Photometry of Recent Outbursts of Dwarf Nova AL Com

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PHOTOMETRY OF RECENT OUTBURSTS OF DWARF NOVA AL COM

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PHOTOMETRY OF RECENT OUTBURSTS OF DWARF NOVA AL COM

A Dissertation Presented to the Graduate Faculty of

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Finally, I would like to thank my husband and my children because they are my real strength. Without those people this work can't be successful.
I present results of a search of Dwarf Nova Al Com. I studied the light curve of Dwarf Nova system (2009 Outburst of J094002.56+274942.0) by the ROTSE-III robotic telescope. I perform a photometric analysis of the raw images starting with a source extraction package, and then calibrating to known stellar sources. The analysis of the light curve is performed with RPHOT software, and I compute the change of the Dwarf Nova magnitude (brightness) across the duration of the study. At least two superoutbursts are observed over a 4 week period. Additionally, I use a Lomb-Scargle Periodogram to also look for periodic effects. The variation of the light curve provides clues as to the underlying physical mechanisms of the Dwarf Nova system.
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This dedicated to grandmother's soul who illuminated ways of my life.
Chapter 1:

INTRODUCTION

A key concept in the field of Astronomy is that stars change over time (Templeton, 2010). The complexities of these bodies begin when “[they are] born from clouds of interstellar gas and dust [and end] when they run out of fuel and die, returning some of their mass back into interstellar space” (Templeton, 2010).

According to Pols (2009), stars most have two unique criteria for them to be considered as stars: 1. they should “[radiate] energy from an internal source”; 2. they should be “bound by [their] own gravity” (p.1). Given this definition, it means that planets, asteroids, and comets are excluded as these objects do not comply with the first criterion. Although the brown dwarf complies with the second criterion, it does not have enough mass to ignite nuclear fusion. Since a brown dwarf does not meet the first criterion, it is not considered a star.

These criteria have an even bigger implication. Stars evolve. The birth and death of stars are only milestones in their evolution. When stars run out of their internal source of energy, they collapse and send at least some of their mass back into space. A new generation of stars will then adopt this mass then repeat the entire process of stellar evolution (Templeton, 2010).
The focus of this chapter will be about the complex evolutions of stars and their different systems and behaviors which they exhibit within their lifetime. Understanding these processes is necessary to make sense of the evolution of stars in its later life.

Stars have varying and interesting lifetimes, and according to Temming (2014), one of the dependencies of the life expectancy of these astronomical bodies is their mass. Generally the more massive a star is, the faster that it runs out of its internal energy and burns out. This means that the life of a star has an empirical relationship to its mass. The most massive stars can last for only a few million years, while the smaller ones, about the size of the Sun, would last, on average, for about 10 billion years (Temming, 2014). If we say, for example, a star is only a tenth of the size of the sun, then theoretically, it would live up to more than a trillion years, where this can be determined using the mass-luminosity empirical relationship.

In the context of stars’ lives, millions of years outlive any single individual human, and the capacity of human to view and understand the interstellar space has not even reached more than a thousand years, so how is it possible that scientists and researchers can claim of these facts? Graham (2004), an astronomer at the Carnegie Institution of Washington, explains that there are many different pieces of evidence which support the conclusion.

“Almost all stars shine as a result of the nuclear fusion of hydrogen into helium – their internal energy. This takes place within their hot and dense cores where temperatures could rise up to as much as 20 million degrees Celsius” (Scientific American Editors, 2014). Graham (2004) furthered that the rate of energy generation for a star was very sensitive to two elements: temperature and gravitational compression. Theoretically, the heavier the stars, the faster the rate of en-
ergy generation, and in turn the brighter and hotter the star is. Heavier stars burn their fuel much faster, hence, the faster their life ends. Eddington (2008) derived the relationship between the mass and the luminosity, through relating it with the radius of the star, which gives that the star’s luminosity is equal to the ratio of its mass to the power of 1.5 and the square root of its radius, hence the formula \( L = \frac{M^{1.5}}{R^{0.5}} \), where \( L \) is the luminosity, \( M \) is the mass, and \( R \) is the star’s radius.

