum magnitude rate of decline, see della Valle and Livio
(1995) and Section 1.5.2 of this thesis, although controversial suggests that faster novae have higher ejection velocities and are intrinsically brighter at the peak of their V light output, which is known to be true observationally speaking.

Novae can be characterised by the underlying WD composition, i.e., CO or ONeMg (see Section 1.1). Dust formed in novae occurs after the free-free phase (Evans, 2001). ONeMg novae usually form less dust and tend to be more energetic and faster than their CO counterparts. Novae occurring on ONeMg WDs account for the majority of silicates found in nova dust shells, and these ONeMg novae persistently exhibit the coronal emission line phase (Shore, 2013). Alternatively, Darnley et al. (2014) more recently laid out a new classification scheme for novae based on the characteristics of the secondary star from colour-colour diagrams.

Yet another classification scheme is through spectral identification characterised by prominent He/N or Fe II emission. The spectral characteristics of novae that display prominent Fe II emission (the “Fe II” novae) are characterised by P-Cygni line profiles (i.e. the presence of blue-shifted absorption coupled with standard emission in the one spectral line profile), high wind-mass loss rates, slow photometric evolution, lower expansion velocities, and lower levels of ionisation. This is in contrast with novae with prominent lines of He and N (the “He/N” novae) that show higher-energy ejecta, but overall they eject less matter. Fe II novae give a wind dominated Fe II spectrum that evolves into a standard or neon nebular spectrum, whereas He/N type novae give a shell dominated He/N spectrum that evolves into a neon, coronal or a forbidden line (standard) spectrum (Williams et al., 1991; Shore, 2013).
The He/N and Fe II nova types are believed to be related to fundamental properties of the progenitor binary, such as the WD mass. However, these spectroscopic types are dependent on the underlying stellar population, e.g. della Valle and Livio (1998). Hybrid novae have been detected and begin with high-velocity Fe II features that then evolve quickly into He/N features, e.g. V745 Sco, V3890 Sgr and M31N2008-11a (Shafter et al., 2014). A subclassification of Fe II novae is split Fe II and Fe IIb, where the Fe II type exhibit narrow emission lines and Fe IIb novae exhibit broad emission lines (della Valle et al., 1992). There is one known He nova, V445 Pup, which is thought to be due to accretion from an He-rich star (Woudt et al., 2009).

1.5 The Classical Nova Event

Novae can occur on CO or ONe rich WDs and may undergo thousands of eruptions with inter-eruption periods $\sim 10^3$ to a few $10^5$ years. Most often novae are observed to occur on CO WDs, the remnant of a progenitor star with initial mass $< 8M_\odot$ following the burning of H and He, see Section 1.1. For more massive WD progenitors, non-degenerate C-ignition leads to the formation of a degenerate core that is mainly composed of O and Ne with traces of Mg and Na (José, 2012). It is difficult to derive the nova progenitor population, although galactic and extra-galactic attempts have been made (Williams et al., 2014; Darnley et al., 2014). Through these studies the most common progenitor for classical nova events are found to be CO WDs.

The WD accretes from a binary companion. The orbital binary period is typically a few hours, although the longest binary period of any known
system is 137.1 hrs (V1017 Sgr) (Bode and Evans, 2008). The companion is in general a low-mass main sequence object. For longer-period systems, e.g. GK Per (Shara et al., 2012b), companions need to be evolved as to have their Roche lobe filled, so that the WD can accrete an envelope.

The proper pressure at the core-envelope interface (equation 1.1) is the most important quantity in determining the strength of the nova eruption. Equation 1.1 states that the mass of the accreted envelope depends solely on the mass of the WD. It suggests that, for any given WD mass, the envelope mass required to power a nova eruption is independent of the mass accretion rate. However, detailed hydrodynamic simulations have revealed that the mass accretion rate exhibits some influence on the properties of the eruption (Campbell et al., 2010). From the degenerate equation of state the system is independent of temperature, meaning the material cannot expand and cool, such that there is no safety valve. Temperatures on the order of $10^8$ K are reached once the critical pressure is attained, leading to higher reaction rates.

The proper pressure is given by:

$$P_{\text{star}} = (\delta M_{\text{env}}) \frac{GM_{\text{WD}}}{4\pi R_{\text{WD}}^4}$$  \hspace{1cm} (1.1)

Here $\delta M_{\text{env}}$ is the critical envelope mass needed to attain conditions for onset of TNR. It is lower for higher-mass white dwarfs. $M_{\text{WD}}$ and $R_{\text{WD}}$ are the WD mass and radius respectively, while $G$ is the gravitational constant. To account for mass ejection a pressure corresponding to $P_{\text{star}} > 10^{20}$ dyn cm$^{-2}$ is reached for an envelope of solar composition (Yaron et al., 2005).

Depending on the mass of the WD, peak temperatures from $1 - 4 \times 10^8$
K are expected during TNR. Above $7 \times 10^7$ K degeneracy is unimportant, expansion begins and the TNR initiates, peak temperatures are achieved in a few hundred seconds following the initial eruption (Starrfield et al., 2016). For a higher accretion rate shorter eruption intervals are experienced as more energy is released from gravitational compression. As a result of the longer accretion phase, larger masses and hence larger proper pressures are achieved, giving more violent eruptions (José, 2012).

Nova events on cold-low-luminosity WDs can be delayed by heat conduction into the core (José, 2012; Kelly et al., 2014). On hot-luminous WDs the outermost core layers become convective and produce larger levels of mixing through the core-envelope interface. During accretion, the envelope is degenerate such that the thermal energy is less than the Fermi energy (Warner, 1995). However, if a WD is initially too luminous, the shell is not strongly degenerate when the TNR develops, resulting with a mild runaway without mass ejection (Yaron et al., 2005). Taking this into consideration degeneracy is a key ingredient for successful ejection of a nova shell, i.e. colder WDs are more degenerate and therefore can eject more mass from their surfaces.

1.5.1 Light Curves

The best documented feature of a nova are the optical light curves during eruption, which can vary substantially from system to system. Nova magnitudes and fragmentary light curves are readily accessible. However, not many are followed into quiescence in the professional literature (Strope et al., 2010). Fortunately, the majority of novae are observed and followed by amateur astronomers into quiescence allowing for the characterisation of novae
accordingly. Types of nova light curve include, as described in Strope et al. (2010): smooth light curves (S-type 38% of novae observed); plateau (P-type 21%); those featuring strong dust dips (D-type 18%); jitters (J-type 16%); quasi-sinusoidal oscillations (O-type 4%); flat-topped (F-type 2%); or cusp shaped (C-type 1%). The varying types are illustrated in Fig. 1.4 below.

Over the last three decades, pioneering modelling of optical light curves has been undertaken, such as the theoretical work by Kato (2012) and the UBV colour evolution of novae description by Hachisu and Kato (2014). ‘cusp’ feature is explored in

In a nova light curve, the dust formation episode is identified as a deep dip in the visual light curve, corresponding to a rise in the thermal infrared, known as the ‘dust-dip’. As the newly-formed optically-thick dust shell expands away from the central system the visual brightness increases again. Although recovery can be smooth, it is possible to have cusp-shaped features in this part of the light curve (see for example V4362 Cyg in Fig. 1.4), often associated with radiative shocks in the ejecta (Lynch et al., 2008; Kato et al., 2009), although opinions vary, see e.g. Hachisu and Kato (2009). These shocks are expected in part to contribute to the ionisation of the nova ejecta as well as shaping, clumping, dust formation and destruction processes in the expanding shell. Shocks are detectable in radio, X-ray and gamma wavelength regimes (Metzger et al., 2014). The role that shocks have in the early evolving nova outflow has been analysed in detail by Derdzinski et al. (2017), who found that consequences of a shock treatment over a purely homologous photoionised expansion lead to higher densities and lower temperatures in certain parts of the ejecta. Consequently, the densities in a shocked nova envelope may be \( > 10^{14} \)
Figure 1.4: Prototypes of light curve classes. The seven binned light curves show the distinct features of each class. Note the distinctive cusp feature of V2362 Cyg and dust-dip of DQ Her, these features are discussed throughout this thesis. Adapted from Strope et al. (2010).

cm$^{-3}$ rather than what was, until recently, believed to be closer to $10^9$ cm$^{-3}$, e.g. Warner (1995).

The theoretical work by Hillman et al. (2014) suggests that pre-maximum
halts are due to a change in the convective energy transfer regime. DQ Her is the slow nova archetype, whose progression after maximum is characterised by jitters or oscillations superimposed on an otherwise flat-topped light curve followed by a deep-dip in optical photometry due to dust formation (bottom light curve in Fig. 1.4). The characteristic dust-dip in the optical recovers with ‘cusps’ on the rising slope. DQ Her-like novae show almost all the features of a nova light curve.

There has been consistent effort put towards understanding photometric evolution of novae in the infrared (Banerjee and Ashok, 2013; Evans and Gehrz, 2012), X-ray (Landi et al., 2008; Hachisu and Kato, 2009; Schwarz et al., 2011), and more recently in gamma-rays, e.g. Cheung et al. (2016) (see Hillman et al. (2014) for a multi-wavelength review, with special attention paid to the UV). There are collections of light curves with specific facilities, e.g., SMEI on-board the Coriolis satellite (Hounsell et al., 2010) and GALEX (Cao et al., 2012). A full understanding of how light curves develop and their relationship to each other at different wavelength regimes is invaluable. For instance, a rise in the infrared regime follows that of the decline in the visible regime, corresponding to the formation of dust, first suggested by McLaughlin (1960). Radio observations allow for the most accurate dust-mass estimations to be made (Bode and Evans, 2008), whereas higher-energy wavelengths give information of the ionising sources and of shock interactions between the shell and pre-existing circumstellar matter.
1.5.2 Nova Speed Class

The main characteristic adopted from any nova light curves is its speed class. The speed class is the rate of decline of a nova from maximum magnitude, by two or three magnitudes ($t_2$ or $t_3$). As the speed class of a nova is the most common characteristic catalogued of their eruption episodes many relations are drawn between it and other observables, such as a correlation between speed class and the onset time of dust condensation has been quantified for graphite and amorphous carbon by Williams et al. (2013).

The Maximum Magnitude Rate of Decline (MMRD) is a claim that the rate of decline is related to the maximum magnitude of a nova, which would mean that the MMRD could be used to determine a distance modulus. The MMRD has its roots in della Valle and Livio (1995) where Large Magellanic Cloud and M31 novae were sampled and an arctangent relation between the peak luminosity and the rate of decline was proposed. Darnley et al. (2006) showed the same relationship as della Valle and Livio (1995) using a different sample of M31 novae. Alternatively, Downes and Duerbeck (2000) used sample galactic novae to propose a linear relationship between peak luminosity and the rate of decline. However, The MMRD is an oversimplification because it is characterised solely by the WD mass and consequently, caution should be exercised when using the relation to determine distances to novae, see Kasliwal et al. (2008); Kasliwal (2011) where the MMRD relation is strongly challenged.

The MMRD is described as follows:

$$M_\lambda = b_n \log(t_n) + a_n$$  \hspace{1cm} (1.2)
Here $M_\lambda$ stands for the absolute magnitude of a certain wavelength regime; $t_n$ is the time taken to decline in days by $n$ magnitudes; $a_n$ has a range of -11.32 to -10.70 and $b_n$ from 2.41 to 2.55 for $n = 2$ (Cohen, 1985; Downes and Duerbeck, 2000).

Many nova light curves are missed at their observed peak luminosities causing a substantial error in analysis, this coupled with an over-reliance on the MMRD as a method of determining distances to novae means that the quoted distances to novae in the literature are dubious Kasliwal et al. (2008), unless they are derived via the expansion parallax method, see Section 1.6.

In order to determine what a nova fully depends on we must examine first the observables, these include:

- Luminosity of quiescent system $\sim L_\odot$
- Eruption luminosity $\sim$ few $\times 10^4$ $L_\odot$
- Velocity of ejecta $V_{ej} \sim 10^2$ to a few $10^3$ km s$^{-1}$
- Spectral lines, e.g. CO + ONeMg (early emission)

The eruption luminosity is often at or above $L_{Edd}$ for a 1 $M_\odot$ WD, where $L_{Edd}$ is the Eddington luminosity and is the maximum luminosity obtainable by a star in hydrostatic equilibrium. The observables listed above have led astronomers to characterise nova physics into four main parameters; the following is adapted from Bode (2011):

- WD mass $\sim 0.4 - 1.44$ $M_\odot$ (Yaron et al., 2005; Nauenberg, 1972)
- Ejected mass $= M_{ej} \sim 10^{-5}$ to a few $10^{-4}$ $M_\odot$
• Temperature of ejecta $\sim T_{\text{star}} = 8000 - 100,000$ K;
  $T_{\text{dust-condensation}} = 1100 - 2000$ K

• Accretion rate $\sim 10^{-9}$ to a few $10^{-6}$ $M_\odot$ year$^{-1}$

The four parameters listed above are of importance, however the inclination towards the nova source is rarely considered.

### 1.6 Nova Shells

This thesis focuses on the shells of gas (and dust formed later) expelled during a classical nova eruption. Through analysis of nova shells fundamental parameters of the central binary can be derived. Perhaps most importantly, the derived parameters can be used to determine the distance to the system. The estimation of the angular size of a nova shell in expansion can be given by:

$$\Theta_r(t) = 0''.207 \frac{v_{\text{exp}}}{10^3 \text{km/s}} \frac{d}{\text{Kpc}}^{-1} (t - t_o) \quad (1.3)$$

Here $\Theta_r$ is the angular radius, $(t - t_o)$ is the time elapsed in years, $d$ is distance in kiloparsecs and $v_{\text{exp}}$ is the expansion velocity in km s$^{-1}$ (Warner, 1995). Equation 1.3 allows for the determination of when a nova shell will be resolvable. The most reliable method used to derive distances to novae is the expansion parallax method, taken over at least two epochs, as in Harrison et al. (2013) and Chapter 6 of this thesis.

Spectroscopic data, discussed in Section 1.6.1, gives information about the velocity and ionisation structure of nova shell remnants. Imaging and spectroscopic observations being used to inform nova shell structure is long established.
and has yielded many fruits of labour from implementation, e.g. Hutchings et al. (1972); Lynch et al. (2006); Kamath et al. (2005); Gill and O’Brien (2000); Munari et al. (2010); Ribeiro et al. (2013a, 2009, 2013b).

There remains debate over the shell shaping mechanism and the arguments fall into two categories. First, shaping due to an intrinsically bipolar ejection from the surface of a fast-rotating oblate WD star (Balick, 1994; Scott, 2000). The second is through common envelope evolution, where the shell of expelled material is shaped under the influence of the interacting binary. In the second scenario the ejected material is shaped by drag forces, transferring angular momentum into the shell and therefore shaping it (Livio et al., 1990; Nordhaus and Blackman, 2006; Lloyd et al., 1997; Porter et al., 1998). For examples of the prolate and knotty form of nova shells the reader is referred to T Aur, HR Del, DQ Her and GK Per in Fig. 1.3.

The concepts of position angle (P.A.) and inclination appear many times throughout this thesis. The P.A. is measured in degrees counterclockwise with respect to the north celestial pole. Inclination is the angle made between the plane of observation and the orbital plane of the binary, which is expected to be the same as the shell equatorial structure. When nova shells are discussed a pole on system is said to be at an inclination of 0°, whereas, a side-on system has an inclination of 90°.

1.6.1 Spectroscopy of Novae

Novae have been observed spectroscopically since T Aur (1891), see Payne-Gaposchkin and Helena (1964), and have been studied systematically since Williams et al. (1991).
Developing spectral stages of novae are often commonly described (in order of appearance) as the pre-maximum spectrum, principal, diffuse enhanced, orion, auroral and nebular (McLaughlin, 1942). Changes in the appearance of the spectra are due to temperature, expansion, clumping, optical depth effects and contribution from the secondary star.

A commonly adopted spectroscopy based classification scheme for stages in a nova that resemble characteristic spectra observed in other stellar objects is that known as the Tololo scheme, first presented in Williams et al. (1991); Williams et al. (1994). Nova spectra are characterised by their progression through several observable spectral stages. The spectral fingerprint of a nova may be derived either if the nova shows some critical features, or else if the nova does not show certain stages. The spectral stages in the Tololo scheme are defined by the strength of the strongest non-Balmer line, as long as the nova is not in its coronal stage (given the designation C, defined as when [Fe x] 6373 Å is stronger than [Fe vii] 6087 Å), be they permitted lines, auroral or nebular (P, A or N respectively). Depending on which species is responsible for the strongest non-Balmer transition in the optical spectrum its formulation (h, he, he\(^{+}\) o, ne, s...) is added as a subscript. At any time, if the O i 8446 Å line is present then an ‘o’ is added in superscript.

Traditional nebular diagnostic methods are commonly applied to low density media such as PNe and H II regions. When examining the photoionisation conditions of nova shells during pre-nebular stages of their evolution, such as those described in the previous paragraph, the traditional nebular diagnostic methods fall short. Above atomic densities of \(\sim 10^8\) cm\(^{-3}\) ionisation conditions have a large influence from collisional rates, which are more difficult to discern.
than recombination rates. Only recently have the open source astrophysics
codes been reliably improved to determine ionisation conditions in more dense
media. For this reason new diagnostic diagrams (that allow astronomers to
compare simulated to observed spectral line intensity ratios) must now be gen-
erated to simulate photoionisation conditions in a pre-nebular classical nova
shell, see Section 3.1.2.

The Bowen fluorescence mechanism, discussed in Chapter 4 of this thesis,
is thought to account for a commonly seen ‘flaring’ episode usually observed
after the primary dust formation episode in classical novae. The Bowen fluo-
rescence mechanism invokes the coincidence of He II and O III at 30.4 nm to
excite C III and N III around the 4640 - 4650 Å spectral range. The concept
of nitrogen flaring dates back to 1920 when Fowler (1920) identified an ‘ab-
normal’ strong spectral feature peaking around 4640 - 4650 Å. Following this,
Mr. Baxandall and W. H. Wright exchanged letters regarding Prof. Fowler’s
paper that resulted in an article by Wright entitled “On the Occurrence of
the Enhanced lines of Nitrogen in the Spectra of novae” (Wright, 1921). The
claim has not been challenged since then.

1.6.2 Optical Polarimetry of Novae

Optical linear and circular polarisation measurements of novae to date have
been intrinsically low and therefore difficult to quantify and understand. Po-
larimetry observations of nova systems started with the observation of V446
Her (1960) in Grigorian and Vardanian (1961), while the technique was still
in its early stages of development. T Pyx was the first nova to show variation
in its intrinsic linear polarisation with changes of 1.8% seen over several weeks
(Eggen et al., 1967). Kemp et al. (1974) found variation in the linear polarisation of the DQ Her system and Swedlund et al. (1974) found variations in the circular polarisation associated with the high WD magnetic field. Both the circular and linear polarisations were found to correspond to twice the WD period of 71 s. Later work presented by Penning et al. (1986), in which no reference was made to the work by Swedlund et al. (1974), found no variation in the circular polarisation of DQ Her corresponding to the WDs orbital-spin period.

HR Del, FH Ser and LV Vul were all observed by Zellner and Morrison (1971) where variation greater than 1.2% was seen for HR Del, irregular variability was seen for FH Ser and no variation was identified for LV Vul. The observations presented in Zellner and Morrison (1971) for HR Del fell into two epochs: < 120 days and > 120 days. In the first epoch, lower polarisation was found whereas for the latter epoch higher polarisation was found in the green and red bands. There were many polarimetric studies done of V1500 Cyg, which found that the observed polarisation was mainly interstellar in origin with a possible small intrinsic component (Hull, 1977). NQ Vul was documented by Martin and Maza (1977) who found that the polarisation was constant and mainly interstellar in origin. V1668 Cyg was observed by Hull et al. (1979) and Pirola and Korhonen (1979), each found a changing P.A. with a fractional polarimetric measurement.

Evans et al. (2002) detected polarisation in V705 Cas, V4362 Sgr, V2313 Oph and BY Cir. The most likely scenario for each of the systems respectively, is polarisation due to clumpiness, scattering from small dust grains, electron scattering and polarisation in resonance lines. V705 Cas (1993) was considered
by Elias et al. (2008) with U, B, V and R band polarimetry of Evans et al. (2002) who derive intrinsic polarisation arising from the nova shell 3 days post-eruption, prior to dust formation. Elias et al. (2008) found differences between their measurements and those of El’Kin (1995) from day 26 after eruption detection. Nova And (1986) was studied by Kikuchi et al. (1988) who found an increase in polarisation between days 2 and 22 after the nova’s eruption. Nova And was classified as of the fast type and the polarisation increase was attributed to dust formation. Kawabata et al. (2000) found possible evidence of circumstellar material around V4444 Sgr (1999) from spectropolarimetry. The most recent review-type article available on this subject is by Kucinskas (1990).

Optical polarimetry studies are important but have been heavily neglected in the last two decades, polarimetry gives information on the semi-major and minor axes, through P.A. determinations, as well as the efficiency of dust formation and destruction processes via the change in absolute polarisation across different bands. Polarised light from scattering processes propagate perpendicular to the incident light, in the case of dust grains that are aligned with the magnetic field of the WD the P.A. of the polarised light would be perpendicular field.

1.6.3 Photoionised Gas and Dust in Nova Shells

Ejected nova shells are known to be composed of photoionised gas and dust. The gas shell is mostly composed of hydrogen with CNO enrichments, as well as heavier elements present due to nuclear processing. Dust is formed in the expanding nova shell from around 40 - 100 days post eruption. Observational
spectroscopy and colour evolution of expanding nova shells can be matched to numerical simulations (such as using CLOUDY, see Section 3.1.2) to understand their chemical evolution.

The distinguishing characteristics can be replicated if a reasonable estimate of the effective temperature and luminosity of the ionising source, the density, age and radii of the ionised shell can be met. After establishment of these conditions other dependents must be considered, including the covering factor, filling factor, and abundances. The effect of dependents can be tested with grids while holding other factors constant. Deriving abundances in nova shells is time consuming, many models must be run to test each individual element. In general, despite quoted published uncertainties, the reliability of abundance determinations in nova shells should be taken with a certain degree of distrust due to uncertainty arising from the numerous assumptions and dependents. For example, in a spectral synthesis code such as CLOUDY, see Section 3.1.2, which works on the concept of ionisation balance equations, an ionising stellar atmosphere must be set, however a WD shortly after nova eruption does not have a standard stellar atmosphere.

Abundances in the expanding shell of gas must be derived individually for each element, however to do this one must assume a single density or density distribution in the gas cloud as well as thickness, age, expansion velocity, covering and filling factors. $\chi^2$ minimisation routines are used to justify good fits in the literature, however this is tampered by the fact that observationally it is very difficult to get reliable line ratios due to contributions from blending of lines and contributions from the stellar continuum, so one may get a perfect fit to badly derived line ratios. As line ratio diagnostics are very sensitive
at certain temperature and densities, on top of the fact that nova shells are inhomogenous, quoted errors in the literature in abundance determinations in nova shells are more than likely lower estimates.

Abundance determinations are often derived using line intensity ratios relative to H\(\beta\). A problem that can arise using this method is that the H\(\beta\) line intensity relies on the filling factor. As a nova shell evolves, the filling factor changes. Thus, astronomers following the progression of a nova shell with respect to H\(\beta\) line intensity ratios are observing the evolution of the filling factor. The covering factor and filling factor along the line of sight to any individual nova system are dependent on the viewing angle. If the line intensity ratios vary according to viewing angle then abundance determinations should take this into account.