Another piece of evidence, according to Templeton (2010), was the “observational study of star clusters—or groups of stars all born at the same time and place.” There is also evidence on the physical properties of variable stars. According to Saldyga (2013), variable stars experience changes in brightness varying “from a thousandth of a magnitude to as much as twenty magnitudes over periods of a fraction of second to years”. There are over 300,000 of them known and catalogued, while many more are suspected to be variable – one of the reasons why they are studied. Variable stars change brightness due to a number of reasons, and these are categorized into two types – intrinsic and extrinsic (BSJ, 2012). A variation of intrinsic stars is due to physical changes in the stellar body while extrinsic stars vary due to the eclipse of one star by another such as the effect of stellar rotation. It is evident here that intrinsic stars vary due to their internal system while extrinsic stars vary due to their external system. Moreover, according to BSJ (2012), intrinsic stars are further divided into three classes while extrinsic stars are divided into two more. The former is composed of the pulsating, cataclysmic, and the eruptive variables while the latter is composed of the eclipsing binary and rotating stars.

As one can see, stars are complex astronomical bodies, which make them interesting subjects for a study. According to Saladyga (2013), “stars are the primary engines of cosmic evolution, [which are primarily responsible] in the creation of elements heavier than hydrogen and he-
lium, which [in turn] make [life possible].” Aside from this, information about other stars such as mass, radius, luminosity, internal and external structures, temperature, composition, and evolution would be understood more if these bodies are studied. In this paper, the stellar evolution would be further discussed, along with the white dwarfs, interacting binary systems and cataclysmic variable scenarios. Also included are the dwarf novae, their systems, outbursts, photometric behaviour, and many others.

1.1 Stellar Evolution and White Dwarfs

Stellar Evolution is referred to as “the [complete] process that a star undergoes during its lifetime” (Templeton, 2010). The Hertzsprung-Russell Diagram used to identify a star’s current phase is named after two astronomers, Ejnar Hertzsprung and Henry Norris Russell. They discovered a way of comparing stars.
Fig 1.1 shows an example of an H-R Diagram based on the discovery of both astronomers. According to their findings, when one star’s brightness is plotted “versus their spectral type or color in a graph, the stars lie within well-defined areas within the graph” (Templeton, 2010). Essentially, what this explains is that a star of a given color can only lie within a certain range of brightness whereas a star of a given brightness can only lie within a certain range of color (Templeton, 2010). Spectral class, color, surface temperature, absolute magnitude, and mass are all related through this diagram. Edward Pickering used the alphabet sequence from A to Q to distinguish stars that had similar spectra (Odenwald, 2003); however, due to redundancy on some of his classifications, some were swapped and refined to a more uniformly changing sequence, which gave way to the OBAFGKM sequence (Odenwald, 2003).
This is crucial for both Stellar evolution and variable stars as there are “individual stars [that] have different physical properties and lie at different positions [on] the H-R diagram” (Templeton, 2010). When stars are discussed, they are often described using the H-R diagram. Based on the diagram, a skilled astronomer would be able to identify the current phase of the star in terms of its stellar evolution. There are five phases of a star’s life: birth, the main sequence, leaving the main sequence, old age, and death.

After most stars’ death, the remains are what is called as the white dwarfs (Cain, 2009); Such stars—white dwarfs—are roughly the size of the Earth while extremely dense – possibly about 1,000,000 times denser than that of the sun.

When a star runs out of hydrogen fuel, it runs out of internal energy, its fusion stops, and begins to die. It puffs out its outer layers and what remains is the white dwarf that is the hot carbon core considered as the leftover material from the helium fusion. When the fusion stops, the core of the star heats up and starts fusing helium and then the outer envelope of the star expands and cools, increasing luminosity while decreasing temperature. However, not all stars end up as white dwarfs. This is the ultimate fate of Sun-like stars and most others especially classed under spectral classes A-M. (Cain, 2009).