The ejected envelopes are expected to show signatures of nuclear processing (José, 2012). Observations confirm \(^{17}\)O, \(^{15}\)N, and \(^{13}\)C are significantly overproduced with respect to solar abundances in the ejected shells. A lower contribution of a number of species with A < 40 such as \(^{7}\)Li, \(^{19}\)F, or \(^{26}\)Al are observed.

Several methods have been employed to design models that replicate mixing conditions of the pre-eruption systems which should account for observed ejecta properties. These include pollution by the companion star (Kato and Hachisu, 2011); dredge up from the WD’s underlying layers (Casanova et al., 2011a,b; Kelly et al., 2014); and from pre-existing circumbinary material (Bode et al., 1987; Zaninetti, 2012). According to José (2012), soon all nuclear reactions of interest for novae should be determined experimentally.

Following the deep-dip in the eruption light curve of DQ Her (1934) it was
suggested that some novae produce dust (McLaughlin, 1960). Confirmation had to await the advent of infrared observations and now dust formation in novae is well observed but poorly understood in nova shell environments (Woitke and Niccolini, 2005). Novae produce dust at varying degrees of efficiency, with some novae creating dust shells that completely cover the nova sky, i.e. $\tau \gg 1$. In the other extreme case of dust-forming novae the IR excess is barely discernible, if at all (Bornak et al., 2010). Shells of material moving at a greater velocity will fade quicker and produce less dust (Bornak et al., 2010), as the material will escape the influence of the ionising radiation arising from the source earlier.

Good examples of early attempts to understand the underlying parameters responsible for dust-forming novae are Gallagher (1978) & Bode and Evans (1980). It is clear that several processes are relevant, yet the major difficulty in modelling the events is that the hard radiation and rapid thinning out of the ejecta, amongst other factors, conspire against the creation of dust in a nova environment. Yet, despite this, they remain prolific dust producers.

The infrared regime is especially useful for determining abundances of a variety of metals and dust characteristics (Helton, 2010; Evans and Gehrz, 2012; Gehrz et al., 1992). As in the optical regime, temperatures and densities can be estimated from modelling of emission lines. (Osterbrock and Ferland, 2006; Vanlandingham et al., 2005).

The formation of several dust-types in one nova eruption is possible, and most novae produce carbon dust. Observations and chemical models suggest that CO novae can produce silicates, silicon carbide, and hydrocarbons. The hydrocarbons come either in polycyclic aromatic hydrocarbons or hydro-
generated amorphous carbon form (Helton et al., 2011). Two early examples of these include QV Vul (1987) and V705 Cas (1993), who produced all four known types of dust grains (Gehrz et al., 1992; Helton et al., 2011).

Observationally, CO formation does not seem to go to saturation in novae, with $\sim 10^{-4}$ of the C ending up in the form of CO. The failure of the CO to completely lock up either C or O in the ejecta gives rise to the formation of both carbon-rich and oxygen-rich materials condensing simultaneously in nova winds (Bornak et al., 2010).

Nucleation of dust grains is thought to occur at the extremities of the outflow of the expanding nebula in high-density clumps (Williams et al., 2013), as they are shielded from the high-energy dissociating UV/X-ray radiation of the WD. The inclusion of hydrocarbon chemistry effects, see Joiner (1999), helped solve some of the field’s ongoing problems until then. Prior to Joiner (1999), modellers found an overproduction of seed nuclei leading to either a large amount of very small grains or else the lack of dust-grain growth.

Important considerations when modelling dust formation in nova outflows are radiative transfer, which allows for the study of clumping effects (Woitke and Niccolini, 2005; José, 2012), the temperature of the grains, as well as the radiation field at different positions in the outflow (Bornak et al., 2010). Mean intensities are calculated from radiative transfer models integrated along different optical depths (Yaron et al., 2005). Optically thick and thin nova wind models should be considered separately (Kato and Hachisu, 1994).

If the well resolved old nova shells surrounding GK Per (Harvey et al., 2016), and AT Cnc (Shara et al., 2012a) are examined their shells are obviously composed of clumps. Clumpy structures are the most probable birth
places of carbon and oxygen rich grains, as the outer clump shields the interior from high-ionising radiation from the hot WD. The clumping phenomenon is most likely due to the Richtmyer-Meshkov instability (Toraskar et al., 2013) or early interacting winds (Metzger et al., 2014). The Richtmyer-Meshkov instability arises in the case of nova ejecta as a shock wave interaction between the high-density ejecta and the low-density circumbinary material. The instability develops linearly through transmitted and reflected waves (Brouillette, 2002).

A review of dust formation in novae is given in chapters by Evans & Rawlings, Gehrz, and José & Shore in Bode and Evans (2008).

The way in which the structure is formed in the shells observed around novae during eruption remains virtually unexplored (Chesneau et al., 2012). Whether the ejection is intrinsically non-spherical remains unanswered; efforts towards defining the kinematical ages of different shell features should clarify the ejection sequence scenario, if relevant. The effect of WD rotation on the shell formation cannot be neglected, since rotation is accelerated by incoming angular momentum carried by accreting matter. The spin and orbital period of the central binary have a role in the shaping of nova remnants through ejection of angular momentum (Lloyd et al., 1997), similar to planetary nebulae (Balick, 1994).

Poorly understood astrophysical processes related to classical novae are highlighted in the review article by Bode (2011), and are reproduced here:

- Mass transfer - The accretion rate and shape of the accretion structure are important factors but difficult to determine

- Optically thick winds - Multi-epoch simultaneous observations at all
wavelengths are needed

- Common envelope evolution - The influence of the binary orbit on the ejected shell during common envelope evolution plays a crucial role in understanding the shaping mechanism behind nova shells

- Molecule and grain formation - The high ionisation environment during nova events are unlikely birth places for fragile grains

- Coronal line emission - Spectral features during the coronal line emission stage hint at higher than accepted densities

Furthermore, there remains the open question of whether or not classical novae may be used as standard candles (Soraisam and Gilfanov, 2015; Kato and Hachisu, 2012). Since nova shells are generally non-spherical, they must be inclination-corrected for more reliable distance estimates, e.g. PG 300 Bode and Evans (2008). There has been doubt cast on the suitability of classical novae as SNIa progenitors (Schaefer and Pagnotta, 2012; Weidong et al., 2011), although contrarily there has been strong theoretical evidence that recurrent counterparts occurring on CO WDs could be Hillman et al. (2016).

With efforts to image old nova shells (Gill and O’Brien, 2000; Slavin et al., 1995), examination of their three-dimensional structure by observation (Limets et al., 2012a; Ribeiro et al., 2009; Munari et al., 2010; Ribeiro et al., 2013a), and theoretical efforts (Campbell et al., 2010; Hillman et al., 2016) a comprehensive view of classical novae in their evolved quiescent form should be attainable soon. This will require continued spectroscopic analysis of nova systems during quiescence (Maxwell et al., 2014).
1.7 Thesis Outline

In this thesis, a methodology is developed for studying classical nova shell evolution using optical imaging, spectroscopy and polarimetry to inform simulations conducted using a newly developed pipeline involving the *pycloudy/shape* packages. The observatories employed for retrieving archival data and where new data was acquired are summarised in Chapter 2. Whereas, Chapter 3 illustrates the software used and developed to gain 3D morpho-kinematic and photoionisation knowledge of nova shells at various stage of evolution.

Chapters 4, 5 and 6 present the results. In Chapter 4, a classical nova in eruption is observed and analysed from discovery to 822 days post-discovery; an attempt to understand the early-evolving shell around the nova system is presented. In Chapter 5, the underlying structure of a well-studied classical nova shell (GK Persei) is untangled and the kinematics of an associated jet-like feature uncovered. Chapter 6, presents the reader with the discovery of two classical nova shells, as well as revealing newly discovered features around four other well studied nova shells, the nova shells are subsequently simulated using the *pycloudy/shape* pipeline discussed in Chapter 3. Ending Chapter 6 are a proposed sequence of shells surrounding the suspected RN V2275 Cyg.

Finally, Chapter 7 includes a discussion, conclusion and suggestions for future work that builds upon the results found in Chapters 4, 5 and 6.
Chapter 2

Observations

2.1 Observations

To gain a fuller understanding of the character of evolving nova shells a campaign to study their morphology, structure and ionisation was undertaken. As there are few (∼40) known nova shells, a search through infrared archives followed by an optical search has led to the discovery of additional shells. Long-slit high-resolution spectroscopy was employed to decipher the spatial and velocity constraints of these objects.

Both new and archival observations were collected for this thesis to monitor the ageing of nova shells. New observations acquired during and shortly after eruption of a nova included polarimetry, spectroscopy and photometry. Observations of novae during nebular stage include imaging and spectroscopy.

In comparing observations from different telescopes and different filters difficulties arise. Highly blue- or red-shifted emission from a nova shell may
not be included in the resultant image if the filter is too narrow. The most extremely shifted material is towards the centre of the shell on the plane of the sky. To compensate for such errors the most consistent data were used, allowing for the longest exposure times when searching archives.

The following chapter describes the facilities and instruments used over the course of this work and are tabulated in 2.1 and discussed in Section 2.2.

2.2 Facilities and Instrumentation

2.2.1 Aristarchos

Imaging

Using the Aristarchos telescope in Greece (see Table 2.1 for a list of all facilities used) deep imaging was collected of the vicinity surrounding several classical nova producing systems. The observations consisted of either one or two narrow-band filters focused on H\(\alpha\) + [N \(\text{II}\)] and nebular [O \(\text{III}\)] with exposures of 30 or 40 minutes in each filter. Broad-band imaging in B and R was collected for most objects in order to subtract stellar contributions. Seeing varied from 2-5 arcseconds. A CCD detector with dimensions of 1024 × 1024 pixels, with each 24 \(\mu\)m square being \(\equiv 0.28\) arcsec per pixel, was used during and before observations taken in 2015 (known as LNCCD). Later 2016 and 2017 observations from the Aristarchos telescope were taken using a 2048 × 2048 pixel array CCD (known as LN2CCD), with a resolution of 0.16” per pixel. Imaging was reduced using standard routines in IRAF\(^1\).

\(^1\)IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., NSF.

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Table 2.1: Listed here are the facilities from which observations were acquired and/or used throughout this thesis.

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Location</th>
<th>Primary Mirror</th>
<th>Elevation</th>
<th>Configuration</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aristarchos</td>
<td>22.1961E 37.9844N</td>
<td>2.3m</td>
<td>2340m</td>
<td>Ritchey-Chrétien</td>
<td>LN &amp; LN2 CCD</td>
</tr>
<tr>
<td>San Pedro Martir</td>
<td>244.5364E 31.0442N</td>
<td>2.12m</td>
<td>2830m</td>
<td>Ritchey-Chrétien</td>
<td>MES</td>
</tr>
<tr>
<td>Liverpool Telescope</td>
<td>342.1184E 28.7606N</td>
<td>2.0m</td>
<td>2326m</td>
<td>Ritchey-Chrétien</td>
<td>SPRAT</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FRODOSpec</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RINGO3</td>
</tr>
<tr>
<td>William Herschel Telescope</td>
<td>342.1184E 28.7606N</td>
<td>4.2m</td>
<td>2326m</td>
<td>Ritchey-Chrétien</td>
<td>Dipol-2</td>
</tr>
<tr>
<td>KVA Stellar Telescope</td>
<td>342.1184E 28.7606N</td>
<td>0.6m</td>
<td>2326m</td>
<td>Cassegrain</td>
<td>Dipol-2</td>
</tr>
<tr>
<td>Archival</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WISE</td>
<td>Orbit</td>
<td>0.4m</td>
<td>525km</td>
<td>Cassegrain</td>
<td>Survey Camera</td>
</tr>
<tr>
<td>Isaac Newton Telescope</td>
<td>342.1184E 28.7606N</td>
<td>2.54m</td>
<td>2326m</td>
<td>Wide Field Camera</td>
<td></td>
</tr>
<tr>
<td>Nordic Optical Telescope</td>
<td>342.1184E 28.7606N</td>
<td>2.56m</td>
<td>2326m</td>
<td>Ritchey Chrétien</td>
<td>ALFOSC</td>
</tr>
<tr>
<td>Mayall Telescope</td>
<td>248.4000E 31.9633N</td>
<td>4.0m</td>
<td>2120m</td>
<td>Ritchey Chrétien</td>
<td>RC-Spec</td>
</tr>
<tr>
<td>Hubble Space Telescope</td>
<td>Orbit</td>
<td>2.4m</td>
<td>547km</td>
<td>Ritchey Chrétien</td>
<td>CCD Mosaic</td>
</tr>
<tr>
<td>Mount Wilson</td>
<td>241.8794E 34.1330N</td>
<td>100” &amp; 60”</td>
<td>1741m</td>
<td>Cassegrain</td>
<td>Photographic plates</td>
</tr>
</tbody>
</table>
Narrow-band filters, essential to deduce nebula structure, miss emission that is Doppler shifted out of the filter bandpass. The Aristarchos narrow-band images in Hα and [N ii], which were normally combined in this work, cover 6558.5 - 6575.5 Å and 6579.5 - 6596.5 Å respectively, giving a contribution over 4 Å from Hα therefore missing information below -200 km s\(^{-1}\) and accounting for information from +560 up to +740 km s\(^{-1}\) by the 6548 Å emission, which is about three times weaker than its 6583 Å counterpart. For 6583 Å [N ii] information from -160 to -340 km s\(^{-1}\) and +610 km s\(^{-1}\) are missed. From the observations the Hα line and [N ii] at 6583 Å have the strongest emission of the triplet (i.e. Hα is straddled by the two close [N ii] lines) and together contribution from all nebular velocities except those from -200 to -340 km s\(^{-1}\) are observed. Overall, in the -1000 km s\(^{-1}\) to +1000 km s\(^{-1}\) range 7% of velocity information is lost from an expanding nova shell at the constraints of the Aristarchos narrowband filters. The coverage shows higher velocity features down to -1100 km s\(^{-1}\) and up to 1500 km s\(^{-1}\). Due to the variable emission between the lines covered and differences in sensitivity, caution is to be exercised when judging differences.

2.2.2 San Pedro Mártir

High-Resolution Spectroscopy with MES

Echelle spectroscopic data was obtained to measure the extinction velocities of nova shells. These were collected using the Manchester Echelle Spectrometer (MES) mounted on the 2.1 m telescope at the San Pedro Mártir (SPM) observatory in Mexico (Meaburn et al., 2003), see Figs. 2.1 and 2.2 for the in-
strumental setup. Two MES instruments are in existence, one at SPM and the other at the Aristarchos telescope site, although not yet in commission. Data were collected over the course of four observing periods between November 2014 and September 2016. The slit positions were observed with the instrumentation in its f/7.5 configuration. A Marconi 2048 × 2048 CCD was used with a resultant spatial resolution $\equiv 0.35$ arcsec pixel$^{-1}$ after $2 \times 2$ binning was applied during the observations with the $\sim 6'$ long slit. Bandwidth filters of 90 and 60 Å were used to isolate the 87$^{th}$ and 113$^{th}$ orders containing the H$\alpha$+$[N \, ii]$ $\lambda\lambda\, 6548$ Å, 6583 Å and $[O \, iii]$ $\lambda\, 5007$ Å nebular emission lines.

Figure 2.1: Optical pathway of the MES spectrometer (Meaburn et al., 2003)

Figure 2.2: Image of the MES spectrometer at the Aristarchos telescope site before being mounted. Image credit: Dr. Panos Boumis
2.2.3 Liverpool Robotic Telescope

Low-Resolution Spectroscopy with FRODOSpec

FRODOSpec (Fibre-fed RObotic Dual-beam Optical Spectrograph) (Barnsley et al., 2012) is mounted on the Liverpool Telescope (LT) Steele et al. (2004), see Fig. 2.3. It as a multi-purpose integral-field input spectrograph whose beam is split before the entrance to the individually optimised collimators.

![Figure 2.3: FRODOSpec schematic from Barnsley et al. (2012).](image)

Figure 2.3: FRODOSpec schematic from Barnsley et al. (2012).
Figure 2.4: FRODOSpec pipeline details adapted from appendix of Barnsley et al. (2012).
Data acquired with FRODOSpec are reduced and wavelength calibrated through the appropriate pipeline, detailed by Barnsley et al. (2012), see Fig. 2.4, and can then be flux calibrated using standard routines in IRAF (Tody, 1993). The instrument was used in both low and high resolution modes during the course of the study. The resolving power of the low-resolution mode is 2600 (0.8 Å/pix) for the blue arm and 2200 (1.6 Å/pix) for the red arm. The high resolution mode has a resolving power of 5500 (0.35 Å/pix) for the blue arm and 5300 (0.8 Å/pix) for the red arm.

RINGO3

RINGO3 is a polarimeter mounted on the LT and works simultaneously in three bands: red 770 - 1000 nm, green 650 - 760 nm and blue 350 - 640 nm (Steele et al., 2006), see Fig. 2.5. Observations can be obtained in two EMGAIN settings of 20 and 100.

The polarimetric data comes de-biased and flat-field subtracted from the LT pipeline. The polarimetry measurements can be derived using the relations of Clarke and Neumayer (2002). The reduction of data from RINGO3 is an involved process, a brief description of the methodology employed follows. Each observation comprises of 8 exposures, corresponding to different rotations of the polariser, these are initially summed in order to get the total flux (S1) for each of the red, green and blue bands. S2 and S3 are calculated at this time, see Fig. 7 of Clarke and Neumayer (2002) for an illustration for how the exposures are to be summed. From S1, S2 and S3, the q and u values are calculated, it is from the q and u values that the Stokes parameters are derived, denoted as I, Q and U (q = Q/I and u = U/I) and who can be combined into
a vector that describes the polarisation state of light, see Słowikowska et al. (2016). For each EMGAIN (i.e. 20 or 100) a different set of polarisation standards must be used and these are observed automatically most nights.

Both polarised and non-polarised standards must be analysed in order to derive correct polarisation measurements for the source. It is from the zero polarised standards that the q and u shift measurements are derived. The extent of polarisation of the object is scaled according to the shift between their derived measurements with RINGO3 and published values in the literature, i.e. from Słowikowska et al. (2016).
RINGO3 polarimetry data can be used to conduct differential photometry. The integrated flux from the 8 rotated exposures (S1) from each observation are used. For accuracy the brightest field stars are chosen for photometric comparison.

2.2.4 William Herschel Telescope & KVA Stellar Telescope

Polarimetry with Dipol-2

The Dipol-2 instrument, see Fig. 2.6, records simultaneously in three filters, standard Johnson BVR, Piirola et al. (2014). The instrument was mounted on the 4m William Herschel Telescope and on the KVA stellar telescope, see Table 2.1, during observations conducted for this thesis.

Description of the polarimeter design is given by (Piirola et al., 2014). Detailed descriptions of the observational routine and data reduction procedure can be found in Kosenkov et al. (2017).

Regarding observations in this thesis, for determination of instrumental polarisation, a set of nearby (d < 30 pc) zero-polarised standard stars were observed. The magnitude of instrumental polarisation for Dipol-2 mounted in Cassegrain focus on both telescopes was found to be less than 0.01% in all pass-bands. For determination of the zero-point of polarisation angle highly polarised standards were observed. The internal precision is ~ 0.1°, published values are used for the standards, giving an estimated uncertainty in determination of the zero point of less than 1 - 2°.
2.3 Archival data

2.3.1 Surveys

WISE

The Wide-field Infrared Survey Explorer (WISE) is an infrared space telescope operated by NASA (Wright et al., 2010). At an orbit of height 528 km, the primary mirror of diameter 0.4 m images in the four bands of the survey camera. The optical assembly is highlighted in Fig. 2.7, adapted from the WISE Science Data Centre. The primary mission of WISE was completed between December 2009 and February 2011 before being reactivated as NEOWISE in September 2013.
The four WISE bands are known as W1, W2, W3 and W4 corresponding to central wavelengths of 3.4, 4.6, 12, and 22 µm respectively. The resolution of the four bands is 6.1", 6.4", 6.5" and 12.0" in ascending order (Wright et al., 2010). Examples of images retrieved from the WISE archive are of the extended circumstellar material surrounding the nova progenitors of GK Per in Fig. 5.15 and V2275 Cyg in Fig. 6.13.

The WISE survey was used for this thesis work as motivation for follow up in the optical for potential previously undiscovered ejected nova debris. From the sample of observed nova systems by WISE the best candidates can be seen in the final results chapter of this thesis in Fig. 6.1.

Figure 2.7: Optical path of the WISE space telescope. Adapted from the WISE Science Data Centre http://wise2.ipac.caltech.edu on 8/8/2017.
**IPHAS**

The Isaac Newton Telescope Photometric Hα Survey of the Northern Galactic Plane (IPHAS), is described in Drew et al. (2005). The latest data release of this survey is summarised in Barentsen et al. (2014). The archive was used to retrieve images of Hα bright nova shells for Chapter 6 of this thesis, e.g. the nova shell of T Aur in panel G of Fig. 6.10. The IPHAS catalogue was also used to try and identify novae within the cataclysmic variable source list. Colour-colour diagrams were generated for the final year undergraduate project of Ms. Nikki Keaveney, for which I was co-supervisor along with Dr Matt Redman, using the IPHAS and WISE catalogues. The project was successful in identifying nova systems from the sample that had erupted in the last 5-10 years. The results of this project were also considered for a future search for novae masquerading in the more generalised cataclysmic variable population.

**Mount Wilson Photographic Plates**

An online search of the Carnegie Observatories archive for long exposure images of classical nova systems was conducted. The images recovered were originally taken by Duncan, Hubble, Pettit or Baade using the Mount Wilson 60” and 100” telescopes.

For each of the photographic plates there is a reproduction of its sleeve and three exposures of the plate itself (using a light box), with one stop underexposed, the base exposure, and one stop over exposed. The reproductions were conducted by Dan Kohne, a librarian at Carnegie. Help was received from
another librarian, John Grula, in finding the plates. The base exposure for
each plate was 1/8th of a second. The search recovered otherwise lost images
of nova shells, most of which were never published. For example the sleeve and
a reproduced photographic plate can be seen in Figs. 2.8 and 2.9 respectively.

Figure 2.8: Original sleeve overlaid on a newer sleeve for the photographic
plate that follows (Fig. 2.9) of Nova Cyg 1920. In the remarks section it is
common for the seeing and type of emulsion used to be noted.
Figure 2.9: Nova Cygni (1920) captured on a plate from May 23 1927, part of a collection of 30 + Mount Wilson images and spectra that were analysed over the course of this study.
Chapter 3

Modelling Techniques

3.1 Overview

It was the intention of this project from the outset to have a straightforward modelling element to the work. It can be difficult for a modern observer to appreciate what they are looking at without exploring some of the codes made available by the astrophysics community. With the use of a visualisation tool, such as SHAPE (Steffen et al., 2011), the user can in real-time match simulated 2D Position-Velocity (PV) arrays to long-slit spectral observations. This technique aids in untangling the 3D structure of nebulae when paired with narrow-band imaging.

Observed emission from classical nova shells can be shown to be dominated by photoionisation processes, see Morisset and Pequignot (1996a), Morisset and Pequignot (1996b) and references therein. The time-evolution of the ionisation-structure of novae can be followed using multi-epoch archival low
and medium resolution spectra, which can be simulated using CLOUDY (Ferland et al., 2013). The 1D photoionisation capabilities of CLOUDY and 3D morpho-kinematic software SHAPE (Steffen et al., 2011) were combined via pyCLOUDY (Morisset, 2013), a python wrapper for CLOUDY. The result is a spatial map of specified emission lines. Thus modelling a nova shell in pseudo-3D that can act as a tool in understanding nova shell evolution.

3.1.1 SHAPE

The 3D morpho-kinematical modelling software SHAPE (Steffen and Lopez, 2006) was used from the start of this doctoral project. It acts as a quick and useful visualisation tool to aid in understanding complicated nebular objects. The user creates morphologies based on a set of primitives, i.e. basic cone shape, sphere, cylinder, plane etc... and then modifiers can be applied to these basic shapes. The modifiers range from density, temperature and velocity controls to geometrical transformations and distortions\(^1\). The modifiers can be in cartesian, cylindrical or spherical coordinates and can be set analytically or interactively. A practiced user can generate a range of common astrophysical morphologies within minutes, apply density and velocity variations to compare with observations.

In the work carried out for this thesis narrow-band H\(\alpha\) + [N II] Aristarchos imaging coupled with the MES spectroscopy were interpreted with SHAPE. PV arrays are the most often used output of SHAPE, a wealth of other functionality is available. The software is split into a series of modules, with the 3D Module

\(^1\)A full discussion on SHAPE modifiers can be found at http://bufadora.astrosen.unam.mx/shape/
(where the model is constructed) and the Rendering Module being the most commonly used, see Fig. 3.1. A versatile plotting module is available that allows the user to plot data both from generated models or preloaded data.

Nebulae, in general, consist of a variety of complex structures that are not necessarily dependent on rotational symmetry. The correct interpretation of any type of nebula’s morphology and kinematics should lead to a clearer understanding of evolution of that object. The projected 2D geometry of these objects on the plane of the sky is usually complex, as are the shape of their positionally resolved emission line profiles that are key to deprojecting the 3D nebular structure.

The general modelling procedure that was followed to produce 3D morphokinematical models in SHAPE follows. Initially one must have their data prepared; have the optical images processed and have PV arrays or channel-maps available to them; then a 3D guess for the surface or volume must be implemented in the 3D construction module. In this example let us say a user wants to create a typical hourglass bipolar nebula, often seen in the context of PNe. To do this start with a sphere primitive, the inner and outer radii of the sphere are set at this time. Then the user turns their attention to the modifier options. Once any object is created it is assigned a density and a temperature modifier by default. These modifiers can be used to set various temperature and density conditions on the simulated nebula either analytically or interactively. SHAPE generates images from particle or mesh distributions and outputs PV arrays, channel maps and one dimensional spectral line shapes to compare with their observed counterparts.

Squeeze, translation and an array of other modifiers are available to the
Figure 3.1: Example of a SHAPE render window (top) showing a radially expanding spherical nebula and a characteristic velocity ellipse in the right panel. The bottom left panel shows a rendered version of the bipolar hourglass nebula depicted in mesh form in the four bottom right panels. These examples were adapted from http://bufadora.astrosen.unam.mx/shape/.

user at this point to improve on the models structure if necessary. Modifiers such as velocity fields, brightness adjustments and opacity distribution can
then be applied to the structure. A number of observing parameters can be set in the main interface, i.e. the user adjusts for seeing through the implementation of a Gaussian blur or by convolving the simulated image. The angular size of the object in the sky is established at this point. Rotation of the model, slit position and width amongst a range of other options can be changed in this interface. The model can be rendered at this stage and observation comparisons allow the user to establish what changes to the model are necessary. This procedure is followed iteratively until a satisfactory result is achieved.

Application of geometry modifiers that use analytical functions to apply to an object is possible. Control points of an interactive curve can be loaded from an ascii file either. In the Plotting Module the graphs are used to display spatial variation of a quantity. In the physics module variables are applied as a function of wavelength. One can set a range for the independent variable, outside of which the function is set to zero. There includes reserved variables: e (Euler number), pi (π), n (number density taken from the density modifier), T (temperature). With regards to the constants, if the user has set the global variables in the Math Module then they can use them by activating the ‘Use Global Variables’ button at the bottom of the constants tab.

When the user chooses to follow the analytical route, using for example ‘the squeeze modifier’ on a cylinder or sphere primitives to form a bipolar morphology, several functions can be attempted in order to achieve best fit modelling of the nebula, e.g. a sinusoidal wave function.

The shape toolbox includes an optimiser module to be used to improve a fit to set parameters using least squares minimisation. A downside to this module is that it does not provide errors in the final output of its calculations.
To simulate nebular expansion the time modifier was conceived by Dr. Valério Ribeiro. This modifier extrapolates the motion of an object from the initial velocity of the particles that are applied to calculate their past and future positions. Velocity is assumed to be constant, and time is advanced in the animation modifier, Ribeiro et al. (2009) is a practical example using this feature.

After arriving at a model solution, the result may be inspected in various ways and scientific conclusions regarding the object structure, kinematics and orientation may be drawn. In most cases observational data, such as broadband imaging of astrophysical nebulae are insufficient to derive a unique solution for its 3D structure and kinematics, moreover, when considering if the nebula is optically thin or thick. Objects with simple topology or recognisable symmetry can be solved uniquely.

3.1.2 Cloudy & pyCloudy

Emission from classical nova shells is predominantly due to photoionisation processes, as stated by Evans (2001) the nebular phase arises when the optically thin ejecta is subjected to the hot underlying source. CLOUDY has been in development since 1978 and works off the principle that if the microphysics is properly described and self consistent then the macro physics can be reliably estimated. CLOUDY is a spectral synthesis code that can simluate a broad range of density and temperature regimes. Although especially designed for astrophysical applications the code is able to simulate closer to home photoionisation conditions such as the Sun’s interaction with Earth’s atmosphere or laser-material interactions.
**CLOUDY** is versatile, well bench-marked code that has been extensively used by the nova community. A Python wrapper has been developed for the **CLOUDY** code by Dr. Christophe Morisset, called **pyCLOUDY** ([Morisset, 2013](#)). The **pyCLOUDY** environment allows for more manageable handling of **CLOUDY** output files. The added control given to the user via **pyCLOUDY** allows the user to create pseudo-3D photoionisation models by running multiple 1D simulations that characterise a certain structure when combined. The pseudo-3D modelling abilities are a step up from the sphere or plane-parallel approximations otherwise given in **CLOUDY**. An alternative, the fully 3D photoionisation code **MOCASSIN**, was found to be too computationally heavy for the task at hand and could later be considered to aid in benchmarking models presented in this thesis. The most complete photoionisation study of a nova to date was conducted in [Morisset and Pequignot (1996a,b)](#), where in the latter paper a brief historical perspective of classical nova photoionisation simulations is provided.

The general modelling procedure in **CLOUDY** requires knowledge of data from spectroscopy, in an ideal world the user would have multi-epoch high-resolution spectra covering a broad wavelength range. Photoionisation models can be built in either **CLOUDY** or **pyCLOUDY**, depending on the user preference. Let us first deal with a typical simulation, take a classical nova shell a year post-eruption in **CLOUDY**. Physically the nova shell will have an inner and outer radius. The shell may still be radiation bound after a year, as was found for GQ Mus by [Morisset and Pequignot (1996a)](#). Parameters that need to be set in order to run a model include the blackbody temperature of the central source as well as its luminosity. The nova shell radii are set, as well as the
density and abundances. Many options are available to the user if they wish
to speed up or add more to their model. The cosmic microwave background is
generally set, as well as the distance to the source, although not mandatory to
run a model. In the CLOUDY input file the user sets the output to generate; be
it output on optical depth, heating, cooling or other physical conditions that
they wish to monitor. It is a good idea to set what spectral lines to monitor
at this time. Additional ionising sources can be set in a single CLOUDY input
file or there are libraries of stellar atmospheres that are available to the user.
Grids can be run in order to test the effect of changing a parameter, such as
density or the abundance of a certain element.

As mentioned previously, pyCLOUDY is a python wrapper for CLOUDY. In
its current form it allows the user to generate CLOUDY input files in organ-
ised batches and makes handling output files from CLOUDY more manageable.
Available routines allow the user to create diagnostic diagrams from a set of
models that they generated or through the access of a model database using
MySQL. The functionality that attracted the author to pyCLOUDY was its
pseudo-3D capability. As it is offered in pyCLOUDY a user can modify pa-
rameters regarding the equation of an ellipse, with the axial ratio being most
relevant. Models are run through a preset number of angles within a 90° cut.
The cut, however, does not need to be from 0-90° of the ellipse instead a range
of angles can be specified, with some testing hourglass structures and a variety
of other common axisymmetric geometries can be created. Filling factors can
be included in these analytical models.

A modification of pyCLOUDY was necessary in order to read in SHAPE
output files. After a meeting with Dr. Christophe Morisset at UNAM in
Mexico City in late 2016, real progress towards this effort became realisable. Dr. Morisset provided the author with a script used to interpret data from a 3D radiative transfer code. This script was subsequently modified to suit the task at hand. After collaboration with another PhD student in NUIG, Mr. Karol Fitzgerald, a GUI was developed that allows the user to select their SHAPE output files and what dimensions to be applied. As it stands positional arguments and density conditions are read from the SHAPE file, see Fig. 3.2 and pyCLOUDY creates ‘.dens’ files that correspond to each model for each angle to run through the geometry. A ‘.dens’ file is a list of radii with corresponding densities. As pyCLOUDY works by taking a 90° cut through the proposed geometry before rebuilding the complete pseudo-3D model, SHAPE output must first be correctly centered and oriented. In order to do this the user must centralise the object to the bottom left hand corner of the SHAPE render window and apply a cut so that a 2D slice of a quadrant of the trial geometry is left, see Fig. 3.3. This slice can then be extrapolated after
Figure 3.3: The far left panel shows a 3D bipolar mesh of a nova shell. Through the use of pycLOUDY the SHAPE model is used as a geometry to run multiple 1D CLOUDY models thus showing the expected emission from a hypothetical simulated old hourglass nova shell with V1500 Cyg nova abundances, in this case shown in [N II] and [O III].
the appropriate CLOUDY models have been run under the managerial eye of pyCLOUDY.

The consequences of the functionality outlined above allows now for any user to set up an axisymmetric nebula in SHAPE and visualise how this nebula would appear in any spectral region given parameters of an ionising source. The advantages of the approach outlined above over fully 3D codes, such as MOCASSIN (Ercolano et al., 2003), is the vastly reduced computational time due to the simplified approach. Running the simulations through a well bench-marked code like CLOUDY adds robustness to the results. Disadvantages the pyCLOUDY interface has over MOCASSIN, however, are that shielding is not taken into account and only axisymmetric nebulae can be simulated.
Chapter 4


4.1 V5668 Sagittarii

The object studied in this chapter is V5668 Sgr (PNV J18365700-2855420 or Nova Sgr 2015b) a slow-evolving dust-forming nova that is a clear example of a DQ Her-like nova. V5668 Sgr was confirmed as an Fe II nova in spectra reported by Williams et al. (2015) and Banerjee et al. (2015) after it was discovered at 6.0 mag on 15.634 March 2015 (Seach, 2015). As a slow, close and bright nova with a deep dust-dip, this object might be expected to produce a visible shell discernible from the ground within ten years using medium class telescopes. Banerjee et al. (2016) calculated a distance of around 1.54 kpc to the nova system. The distance was calculated by fitting an 850 K blackbody to their dust SED on day 107.3 post-discovery to find $\theta_{bb}$ and assuming an
expansion velocity of $530 \text{ km s}^{-1}$, where $\theta_{bb}$ is the blackbody angular diameter. The $\theta_{bb}$ is given as 42 mas in Banerjee et al. (2016), which corresponds to a physical diameter of $9.6 \times 10^{14} \text{ cm}$. It was found in the same work that V5668 Sgr was a rich CO producer and one of the brightest novae (apparent magnitude) of recent times, reaching 4.1 mag at visual maximum.

As V5668 Sgr is a clear example of a DQ Her-like nova light curve (see Fig. 4.1), it is interesting to look for similarities between the two systems. A $71 \pm 2 \text{ s}$ oscillation in the X-ray flux was observed by Page et al. (2015) and this value may be related to the white dwarf spin period in the V5668 Sgr system, which is coincidental to the value of 71 s for the white dwarf spin period of DQ Her, e.g. Swedlund et al. (1974). DQ Her-type nova light curves are generally associated with eruptions on the surface of CO white dwarfs and their maxima can be difficult to identify due to their jitter or oscillation features superimposed on an otherwise flat-top, seen immediately prior to a distinguishable dust formation episode. Throughout this work, this early phase is referred to as the ‘flat-top-jitter’ phase. The flat-top-jitter phase of the V5668 Sgr eruption was monitored by Jack et al. (2017), where it was seen that the appearance of an increasing number of ‘nested P-Cygni profiles’ (P-Cygni profiles with multiple absorption components, see Section 1.4.1) in individual spectral lines could be associated with multiple ejection episodes or evolving components.

Several constraints of the system during the deepest part of the dust-dip are presented by Banerjee et al. (2016) from infrared high-cadence observations. Their observations resulted in a gas/dust temperature of $\approx 4000 \text{ K}$, a dust mass of $1 \times 10^{-8} \text{ M}_\odot$, and an an expansion velocity of $530 \text{ km s}^{-1}$.
Figure 4.1: AAVSO light curve. Marked are the three major light-curve stages observable in the figure, i.e. the flat-top-jitters, the deep dust-dip and the cusp shaped features seen on the rise out of the dust-dip. Marked are the times of polarimetric observations of the nova by both the Muneer et al. (2015) team and those presented in this paper, i.e. the Dipol-2 measurements. The y-axis demonstrates the change in visual magnitude whereas the x-axis contains the Julian date on the bottom and days since discovery on the top.

Data is presented here from five nights of polarimetric observations acquired during the nova’s permitted spectral phase with the Dipol-2 instrument mounted on the William Herschel Telescope and the La Palma KVA stellar
telescope, see Section 2.2.4. The observations were obtained directly follow-
ing the deep dust minimum during and the nova’s rise through its observed
cusps. The nova shell of V5668 Sgr is not yet resolvable with medium-sized
ground-based telescopes given the recent eruption, however a pseudo 3D pho-
toionisation model is presented based on 1D CLOUDY (Ferland et al., 2013)
models to demonstrate the ionisation structure of V5668 Sgr following its dust
formation episode. Throughout the course of this chapter observations are
mentioned in terms of days since discovery of the nova source.

4.2 Observations

4.2.1 Polarimetry

The polarisation measurements of V5668 Sgr after the dust-dip stage were
made with the Dipol-2 polarimeter mounted on the 4.2 m William Herschel
Telescope telescope during three nights: MJD2457207, 2457208 and 2457210
(days 111, 112 and 114 post-discovery). Two more measurements were recorded
two weeks later with the 0.6 m KVA stellar telescope (on MJD2457226 and
2457229, i.e. days 130 and 133 post-discovery, see Fig. 4.2). Each night, 16
measurements were made of the modified Stokes parameters \( q = Q/I \) and \( u = U/I \)
and the weighted mean values computed, see Slowikowska et al. (2016).
The exposure time was 10 sec for the William Herschel Telescope and 30 sec
for the KVA. The polarisation data, which have been acquired simultaneously
in the standard B, V and R passbands, are given in Table 4.1.

Description of the polarimeter design is given by (Pirola et al., 2014). De-
tailed descriptions of the observational routine and data reduction procedure
Figure 4.2: Panels from top to bottom: (B-V) colour index as derived from AAVSO data during Dipol-2 observation epoch; the middle panel shows the measured absolute polarisation degree in percentage and the bottom panel shows the recorded position angles for the polarisation measurements. The filled circles shows the data for the B-band, hollow circles - V-band and filled triangles - R-band. Days since outburst are marked along the top x-axis. The error bars ($\pm 1\sigma$) are smaller than the plotting symbol for the William Herschel Telescope data (days 111-114 post outburst). Plot created in collaboration with Dr. Berdyugin.
Table 4.1: Polarimetry observations gathered with the Dipol-2 instrument, during and rising out of the deep-dust dip experienced by V5668 Sgr.

<table>
<thead>
<tr>
<th>Date (J.D.)</th>
<th>Telescope</th>
<th>Filter</th>
<th>Pol (%) ± err</th>
<th>P.A. (deg) ± err</th>
</tr>
</thead>
<tbody>
<tr>
<td>2457207.5</td>
<td>William Herschel Telescope</td>
<td>B</td>
<td>1.699 ± 0.017</td>
<td>144.1 ± 0.3</td>
</tr>
<tr>
<td>2457207.5</td>
<td>William Herschel Telescope</td>
<td>V</td>
<td>0.601 ± 0.014</td>
<td>144.9 ± 0.7</td>
</tr>
<tr>
<td>2457207.5</td>
<td>William Herschel Telescope</td>
<td>R</td>
<td>0.344 ± 0.007</td>
<td>148.3 ± 0.6</td>
</tr>
<tr>
<td>2457208.5</td>
<td>William Herschel Telescope</td>
<td>B</td>
<td>1.471 ± 0.015</td>
<td>145.4 ± 0.3</td>
</tr>
<tr>
<td>2457208.5</td>
<td>William Herschel Telescope</td>
<td>V</td>
<td>0.566 ± 0.012</td>
<td>148.3 ± 0.6</td>
</tr>
<tr>
<td>2457208.5</td>
<td>William Herschel Telescope</td>
<td>R</td>
<td>0.330 ± 0.006</td>
<td>153.2 ± 0.5</td>
</tr>
<tr>
<td>2457210.6</td>
<td>William Herschel Telescope</td>
<td>B</td>
<td>1.338 ± 0.018</td>
<td>147.6 ± 0.4</td>
</tr>
<tr>
<td>2457210.6</td>
<td>William Herschel Telescope</td>
<td>V</td>
<td>0.565 ± 0.023</td>
<td>151.3 ± 1.2</td>
</tr>
<tr>
<td>2457210.6</td>
<td>William Herschel Telescope</td>
<td>R</td>
<td>0.357 ± 0.009</td>
<td>152.4 ± 0.7</td>
</tr>
<tr>
<td>2457226.5</td>
<td>KVA</td>
<td>B</td>
<td>0.723 ± 0.088</td>
<td>152.0 ± 3.5</td>
</tr>
<tr>
<td>2457226.5</td>
<td>KVA</td>
<td>V</td>
<td>0.616 ± 0.097</td>
<td>155.0 ± 4.5</td>
</tr>
<tr>
<td>2457226.5</td>
<td>KVA</td>
<td>R</td>
<td>0.416 ± 0.051</td>
<td>151.7 ± 3.5</td>
</tr>
<tr>
<td>2457229.5</td>
<td>KVA</td>
<td>B</td>
<td>1.132 ± 0.106</td>
<td>170.9 ± 2.7</td>
</tr>
<tr>
<td>2457229.5</td>
<td>KVA</td>
<td>V</td>
<td>0.770 ± 0.092</td>
<td>183.1 ± 3.4</td>
</tr>
<tr>
<td>2457229.5</td>
<td>KVA</td>
<td>R</td>
<td>0.440 ± 0.035</td>
<td>177.3 ± 2.2</td>
</tr>
</tbody>
</table>

can be found in Kosenkov et al. (2017).

Details on the reduction procedure can be found in Section 2.2.4. For determination of the zero-point of polarisation angle, the highly polarised standards HD 161056 and HD 204827 were observed. The Dipol-2 measurements were observed by Dr. Berdyugin and Prof. Piirola at the request of the author. The data was reduced by Dr. Berdyugin.

Effects that may be responsible for the observed variations in polarimetric measurements over the course of the observations include uncertainties regarding the standards, lunar proximity or orbital phase. Lunar distance and seeing effects add noise and contribute to larger errors rather than systematic deviations (private communication Vilppu Piirola).
Photometry

Polarimetric observations were collected on 22 nights with the RINGO3 polarimeter (Steele et al., 2006) on the LT (Steele et al., 2004) spanning days 113-186 after eruption detection. Unfortunately, it was found that the instrument’s performance at low levels of absolute polarisation were not sufficient in the present context due to intrinsic non-negligible changes in the value of the EMGAIN parameter of the EMCCD detectors at the eight different positions of the polaroid rotor. This being said, the observations were of sufficient quality to perform differential photometry. The RINGO3 passbands were designed to incorporate the total average flux of a gamma-ray burst equally across the three bands and are thus unique to the instrument. The bands: known as red, green and blue, correspond to wavelength ranges 770-1000 nm, 650-760 nm and 350-640 nm respectively - roughly equivalent to the Johnson-Cousins I, R and B+V optical filter bands (Steele et al., 2006).

The integrated flux from the 8 rotated exposures (S1) from each night of observation of the nova was recorded. The four brightest field stars were chosen for photometric comparison. The same field stars were not always within the frame on different dates. In essence, differential photometry was conducted with each one of the four field stars and the derived values were found to agree closely, in the end the brightest of the field stars was chosen as it gave the most reliable results and was present in the most frames across the different filters on the relevant nights. The results of this analysis can be seen in Fig. 4.3. Performing photometry on this dataset allows for information to be gained on the nova systems behaviour during the sparsely populated
Figure 4.3: Results of differential photometry from the RINGO3 polarimetric data. The cusps on the rise out of the nova’s dust-dip are clearly visible in the plot. The first cusp corresponds to the grain destruction seen in the Dipol-2 data days 111 - 114 post-discovery. The rise on the third cusp feature visible in the plot is from the grain growth period suggested by the Dipol-2 observations, these observations lie between the dashed lines on the plot. The lines are colour-matched with the RINGO3 bands, blue is blue, red is red and green is black.
AAVSO data during the Dipol-2 polarimetric as well as the densest auroral stage (see Section 1.6.1), during the FRODOSpec spectroscopic observation epochs.

### 4.2.2 Spectroscopy

Using FRODOSpec (Barnsley et al., 2012) mounted on the Liverpool Telescope (Steele et al., 2004) in low resolution mode, spectra were taken over 103 nights from outburst detection until day 822 post outburst. Data acquired with FRODOSpec are reduced and wavelength calibrated through the appropriate pipeline, detailed by Barnsley et al. (2012). The spectra were flux calibrated using standard routines in IRAF \(^1\) (Tody, 1993) against a spectrum of G191-B2B taken on 30 Sept 2015 using the same instrument setup by Dr. Steven Williams. The standard spectral data was obtained from Oke (1990). All spectra were taken in the low-resolution mode of FRODOSpec except for two dates, these being day 411 and 822 post-discovery, whose observations were collected in high-resolution mode. The resolving power of the low-resolution mode are 2600 for the blue arm and 2200 for the red arm. The low-resolution mode in the blue arm therefore gives a resolution of around 1.8 Å or 120 km s\(^{-1}\). High resolution mode has a resolving power of 5500 in the blue arm in 5300 for the red arm. The spectroscopic data were analysed using SPLOT and other standard routines in IRAF. As the vast majority of the spectra involved are from the low resolution mode a systematic error of up to 20% is expected as well as a 10% random error.

\(^1\)IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
4.3 Analysis and Results

4.3.1 Polarimetry

The wavelength dependence of polarisation (sharp increase towards the blue) gives strong support for Rayleigh scattering as the primary source for the observed polarisation after the dust formation stage; see Walter (2015); Gehrz et al. (2015), for more on this particular nova’s primary dust formation episode, see Sections 1.5 & 1.6.3. The directions of polarisation in the B, V and R bands are close to each other for the five dates, which suggests an intrinsic nature to the observed polarisation. The interstellar component is small even in the V and R bands because the angle of polarisation in the V and R bands are always close to that in the B-band.