Interestingly enough, according to Cain (2009), one sugar cube size of a white dwarf would weigh about one metric ton. Eventually, these bodies would cool down to the temperature of the universe, and can only be up to a maximum of 1.4 solar masses. Otherwise, anything beyond that would result in a collapse to a neutron star or possibly a black hole.
1.2 Interacting Binary Systems

Approximately half of the stars in the sky are in binary systems, or generally, clustered in multiple systems where the orbital periods range from only 11 minutes up to millions of years (Podsiadlowski, n.d.). Some of the properties of binary stars are categorized into two types: Algol and contact binaries. The former is made up of a main sequence star with a mass of 3.7 solar mass, and a giant star with a mass of 0.8 solar mass. The latter indicate that similar to Shen’s (2015) findings, some binaries contain white dwarfs or other stellar remnants that have periods of greater than 2 hours implying a separation of more than the radius of the sun (ASTR 3730, 2003).

When a component star or two has filled or exceeded its Roche lobe, “the distinctively shaped region surrounding a star in a binary system (see Fig. 1.3)” (Roche Lobe, n.d), it creates a binary interaction. When this occurs, the donor star will flow towards the accretor star (see Fig. 1.4) (Boffin et.al, 2012).
1.3 Cataclysmic Variable Scenarios

Szkody et al. (2012) describes a cataclysmic variable (CV) “as a mass-transferring close binary [containing] a white dwarf primary and secondary [which is] usually [a] late-type main sequence star.” These stars are thought to form from wider binaries that are composed of two main sequence stars. When the larger of the two becomes a giant and forms a common envelope around the system. Templeton (2010) identified main sequence stars like those which still continuously burn hydrogen in their cores.
Fig 1.5 illustrates a phenomenon known as the dwarf novae. A dwarf nova is a CV wherein the accretor star is a white dwarf. A common characteristic of this CVs is that its outburst last from a few days up to 14 days (Jensen et al., 1995). They usually have an accretion disk as illustrated in Fig 1.5. There is mass transfer to the accretor, and usually a hot spot where the mass stream collides with the accretion disk. This point, according to Jensen et al. (1995), is “where the stream of gas from the secondary [star – the main sequence star], impacts the disk” (p. 43). The brightness of the hotspot accounts for the majority of the brightness being emitted by the binary system. Once the common envelope between the two stars dissipate, the resulting white dwarf-main sequence binary system evolves without mass transfer (Szkody, 2012). When this happens, it will continually lose momentum through a breaking wind interaction which then decreases the orbital period until the main sequence star fills its Roche lobe. This is the point when the mass transfer begins towards the white dwarf.
CVs are usually identified by their variability on timescales of minutes to hours to weeks to years. One of the shortest recorded ranges of their timescale variability is “a little over 1 hour to 15 hours” (Jensen et.al, 1995, 43).

A good example of a CV is the DW Ursa Majoris where its brightness varies between magnitude 14 and 18 with a period of 3.26 hours. Fig 1.6 shows the brightness variation which occurs because the bright spot formed by the collision between the matter stream and the donor star while the white dwarfs’ accretion disk is eclipsed by the donor star as they revolve around the center of mass.

Overall, as the orbital periods of the systems indicate, CVs are very small interacting binary systems and are often said to be comparable to the solar system’s diameter.
Chapter 2

DWARF NOVAE

Cataclysmic variable stars (CVs) are phenomenon astronomers are yet to fully understand. There is another phenomenon that is closely associated with CVs, and they are known as the Dwarf Novae.