Unfortunately, photometry data at the dates when the polarisation with the Dipol-2 instrument was measured is not available. As can be seen from Fig. 4.2, however, the color index (B-V) did not change significantly over the range of dates from when the absolute polarisation was measured. Consequently, the rapid changes in the B-band polarisation seen on days 111-114 and 130-133 post-discovery are not due to decrease or increase of the fraction of the polarised scattered light in the system.

Variations in the absolute polarimetry over the five nights observing of V5668 Sgr with Dipol-2 covered days 111-133 post-discovery are after the formation of dust and during the local minimum in the transitional-stage of the optical light curve. The observed flux in the R-band is likely dominated by Hα in these observations. The most probable explanation for the observed variations in the absolute polarisation is the small dust particles which are
responsible for the appearance of the polarised scattered light. During days 111-114 post-discovery, the destruction phase could be observed while during 130-133 post-discovery, the creation phase was recorded.

X-ray counts increased during the observations reported here, see Page et al. (2015), Gerhrz et al. (in prep.), exposing the nova shell to a harsher radiation field. Infrared SOFIA observations (Gehrz et al., 2015), that coincided with the commencement of the observations presented here, revealed that the dust emission on day 114 post-discovery had increased since day 83 post-discovery and that a reduction in grain temperature suggested rapid grain growth to sub-micron radii. These observations suggest that the hydrogen emission in the NIR was blanketed by the dust and the effect of this can be seen in the strengthening of the Paschen series, see Figs. 4.5 & 4.6. Emission at this time is expected to arise from a cold dense shell as well as hotter, less-dense ejecta, see Derdzinski et al. (2017). Gehrz et al. (in prep) are presenting Swift and SOFIA observations of this nova covering the IR, UV and X-ray behaviour of the nova system.

UBVRI polarimetry before the dust-dip, taken during the flat-top-jitter phase over the first observed major primary jitter, was reported by Muneer et al. (2015), providing knowledge of the absolute polarisation of the system before the major dust formation event. Although the measurements by Muneer et al. (2015) are not corrected for interstellar polarisation toward the source, the correction is not made here either. The earlier Muneer et al. (2015) results are lower than those of the Dipol-2 observations directly following the dust-dip, with P.A. measurements being consistent. The earlier observations with lower recorded absolute polarisation of Muneer et al. (2015) fit with electron scatter-
ing or interstellar polarisation, as expected before the dust formation episode. Of interest regarding the observations of Muneer et al. (2015) is that between days 2 - 4 post-discovery, P.A. of the polarisation varies between roughly 150° and 10° (i.e. 190°) - very similar to that in the Dipol-2 measurements, see Table 4.1. In the observation presented here, values between 144° - 183° were found for the P.A. The origin location of the source of the polarisation is indicative of the opening angle of the component, be it the equatorial or polar nova shell components is unknown. The work of Derdzinski et al. (2017) would suggest the opening angle to be related to the equatorial disk, since the work supposes that dust in primarily formed in the equatorial disk.

These observations can be understood in terms of dust resulting from seed nuclei that formed during the optical dust-dip and increase of the density in the forward shock zone. Lynch et al. (2008); Kato et al. (2009) and Strope et al. (2010) discuss cusps as possibly arising from shocks in the nova outflow. Since V5668 Sgr is a slow nova, strong shaping of the ejected nova material is expected. A strong correlation in position angle of the polarisation is needed throughout the observed epochs if it is related to either the equatorial or polar components of the nova outflow. The shock passes through the layer of fresh-formed small dust grains and destroys them, yet retaining seed nuclei, thus allowing for the process to repeat over the next shock cycle. Swift X-ray data to be presented in Gehrz et al. (in prep) shows the X-ray count rising on entering the dust-dip and increasing again when the cusps start (post dust-dip-minimum). The phenomenology of the hard X-rays can be understood in the context of shocks and sweeping up material, allowing the local densities to increase, which creates favourable conditions for dust formation. The soft
component (energies from 0.9 - 2.5 keV) of the X-ray emission should be due to continued nuclear burning on the surface of the central white dwarf (Landi et al., 2008), whereas the hard component (1-20 keV) is expected to arise from shocks, e.g. Metzger et al. (2014).

Gamma-ray emission was observed for the V5668 Sgr nova event and is described by Cheung et al. (2016). The emission of gamma-ray photons of energy $\geq 100$ MeV lasted around 55 days, longer and intrinsically fainter than any of the six other nova observed to produce gamma-ray emission. The onset of gamma-rays occurred two days following the first optical peak and were followed for 212 days. Due to low photon counts the team who discovered the sixth confirmed gamma-ray nova, were unable to correlate gamma variability with that in the optical, although the gamma emission peaks during the third major jitter (around days 30 - 40 post-discovery) on the nova’s otherwise flat-top light curve. The Fermi-LAT observations of this nova ended one month previous to the observations discussed here and before V5668 Sgr’s dust formation event.

4.3.2 Spectroscopy

Observed spectra were calibrated and subsequently interpreted using published results from the literature and CLOUDY simulations (Ferland et al., 2013). Shocks suggested by the polarimetry and multi-wavelength observations discussed in 4.3.1.

The earliest spectra observed here are interesting from the point of view of a suggestion of multiple components during the flat-top-jitter phase. A spectrum obtained on day 0 post-discovery shows P-Cygni profiles with absorption
components at -1200 km s\(^{-1}\). Further observations 14 days later revealed two absorption components in the strongest spectral lines with each having a measured velocity of -950 and -520 km s\(^{-1}\) in the Balmer lines. In spectra taken in mid April, the highest velocity component of the maximum spectrum increased again to approximately -1125 km s\(^{-1}\) and with a new lower-velocity component of -610 km s\(^{-1}\). These observations hint at optical depth effects where in the 14 days post-discovery spectrum, the inner side of the expanding shell is visible. Then by day 27, an outer shell section may becomes visible when three absorption components appear with velocities of -554, -945 and -1239 km s\(^{-1}\), respectively. The expanding shell is still expected to be radiation bound at this stage due to the high densities present. On day 28, the observed velocities decrease to -507, -887 and -1065 km s\(^{-1}\). The next spectrum was observed on day 31 with FRODOSpec, where it can be seen that the middle absorption component disappeared and leaving two components at -537 and -1047 km s\(^{-1}\). In spectra taken on days 32 and 33 post-discovery, a slight increase is seen in the absorption components which then levels off until the absorption systems disappear and are replaced by emission wings. In the subsequent spectra it appears that only the slower component remains visible as part of the expanding shell. It is worthy to note that the appearance of additional absorption components appear to be correlated with the local maxima in the nova’s early light curve.

The spectra presented in Figs. 4.5 and 4.6 show 10 nights from 6 July to 14 August. It was found that the earlier July spectra (days 114, 116, 120, 122 and 123 post-discovery), see Fig. 4.5, are all quite similar in appearance and it can be noted how the observed flux from the system recovers. These five
spectra correspond to the early-rise out of the dust-dip while the shell is known to be mostly optically thick, exhibited by the presence of strong permitted lines. During the optical light curve’s ascension out of the dust-dip, the most interesting changes are observed in the spectra from 130, 141, 143, 145 and 153 post discovery (see Fig. 4.6). The final three spectra presented from days 143, 145 and 153 following the eruption straddle a major cusp on the way out of the nova’s visual dust-dip, see Fig. 4.3. As discussed in Section 4.3.1, these cusps are commonly associated with shocks that occur in the immediate aftermath of the eruption. The most striking feature has been referred to as ‘nitrogen flaring’ in many previous works, see e.g. Williams et al. (1994); Zemko et al. (2016), around 4650 Å.

Over the same time frame, Ca II is observed to decline whilst He I and He II are both observed to increase. Fe III and N I emission strength decrease along with the Paschen series with respect to Hβ; for more details see Table 4.3. The observed behaviour is consistent with the thinning out of ejecta, which subjects the gas mix to harder radiation from the central source.

The evolution of the earlier absorption components can be seen in Figs. 4.7 & 4.8. The Ca II lines during these early days display a similar structure to Balmer and nebular [O III] lines at late times.
Figure 4.4: Spectra showing the two main spectroscopic stages observed during the polarimetric observations. Note the fall in O I corresponding to a rise in O II and O III lines.
Figure 4.5: Early July 2015 spectra from FRODOSpec with the blue arm spectra in the left hand series and red arm on the right. Spectra were flux calibrated by Dr. Steve Williams, and are all scaled to the bottom panel of each column. Note the change in flux over the dates.
Figure 4.6: Same as in Fig. 4.5 except for spectra taken in late July and early August 2015, using FRODOSpec. Note the flaring feature around 4650 Å in the blue arm of the spectra identified in this work as arising from the O II V1 multiplet, see Section 4.3.4.
Figure 4.7: Spectroscopy from the flat-top-jitter phase in the FRODOSpec blue and red arms. Dates post-discovery are marked on the upper-right-hand corner of the plot.
Figure 4.8: Radial velocities of the flat-top-jitter epoch spectra from H$_\beta$ on the left and O I on the right.
Figure 4.9: Spectra of $[\text{O III}]$ nebular and auroral lines on day 822 post-discovery. The observed line profiles (blue-solid lines) were used in the fitting of a morpho-kinematical model with the SHAPE software, seen as the overlaid black dots. The auroral line is fitted with an equatorial disk whereas the nebular lines fit an equatorial waist and polar cones morphology with a Hubble outflow velocity law, see Fig. 4.10.
4.3.3 Simulations

In order to achieve a pseudo 3D photoionisation model of the V5668 Sgr nova shell, first a 3D spatio-kinematic shape (Steffen and Lopez, 2006) model is needed along with estimations on the ionisation conditions from a 1D cloudy parameter sweep (Ferland et al., 2013). The shape (Steffen and Lopez, 2006) line profile model fits are to day 822 post-discovery, by when the line structure had frozen, and can be seen in Figs. 4.9 & 4.10. In order to create the shape model, subsequently used for input into pycoudy, three components were used comprising the equatorial waist and the two polar cones, see Fig. 4.10. The ring-like waist was constructed from a cylinder primitive in which a density, Hubble velocity law and thickness were applied. The two polar features were constructed using cone primitives. The densities applied to the features were estimated using cloudy parameter sweep simulations and the velocity components were found from measuring Doppler broadening of the Balmer emission lines. Emission line structure in fast outflows depend strongly on their velocity field and orientation, shape allows the user to untangle the projection effects. The frozen line shapes of the nebular stage modelled in Fig. 4.9 are with an inclination of 85° a polar velocity of 940 km s$^{-1}$ and equatorial velocity of 650 km s$^{-1}$ at their maximum extensions. The proposed structure is similar to that found in other slow novae such as T Aur (see Gallagher et al. (1980) and Section 6.3.3 of this thesis) and DQ Her (see Fig. 1.3 and Williams et al. (1978)).

Initial 1D parameter sweeps were coarse and broad covering densities of $10^4 - 10^{14}$ cm$^{-3}$. It was found that densities from $10^8 - 10^{10}$ cm$^{-3}$ better
Figure 4.10: Mesh display of the spatial structure of the nova shell around V5668 Sgr as determined from the nebular [O III] line shapes with the SHAPE software, see Fig. 4.9. The four panels show different orientations of the structure, the bottom-right-hand-panel shows the nova shell placed at the P.A. suggested from the polarimetry and as visualised in the pyCLOUDY renderings seen in Fig. 4.12. If the detected polarisation has its origin in the equatorial waist then the shell should be titled at 90° in the plane of the sky. The saddle shaped 4363 Å [O III] line feature, as well as other higher excitation species, can be understood as arising from the equatorial-ring-waist.

explained the structure of the observed spectrum and refined grids were run over these constraints. It is cautioned that, at the densities studied here, the Nussbaumer and Storey (1984) CNO recombination coefficients used are not as reliable since the LS coupling scaling law assumed in Nussbaumer and Storey (1984) diverges for atoms with upwards of two valence electrons. A Perlin noise modifier was applied to the hydrogen density distribution of the
polar cones and equatorial ring, with the average density being $1.0 \times 10^9$ cm$^{-3}$.

Inherent errors in the density estimates arising from the 30% error in line ratio observations are partially compensated by the Perlin noise modifier. The luminosity was set to $\log(L/\odot) = 4.36$ and an effective temperature of $1.8 \times 10^5$ K was assumed based on the parameter sweep, see Fig. 4.11. To simulate the nova conditions on day 141 post-discovery an inner radius of $3.2 \times 10^{14}$ cm and an outer radius of $6.4 \times 10^{14}$ cm were assumed, from expansion velocity considerations.

The spectral development of V5668 Sgr is dominated by the Balmer series plus He, N, O and Fe lines as the nova progresses through its permitted, auroral then nebular spectral stages. According to the Tololo classification, see Section 1.6.1, scheme the nova is in its P$_o$ stage during the observations presented in this work. A parameter sweep was conducted using the python wrapper for CLOUDY (Ferland et al., 2013) known as pycLOUDY (Morisset, 2013) to examine the line ratios for the hot-dense-thick nova shell that is still close to the burning central system. It was found that the dust shell size of Banerjee et al. (2016), when extrapolated to the expected size for the dates under study in this work, can fit the observed spectra although better fits can be achieved with marginally smaller radii, hinting that the optical emission lines in the optically thick region is inner to the dust shell. An implication is that dust clumps should appear and then disappear along the line of sight to the observer, further complicating the analysis.

Fig. 4.11 shows the results of a parameter sweep (consisting of 156 CLOUDY simulations - see Section 3.1.2) conducted to find fits to observed spectral line ratios. The parameter sweep varied with log densities $8.60 - 9.20$ in 0.05 dex,
and the effective temperature of the central source from $6 \times 10^4 - 3.0 \times 10^5$ K in steps of $2 \times 10^4$ K. For the parameter sweep pyCLOUDY was used to control cloudy. An average of Fe II type nova abundances adapted from Warner (1995) were included. The Eddington luminosity of a 0.7 $M_\odot$ white dwarf was assumed, with $r_{\text{min}} = 3.2 \times 10^{14}$ cm and $r_{\text{max}} = 6.4 \times 10^{14}$ cm. As the binary characteristics of this system are not known, a 0.7 $M_\odot$ white dwarf was chosen based on the turn-on time in X-rays (Gehrz et al. 2017, in prep.) and the nova’s $t_2$ value in comparison to Fig. 4(c) of Henze et al. (2014). From this type of analysis, it is possible only to say in a crude manner that the white dwarf must be on the lower end of the scale found in nova progenitor systems and that it is most probably a CO white dwarf.
Figure 4.11: 1D CLOUDY parameter sweep of temperature and density of two O II multiplets relative to H\(\beta\). (a) shows O II 4650 Å/H\(\beta\) and 7325 Å/H\(\beta\) diagnostic diagram, whereas (b) shows a [O i] 8446 Å/H\(\beta\) and [O III] 5007 Å/H\(\beta\) diagnostic diagram. Displayed here is a zoomed in version of the parameter sweep covering the log of the nebular densities vary from 8.60 - 9.20 in 0.05 dex (where the smaller circles indicate 8.60), and the effective temperature of the central source from \(6 \times 10^4\) - \(3.0 \times 10^5\) K in steps of \(2 \times 10^4\) K. The black squares mark the measured ratios on day 141.
The best fitting densities from the CLOUDY parameter sweep were in the range $6.3 \times 10^8$ - $1.0 \times 10^9$ cm$^{-3}$ and an effective temperature of $(1.8 - 2.4) \times 10^5$ K was found for the chosen radial distance, luminosity and abundances for day 141 post discovery. With information from the polarimetry and spectroscopy on conditions present in the expanding nova shell, an attempt to visualise the unresolved shell is presented in Fig. 4.12, where the models are valid for day 141 post-discovery. In the top six panels of Fig. 4.12, are the simulated emission of oft-seen oxygen emission lines in erupting nova systems. The O I line the strong emission produced from the simulated 6 level oxygen atom line of 8446 Å at the inside of the shell is in good accordance with observations, see also Fig. 4.13(b). The O II panels (middle column Fig. 4.12) simulate both the V1 and V2 multiplets that are shown relative to Hβ in Fig. 4.13(a) and discussed in 4.3.4 of this work. The [O III] panel demonstrate the locality and relative strength of the nebular 5007 Å line. The observed nebular lines of [O III] are due to de-excitation after the auroral 4363 Å transition. The bottom three panels are, from left to right are the ionic distributions of C, N and O, respectively.

4.3.4 Oxygen Flaring

It is well known that identification of emission lines in nova eruption spectra is difficult, largely due to blending and large Doppler widths. Table 4.2 and Fig. 4.13 demonstrate two cases where important diagnostic lines can easily be confused for other lines or are heavily blended without realisation. Through simple additive arguments based on $A_{ki}$ values it was found that the O II V 1 multiplet is comparable to the commonly identified N III and C III lines. As
there is mention but no modern discussion on O II being responsible for this ‘flaring’ feature, its nature was investigated. Collisional rates are of importance but are not well constrained.

Focusing on the five spectra presented in Fig. 4.6, we observe the ‘flaring’ episode around 4650 Å. This type of flaring episode is often attributed to
Figure 4.13: Temporal shape evolution of the blending lines in the area surrounding the 4341 Å and 4650 Å V2 and V1 oxygen multiplets. Days since detection are marked in the top-right-corner of each subplot in the V1 column. The most pronounced flaring episodes are between days 140 - 150 post-discovery, as seen in Fig. 4.6. Note in the V1 multiplet column plot (right hand side) a saddle-shaped He II line at 4686 Å fits the 4676 and 4696 Å lines if they are the red and blue wings of the He II line.

‘nitrogen flaring’, although in the photoionisation simulations (Fig. 4.11) the lines under derived conditions do not favour pumping of N III lines through
the Bowen fluorescence mechanism (see Section 1.6.1) nor the ionisation and subsequent recombination of the C III lines. Instead, the recombination of O II around 4650 Å appears responsible for the majority of the emission, with some contribution expected from pumping of the same and contribution from the Fe III 4658 Å line. The He II line at 4686 Å may contribute to the red end of the observed blend, which can be seen in Table 4.2 and Fig. 4.4, He II 4686 Å in a saddle-shaped line profile with emission components around ± 520 km s\(^{-1}\) would appear the same as the two longest wavelength lines in the O II multiplet in the region, i.e. at 4676 and 4696 Å. As a consequence of this the presence of He in a nova cannot be confirmed with only the presence of the He II 4686 Å emission line.

The concept of nitrogen flaring dates back to 1920 when Fowler (1920) identified an ‘abnormal’ strong spectral feature peaking around 4640 - 4650 Å. Following this, Mr. Baxandall and W. H. Wright exchanged letters regarding Prof. Fowler’s paper that resulted in an article by Wright entitled “On the Occurrence of the Enhanced lines of Nitrogen in the Spectra of novae” (Wright, 1921). It is noted there that the “4640 stage” occurs first on entering the nebular stage and then can occur recurrently.

In the data presented herein, the flaring episodes reoccur in stages corresponding to the cusps observed in the nova light curve during the transition from the auroral to nebular spectral stages. The proposition that N III is responsible for this flaring episode is justified in Basu et al. (2010) by a decrease in [O III] and the “great width of N III lines corresponding to a velocity of 3200 km s\(^{-1}\)”. In the observations, no decrease in [O III] was witnessed, but instead an increase. Also, the large Doppler width is not necessary if the feature is
assigned to the eight lines of the O II V1 multiplet, see Table 4.2. If these eight lines were fully resolved in the observations, further diagnostics could be conducted, as was done in Storey et al. (2017), except for higher density media. It must be noted that these results have only been shown for slower CO nova eruptions and the Bowen fluorescence mechanism may still be responsible for the “4640” feature observed early after eruption in faster nova events as well as a feature present in this region during the late nebular stage of some novae.

Concentrating on the nova during its auroral spectral phase, multiple components of the nova system are observed simultaneously. As the dust shell clears, the central source is revealed, evident from the rise out of the dust-dip in the optical and appearance of the super-soft-source in X-rays. From the suggestions of multiple ejection episodes from the flat-top-jitter phase, internal shocks can be expected, leading to a fracturing of the shell into cold and dense clumps. The nova shell is already expected to have been a shaped bipolar structure, implying that the polar and equatorial outflow do not have common distances from the central ionising source, which continues burning the residual nuclear material remaining on the surface.

While studying V356 Sgr (1936), McLaughlin (1955) found that Wright (1921) was probably mistaken in his derivation of N III being the dominant component in the “4640” blend. McClintock et al. (1975) analysed the origin of the same emission lines where a dense $10^{10} \text{ cm}^{-3}$ shell is ionised by the stellar super-soft X-ray component and collisionally. Warner (1995) states that during these spectral stages, the electron density of the visible gas is of the order $10^7 - 10^9 \text{ cm}^{-3}$. Under these density constraints, CLOUDY models reveal that the previously expected N III lines do not appear due to Bowen fluorescence.
but instead are heavily dominated by the aforementioned O II blend. With densities intermediate to those suggested by Warner (1995) and Derdzinski et al. (2017), the O II V1 multiplet can account for all the emission seen peaking around the 4640 - 4650 Å region on day 145 post-discovery spectrum in Fig. 4.4 (bottom panel).

Excess Hγ emission at 4340 Å may come from the O II V2 multiplet around 4340Å as well as the [O III] 4 363 Å auroral line, see Fig. 4.13. Supported in the presented observations as a decrease in the population of O I perceived along with a corresponding increase in the O II and O III species. The emission from N III at 4640 Å is associated with O III emission in the UV as it is also pumped through Bowen fluorescence. The C III line often associated with the 4650 Å region begins to be important at lower densities than those considered here (< 10^{7.7} cm^{-3}). The O II V1 multiplet appears under high-density and low-temperature conditions, suggesting that the emission originated from a cool and dense shell. Metzger et al. (2014) explored the conditions present in a nova outflow, concentrating on shocks, and Derdzinski et al. (2017) compared the rate of change of density and temperature from regular expansion to expansion with the presence of shocks. The top two panels of Fig. 2 in Derdzinski et al. (2017) compare well to the expected values from the photoionisation model grid displayed in Fig. 4.11 of this work.
Table 4.2: List of wavelengths of V1 and V2 O II multiplet wavelengths along with the lower and upper terms of their transitions respectively, from Storey et al. (2017). Possible blending lines are listed along with their A_{ki} values from the NIST database. The initial and final levels are given next to the line.

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4.4 Discussion

The slow novae with observed polarisation and visible nova shells are DQ Her, HR Del, V705 Cas, T Pyx, FH Ser, LV Vul and V4362 Sgr. These seven novae all share similarities with V5668 Sgr (2015) in terms of light curve shape and suspected white dwarf composition. It is even possible that DQ Her and V5668 Sgr coincidentally both have white dwarf spin periods of 71 s. It was found that densities of nova shells during the spectral stages studied in this work are poorly constrained in the literature and that the upper limit of $10^9$ cm$^{-3}$ in Warner (1995) may be an underestimation. The observed nebular lines of [O III] are due to de-excitation after the auroral 4363 Å transition.

An analytical problem that arises in this work is that the plasma diagnostics from the literature are only applicable to lower density gas, such that further simulations are required to properly numerically reproduce and understand nova shells during these early stages of evolution post-eruption novae. Correct identification of observed lines are therefore of great importance and there is strong evidence that lines get systematically misidentified in the literature. Analysis is hampered by the blending of many lines in erupting nova systems, which is exacerbated by their large Doppler broadening.