As discussed in the first chapter, CVs are interacting binary stars consisting of a main sequence star and a white dwarf. The main sequence star, usually in its later stages, “is in close orbit with [the] white dwarf. [Because of] the [close] orbit [between the two], the secondary star fills its Roche [Lobe] volume and hence loses [its mass]” (Jenset, et al., 1995, p. 43), which then transfers to the white dwarf which develops an accretion disk as previously illustrated in Fig 1.5. A hot spot develops when the mass flow coming from the main sequence star collides with the formed accretion ring, which is then considered as the brightest spot in the system.

Jensen et.al (1995) states on their research that Dwarf Novae are classified as being closely associated with CVs. What exactly are they anyway? Nova is a Latin word which literally translates to new, which is described to be the appearance of a new star (Ockham, 1999).
Novas are described as brilliant objects where there previously was a very faint star or none at all. Furthermore, Ockham (1999) states that “a Nova is a phenomenon that happens in a binary system containing a white dwarf and a stable companion star.”

In 1855, the first dwarf nova was discovered by John Russell Hind, who was searching the skies with the intention to find new minor planets within the constellation of Gemini. During his search, he discovered a glowing object of approximately 9th magnitude and thought of it as an asteroid (Jensen et al., 1995, p. 43). However, during his further observations, he discovered that it did not move – hence, he concluded that it was a star. Within the next few days, he continued to observe it, and it became fainter until it became invisible to the telescope. Hind classified this as a faint nova (Jensen et al., 1995).

Three months after that, another amateur astronomer, Norman Robert Pogson saw the same star and monitored it more systematically. Pogson soon discovered that what he and Hind found was not a faint star, but a new kind of star which has numerous outbursts observed, spaced at approximately 100 days apart. The two scientists were then known as the first ones who discovered the dwarf nova. The star was named as U-Geminorum, and it was only 40 years after that SS Cygni, the second dwarf nova, was discovered. Since then, astronomers, both the experienced and the amateur ones, began to discover many more dwarf nova.

Based on these observations, it can be inferred that dwarf nova erupt multiple times during which their brightness increased by 2 to 5 magnitudes (Dwarf Novae, n.d.). “Each eruption lasts between 2 and 20 days with the Nova duration related to the interval between outbursts” (Dwarf Novae, n.d.). Dwarf nova exhibit quasi-periodic eruptions but most of the time they stay
in their minimum states that are only interrupted by abrupt outbursts (Jensen, et al. 1995, p. 43).
Based on observed data by astronomers and researchers, the recurrence for outbursts for dwarf nova is not constant, even for a single one. For instance, SS Cyg’s outbursts range from 15 to 95 days, with an average of 50 (Jensen et.al, 1995). The same holds true for all Novae, and to date, there has been no nova discovered yet with a constant period between outbursts.

So, if the CVs and the Dwarf Novae as explained in the preceding discussions are relatively almost the same, what sets them apart? The answer lies with the outburst activity. Wargau (1999) puts it this way – CVs reveal less frequent outbursts with a quiescent phase of about $10^4$ to $10^5$ years between explosions while the dwarf novae erupt more frequently.

Dwarf novae have two different models that attempt to explain the outbursts that occur – the mass transfer burst model and the disc instability model (Dwarf Novae, n.d.). The Mass Transfer Burst Model is the alternate model, which states that where a “sudden increase in the transfer of [mass] from the companion star to the accretion disk causes the [entire] disk to collapse” (Dwarf Novae, n.d.). The result of this course of action is that the mass of the disc would suddenly be dumped into the “white dwarf, releasing large amounts of gravitational energy” and thus causing outbursts (Dwarf Novae, n.d.). It is evident why the model is commonly called the mass transfer burst – due to the sudden and outright burst of the matter.

The more prominent model, according to Buat-Menard et.al (2001), is the disc instability model (DIM), which describes the whole dwarf nova outburst cycle.
Buat-Menard et.al (2001) stated that the reason DIM is the model which most likely explains dwarf nova outbursts is that this model “identifies the physical mechanism giving rise to the outbursts” (p. 1).

Dwarf Novae (n.d.) explains that, in a nutshell, “the accretion dis[c] [that surrounds] the white dwarf is able to accumulate a certain amount of gas at a steady rate before [it becomes] highly unstable.” After which the rate of mass flow increases rapidly, resulting in the release of high gravitational energy causing what is described as the outburst. After enough mass has been released, the mass flow rate of the disc gradually becomes normal again, resulting in the disc’s stability, and the system finally returns to its quiescent state (Dwarf Novae, n.d.).

It is evident that there is a significant difference between the two models, but both point out two common thing – the instability of the accretion disc and the release of massive gravitational energy causing the outbursts. Wargau (1999) attempts to explain why the accretion disc becomes unstable, and this is due to different viscosity values, which evidently are the primary cause of outbursts. Whether one uses the DIM or the alternate model, the viscosity of the mass which flows from the main sequence star to the white dwarf causes the “upset” or instability of the ring.

At low density, similar to any fluid, the viscosity is low, and the mass flow is relatively constant. However, when the accretion ring becomes more massive due to the constant mass flow towards it, it becomes denser, and its viscosity tends to become higher until it reaches a critical level. When the viscosity exceeds its critical value, it increases very rapidly, and the disc expands further where a large portion of its mass is accreted to its white dwarf. This pull towards
the white dwarf causes a significant amount of gravitational energy resulting in the outburst. However, the outburst that “shines” bright is not really the gravitational energy per se, but rather, the radiation that is the result of the higher gravitational energy release. In other words, the gravitational ‘potential’ energy is released or converted to radiation energy.

The DIM is only one of the models that describe the behaviour of the outbursts. Aside from this, dwarf novae are further divided into 4 sub-classes; all are in accordance with their specific behaviours, namely:

1. SS Cyg type, UGSS – U Gem and SS Cyg, classical dwarf novae, belong to this class. These classical novae are also considered as CVs, and their outbursts “are generated by thermonuclear runaway reactions at the surface of the white dwarf, following long periods of accretion from the [main sequence star]” (Jensen et al., 1995, p. 43). The behaviour of their outbursts includes always being “accompanied by an expulsion of a shell of material” (Jensen et al., 1995, p. 43).

Fig 2.1 A portion of the SS Cygni light curve (AAVSO, 2014a)
2. Z Cam-type, UGZ – stars belonging to this sub-class has the same characteristics with that of the SS Cyg type with the addition that they are characterized by standstills in their light curves. According to Jensen et al. (1995), this “eruption light curve is occasionally interrupted by periods of [standstills] lasting from [a few] days to several years. During [these] standstills, the star [has] a brightness [ranging] between the normal maximum and [the] minimum magnitudes” (p.43). Honeycutt, Robertson, Turner, and Mattei (1998) added that during this phenomenon, Z Cam systems are as bright as, if not brighter, than their mean brightness when they are outbursting. Also, the authors noted that Z cam’s “exits from standstill tend to be somewhat more rapid with $\tau \approx 5–8$ days.”

![Figure 2.2](image.png)

Fig 2.2 Comparison of Z Cam’s ultraviolet spectrum (histogram) with spectra produced by an SA disk model with g s~1 (solid line) and M 0 acc \( \geq 10^{17} \) a BB disk model with g s~1 (dashed line), (Knigge, Long, Blair, Wade, 2009)
3. SU UMa type, USGU – The outbursts in this subtype are usually frequent and narrow, although superoutbursts occur from time to time. Superoutburst is when the outburst is about 10-18 days, longer compared to the 1-3 days of normal outbursts, and the magnitude is brighter than the normal one (AAVSO, 2014b). During one of these so-called super outbursts, some superhumps or light short-period variations are observed. These superhumps are characterized by and are visible because they are a few percent longer than the orbital period. It is definite that the superhumps are essential “to determine the orbital period of systems where [it] is otherwise very difficult to identify” (Jensen et al., 1995, p. 43).