It is significant that an intrinsic change in absolute polarisation should be detected in the dataset, see Evans et al. (2002) for a discussion on polarisation detection regarding novae. From a qualitative review of polarimetric studies of novae it is the slow novae that have the largest observed intrinsic change in polarimetric measurements over time.

Densities above $10^8$ cm$^{-3}$ are rarely treated in novae, as higher densities,
due to shock compression, have been recently called for to explain the observed gamma-ray emission from novae. This lack of treatment for shock compression early in an erupting nova’s lifetime, see Derdzinski et al. (2017) is because densities of the ejecta at this stage of the eruption were previously thought to be of the order of $10^6 \text{ cm}^{-3}$ and therefore within the normal nebular diagnostic limits. The nova shell of V5668 Sgr is expected to be photoionised by low-level nuclear burning on the white dwarf, peaking in the X-ray (BB peak 14 - 30 Å). The emission-line spectrum is dominated by permitted, auroral and nebular lines, e.g. $\text{O}^{+}$, $\text{O}^{++}$, $[\text{O}^{+}]$. Referring to Williams (1994) where there is an in depth discussion on the optical depth of the $[\text{O}^{+}]$ 6300 + 6364 Å lines, it is understood that high densities and strong radiation fields are responsible for their strength in novae. These lines are not well reproduced in the CLOUDY modelling presented in this work. It is thought that the $[\text{O}^{+}]$ lines originate in the same zones as the dust resides where densities are greatest. It is known that some lines are particularly sensitive to temperature (such as $\text{O}^{+}$ transitions), whereas others are sensitive to density ($\text{O}^{++}$ recombination), but this does not always hold true outside the normal nebular diagnostic limits.

On the dust condensation timescale, a relation was derived by Williams et al. (2013), see their Fig. 2, where a comparison was made between a nova’s $t_2$ value and the onset of dust formation. Speed class relations are subject to scrutiny, see Kasliwal (2011), especially in flat-top-jitter novae as they vary considerably in their early light curves, unlike their faster and smoother counterparts. It is therefore prescribed that the $t_2$ and $t_3$ values for this type of nova should be taken from their final drop in the early observed maxima, giving a value for V5668 Sgr of around 60 days for $t_2$. The relation from Williams
et al. (2013) gives an onset of dust formation at day 80, in accordance with the beginning of the deep dust-dip marked in Fig. 4.1. In Evans et al. (2017), the relationship between the dust formation episode and the duration of the X-ray emission of V339 Del were studied where it was found that the end of the super-soft-source phase corresponded with the end of the strong dust-dip of the nova. This work found that the hard radiation field it is exposed to during the super-soft-source phase likely destroys dust.

Gamma-ray emission from novae has been proposed to be intrinsically linked with the nova shell’s geometry. In order to explain observed gamma emission from novae, shocks between a slow-dense-ejecta and a faster-chasing-wind appear necessary, e.g. Finzell et al. (2017); Cheung et al. (2016). The 55 day period over which gamma rays were detected for this nova in Cheung et al. (2016), during the flat-top-jitters of Fig. 4.1, implies a lengthy cycle of shocks between the slow dense ejecta and fast chasing wind, possibly leading to strong shaping of the nova remnant. The current understanding of gamma-emission from classical novae suggests that a denser equatorial waist and lower density polar ejecta should exist for this nova, which is strongly supported by the polarimetric and spectroscopic observations presented in this work as well as in the NIR study conducted by Banerjee et al. (2016).

Morpho-kinematic modelling of nova shells suggests that DQ Her-like novae are seen edge on and that the long eruption light curve is due to reprocessing of light in the dense outflow.
4.5 Conclusions

The observations reveal variability of the absolute polarisation before and after nights that hint towards internal shocks in the nova outflow. Along with the available high-quality gamma, X-ray, UV and IR observations on this nova, the polarimetry allowed for the estimation of the nova shell P.A. and provided information on the dust grains causing the scattering. The spectroscopy then allowed for derivation of the physical conditions on separate nights, including outflow velocity and structure, nebular density, temperature and ionisation conditions. Following on from this extensive analysis, morpho-kinematic and photoionisation models were formulated and combined to give a deeper insight into the nova system as a whole. Finally it is noted that, for slow novae in particular, the regularly referred to ‘nitrogen flaring’ is in fact more likely to be ‘oxygen flaring’.
Table 4.3: H\(\beta\) flux measurements on the days after detection relevant to the ratios in table below. The flux measurements are in units of ergs/cm\(^{-2}\)/s/\(\AA\) and have not been corrected for extinction. In the long table below the ratio of observed line fluxes to that of H\(\beta\) are presented over the same 10 nights covering days 114, 116, 120, 122, 123, 130, 141, 143, 145 and 153 post-discovery respectively. The relevant spectra can be seen in Figs. 4.5 and 4.6. The H\(\beta\) fluxes have been normalised to 100 from the values stated for the relevant dates. As H\(\beta\) flux is dependent on the filling factor of the nova shell the quoted line ratios are sensitive to such. No reddening correction has been applied to the values in the following table.

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Chapter 5

An Old Nova Shell: GK Per (1901)

5.1 GK Persei

With a distance of 470 pc (McLaughlin, 1960; Harrison et al., 2013), GK Per (1901) is a nearby, historic, and spectacular post-nova source. As the nearest and brightest of only two classical nova remnants observed within a PN to date, the other being V458 Vul (Wesson et al., 2008b; Roy et al., 2012), it offers the best chance to study the evolution of nova eruption debris within a PN and thus potentially aids the understanding of both types of object.

As an old, bright, and close nova shell with published kinematics, GK Per is an ideal object to study and enrich knowledge regarding the mechanisms at work in a nova system, see Fig. 5.1. The 1901 GK Per nova event was possibly its first (Bode et al., 2004) and it has emerged as a well-studied and
peculiar object. The central system has changed state, in line with hibernation theory (Shara, 1981) although sooner than the theory predicts. It was the first classical nova remnant discovered in X-rays (Balman, 2005) and non-thermal radio emission (Seaquist et al., 1989), implying an interaction with pre-existing material surrounding the system. Bode et al. (1987) first observed that a probable PN surrounds GK Per and thus is a likely candidate for the preexisting material detected in radio and X-rays. The spectacular superluminal light-echo observed by Wolf, Perrine and Ritchey in the years directly following the nova event (explained by Couderc, 1939 as the forward scattering of light along dust sheets) reveal an abundance of material in the vicinity of the system, see the 1901 from Lick Observatory shown in Fig. 5.3 adapted from Hessman (1989). The first direct image of the nebulosity associated with the classical nova event was taken in 1916 (Barnard, 1916).

GK Per has the longest period classical nova progenitor binary known to date, see Table 5.1, with a carbon deficient secondary star (Harrison and Hamilton, 2015). After undergoing several dwarf nova outbursts, observed since 1963, the object has been reclassified as an intermediate polar, which implies the presence of a strong magnetic field (1-10 MG, Watson et al., 1985). The dwarf nova outbursts on GK Per were first observed in 1963 and have a recurrence timescale of 3 years and a duration of 2 to 3 months. However, strong optical outbursts can be traced back to 1948 in the AAVSO data, once the central system had settled down to its quiescent state. Two more outbursts followed the 1948 eruption in quick succession, one in 1949 and another in 1950 (Sabbadin and Bianchini, 1983).

The central system is seen drifting through the local environment at about
Figure 5.1: Positions of the slits from MES-SPM overlaid on the stacked Hα Mayall image first presented in Shara et al. (2012b). The slit marked 1 was placed at a P.A. of 45°, slit 2 at 30° and slit 3 at 9°. All three slit positions cover the jet-like feature to the NE of the nova remnant as well as sections of the nova shell. Slit 1 & 2 observations were obtained on 2014-Nov-28 and slit 3 on 2015-Mar-27/28, see Table 5.2(a). Slits marked A, B, and C are those at P.A. = 173°, 31°, and 49°, respectively. It is from these slit positions that the PV arrays were simulated in Figures 5.4, 5.5, and 5.6. The overlaid boxes cover the knots used in the same figures.

45 km s⁻¹, a value derived from proper motion studies (Bode et al., 2004). X-ray and radio observations reveal evidence of interaction between the SW
quadrant of the shell with pre-existing material (Anupama and Kantharia, 2005; Balman, 2005; Takei et al., 2015). The apparent box-like appearance of the nebula has long been observed, e.g. Seaquist et al. (1989). In the past arguments for flattening of the southern part of the shell through interaction with pre-existing material would not explain the flattened northern part of the shell. There have, however, been hints of an intrinsic symmetry to the nova shell such as the prolate structure proposed in Duerbeck and Seitter (1987). They suggested a broken prolate structure, a missing southern cap, and an
extended northern cap spanning a P.A. of 130 - 300°. Lawrence et al. (1995) conducted three-dimensional Fabry-Perot imaging spectroscopy of GK Per’s nova shell, where they presented channel maps and a spatial model.

It had been previously believed that the expanding nova remnant was decelerating at a faster rate, based on rigorous analysis of proper motions and radial velocities of individual knots (Liimets et al., 2012b) (hereafter L12) came to the conclusion that the system is decelerating at a rate of at least 3.8 times
slower than that derived by Duerbeck (1987). An eventual circularisation of the shell was proposed in L12. From considerations of the data presented in L12 as well as others, such as Duerbeck and Seitter (1987); Lawrence et al. (1995); Tweedy (1995) and Shara et al. (2012b), the opportunity to explore the structure and kinematics of the GK Per nova shell was undertaken. Knots associated with the shell are expanding almost radially away from the central system and have been followed over the decades; high-quality spectroscopy is also available. New data were collected to complement those found in the archives. GK Per exhibits a distinct arc of emission to the NE of the nova shell that is reminiscent of a jet but whose origin has not been settled (Bode et al., 2004; Shara et al., 2012b). This study aims to determine the relationship between the expanding knotty debris, the dwarf nova winds, the nature of the jet-like feature and the planetary nebula.

Table 5.1: GK Per, characteristics of the central binary system. T = Period; e = ellipticity; inc = inclination; $M_1$ = WD mass; $M_2$ = Mass of companion. Orb T, $M_1$, $M_2$ and e = 1 are from Crampton et al. (1986); whereas, e = 0.4 is from Kraft (1964); WD T is from Watson et al. (1985); and inc is taken from Morales-Rueda et al. (2002)

<table>
<thead>
<tr>
<th>Orb T</th>
<th>WD T</th>
<th>e</th>
<th>inc(°)</th>
<th>$M_1$</th>
<th>$M_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.997 d</td>
<td>351 s</td>
<td>0.4 or 1</td>
<td>50-73</td>
<td>0.9M$_\odot$</td>
<td>0.25M$_\odot$</td>
</tr>
</tbody>
</table>

This chapter follows the structure outlined here: Observations, both archival and new, are presented in Section 5.2; in Section 5.3 the analysis of the observations is explained; a discussion follows in Section 5.4; and conclusions in Section 5.5.
5.2 Observations

5.2.1 Imaging

Using the 2.3 m Aristarchos telescope in Greece, new imaging was collected of GK Per on 27 August 2014. The observations consisted of two narrow-band filters that cover Hα and [N ii] with exposures of 1800 s in each filter. The seeing was of the order of 2 arcseconds. A 1024 × 1024 CCD detector was used where each 24 μm square is ≡ 0.28 arcsec pixel$^{-1}$ after 2 × 2 binning, see Section 2.2.1. The observations, requested by the author and collected by Dr. Panos Boumis and Ms. Maria Kopsacheili, are summarised in Table 5.2(a). The imaging data were reduced and world coordinate system matched using standard routines in IRAF.
Table 5.2: observations: (a) are newly acquired for this work whereas (b) were obtained from data archives.

(a)

<table>
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<tr>
<th>Date</th>
<th>Type</th>
<th>Telescope</th>
<th>Instrument</th>
<th>Filter CWL/FW(Å)</th>
<th>P.A.</th>
<th>Exp. (sec)</th>
</tr>
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<td>Hα 6567/17</td>
<td></td>
<td></td>
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<tr>
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<td>Imaging</td>
<td>Aristarchos - 2.3m</td>
<td>LN CCD</td>
<td>[N ii] 6588/17</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>Spectroscopy</td>
<td>SPM - 2.12m</td>
<td>MES</td>
<td>[O iii] 4984/60</td>
<td>45°</td>
<td>1800</td>
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<td>SPM - 2.12m</td>
<td>MES</td>
<td>[O iii] 4984/60</td>
<td>9°</td>
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</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th>Date</th>
<th>Type</th>
<th>Telescope</th>
<th>Instrument</th>
<th>Filter/grism CWL/FW(Å)</th>
<th>P.A.</th>
<th>Exp. (sec)</th>
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</thead>
<tbody>
<tr>
<td>1995-Nov-8</td>
<td>Imaging</td>
<td>HST - 2.4m</td>
<td>WFPC2</td>
<td>F658N 6591/29</td>
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<td>1997-Aug-1</td>
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<td>WFPC2</td>
<td>F658N 6591/29</td>
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<td>ALFOSC</td>
<td>Hα 6577/180</td>
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<td>3600</td>
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<tr>
<td>2010-Feb-6/7</td>
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<td>KPNO- 4m</td>
<td>CCD Mosaic</td>
<td>Hα 6563/80</td>
<td></td>
<td>7440</td>
</tr>
<tr>
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<td>WISE - 40cm</td>
<td>Survey Camera</td>
<td>B3 (12μm)</td>
<td></td>
<td>4422</td>
</tr>
<tr>
<td>2007-Sep-3</td>
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<td>NOT - 2.5m</td>
<td>ALFOSC</td>
<td>g17 6600/500</td>
<td>31°</td>
<td>3600</td>
</tr>
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<td>NOT - 2.5m</td>
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<td>g17 6600/500</td>
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<td>1800</td>
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<tr>
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<td>NOT - 2.5m</td>
<td>ALFOSC</td>
<td>g17 6600/500</td>
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<td>1500</td>
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<td>g17 6600/500</td>
<td>312°</td>
<td>1800</td>
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<td>KPNO - 4m</td>
<td>RC-Spec</td>
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<td>89.7°</td>
<td>9600</td>
</tr>
</tbody>
</table>
5.2.2 Spectroscopy

Echelle spectroscopic data were obtained in order to measure the expansion velocities of several interesting knots, to build a more complete view of the remnant, and to examine the jet-like feature. These were obtained using MES at SPM (Meaburn et al., 2003), Section 2.2. The data were collected over the course of two observing periods, November 2014 and March 2015, and in three different positions. The slit positions are overlaid on an image of the system in Fig. 5.1.

5.2.3 Archival data

Archival imaging and spectroscopy from different epochs and telescopes were obtained from the NOAO, NOT, IRSA, and MAST databases. The archival observations are from the Hubble Space Telescope, the WISE satellite, the Nordic Optical Telescope and the Mayall telescope, and are summarised in Table 5.2(b). The principal data sets used were Mayall and HST observations reported by Shara et al. (2012b) (hereafter S12, see Fig. 5.2), NOT data by L12, and WISE nova data, first studied in Evans et al. (2014a). Further details and analyses of these data are contained in the aforementioned references. Here, the data were collated and reduced in the same manner as the more recent MES and Aristarchos observations in IRAF.

Archival echelle spectroscopy 2D line profiles (or PV arrays, see Section 3.1) were generated for the six ALFOSC P.A. listed in Table 5.2(b). For each P.A. there were between four and eight individual knots or knot complexes, for which PV information could be subtracted. The PV arrays were created
by comparing rest wavelengths to the position of the strongest spectral lines of wavelength calibrated spectra. In this way velocity scales were made available for subsequent analysis using the Doppler-redshift relation.

5.3 Analysis

The PV arrays were mostly created from archival ALFOSC data and for one P.A. they are complemented by more recent echelle spectra from MES-SPM (P.A. = 30° and 31°, respectively, see Table 5.2 and Fig. 5.1), allowing for constraints to be made on spatio-kinematics of individual systems. The PV arrays were simulated using the morpho-kinematic code SHAPE (Steffen et al., 2011).

Modelling with SHAPE is carried out on different spatial scales. The nova shell as directly modelled from observations of the knots is described first in Section 5.3.1. Whereas, Section 5.3.2 explores the structure of the overall distribution of the knots and Section 5.3.3 reveals new results on the jet-like feature associated with the remnant.

5.3.1 Modelling individual knots

In the first instance, a direct model from published data associated with L12 was made. For this initial model, 115 knots (from the online table of L12) with the most substantial data were modelled as individual cylinders with expansion velocities, distance from the central star, P.A., and inclinations derived using the prescriptions of L12. In order to achieve this, each individual knot was modelled as a cylinder with $x$, $y$, $z$ positions in arcseconds specified with the
translation modifier; the P.A. and inclination were replicated using a rotation modifier; and the expansion velocities specified explicitly with the velocity modifier. The modelled microstructure in panel (c) Fig. 5.8 is noted here. Later a radial velocity component was added to knots to match the ALFOSC PV arrays in Figures 5.4, 5.5, and 5.6. Irregularities in knot structure were then simulated by modifying the cylinder primitives to match their respective PV arrays using bump, stretch, and squish modifiers. For another recent application and further explanation of these shape modifiers see Clyne et al. (2015).

High-resolution images from several epochs were analysed in order to gain further knowledge on the interaction and fragmentation of clumps. Variations in the knot morphology and velocity distribution between different clump systems can be seen in Figures 5.4, 5.5, 5.6, and 5.7. The long-slit spectroscopy discussed in L12 was re-analysed with a different intent, with the addition of new data. As L12 derived the kinematics based on single Gaussian peaks, an attempt to explore further and examine the extended profiles of individual knots was undertaken. To gain an understanding of the knot kinematics and morphology, spatially orientated PV arrays were created using IRAF and Octave (Eaton et al., 2015). The PV arrays were difficult to reproduce with SHAPE owing to the amorphous nature intrinsic to the knots and the complex velocity field in which they reside.

Possible mechanisms were explored to explain the irregularities observed in the individual knot shapes, including dynamical instabilities with a main contributor thought to be the fast periodic winds produced by the frequent dwarf nova episodes. Interestingly, clumping of the ejecta began before the
dwarf nova episodes had been observed first in 1963, as the clumpy nature of the shell is already noticeable in a photographic plate from a 1953 Digitized Sky Survey image taken with the Palomar 48”, see L12. The initial clumping was most likely due to early interacting winds (Balman, 2005). In Fig. 5.4 extended velocity-tails of individual knots are apparent; these tails appear wavy, which indicates their complex velocity structure. The longest tails in velocity space are closer to the central system in the plane of the sky (the lower row in Fig. 5.4 is closer to the central star in the plane of the sky than the upper row and thus has a longer tail in velocity space since more velocity information is contained in these knots owing to their inclination towards the observer), hinting that their true structure is similar to those with the ‘wavy’ tails, most obvious in the HST imaging of S12 (see Fig. 5.2), attributed in this work to shaping by dwarf nova winds (see Sect. 5.4). The longer tails present towards the central system was shown previously by L12, see their Fig. 8, where they mention that this could be a projection effect. Looking at Fig. 5.5, the first row demonstrates overlapping of knots that can be separated by morpho-kinematic modelling, whereas the second row demonstrates clear evidence of a bow-shock and low expansion-velocities attributable to interaction between knots.
Figure 5.4: Examples of single knots progressing over time (2007-2014) and their corresponding PV array and morpho-kinematic SHAPE simulations. Spatial extent is 12.5 arcseconds on each side, and the velocity ranges are 500 km s$^{-1}$. The central star is at (0, 0) in the imaging panels and the angle of position is related to their proper motion direction. Positive values represent north in the $y$ direction and west in the $x$ direction. On the NOT panels the overlaid slit width and positions are shown. The Aristarchos and NOT panels in the bottom row are contaminated by the central star leading to a very strong contrast between knots and star. Here, and in Figures 5.5 and 5.6 the displayed knots are positioned along the observed slit axis highlighted in Fig. 5.1, where the top row corresponds to a slit P.A. of 49° and the bottom row to 173°. The spatial axis distance from the central star is positive towards the top of the slit and negative towards the bottom.
Figure 5.5: Same as in Fig. 5.4 except with examples of more than one knot in each image. Spatial extent is 12.5 arcseconds and velocity scales are 500 km s\(^{-1}\). The top row shows the separation of knots just to the bottom right of the multiple knots covered with the 173° slit, the bottom row corresponds to a P.A. 49°. The knot marked ‘X’ can be seen to break away from the knot covered by the slit next to it in HST images from 1995 and 1997; the corresponding PV array of this knot shows ongoing separation of knots in this clump.
Figure 5.6: Same as in Figures 5.4 and 5.5 except with additional epoch PV information. The knots here are along an axis of symmetry of the nova shell (slit P.A. of 30° and 31° for the ALFOSC and MES observations respectively). The ALFOSC PVs correspond to the 2007 NOT image and the MES, [N ii] 6583.39 Å, PVs correspond to the Aristarchos observations epoch.
Figure 5.7: Radial profiles of five bright knots from the ALFOSC slit with PA = 31° in the top row, and the corresponding MES knots with slit at PA = 30°, in the bottom row. The knots displayed are seen in their [N II] 6583.39 Å emission line, knot ‘a’ corresponds to the top row of Fig. 5.6 and knot ‘e’ to the bottom knot of the same figure.
The difference in the PV arrays in Fig. 5.6 over the seven year interval appear significant. The MES data has higher velocity resolution ($22 \text{ km s}^{-1}$ versus $32 \text{ km s}^{-1}$), but lower sensitivity, see Table 5.2. As can be seen in Fig. 5.6, top row of panels, the ALFOSC PV array and MES PV array show differences in position as the proper motion and velocity-structure differences are due to a combination of different sensitivity and resolution, and are due to a slight ($1^\circ$) difference in the slit positions. However, the $1^\circ$ difference in P.A. gives a separation of the slits of around 1” at a distance of 60” from the central system, which is within the seeing of both sets of observations. In addition the MES slit is 3.8” wide on the plane of the sky. The MES spectrum was placed $1^\circ$ off the previous ALFOSC spectrum as to better cover the jet-like feature discussed later in this chapter.

The pattern of a bow shock around one or more knots remains evident with comparison to the SHAPE model, see the bottom row of Fig. 5.4 and the top row of Fig. 5.5. The bow shock is apparent by the spread in velocity of the top of the knot in comparison with the higher velocity narrow tail. Also, in Fig. 5.5, the knots marked ‘X’ are seen to undergo shaping changes and bifurcation over the time interval of the presented observations. Tracing these knots back to the HST imaging campaign of S12, they are seen to separate from the knot complex covered by the slit in the same panels as knot ‘X’. In Fig. 5.4 the knot at the upper panel appears to have a tail that is bending back; this knot has a radial velocity of about -650 km s$^{-1}$ and the knot possibly associated with it to the left has a radial velocity of -570 km s$^{-1}$ $31^\circ$ in the ALFOSC long-slit observation and -530 km s$^{-1}$ seven years later in the MES data, see knot ‘c’ in Fig. 5.7 and Table 5.4, which may be indicative of knot
changes due to the complex dynamics of the environment. Note that Fig. 5.7 is complemented by Table 5.4 where the velocity widths and signal-to-noise ratios of the observations are shown.

Also, note that the analysis of observation leads to a small number of knots (8 out of 115) that have large uncertainties in their deprojected true positions within the population of knots; these uncertainties are caused by large relative errors in one or more components of the deprojected distance estimates, or else are ballistic knots like those discussed in S12.