Fig 2.3 SU UMa Light Curve (AAVSO, 2014b)
4. WZ Sge type, UGWZ – this is the rarest and very “special type of dwarf nova [because it] has outbursts [that occur] very seldom” (Jensen et al., 1995, p. 43). Normal novae have outbursts within an average period of days, but this type of nova has a recurrence time of several decades. It is very clear that the detection of the outbursts of these novae is very rare, and hence, observing one is extremely important.

Fig 2.4 WZ Sge Light Curve (AAVSO, 2014c)

Fig 2.5 Radial velocity curve of CPD-48°1577 (Wargau, 1999)

To further explain the concept of the differences between the types of dwarf novae, the results derived in Wargau’s (1999) research – CPD-48°1577 and HLCMa are put into context on Fig 2.5 and 2.6.
The one shown in Fig 2.5 has five spectra continuously over a time interval of several hours, while, in the case of HLCMa in Fig 2.6, 31 spectra could be taken on three consecutive nights. The curves presented in Fig 2.5 and 2.6 are their corresponding radial velocity curves, and the dots are representations of the velocities of the hydrogen lines.

The results of these data, according to Wargau’s (1999) analysis, state that for CPD-48°1577, the orbital period is at 4h 29m, while for HLCMa, the orbital period is at 5h 09m. The orbital periods also are distinguishing characteristics of the dwarf novae.

According to Wargau (1999), the orbital periods of CVs generally range from 80 minutes to 10 hours. After a thorough inspection of all the available orbital periods, one would find out that there is a clear gap between the two and three-hour range. This two-three hour range gap distinguishes the four types of dwarf novae.
On the build-up of the fourth type, Fig 2.3 “shows an example of a light curve [that has been] obtained for a programme star: UGWZ [types] dwarf nova UZ Bootis” (Jensen et al., 1995, p. 44).

Fig 2.7 UZ Bootis light curve (Jensen et.al, 1999)

The UZ Bootis light curve shows a documentation of a superoutburst that has occurred on August 1995. The previous one was observed in 1978. Fortunately, it was only separated by less than 20 years, making it observable by astronomers and scientists. With the variability of the
outbursts of the stars, the question is, how do scientists classify and categorize the dwarf novae especially when they become too variable? The answer lies with the program created by The Astronomer, an organization based in the United Kingdom, which has a base of 75 objects of various types with different ranges and classified under one of each type of the novae (Beardmore, 2016).

This program is known as the Recurrent Objects Programme (Jensen et.al, 1995), which presents two main criteria for the classifications of the objects:

1. “[The] star must have an outburst period of at least one year” (Jensen et.al, 1995, p.44).
   Probable or suspected outburst periods are also acceptable, although they are mostly put under strict observation.

2. “Information on the precise cycle length or amplitude is available” (Jensen et.al, 1995, p.44).

More dwarf novae have been classified and were added to the list covered by the program as long as they satisfy the two criteria above. Some of the novae under the list have only about one or two outbursts but are still placed under observation.

All dwarf novae with periods of greater than or equal to three hours belong to either the UGSS or UGZ type while those which fall below or equal to two hours belong to the SU UMa type. It is quite distinguishable that the SU UMa type have less orbital periods, and although astronomers are yet to pinpoint the main reason behind, but some say that there is a correlation to
the fact that dwarf novae belonging to this type have superoutbursts. Fig 2.5 may be classified under the UGZ type based on Wargau’s findings (1999, p. 10) while Fig. 2.6 was not clearly identified under any of the abovementioned subtypes. However, Wargau (1999) noted that HL CMa and CPD- 48°1577 are “closely related systems” (p. 9). The question now is, why is it that the WZ Sge type not classified? It is because it has been observed only on rare occasions, and little information has been known pertaining to these stars. Aside from this, astronomers have yet to discover how to measure their orbital period, especially because they are very rare.