Examination of the radial velocity distribution with respect to $x, y$ positions of the knots is suggestive of an overall symmetry in the total distribution. The low-resolution channel maps of Lawrence et al. (1995) show similar symmetry on reinspection, see Fig. 5.9.

### 5.3.2 Overall distribution

The second modelling approach involved testing of basic shapes to fit the overall distribution of the knots with x-y positions and radial velocity measurements; the sample size was increased to 148 through the inclusion of knots covered in the new observations, see the Table 5.5. As an example of the versatility of this approach consider a sphere with a thin shell and the knots added by means of a texture modifier given the appropriate filling factor. The positions of the knots can be matched by adjusting their position on the shell so that the model and actual PV arrays agree. The sphere can be deformed appropriately to simulate the somewhat box-like appearance of the remnant, or it can be manipulated to have a bipolar, prolate or oblate shape. The size of the structure can be easily modified to see if the same shape can match
Comparison of the brightness distribution between epochs give clues on the sequence of which components and sides started becoming shock illuminated. However, a sphere primitive was found to be unable to reproduce the channel maps of Lawrence et al. (1995).

This second approach was then applied to several common nova shell morphologies that can be manipulated in the same ways as the sphere. To achieve the best fit an inclination, P.A., and expansion velocity were specified (see Table 5.3) implemented using the rotation and velocity modifiers in shape. To simulate the knots a texture modifier was added and the knots were projected radially through the thickness of the cylindrical shell. Structure was added subsequently to the cylindrical model to account for spatial and Doppler shift irregularities. This structure consists of polar cones, see Fig. 5.8 and Table 5.3, the polar features have low-equatorial-velocities and higher-polar-velocities.
Figure 5.8: Panel (a) shows the red-blue Doppler distribution from observed radial velocities of 148 knots overlaid on an image from the Mayall telescope; North is up and East is to the left. Panel (b) shows the fit of the cylinder on the observed radial velocity distribution, as is observed in the plane of the sky. Panel (c) shows the model fit to the deprojected observations of L12 in the x - z plane, looking top down on the nova shell, i.e. a 90° rotation. Note the extended ballistic knots and the larger plotted area here.
Table 5.3: Best fit SHAPE orientation and velocity model parameters of the GK Per nova shell.

<table>
<thead>
<tr>
<th></th>
<th>P.A.</th>
<th>inc</th>
<th>R_{in}</th>
<th>R_{out}</th>
<th>L</th>
<th>D</th>
<th>V_{exp}</th>
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<tbody>
<tr>
<td>O</td>
<td>120</td>
<td>54</td>
<td>0.093</td>
<td>0.109</td>
<td>0.125</td>
<td>0.093</td>
<td>1000</td>
</tr>
<tr>
<td>E</td>
<td>120</td>
<td>54</td>
<td>0.027</td>
<td>0.091</td>
<td>0.027</td>
<td>0.080</td>
<td>750</td>
</tr>
<tr>
<td>W</td>
<td>120</td>
<td>126</td>
<td>0.027</td>
<td>0.091</td>
<td>0.027</td>
<td>0.080</td>
<td>750</td>
</tr>
</tbody>
</table>

The size of the shell features are normalised to the shell’s size during the 2007 observations of L12. P.A. = P.A., inc = inclination, R_{in} = inner radius of feature, R_{out} = outer radius of feature, L = length, D = distance to central binary, V_{exp} = expansion velocity. With regards to the features O = outer cylinder, E = eastern cone, W = western cone.

Previous efforts towards the understanding of the shell structure were unable to derive the nova shell’s true morphology; the shell is almost consistently referred to as roughly circular and asymmetric. The flattened SW part of the shell has been given much attention since it is the location of interaction with pre-existing material; however, previous authors failed to address the flattened NE part of the shell, although it is remarked upon in several works, e.g. Lawrence et al. (1995). L12 argues for the eventual circularisation of the shell; however, here is found that the main shell most probably consists of a barrel-like equatorial structure (Fig. 5.8; Table 5.3) and will therefore not experience such a progression towards spherical symmetry. The P.A. derived for the nova shell here fits that of the fossil bipolar PN (Scott et al., 1994). In the literature Duerbeck and Seitter (1987) provided a symmetric model for the morphology by using a similar methodology to that employed here. Their model has a prolate structure, but an axial ratio closer to 1:1 if found here. More importantly, it is found that the equatorial and polar re-
Table 5.4: Comparison of RV profiles of the five brightest knots in common of the 30 and 31 slits. ALF = ALFOSC on the NOT telescope, MES at San Pedro Martir.

<table>
<thead>
<tr>
<th>Knot</th>
<th>FWHM km s(^{-1}) MES</th>
<th>FWHM km s(^{-1}) ALF</th>
<th>FW10% MES</th>
<th>FW10% ALF</th>
<th>SNR MES</th>
<th>SNR ALF</th>
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<tbody>
<tr>
<td>a</td>
<td>112</td>
<td>114</td>
<td>297</td>
<td>214</td>
<td>102</td>
<td>106</td>
</tr>
<tr>
<td>b</td>
<td>54</td>
<td>59</td>
<td>97</td>
<td>112</td>
<td>47</td>
<td>27</td>
</tr>
<tr>
<td>c</td>
<td>75</td>
<td>120</td>
<td>177</td>
<td>243</td>
<td>35</td>
<td>46</td>
</tr>
<tr>
<td>d</td>
<td>116</td>
<td>92</td>
<td>266</td>
<td>254</td>
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<tr>
<td>e</td>
<td>164</td>
<td>106</td>
<td>231</td>
<td>305</td>
<td>81</td>
<td>94</td>
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</table>

regions are perpendicular to the orientation suggested by Duerbeck and Seitter (1987), Seaquist et al. (1989), and Anupama and Prabhu (1993). The newer data, however, firmly indicates that this previous model cannot fit the overall Doppler distribution of the knots or channel maps of Lawrence et al. (1995), see Fig. 5.9 for the fit of the model to their channel maps and Fig. 5.10 for an overlay of the model on their z projection of the shell. Lawrence et al. (1995) interpreted the structure of GK Per as “approximately spherical (with) striking deviations in the symmetry.” The aforementioned deviations were (i) a northern blue-shifted region, (ii) a low-radial-velocity “central” region and (iii) a small bulge to the south-southwest. These apparent irregularities can be explained within the context of the model as (i) the blue-shifted face of the cylinder, (ii) the northern and southern sides of the main barrel shell, and (iii) a combination of the eastern-polar-feature (blue-shifted knots) combined with some knots attributable to the main shell (those that are red-shifted). A comparison of the fit of two separate proper motion studies of the knots associated with the shell (L12 and S12) can be seen in Fig. 5.11, and a comparison of the radial velocity measurements of L12 to the model can be seen in Fig. 5.12.
Figure 5.9: Channel maps from Lawrence et al. (1995) (dots) compared to the scaled morpho-kinematic model (overlaid shadow). Frames 1-14 start at -840 km s\(^{-1}\) and go up to 980 km s\(^{-1}\), the velocities being relative to the [N \text{II}] 6583 Å emission line in steps of 140 km s\(^{-1}\) with a resolution of 240 km s\(^{-1}\). The first four frames have the red side dominated by H\(\alpha\) emission (the first two extremely so and whose SHAPE models have been left out for this reason) and the final frame is a sum of all those previously overlaid with the red-blue Doppler model distribution. Influence of the H\(\alpha\) emission is visible in the form of the persistent S/SE feature up to frame 7.
Figure 5.10: Z cut (i.e. viewed side on) model presented by Lawrence et al. (1995) (greyscale, adapted from their Fig. 6, panel C) with the SHAPE model overlaid on the observations (the mesh). The model polar features trace out the morphology well.
Referring to Fig. 5.8, several knots possibly associated with the western polar region of the oblate structure (i.e. along the minor, NW-SE, axis of the cylinder) have higher expansion velocities than the model suggests, which is a likely analogue to the diametrically opposed feature (iii) mentioned above. These features could be due to recent significant interaction of these knots with pre-existing circumstellar material which is enhanced in this direction (see Fig. 5.15 bottom panel). Finally, the inhomogeneous nature of the circumstellar matter evident in Fig. 5.15 gives a natural explanation as to why some knots in this direction are not significantly slowed and appear as outflows with large spatial displacements in Fig. 5.8(c). Their displacement may be apparent as the majority of such knots have substantial errors in their distance determinations.

With reference to Table 5.5 the positional matching of knots between the two WCS matched data sets was done through comparison of knot shapes and centroids with consideration of their expected motion in the plane of the sky. Given that additional positional matching errors may arise from flux variations along a single knot between the two epochs (see S12, Fig. 10) or misidentification of a knot, average errors are of the order of ± 1” and maximum errors are expected to be up to 3”. The errors in the radial velocity are of the order of ± 22 km s⁻¹. As the MES wavelength range does not fully cover the three [N ii] 6548 Å, Hα 6563 Å, and [N ii] 6583 Å emission lines, the following measurements were done with the [N ii] 6583 Å where possible, and the [N ii] 6548 Å elsewhere; the Hα 6563 Å line velocities were measured as a sanity check.
Figure 5.11: Fit of the model presented here to the proper motion versus radial distance. The filled black squares are proper motion measurements from the online data table of L12 in terms of radial distance. The deviation from pure radial expansion is accounted for by the polar cones (blue overlay). The red corresponds to the cylinder fit to data presented in L12.

Figure 5.12: Equivalent fit to Fig. 5.11, upper panel, in L12. The yellow represents the main cylindrical shell, whereas the red and the blue cover the polar features.
**Criss-cross mapping**

Criss-cross mapping is a relatively new technique presented in Steffen and Koning (2011) for the first time, see Akras and Steffen (2012) for an application. The technique stretches observed proper motion vectors to infinity to see where they converge, which leads to clues in the analysis of internal proper motions of gaseous nebulae.

Applying this technique to the proper motion measurements in the online data table of L12, see Fig. 5.13, an apparent offset of about 2” to the north of the geometric centre of the nova shell is observed. Apart from the nice radial outflow seen in these maps, pairing Fig. 5.13 with the proper motion measurement of the central star of 0.015” year$^{-1}$ (Bode et al., 2004), a kinematical age of 130 years is obtained for the offset of the geometrical centre in good agreement with the age of the shell. However, these results lie within the observational noise and should be taken with caution. Another interpretation for the geometrical offset is that the nova shell is partially bipolar and that the expansion is not exactly radial at mid-latitudes (private communication with Dr. Wolfgang Steffen).
Figure 5.13: Criss-cross mapping technique applied to GK Per observations. The criss-cross map shows a radial outflow with a discernible shift 2" to the north, although within the noise of the observations.
5.3.3 Kinematics and imaging of the jet-like feature

Deep imaging reveals a faint jet-like feature (Anupama and Prabhu, 1993) which protrudes from the NE of the nebula and stretches out into finger-like structures until it eventually disappears, see Fig. 5.15, top panel. Previously there have been several theories for the origin of this enigmatic feature, (Anupama and Kantharia, 2005; Bode et al., 2004; Shara et al., 2012b). Light-echo contours over IRAS imagery (Bode et al., 2004) hinted that it predated the nova shell. Shara et al. (2012) discussed three possible origins for this feature including a Mira-like tail (which they finally rule out), a collimated jet, and a rotating feature.

New observations presented here, corrected for the barycentric and heliocentric velocities towards the source, give averaged radial velocities over three intersecting slit P.A. of 14, 14, 16, and 17 ± 22 km s\(^{-1}\) for the [O\(^{\text{iii}}\)] 5007 Å, [N\(^{\text{ii}}\)] 6548 Å, H\(^{\alpha}\) 6563 Å, and [N\(^{\text{ii}}\)] 6583 Å emission lines, respectively. The full width at half maximum for each emission line is around 30 km s\(^{-1}\), see Fig. 5.14. The inclination (54°) and P.A. = 120° proposed here for the nova shell pose a problem if they are related to the P.A. of the jet (P.A. ∼ 30°) or related to the orientation of the underlying binary. Even if the P.A. for the shell in this work is dismissed and the work of Bianchini et al. (1982) is considered, where they derived an inclination angle of 66° for the accretion disk, then if the jet was indeed launched by the accretion disk larger radial velocity measurements would be expected rather than those of a typical PN. Since the new kinematic data strongly suggests a low velocity for the jet-like feature, the idea that the feature may be an illuminated section of the ancient PN is
Figure 5.14: Top panel: Resolved [O III] 5007 Å line of the jet-like feature taken on 2014-Nov-28 at a P.A. = 30°, as illustrated in Fig. 5.1. The two lower panels are of the Hα 6563 Å and [N II] 6583 Å spectral lines from a slit placed at P.A. = 45°. These observations are summarised in Table 5.2(a).

put forward. A well-defined hourglass shaped nebula could naturally account for the curvature of the jet-like feature. Low-velocity features are regularly seen at the waist regions of extreme bipolar PNe, e.g. NGC 2346 (Kastner and Gatley, 2000). Evidence for the association of this feature with the PN
Figure 5.15: Top panel: Binned and stretched Hα image from the Mayall telescope where the jet-like feature is clearly visible to the NE, while the surrounding PN can be seen. Bottom panel: WISE band 3 (resolution = 6.5″) illustrates the IR emitting material with which the optical shell is colliding. Strong outflow in the polar directions derived from the model presented here can be seen.
shell is seen in the faint enhancement of the Hα and [O III] 5007 Å lines at the interaction region to the SW of the nova shell, as noted by Anupama and Kantharia (2005), Balman (2005), and Takei et al. (2015). In further support of this hypothesis Anupama and Kantharia (2005) find emission extending from 20 km s$^{-1}$ to -25 km s$^{-1}$ from the 21cm H I line, with emission near -5 km s$^{-1}$ west of the nova shell corresponding to the shell’s ‘blue’ side. This suggests the ‘jet’ belongs to the red-shifted eastern bipolar lobe of the ancient surrounding PN.

5.4 Discussion

The newly derived morphology of the nova shell in this work is consistent with observations of the GK Per system. One of the main findings in L12 was that there was no significant deceleration of the knots in the SW quadrant of the nova shell, yet it had been long believed that the shell is experiencing a stronger interaction with circumbinary material in this quadrant (Duerbeck and Seitter, 1987), although L12 found a higher kinematical age for the NE part of the nova shell. In Section 5.3.3 it was shown that the jet-like feature must simply be an illuminated part of the ancient PN. A contrast in the shape of the PN and nova shell would lend valuable clues to the efficiency of the underlying shaping mechanism.

As there has been some discussion on the effect of the surrounding pre-existing material on the shell morphology, the bullet crushing time (Redman et al., 2002; Poludnenko et al., 2004) was calculated based on density ratios and clump properties, see Fig. 5.16. The bullet crushing time is the hydrody-
namical timescale of an individual knot $t_d$ and is given by $\chi$, the density ratio of the circumbinary material to that of an individual clump, the clump radius $R_c$, and the velocity of the clump moving through the local medium is $V_s$:

$$t_d = \frac{R_c}{V_s}. \quad (5.1)$$

![Figure 5.16: Bullet crushing time calculations. The blue line (dot-dashed) shows the maximum length of time, depending on density, that an individual clump would remain in motion given observed constraints on the system. The red line (dashed) represents the shortest amount of time. The area of maximum likelihood is the area between the curves.](image)

The density estimates of the circumbinary material of two different works

The density estimates of the circumbinary material of two different works
have been considered (Anupama and Kantharia, 2005; Takei et al., 2015). The radius of a ‘bullet’ or knot was taken to vary between $5 \times 10^{14}$ to $1 \times 10^{15}$ cm and the density from $1.5 \times 10^3$ cm to $5.5 \times 10^3$ cm, following S12 and L12, see Fig. 5.16. Density estimates from Takei et al. (2015) lead to hydrodynamic timescales of 333 to 1965 years, whereas those of Anupama and Kantharia (2005) vary from 1775 to 8239 years. Using the densities mentioned above, an estimate on the hydrodynamic timescale according to the velocity half-lives of S12 (58 years and 220 years) and of L12 (100 to 6000 years). L12 made their velocity half-life calculation based on a value for the initial expansion velocity of $1340$ km s$^{-1}$ from Pottasch (1959) and compared it to their own observations. However, there is a range in the initial expansion velocity values for GK Per from 1240 to 1700 km s$^{-1}$ (Anupama and Kantharia (2005) and Seaquist et al. (1989), respectively) rendering this type of treatment subject to large uncertainties. Destruction of a knot follows several crushing times (Pittard, 2007). Given the uncertainties, it is not possible to determine whether the main body of knots have been slowed or continue to expand more or less freely. However, analysis presented here suggests that some knots in the polar directions, where the densities are higher, have been slowed enough to significantly shape the nebula. Future monitoring should yield further details of the evolving knot interaction pattern, see bottom panel of Fig. 5.15.

Over time a knot will undergo several mass changing and shaping effects due to its environment such as photo-evaporation and thermal evaporation. Hydrodynamic ablation can occur via a shock transmitted through a clump; on reaching the end of the clump a strong rarefaction is reflected leading to expansion downstream that is accompanied by a lateral expansion (Pittard,
Lateral expansion from hydrodynamic ablation gives values of the order of 14% of the velocity of a knot away from the GK Per central system, which is caused by the high pressure in the knot versus the lower pressure of the surroundings and should be uniform along the length of the tail. The knot tails may be experiencing Kelvin-Helmholtz instabilities. However the knots of GK Per are distorted on a longer wavelength and amplitude than would be expected from Kelvin-Helmholtz instability alone.

In a clump-wind interaction their relative velocities must be considered as it is believed to be the main mechanism in the shaping of the clumps. Under more uniform conditions, subsonic clumps have long tails and their supersonic counterparts display short stubby tails (Pittard et al., 2005). There are a variety of tail shapes present in GK Per suggesting diverse local flow conditions. Nevertheless, it is suggested that the tail shapes are due to winds external to the clumps, specifically that they are due to dwarf nova winds. Several knots that appear to be experiencing an interaction with a following wind can be identified in the HST images. Five of the best examples were selected that had a sinusoidal tail shape of similar wavelength and amplitude along the outer edge of the shell such that inclination assumptions of individual knots are avoided. These wavy tails can be attributed to shaping by the dwarf nova winds that are thus found to have a velocity of \(~ 4400\) km s\(^{-1}\). However, it should be noted that the dwarf nova outbursts vary in peak magnitude, meaning different energetics leading to different wind velocities. Bianchini et al. (1986) gave a velocity estimate of the dwarf nova winds associated with GK Per of a few 1000 km s\(^{-1}\). Evidence for these wavy tails can be seen in the PV arrays in velocity space in Fig. 5.4, where a sinusoidal change
in velocity can be seen while looking down the length of the knot. Simply considering the time to traverse the system the dwarf nova responsible for the shaping of the tails in 1997 would be from ~ 1969. A better understanding of the interaction between knots and the dwarf nova winds could be achieved with detailed hydrodynamical simulations equivalent to Pittard et al. (2005, 2009) and Alūzas et al. (2014) where alternative hydrodynamical mechanisms such as the Kelvin-Helmholtz instability could be explained, or even possibly the Richtmyer-Meshkov instability (see Section 1.6.3) since the dwarf nova episodes may be accelerating ejecta and the clump surfaces are irregular.

The southern bar which appears to be interacting with the shock has been the site of the strongest optical emission ever since the first image of the nebulosity by Barnard (1916). The careful examination of individual knots by L12 gave a mean weighted kinematical age of 118 ± 12 years for the nova shell (compared to the shell at 103 years old in 2004), with no hint of directional dependancies. In contrast to the work carried out by L12, Duerbeck (1987) proposed that the GK Per nova shell was decelerating by 10.3 km s\(^{-1}\) yr\(^{-1}\) and calculated the value for the expansion of the shell at 1200 km s\(^{-1}\). The fastest knot found using the formalisms put forward by L12 is 1190 km s\(^{-1}\) and the lowest expansion velocity derived is 267 km s\(^{-1}\). It is interesting to note that all of the knots that exceed 1000 km s\(^{-1}\) (around 7% of all knots measured) are located on the outer limb. The knots below 600 km s\(^{-1}\) (13%) all reside inside the nebular boundary. There are only two recorded exceptions to the latter in the NE and whose PV arrays show them to be interacting, e.g. Fig. 5.6 top row and Fig. 5.7 NE knot. The projected appearance of knots along the barrel morphology means some knots will be orientated perpendicular to
the line of sight, as seen in the NE, e.g. Fig. 5.8(a), or the corresponding blue side of the shell where lack of emission to the NW can be seen.

An unexpected result here is that the derived morphology has a less extended axial ratio than expected, which goes against the grain of some of the shapes of recently modelled nova shells, e.g. RS Ophiuchi, V2672 Ophiuchi, and KT Eridani (Ribeiro et al., 2009; Munari et al., 2010; Ribeiro et al., 2013a). Lloyd et al. (1997) used a 2.5D hydrodynamic code to investigate remnant shaping for a variety of speed classes and produced rings, blobs, and caps as expected, but created oblate remnants. Later, Porter et al. (1998) included the effects of a rotating accreted envelope; surprisingly, the first panel in their Fig. 2 bares quite a resemblance to the morphology derived for GK Per in this work, and to model A used by Ribeiro et al. (2011). Emission in Band 3 of the WISE data (bottom panel of Fig. 5.15) suggests a large amount of material in the polar regions, possibly having a significant effect on the velocity of material moving in the polar directions.

5.5 Conclusions

In this chapter different axisymmetric models were considered in order to put further effort towards the understanding of the complex morphology of the old nova shell associated with GK Per, where a barrel equatorial feature with polar cones is found to give the best fit. In light of new echelle spectra gathered in November 2014, March 2015, and the WISE data archives, a new hypothesis on the origin of the mysterious jet-like feature has been put forward, i.e. that it is part of the ancient PN.
Here it is proposed that the wavy tails of knots in the nova shell may be due to shaping by dwarf nova winds. This allows to derive dwarf nova wind velocities of about 4400 km s\(^{-1}\), although sophisticated hydrodynamical simulations are needed to test the robustness of this hypothesis. Based on Doppler map profiles of the overall distribution of the nova shell knots it was found that a spherical shell, warped or otherwise, does not adequately explain the red-blue spread found in observations discussed here, although a spherical shell is a good first approximation to the overall shape of the knot distribution. Instead a cylindrical form with an axial ratio close to unity is found to fit best, and shows a remarkable resemblance to the imaging data. After the application of the cylindrical shape to the main body of the nova shell, polar features were included to account for the large number of knots not explained by the barrel.

The jet-like feature is most likely part of the surrounding PN owing to its low observed velocity and structure. Following the emission lines in new observations through the shell, they are enhanced at a lower velocity at the area of interaction as observed in radio and X-ray observations. From the spatial modelling conducted it cannot be said whether the surrounding PN is indeed bipolar or cylindrical in structure with the polar over-densities (e.g. WISE band 3) attributable to both scenarios. Deep high-resolution echelle spectroscopy is needed to decipher between the two scenarios and to then test the efficiency of the shaping mechanisms.
Table 5.5: $x$ and $y$ positions of knots normalised to 2007 NOT data epoch for easier comparison with L12.

<table>
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<th>$x$ (&quot;)</th>
<th>$y$ (&quot;)</th>
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Chapter 6

Ageing Nova Shells

6.1 Overview

Models of nova shells have previously incorporated a snow plough affect from the expanding shell interacting with the interstellar medium, e.g. Duerbeck (1987). However Duerbeck (1987) found a range of results for deceleration of the nova shells in the study and it is still not clear how the interaction takes place. Also, for GK Per (see Chapter 5) it was found by Liimets et al. (2012b) that no real deceleration took place contrary to findings by Duerbeck (1987).

It is worth then examining other nova shells over time to see if any such deceleration is taking place and the general implications for nova shell models.

This chapter features three main sections. First, results on a survey for previously undiscovered visible classical nova shells. Second, a discussion of imaging and spectroscopy of previously discovered and published classical nova shells. Finally, observations of possible incarnations of unobserved nova erup-
tions surrounding a single nova system are illustrated.

Constraining the inclination of interacting binary stars is difficult, especially when they are non-eclipsing. In most of these cases one can put upper and lower constraints on their inclination based on if they are eclipsing or not. Since bipolar nebulae can be shown to be consistently orientated relative to the inner binary, see Table 7.1, estimates of binary orbital characteristics can be reached if the geometry of the shell can be untangled.

One of the aims of this work was to expand on that done by others in recovering known nova shells and discovering previously unrecovered nova shells. In the summary of Slavin et al. (1995) they present several interesting conclusions to be tested. These are that a correlation exists between remnant shape and speed class, the orientation of the equatorial rings can be used to determine the orbital inclination of nova systems. An explanation for the existence of tropical rings and polar blobs is given within the context of the hydrodynamical work done in Lloyd et al. (1997), in that “tropical rings are formed by sweeping up conical regions of enhanced density local to the matter ejected by the white dwarf.” Polar cones are attributed to frictional interaction of the main sequence binary companion and a wind.

Shells around classical novae have been searched for and presented in three major published articles Cohen (1985); Gill and O’Brien (1998); Downes and Duerbeck (2000). The success rate of these searches respectively were 8/17, 4/17 and 13/30 nova shells found around potential candidates. Those found in these three works comprise roughly half of the known nova shells, the other half have been discovered individually for the most part. Deep optical imaging studies of known shells are also available in the literature with Slavin
et al. (1995) presenting newly discovered shells around NQ Vul and 450 Cyg. Four new nova shells were revealed in the O’ Brien & Bode chapter in Bode and Evans (2008), namely surrounding the progenitor nova systems OS And, V4077Sgr, V4121 Sgr and V960 Sco. It is expected that slower novae experience stronger shaping than faster novae, as the ejected material spends longer under the influence of the binary, although shaping may be due to the eruption happening on a fast-rotating oblate white dwarf and interactions with pre-existing circumstellar media. Classical novae can be divided into two basic types, fast and slow, although many fall between. In this chapter the focus is put on three slow novae, one medium speed class nova and two fast novae.

An initial discussion of new and archival observations is presented. Following this, an analysis of the observations are conducted. The first two sections follow an order of imaging and then spectroscopy. Finally it is seen how modelling techniques developed throughout the study for this thesis can, to first order, recreate shell emission observed in ageing nova shells if initial densities produced of shock considerations are taken into account in early expanding nova eruption outflow.

6.2 Observations

Difficulties arise in comparing observations from different telescopes and different filters. These include the fact that highly blue- or red-shifted emission from a nova shell may not be included in the resultant image if the filter is too narrow. The most extremely shifted material is towards the centre of the shell on the plane of the sky, see Section 6.2.1. To compensate for such errors the
most consistent data was extracted from the archives, covering the same strong emission lines, and allowing for the longest time coverage. A table of newly acquired images for this work can be found in Table 6.1, whereas observations listed in Table 6.2 have been obtained from data archives.

6.2.1 Imaging

Using the Aristarchos telescope in Greece deep-imaging was collected of the vicinity surrounding several known classical nova progenitor systems, which showed plausible hints of nebulosity in the WISE survey (Wright et al., 2010), see Fig. 6.1.

The observations consisted of either one or two narrow-band filters focused on Hα + [N II] and [O III] with exposures of 30 or 40 minutes in each filter. Broad-band imaging in B and R was collected for most objects in order to subtract stellar contribution. Clarifying that B band images were captured to remove stellar signatures from the deep [O III] images and R to subtract from Hα + [N II]. The seeing was of the order of 2-5 arcseconds, see Table 6.1. The imaging data was reduced using standard routines in IRAF.

The author wrote the successful observation proposals for the Aristarchos imaging runs and was helped with many of the observations. Those who aided the author in obtaining observations and when this was carried out is listed here. The 2015 and July 2016 observations were taken by Dr. Panos Boumis and Ms. Maria Kopsacheili. The August 2016 observations were obtained by the author, on site with Dr. Panos Boumis, Ms. Maria Kopsacheili and Ms. Vasiliki-Georgia Kontimpa. The 2017 imaging observations were carried out by Dr. Panos Boumis, Ms. Sophia Derlopa and Mr. Karol Fitzgerald.
Figure 6.1: Examples of novae that revealed possible shells or other interesting features for follow up from the WISE image archive. The images are summed and averaged WISE band 3 and 4, the single colour images are from band 3. For details on the follow up campaign see Table 6.1. All images are 400” × 400”, with north up and east to the left.

Table 6.1: List of objects observed during the search for previously unknown visible classical nova shells. The inspiration for all listed observations came from a search through WISE archive images, see Fig. 6.1.

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<th>seeing (&quot;)</th>
<th>Exp. (sec)</th>
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Table 6.2: Archival imaging data collected for use in this chapter. In the telescope column MW stands for Mount Wilson, these observations were taken with the 60” or 100” telescopes, however this information is not included on the sleeves containing the photographic plates. KPNO is the Kitt Peak 4m telescope, WHT is the 4m William Herschel telescope, INT is the Isaac Newton telescope (2.54m), the Skinakas telescope has a 1.3m diameter primary mirror. The WISE survey is described, along with the other observatories in Chapter 2 of this thesis. In the source column Carnegie refers to the Carnegie Observatories library. Some of the sources are journal articles: Gallagher (Gallagher et al., 1980), Slavin (Slavin et al., 1995), Becker (Becker and Duerbeck, 1980), Cohen (Cohen, 1985), Wade (Wade et al., 1991), Sahman (Sahman et al., 2015) and Boumis (Boumis et al., 2006).

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<td>Halpha</td>
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<td>2957x2</td>
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<td>8</td>
<td>Halpha</td>
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6.2.2 Spectroscopy

Echelle spectroscopic data were obtained to measure the expansion velocities of nova shells. These were obtained using MES (Meaburn et al., 2003) on the 2.1 m telescope at the SPM complex. The data were collected over the course of two observing periods, during January and August/September 2016, see Section 2.2.2 for details of the configurations used.

The January 2016 observations were conducted by Dr. Laurence Sabin at the request of the author. The later 2016 observations were carried out by the author.

One of the nova shells, that surrounding DO Aql, was observed using the SPRAT spectrograph on the LT during July 2017. SPRAT (SPectrograph for the Rapid Acquisition of Transients) is a high throughput spectrograph with a dispersion of 4.6 Å/pix and spatial pixel scale of 0.44 arcsec/pix Piascik et al. (2014). The resolution of the long slit spectrograph is around 350, covering wavelengths 4000 - 8000 Å. This type of observation is of lower spectral resolution than the others but still allows for rudimentary velocity determinations and tells what emission lines are present in the old nova shell at this stage.

For a summary of the spectroscopy observations obtained for this work see Table 6.3.

6.3 Results and Analysis

This chapter is primarily based on a search for nova remnant shells using the Aristarchos optical telescope following a search for hints of nebulosity
Table 6.3: Spectroscopy observations obtained for this chapter. The slit P.A. are listed according to the convention of a horizontal slit pointing due East is 0°, taken counterclockwise.

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152
around candidates in the WISE survey database, see Table 6.1 and Fig. 6.1. Since some of the objects observed did not reveal detectable nebulosity and others showed only faint tentative wisps, concentration is given to those with discovered shells in the following sections.

6.3.1 Novae Without Discovered Shells

In this subsection a brief synopsis of one of the objects with no shell found and possible reasons for null detections are discussed.

**V1493 Aql (1999)** - A fast nova with $t_2 = 9$ days, $t_3 = 50$ days V1493 Aql displayed a peak magnitude at $V_{peak} = 8.8$ with broad Balmer lines with FWHM of about 3400 km s$^{-1}$ Bonifacio et al. (2000). As the nova progenitor system is an eclipsing binary, Friedjung et al. (2006) were able to calculate a binary orbital period of 0.156 days. As an interesting nova in many respects, such as a secondary eruption that lasted 40 days, studied in detail by (Bonifacio et al., 2000), Arkhipova et al. (2002) and Venturini et al. (2004) it was found to be placed at a reasonably large distance based on the average of three methods at $18.8 \pm 3.6$ kpc and to have a quiescent visual magnitude of 21. This large distance places the object on the outer edges of the galaxy or within a close neighbour.

The large distance to the source and low visual brightness suggest that a visible shell would be difficult to detect. If the expected size of the shell is calculated from the distance modulus according to the MMRD: $t_2$ gives an expected shell size of 1.8" and from $t_3$ gives 1", smaller than normal seeing at the Aristarchos telescope site. With these factors conspiring against the possible detection of a shell around this object, why it would be added to an
observation list must be justified. The inspiration for the search for nova shells discussed in this chapter came from analysis of the GK Per nova shell from the WISE database. Following this a search was conducted in the survey images of the WISE catalogue where each available band used to image a nova shell candidate was analysed for hints of nebulosity or relatively large amounts of flux in the WISE bands 3 and/or 4 at the position of the nova.

During the survey V1493 Aql proved to be a likely candidate for harbouring an ancient nova shell with a striking feature with maximum extension of just under 30” to the south, see Fig. 6.2(a). The radial cuts of Fig. 6.2(b) are of V1493 Aql in comparison to field stars of similar brightness. After multiple tests, including deconvolution using MEM and Lucy algorithms as well as continuum subtraction it was not possible to deduce the existence of a discernible nova shell or of any older structure from a possible previous ejection episode, in the Aristarchos image.

Other objects of which narrow-band imaging was acquired but that showed no detectable evidence of a shell are V356 Aql, V1419 Aql, V528 Aql, V465 Cyg, DM Gem, CP Lac, GI Mon and V3964 Sgr. BC Cas and V606 Aql showed tentative evidence of harbouring visible evidence of shells, albeit not enough to confirm their presence and have been left for further investigation.

6.3.2 Two New Shells around DQ Her-like Novae

V4362 Sgr (1994)

V4362 Sgr (1994) was discovered on M.J.D. 49492, i.e. 10 April 1994, with a maximum observed magnitude of 8 although its maximum was likely missed. It was a poorly observed nova through eruption and it is therefore difficult to
determine its light curve type, although it seems to resemble that of DQ Her. This resemblance is supported by the fact that V4362 Sgr is known to have been a nova of the Fe II class (Austin et al., 1994). Early-time broadband polarimetry of the object, presented in Evans et al. (2002), covers days 51 - 83 (before the dust-dip) where the observed absolute polarisation is mostly due to scattering off of small dust grains, within a shell consisting of narrow-conical-polar caps and a flattened-circular-equatorial ring. The proposed structure from the polarimetry in Evans et al. (2002) is similar to that proposed for V5668 Sgr in the first results chapter of this thesis.

Here, a newly discovered nova shell surrounding V4362 Sgr is presented, see Table 6.4 and Fig. 6.3. The nova shell was observed but misclassified as a planetary nebula in Boumis et al. (2006). Coupled with observations
from 2016 it is possible to present multi-epoch narrow-band imaging of the expanding shell. In Boumis et al. (2006) the diameter of the object is given as 4″. However, after retrieving the original data, the continuum subtracted images give measured values in Skinakas observations from 2002 in Hα + [N II]: minor axis = 2.53″, major = 3.05″, ratio 1.20. From new observations the following values are found from the Aristarchos 2016 broad-band subtracted images: Hα + [N II] 6.40″ × 7.10″, giving a 1.10 ratio; [O III] 5.23″ × 5.52″, ratio 1.06 see Fig. 6.3.

While communicating with Dr. Boumis and Dr. Akras regarding their imaging data from Boumis et al. (2006), Dr. Akras offered the author high-resolution MES spectroscopy observations of V4362 Sgr from 2012. The unpublished MES spectra from 2012 and newer 2016 spectra show a low-velocity shell, see Fig. 6.3 (top row) with suggestions of structure matching the description of Evans et al. (2002). The polar-cone and equatorial-ring structure were fit to very similar line profile shapes of V5668 Sgr in the nebular stage, see Fig. 4.9, as of those presented of V4362 Sgr, Fig. 6.3.

From the information gathered on the nova shell it is possible to start building a 3D model. The polarimetry of Evans et al. (2002) suggests a P.A. of around 150°, however, this angle appears to be related to the equatorial disk. Instead a P.A. of 40° was adopted. If the polarimetric P.A. is related to the equatorial disk then it adds context for the V5668 Sgr polarimetry P.A. This would point to equatorial disks in nova outflows to be the main location of dust formation, as suggested in Derdzinski et al. (2017). No inclination angle for the binary exists that can be shown to be related to the inclination angle of the resultant nova shell, although the author believes the system to be
close to edge-on, i.e. of high inclination from its eruption light curve structure, see Section 7.1. With averaged abundances from CO novae in Warner (1995), a pseudo 3D recreation of the ionisation structure of V4362 Sgr is viewable in Fig. 6.4. The main implications of the pycLOUDY modelling of the V4362 Sgr and the following novae are discussed in Section 7.1.

Using the expansion parallax relation presented in Warner (1995) (and reproduced as equation 1.3 in this thesis), an expansion velocity of 470 km s\(^{-1}\) and an age of 22.313 years, a distance of 0.61 kpc is found, making it one of the closest known nova shells. The low recorded maximum magnitude is apparently at odds with the low distance, this is most satisfactorily explained by its maximum being most likely missed.
Figure 6.3: V4362 Sgr multi-epoch spectroscopy (top) and narrow-band imaging (bottom).

(a) V4362 Sgr spectral lines from 2012 and 2016 observations described in 6.3

(b) V4362 Sgr continuum subtracted images: (i) Skinakas May 2002 (ii) Aristarchos 2016 - Ha (iii) Aristarchos 2016 5.2” x 5.5”.
North is up and East is to the left.
DO Aql (1925) -

With a poorly observed optical light curve and no early spectrum this system was not recognised initially as a nova and was referred to as ‘Wolf’s Variable’. The system was proposed to be a RN, through association with the biblical star of Bethlehem in the book Kidger (1999), which was refuted in Schaefer (2013) as the nova progenitor system is low mass and more probably has a recurrence rate of over a million years. DO Aql is known to have been a slow nova and was thought to have experienced a long plateau at maximum of approximately 250 days, with a 53 day gap in observations. The $t_3$ of the
Table 6.4: Summary of parameters used in the first pass modelling of four nova shells discussed in this chapter. \( D_1 \) is the density assuming an initial density of \( 10^{14} \) (early shocks), whereas \( D_2 \) assumes an initial density of \( 10^{10} \) (no-shocks), see Derdzinski et al. (2017). Density is assumed to decline as \( t^{-3} \), where ‘t’ is in weeks. \( T_{\text{eff}} = 1 \times 10^5 \) and \( L = 1.2 \, L_\odot \) for each model.

<table>
<thead>
<tr>
<th>Object</th>
<th>Max Date</th>
<th>Model Date</th>
<th>Age (d)</th>
<th>( D_1 )</th>
<th>( D_2 )</th>
<th>( R_{\text{in}} )</th>
<th>( R_{\text{out}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>V4362 Sgr</td>
<td>16/05/1994</td>
<td>02/08/2016</td>
<td>8114</td>
<td>6.7</td>
<td>2.7</td>
<td>16.6</td>
<td>16.75</td>
</tr>
<tr>
<td>DO Aql</td>
<td>14/09/1925</td>
<td>19/08/2015</td>
<td>32846</td>
<td>4.9</td>
<td>0.9</td>
<td>17.20</td>
<td>17.36</td>
</tr>
<tr>
<td>V1500 Cyg</td>
<td>29/08/1975</td>
<td>30/08/2016</td>
<td>14977</td>
<td>5.9</td>
<td>1.9</td>
<td>17.00</td>
<td>17.2</td>
</tr>
<tr>
<td>T Aur</td>
<td>15/12/1891</td>
<td>30/08/2016</td>
<td>45914</td>
<td>4.5</td>
<td>0.5</td>
<td>17.35</td>
<td>17.50</td>
</tr>
</tbody>
</table>

Nova event is reported in Warner (1995) as 900 days, although the maximum, reported as 8.7 in V, was likely missed. Also, the \( t_3 \) value may have been derived from a long decline often seen in slow novae after a strong dust-dip, this being further supported by the fact that early observers of the system described it as a ‘wave nova’ based on the appearance of its early light curve. In Strope et al. (2010) the light curve is classified as ‘flat-top’.

The DO Aql system is composed of an eclipsing binary of period of 4.03 hours whose quiescent light curve is proposed to demonstrate either “obscuration of a hot component or stream overshoot” (Shafter et al., 1994). As this system is eclipsing one can expect to be viewing it almost edge-on. Photometry in the BVRJK pass bands is presented in Szkody (1994), the low values found for B-V, V-R and V-J are suggestive of emission arising from a thick accretion disk. Vorontsov-Velyaminov (1940) provides the reader with a spectrum taken 113 days post-discovery that shows it to be an Fe II type nova with line ratios similar to those of V5668 Sgr at the same time post-discovery, Fig. 4.5 in Chapter 4 of this thesis. Vorontsov-Velyaminov (1940) gave a hydrogen shell

160
expansion rate of 1000 km s$^{-1}$ and an Fe shell velocity of 700 km s$^{-1}$. There are no previous estimates on the distance to this system in the literature.

The observations of the object presented here reveal a previously undiscovered nova shell visible in both H$\alpha$+[N II] and [O III] narrow-band filters. Two epochs are presented for the H$\alpha$ narrow-band imaging taken in 2015 and 2017, i.e. 90 and 92 years since the nova eruption. The [O III] emission appears inside of the H$\alpha$/[N II] shell.

Using the velocities found by Vorontsov-Velyaminov (1940), an age of 90 years, a major axis of 3.3", minor axis of size 2.4", see Fig. 6.5 equation 1.3 gives a distance of 5.5 ± 0.2 kpc to the source. The seeing in the 2017 narrow-band imaging observation is not good enough to measure the proper motion growth of the expanding shell between 2015 and 2017. The major and minor axes are readily confirmed on inspection of Fig. 6.5. Small protrusions at both tips of the major axis, which could be related to the ablated flows in the shell of HR Del, as in Vaytet et al. (2007).

SPRAT was used to acquire a spectrum of one hour exposure, taken June 2017, that shows the presence of the emission lines originating from the side-on photoionised nova shell, i.e. the common forbidden [O III] 5007 Å, [N II] 6583 Å as well as H$\alpha$ are present and resolvable from the stellar component in the 2D spectra. The observation was requested under the time of Dr. Steven Williams, LJMU, as we wanted to test the viability of the instrument in confirming small suspected envelopes of novae. Proper investigation of this spectrum has not yet been conducted and awaits future work.

The P.A. of the nova shell, as measured from the H$\alpha$+[N II] images, is taken to be 98° counterclockwise from the northern celestial pole. In the rough cut
pseudo 3D model of the nova, see Table 6.4 and Fig. 6.6, a P.A. of 98° and an inclination of 85° are assumed.

DO Aql as an old and bright nova shell surrounding an eclipsing binary, is attractive for follow-up studies, especially at other wavelength regimes.
Figure 6.5: Following panels left to right, top to bottom. DO Aql (1925) (i) Continuum R image of DO Aql (ii) H$\alpha$ + [N ii], (iii) Radial cut of DO Aql in comparison to three field stars, (iv) 2017 [O iii] Aristarchos image, (v) 2017 Aristarchos H$\alpha$ + [N ii] image, (vi) SPRAT spectrum of nova shell and remnant June 2017.
6.3.3 Tracing known shells

**V1500 Cyg (1975)** - V1500 Cyg was a very fast, over-luminous, ‘neon nova’, and is the archetype asynchronous polar (Warner, 1995).

To summarise the most relevant published parameters of this nova they are listed below.

1. $M_{\text{Max}} = 2.2$, $M_{\text{Min}} 16.3$. $t_2 = 2.9$ days, $t_3 = 3.6$, $A_v = 1.15$ Warner (1995)

2. Pre-maximum spectrum B0 Warner (1995)
3. $T_{\text{eff}}$ of WD: $70 - 120 \times 10^3$ K (Schmidt et al., 1995)

4. $P_{\text{orb}}$: 3.3507 hrs (Schmidt et al., 1995)

5. Inclination 55° (Warner, 1995)

6. Peak luminosity = $4.7 \times 10^5$ L$_\odot$ (Wu and Kester, 1997)

7. Caught before max, rise took less than a day (Liller et al., 1975)

8. Magnetic field confirmed by (Schmidt, 1991), with a polar magnetic field strength of $\sim 25$ MG for the WD.

Hutchings and McCall (1977) estimated the WD mass to be 1.1 M$_\odot$ and the mass losing companion at 0.5 M$_\odot$. The nova progenitor system is embedded in a well documented nova shell. The shell was first imaged four years after eruption by Becker and Duerbeck (1980). Wade et al. (1991) published imaging data of the nova with a radius of 1.9" giving an expansion rate of 0.16" per year. Slavin et al. (1995) presented a 1993 image of the nova shell with 3" radius. More recently, Sahman et al. (2015) illustrated the nova shell from IPHAS imaging. The IPHAS image has roughly 5" radius taken on 7 August 2004, see Table 6.2 and Fig. 6.7. A new image of the vicinity surrounding the nova shell was obtained using the Aristarchos telescope, see Table 6.1, where the shell has nearly faded into obscurity.

For knowledge on the velocity constraints of the system Lance et al. (1988) provide velocity profiles in different bands. On 1 September 2016 the author observed the system using high-resolution spectroscopy using the MES instrument at SPM, see Table 6.3. This observation revealed the presence of a fast
moving component of the shell, however the spectral range was too narrow to
distinguish if the observed signal belonged to Hα or [N II].

Lance et al. (1988) calculated a distance of 1.1 kpc to the object, whereas
Wade et al. (1991) found a distance of 1.3 kpc, and Cohen (1985) found 1.56
kpc.

Hutchings and McCall (1977) proposed a model of an equatorial ring with
\( V_{eq} = 720 \text{ km s}^{-1} \), a polar velocity of 660 km s\(^{-1}\) and an inclination of 60°.
Although, Warner (1995) gives a maximum Doppler radial velocity of 1180
km s\(^{-1}\). Boyarchuk and Gershberg (1977) discuss 30° and 60° models are
discussed.

Analysis done for this thesis suggests a distance of 1.1 kpc from expansion
parallax methods, corresponding to that of Lance et al. (1988). The nova shell
inclination is also derived and expected to be orientated relative to the binary,
i.e. at 55°. The P.A of the nova shell along its polar axis, counterclockwise
to the northern celestial pole, was measured here to be 26°, see Table 6.4 and
Fig. 6.8. Thus providing new constraints on the distance to and orientation
of the V1500 Cyg nova shell.
Figure 6.8: V1500 Cyg `pyCLOUDY` model, P.A. 26°, inclination 55°. Note the final result bares resemblance to the shell of GK Per (see Fig. 5.10 for example).

V476 Cyg (1920)

A moderately fast nova, with a $t_3$ of 16.5 days Duerbeck (1987), V476 Cyg is the first of two novae presented that includes archival Mount Wilson photographic plates. The addition of the three Mount Wilson observations, from 1942, 1950 and 1957, gives a total of six comparable multi-epoch images, see Fig. 6.9. In Adams (1944) the 1943 image taken of the shell surrounding V476 Cyg is mentioned where it is said the “diameter in red light of shell nova Cygni is 4.3”. In Mustel and Boyarchuk (1970) the radial extent is given
as 2.2” for the nova 23.4 years after eruption and 5.6” following 64.0 years post-eruption evolution.

A distance of 1.47 kpc was derived from radial velocities in Duerbeck (1987) where an absolute magnitude of -8.9 and deceleration of the nova shell of 3.1 km s\(^{-1}\) were calculated. In Table 5.2 of Warner (1995), a shell expansion velocity of 790 km s\(^{-1}\) and \(A_v\) is given as 0.85 towards the system. The nova was observed using the narrow band F656N, H\(\alpha\) + [N \(\text{ii}\)], filter using the Hubble Space Telescope, reported in Gill and O’Brien (1998) but was not detected with an exposure of 2600 seconds. The Hubble images were recovered by the author from the archive and on reinvestigation of the data they do not appear to demonstrate detectable nebulosity.

The 2016 Aristarchos image presented here reveals previously unobserved detail of the nova shell. To the north of the nova shell three protrusions are visible apparently arching away from the system. It is thought that these protrusions are part of the polar outflow of the nova, and that the main nebulosity seen is part of the equatorial disk. From the 2016 observations a radial extent of 7.3” is measured. Using expansion parallax (equation 1.3 in introduction) a distance to the source of 2.15 kpc is found using the expansion velocity from Warner (1995), this distance being larger than that derived by Duerbeck (1987).

Two long-slit high-resolution spectra, using MES, were obtained for this object with P.A. of 66° and 146° on the plane of the sky. These P.A. were chosen as they are suspected to be the orientation of equatorial and polar shell components respectively. Unfortunately the observations were not deep enough to pick up the nebulosity spectroscopically.
T Aur (1891)

From examining Harvard plates Walker (1962) found that the eruption light curve was very similar to the archetypical slow nova DQ Her, T Aur hosts an eclipsing binary, again like DQ Her. The binary inclination is given as 68° by Bianchini (1980) and as 57° by Ritter (1984), the binary orbital period is given as 4h 54m by Mustel and Boyarchuk (1970), with the orbital modulation showing shallow dips of 0.2 mag.

There is a discrepancy in the distance derived to the source as it is quoted as 600 pc by Duerbeck (1981) and as 0.96 ± 0.22 kpc by Slavin et al. (1995). Also, the time to decline by 3 magnitudes (t₃) is given as 50 days by Downes and Duerbeck (2000) and as 100 days by Slavin et al. (1995). Gallagher et al. (1980) discusses a He overabundance with respect to H of a factor of 3 in T Aur, which is interpreted as H deficiency in the ejecta similar to DQ Her. Gallagher et al. (1980) provides an electron temperature measurement of about 10³ K and ascribes it to the recombination line region.

T Aur harbours a well known old nova shell and was the first nova to be followed with photographic spectroscopy (Payne-Gaposchkin and Helena, 1964). The nova shell was discovered by Walter Baade with a diameter of 12” Adams (1943) on a December 1942 photographic plate. Apart from the the 1942, and the shorter exposure 1943 photographic plates retrieved from Carnegie library for this work that show the T Aur nova shell, there are images from 1950 and 1956 that reveal the nebulosity, see Fig. 6.10. The later images presented for the time-evolution comparison of this nova are from: Gallagher et al. (1980) who present an image from 1978, then Slavin et al. (1995), IPHAS catalogue from 2003 that is mentioned in Sahman et al. (2015). The final two
images presented are new for this work. The 2015 image is from the LT, and was found in the appropriate archive. The last image presented is from 2016, captured using the MES spectrometer with the slit removed at SPM. The bottom-right panel in Fig. 6.10 shows the slits that were overlaid on the nova shell to measure the shell velocities.

A SHAPE model was fit to the imaging and spectroscopy. It was found that a radially expanding barrel, segmented into equatorial and tropical rings, with polar cones provided the best fit. An inclination of $68^\circ$ was found, with a P.A. of $65^\circ$ measured to give $a$, the SHAPE model fit can be seen in Fig. 6.11. Using an expansion velocity of $600 \text{ km s}^{-1}$ a distance to T Aur is estimated at 1.04 kpc here, similar to the 0.96 kpc estimate of Slavin et al. (1995). A generic pycLOUDY model was generated based on simplified assumptions, see Table 6.4 for input and Fig. 6.12 for results. It is noted that a single equatorial ring was used for the pycLOUDY modelling whereas an equatorial ring plus two tropical rings were used for the SHAPE model. The pycLOUDY emission line simulations for the T Aur nova shell suggest that the polar cones should no longer be visible. However, this is dependent on the decline in density of a nova shell assumed in a non-clumpy nova shell, as is previously assumed in other works, e.g. Warner (1995). Conclusion drawn from the pycLOUDY simulations, Fig. 6.12, are discussed in Chapter 7 as the results of T Aur and the preceding novae with shells are synthesized to suggest how nova observables are inclination dependent.
Figure 6.11: Observed PV arrays (top row) of T Aur and results of SHAPE model (bottom row). First column slit P.A. of 155° (i.e. bottom 155° slit in bottom right panel of Fig. 6.10), second P.A. 35°, third P.A. 77° offset from centre.
6.3.4 Ancient Nova Shells?

**V2275 Cyg** The nova progenitor system of V2275 Cyg produced an eruption in October 2001. This was a very fast nova episode, not unlike that of V1500 Cyg, discussed in Section 6.3.3. The early evolution of the nova was most closely followed by Kiss et al. (2002), where a FWHM velocity of the Balmer emission lines are given as $2100 \text{ km s}^{-1}$, a distance of $5^{+3}_{-2} \text{ kpc}$ and an orbital period of $0.315 \text{ hours}$. The V2275 Cyg system is a suspected RN (Sahman et al., 2015).
Through analysis of the IPHAS catalogue, Sahman et al. (2015) identified a light-echo due to the system’s 2001 eruption that illuminated the surrounding material, see bottom row of Fig. 6.13. This material has been detected using the Aristarchos telescope in 2016 and 2017 narrow-band Hα + [N II], as well as [O III] images, see top row of Fig. 6.13. High-resolution MES spectra were collected giving a low central velocity, see Fig. 6.3.4, although the observations also revealed higher velocity components than expected red- and blue-shifted away from the Hα emission line that are to be investigated further in future work, the slit positions are shown in Fig. 6.14 covering ‘Blob A’ and ‘Blob B’ of Sahman et al. (2015). The extended emission appears at -500 km s\(^{-1}\) and -1150 km s\(^{-1}\). However, the wavelength coverage of the observations is not of sufficient breadth as to be able to distinguish velocity patterns between the Hα and [N II] doublet.

On examination of the WISE database the material is again apparent, however of different intensities in different bands. WISE bands 1 and 2 show material residing closer to the system that bands 3 and 4, see middle row of Fig. 6.13. What is most striking is that the material appears to be part of a repeating cylindrical pattern centred on the nova progenitor system. The distance to the inner wall to the suspected ancient nova shells are 375” and 3000”, see Fig. 6.16.
Figure 6.13: V2275 Cyg images. Top row: Aristarchos Hα+[N II] & [O III] narrow-band images from 2016 and 2017 respectively. Middle row: WISE bands 1, 2, 3 and 4 respectively. Bottom row IPHAS images from Sahman et al. (2015). Red circle has radius 5" in first two images in the top row.
Figure 6.14: V2275 Cyg image with the two slit positions used for obtaining the deep spectra, Fig. 6.3.4, overlaid. The orientation of the image is the same as in Fig. 6.13. Within the green boxes are examples of the material with which the light echo was observed to interact with in IPHAS imaging in Sahman et al. (2015), see bottom row of Fig. 6.13.
Figure 6.15: V2275Cyg [O \textsc{iii}], H\textalpha{} and [N \textsc{ii}] emission from the pre-existing material identified in the IPHAS catalogue by \textit{Sahman et al.} (2015), see 6.3.4.
Figure 6.16: V2275 Cyg image of WISE band 3 and 4 (respectively) showing the structure seen in Fig. 6.13 more clearly. The third panel shows a repeated structure on a much larger scale, hinting that V2275 Cyg appears to be a RN.
6.4 Conclusions

The nova shells presented in this chapter do not appear to be measurably slowing down, as opposed to what was shown in Duerbeck (1987). The most plausible explanation for the lack of an observable snow plough effect is of momentum conservation arguments based on higher density bullets (e.g. GK Per Fig. 5.16) composing the shell, rather than a shell of high filling factor.

Distance estimates and shell orientations found in this work are detailed in Table 6.5. The distance estimates are subject to a 10% error. P.A. estimates have an error of 1° whereas inclination estimates are larger, of the order of 20°.

Table 6.5: Estimated distances using the expansion parallax method detailed (equation 1.3). The shell P.A. and the inclination used for each shell for pyCLOUDY modelling are also given.

<table>
<thead>
<tr>
<th>Nova</th>
<th>Distance</th>
<th>P.A.</th>
<th>inc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>V4362 Sgr</td>
<td>0.61 kpc</td>
<td>40°</td>
<td>85°</td>
</tr>
<tr>
<td>DO Aql</td>
<td>5.50 kpc</td>
<td>90°</td>
<td>85°</td>
</tr>
<tr>
<td>V1500 Cyg</td>
<td>1.10 kpc</td>
<td>26°</td>
<td>55°</td>
</tr>
<tr>
<td>V476 Cyg</td>
<td>2.15 kpc</td>
<td>146°</td>
<td>~60°</td>
</tr>
<tr>
<td>T Aur</td>
<td>1.04 kpc</td>
<td>65°</td>
<td>68°</td>
</tr>
</tbody>
</table>

In examining Fig. 6.17, linear fits to the expanding major and minor axes of nova shells are satisfactory, given difficulties inherent in measuring the edges of low-surface brightness objects. Also, what may have been interpreted as deceleration of nova shells in Duerbeck (1987), could be fast/dense material fading sooner than the main shell body. The study of the shells in this chapter allowed for expansion parallax based distance estimates and crude untangling of the shell orientation on the plane of the sky, giving valuable constraints on the binary orbital orientation. Finished the chapter a discussion on a possible
Figure 6.17: Proper motion measurements of the four best resolved novae included in this chapter. The blue lines represent fits to the major axis of each nova shell, whereas, the red line corresponds to the nova shell’s suspected minor axis.

detection of ancient nova debris is presented.

It is found during this thesis from pycLOUDY simulations that the long term evolution of density conditions in nova outflow requires early interacting shocks to sustain a photoionised nova shell at late times, as is observed. This strengthens the conclusions of Chapter 4 where higher densities were invoked,
as suggested by Derdzinski et al. (2017), to explain the spectral signatures of
the erupting V5668 Sgr nova. Higher densities in this way require a low filling
factor to be consistent with the ejected shell mass estimates derived from radio
observations of nova shells.

From extensive shape modelling of classical nova shells they appear to
be consistently comprised of clumps occupying equatorial/tropical rings and
polar cone structures. The acceptance of this simple fact can allow for the
development of a model that can explain the often seen variations in erupting
nova systems, as discussed in Section 7.1.
Chapter 7

Conclusions and Future Work

7.1 Discussion

This thesis consists of an analysis of the spatio-kinematic and photoionisation properties of nova shells. In the first results chapter the expanding shell around a recent nova producing system is considered from multi-epoch optical observations from eruption detection to 2.25 years post-discovery. Following this an analysis on the structure of the GK Per nova shell up to 114 years post-discovery. In the final results chapter a search for and analysis of classical nova shells is presented surrounding several nova producing systems.

From a broad review of the main results of this work, nova shells can be almost universally described as consisting of polar cones and an equatorial barrel or ring waist. Novae are observed as producing a variety of light curve types, better known in the optical regime than at other wavelengths, although considerable progression has been made in gamma-ray, X-ray, UV, infrared and
radio wavelengths. Knowledge of erupting systems that have been observed simultaneously at all possible wavelength regimes reveals the layers at work by probing different depths. To illustrate this, gamma-emission, produced shortly after optical maximum, has been observed to last 55 days (Cheung et al., 2016), probably generated in early shocks from interacting ejecta with either a wind or other ejecta (Metzger et al., 2014). Hard X-rays and radio waves are produced by shocks also, whereas soft X-ray emission is produced by continued nuclear burning on the WD surface. UV, optical and infrared emission are emitted by the central binary as well as arising from several ionisation processes taking place in the ejected material.

In the study of V5668 Sgr (Chapter 4) photometry, polarimetry and spectroscopy allowed to place several constraints on the system.

1. Modelling of the outflow led to a dismissal of N III and instead the importance of O II as being the primary responsible species for the flaring of the optical spectra around 4640 - 4650 Å between days 120 and 150 post-discovery.

2. The expanding nova shell was best described as being distributed within equatorial ring and polar cone structures.

3. Polarimetry observations of the object gave witness to dust grains being created and destroyed in the expanding nova debris.

4. Constraints of the position angle of the shell on the plane of the sky were arrived at through polarimetric studies.

The atypical archetype for novae is GK Per and is generally considered to
host the best observed classical nova shell on record. Information available on this system in both the literature and archives allowed for an in-depth analysis of the overall distribution of clumps in the nova shell. The origin of a faint arching wisp apparently emanating from the central system was shown to be of low velocity, comparable to that of a planetary nebula and was therefore most probably not a jet as was often hypothesised previously.

The final results chapter illustrates the attempts made by the author over the course of study to begin a monitoring campaign of classical nova shells. Nova shells were originally searched for in the WISE NIR satellite archives, this search revealed many interesting results in itself such as showing the material with which the light echo of the 2001 V2275 Cyg nova event was interacting with.

It should not be surprising that it was found during the search for nova shells that, quite like the gamma-ray emission detected from novae, they are most easily observed around close-bright systems. The rule-of-thumb that faster moving material fades faster holds true, and what may be interpreted as deceleration of a nova shell could be the outer material fading sooner. The distribution of ejected material can consistently be described by equatorial and polar structures. It is believed by the author that optical light curves of erupting nova systems are dependent on the systems inclination, as well as line profile shapes and line ratios relative to H/β. To support this hypothesis, consider the archetypical slow, dust-producing nova system DQ Her. The erupting systems light curve strongly resembles that of V5668 Sgr, T Aur, DO Aql and probably V4362 Sgr too, systems known to be eclipsing systems with visible nova shells, demonstrated in this thesis. The flat-top-jitters section of a DQ
Her-like light curve rather than a smooth decline may be due to reprocessing of photons through a thick expanding equatorial waist along the line of sight to the observer. A side-on viewed equatorial waist and polar structure model generates triple-peaked line shapes, like those observed in slow novae. Fast decline novae would then preferentially be viewed pole-on, or the gap between polar and equatorial regions, hence the higher recorded radial velocity measurements for these systems. The mass of the WD is the main determinant of peak temperature reached during TNR, as well as putting restrictions on the amount of accreted mass needed to reach the critical pressure that triggers the TNR.

The development of a theory describing all novae based on inclination seems natural and allows for the description of components. In this picture of novae the inclination of the binary and the nova shell are near identical, for support of this see Table 7.1. The inclination can be used to estimate the optical light curve, the frozen nebular line profile shape, and constraints on the radial velocity of the observed shell. Otherwise, any of the other components if measured should be indicative of the underlying inclination of the binary systems. To give examples take the edge-on slow example of DQ Her-like novae, believed to be in the range of inclination from 70 - 90° with the equatorial ring along the line of sight to the observer. The next subcategory would consist of novae like V1280 Sco or V476 Cyg with several distinct peaks before a shallow dust-dip. Next are novae that are viewed at inclinations from around 35 - 55°, like GK Per or V603 Aql, that exhibit oscillations on the decline of an otherwise smooth light curve. Plateau novae such as the recurrent CO nova T Pyx as well as many smooth nova light curves are then seen nearly pole-
Table 7.1: Demonstration of shell and binary orbital inclination dependence. Values obtained from the literature, apart from the shell inclinations for GK Per, AT Cnc and Z Cam which were derived by the author over the course of this thesis work. The references are as follows: GK Per; Bode et al. (1987); Morales-Rueda et al. (2002), AT Cnc; Shara et al. (012c), Z Cam; Shara et al. (2012a), V458 Vul; Wesson et al. (2008b); Rajabi et al. (2012), HR Del; Harman and O’Brien (2003), DQ Her; Vaytet et al. (2007), Nova Mon 2012; Ribeiro et al. (2013b), RS Oph; Ribeiro et al. (2009), T Pyx; Chesneau et al. (2011), Hen 2-428; Santander-García et al. (2015), Hen 2-11; Jones et al. 2014, A&A, Vol 562, pp 89, HaTr 4 Tyndall et al. (2012), Sp1; Jones et al. (2012), Abell 65; Huckvale et al. (2013)

<table>
<thead>
<tr>
<th>Object</th>
<th>Type</th>
<th>Inc. shell</th>
<th>inc. Binary</th>
<th>$P_{orb}$ (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GK Per</td>
<td>CN &amp; DN &amp; PN</td>
<td>54±5°</td>
<td>50 - 73°</td>
<td>2</td>
</tr>
<tr>
<td>AT Cnc</td>
<td>CN &amp; DN</td>
<td>48±4°</td>
<td>17±3° or 36±12°</td>
<td>0.24</td>
</tr>
<tr>
<td>Z Cam</td>
<td>CN &amp; DN</td>
<td>64±8°</td>
<td>52 - 69°</td>
<td>0.29</td>
</tr>
<tr>
<td>V458 Vul</td>
<td>CN &amp; PN</td>
<td>±30°</td>
<td>~30°</td>
<td>0.068</td>
</tr>
<tr>
<td>HR Del</td>
<td>CN</td>
<td>35 ± 3°</td>
<td>41±4°</td>
<td>0.17</td>
</tr>
<tr>
<td>DQ Her</td>
<td>CN</td>
<td>86.8±0.2°</td>
<td>89.6±0.1</td>
<td>0.19</td>
</tr>
<tr>
<td>Nova Mon 2012</td>
<td>CN</td>
<td>82 ± 6°</td>
<td>“high inc”</td>
<td>0.296</td>
</tr>
<tr>
<td>RS Oph</td>
<td>RN</td>
<td>39±9°</td>
<td>~30-40°</td>
<td>455.72</td>
</tr>
<tr>
<td>T Pyx</td>
<td>RN</td>
<td>~15°</td>
<td>10±2°</td>
<td>0.076</td>
</tr>
<tr>
<td>Hen 2-428</td>
<td>PN</td>
<td>68°</td>
<td>64.7°</td>
<td>0.175</td>
</tr>
<tr>
<td>Hen 2-11</td>
<td>PN</td>
<td>~90°</td>
<td>90±0.5°</td>
<td>0.609</td>
</tr>
<tr>
<td>HaTr 4</td>
<td>PN</td>
<td>65 - 80°</td>
<td>55 - 75°</td>
<td>1.74</td>
</tr>
<tr>
<td>Sp 1</td>
<td>PN</td>
<td>10 - 15°</td>
<td>15 - 25°</td>
<td>2.9</td>
</tr>
<tr>
<td>Abell 65</td>
<td>PN</td>
<td>68 ± 10°</td>
<td>68±2°</td>
<td>1</td>
</tr>
</tbody>
</table>

on, hence the higher recorded radial velocities as one is nearly looking down the ‘barrel’ of the nova. It was realised during this work that observed line ratios are dependent on the viewing angle towards the source. Implying that derived abundances in the outflow of novae may be more local than previously thought. It is for this reason that an average of previously derived abundances from the literature were used to model the nova shells presented in this thesis. These effects should be slightly different but still relatable when comparing nova eruptions in disk and bulge populations, see della Valle et al. (1992).
7.2 Conclusions

When writing holistically about classical nova shells, after going through the literature and conducting research, they appear to be overly complicated. As novae are believed to be quite uniform, as far as a set of progenitors for eruptive stellar events can be, the grand variations of observed nova light curves seems to go against the idea of a homogenous sample. As a result of the work laid out in this thesis, that was heavily based on surveys and previous efforts by ‘ardent students of novae’, a simplistic overview of the phenomenology based only on the inclination angle towards the source and the WD mass appears to be the most natural way to explain the observables of these systems.

As the crossing-time of the ejecta over a typical binary orbital semi-major axis is generally less than the time taken for a couple of orbital periods, shaping of the ejecta via frictional drag deposition from the central system is difficult to reproduce. As one of the main results from the presented work is that even the fast nova archetype, GK Per, has a ‘barrel with cones’ structure despite having an unusually long orbital period adds credence to the school of thought that another ‘shaping mechanism’ may be at work. In the literature there is often talk of well-shaped slow nova shells or clumpy, roughly spherical shells around fast counterparts. If an oblate fast-spinning magnetic WD experiences an eruption on its surface while an accretion disk is still in place, explosion physics may be able to produce the classical barrel and cones morphology, proposed to be common throughout nova systems.

It was found that a barrel and cones morphology can recreate all observed nova shells, including those who appear as hourglass shapes. There are two
ways to produce an apparently hourglass morphology from a barrel with cones. First, it can be an illumination effect through the sections of least shell coverage of the underlying binary. Otherwise, as is stated on the discussion on molecules in planetary nebulae in Osterbrock and Ferland (2006), ‘emission is brightest around the equator of the nebula’ that holds true for classical novae means that the apparent hourglass morphology may be an inclination and resolution effect of the equatorial cylinder. The latter point is reminiscent of the observations of Saturn’s ‘ears’ by Galileo, which were later resolved by Huygens to be a series of thin equatorial rings.

7.3 Future Work

The techniques developed and data gathered over the course of the preceding study may be furthered comprehensively. First, not all data gathered had been fully reduced and analysed, especially the later 2017 data. A lot of the background work done during the last four years has identified a number of interesting targets for follow-up that did not make it into the thesis for reasons of lack of completeness. Both in collaboration and individually, the candidate wishes to apply the techniques learned over the course of this study to the entire sample of known nova shells covering all possible observational epochs. The suggestion of a potentially common underlying 3D structure to all nova systems is enticing to follow-up. This can be done in a similar manner to what was done with GQ Mus by Morisset and Pequignot (1996a) except for a large sample of novae with the SHAPE/pyCLOUDY interface developed in this thesis.

The intention of the work presented here was to monitor a large sample of
nova shells in the hope of contributing to classical nova research. It was only after standing back and assessing this work as a whole that it was realised that these stellar phenomena should be more standardisable. Through knowledge of the orientation in the plane of the sky of the underlying binary system, the structure of the observed emission should be explainable, in the context of both multiwavelength-evolutionary-light-curves and spectral development. The opening angles affect the covering factor of the nova shell around the central binary system. The filling factor is related to the degree of clumping, which in itself should be related to the rate of entropy in the outflow during the first couple of months following eruption.

The majority of the archival work, modelling and new observations performed over the past several years, at the time of writing, is behind Chapter 6. Organising the background materials in the most presentable manner meant the omission of material and some of the observations marked unsuccessful in detecting nova shells do indeed show some evidence, but require more analysis or deeper complementary observations.

The most apparent difficulties that arise are in deriving the opening angles of polar and equatorial features with respect to the central system as well as the degree of clumping. It will be necessary in future work to find methods from which reliable values for these parameters may be derived.

Preliminary modelling to date has shown promise in creating a unification scheme for classical novae, along the same lines as was done for active galactic nuclei (Urry and Padovani, 1995), the scheme would be based on inclination towards the source and the WD mass.
Bibliography


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