Another challenge when it comes to the fourth class is that, occasionally, some stars classified under the dwarf novae are found out to be non-eruptive in nature. This means that the star is wrongfully classified as a dwarf nova. This is one of the good benefits of the programs, as it filters the true dwarf novae from the suspected ones. There are four action points according to Jensen et al. (1999) that interested astronomers take in terms of observing probable dwarf novae:

1. Monitoring – astronomers use instruments to observe constantly the suspected dwarf novae, especially when they are at their quiescence. The reason why they are observed during this stage is to take on the possibility of getting the early signs of an outburst, and warn other interested professionals should such be the case.

2. Confirmation – whenever the beginning of an outburst is observed, or reported by an individual observer, it has been common practice that a confirmation be sought from another observer (Jensen et al., 1995, p.45). CCD, an instrument used to capture images of these novae, may be deployed as their confirmation images are more credible than a second observation.
3. Astrometry/Photometric Sequence – similar to how the solar system is mapped out, observers of the dwarf novae also create a map or chart to plot the different ones that are placed under observation. CCD images provide accurate positional measurements such as the right ascension or declination of the subject stars that make it feasible to plot accurately them on charts. One of the common mistakes is assuming that the ones being currently used are correct. Which leads to mistaken observations and assumptions that an outburst of a particular star is occurring, but upon closer inspection or verification, it would be identified that it is a different star.

4. Photometry – A reliable photometry may be achieved by taking regular images of the subject stars because capturing images is more accurate than writing visual observations, as some may tend to be subjective (Jensen et.al, 1995, p.45).

Although the DIM is the most accepted model by astronomers, there are some studies on DIM, which has found some of its gaps. Buat-Menard et.al (2001) describes these deficiencies as identified by the astronomers and researchers over the course of history:

- “First, models predict a significant increase in the disc luminosity during quiescence, an effect that has not been observed” (Buat-Menard et al., 2001, p. 612).

- Second, in many systems the distribution of the bursts can be classified as bimodal, meaning to say that there are two modes of the bursts. According to the DIM, the reproduction of the burst width is bimodal although the amplitudes are different: narrow outbursts’ amplitudes are lower than wide ones’. This fact, however, is the opposite of the observation.
• Third, according to observations, “the secondary is irradiated which makes the mass flow increase; [however,] the standard DIM does not take these into account” (Buat-Menard et al., 2001, p. 612).

Aside from these deficiencies, more can be derived from DIM, and through answering these gaps, more gaps are identified. It was conclusive “that the standard version of the [model] has to be [further] enriched by [including the] physical processes [taking place]” (Buat-Menard et al., 2001). These were not originally accounted for in the previous versions, but as described, they are important.

2.1 Description of The System

Buat-Menard et al. (2001) puts into perspective that these novae are erupting CVs with varying magnitudes and the variable period between outbursts. Similar to the CVs, there also is a mass transfer between a white dwarf – the primary star, and a main sequence star (usually in its later stages) – the secondary star. Similarly, when the Roche lobe is filled by the secondary star, there is mass transfer to the primary star. The only difference is that an accretion disc is formed around the white dwarf. Recapping Fig 1.5 on the first chapter, the accretion disc surrounds the white dwarf with the mass transferred from the main sequence star.

In a nutshell, the system of dwarf novae is composed of three main components – the white dwarf, the main sequence star, and the accretion disc. Aside from this, hot spots form when the mass flowing from the secondary star collides with the accretion disc and accounting for the majority of the system’s brightness. The concept of the mass flow and the accretion disc
is crucial in understanding what an outburst is. As per Buat-Menard (2001), it is believed that accretion disc instability trigger the outbursts.

There have been previous discussions about outbursts, but what is it really and how is it described? When the accretion disc collapses, the gravitational energy of the white dwarf rapidly increases emitting radiation. According to Ockam (1999), “in a brief but violent cataclysm, the remaining hydrogen on the white dwarf’s surface burns away” and during the process “the white dwarf brightens by as much as a factor of a million (15 magnitudes).” This brightness emitted by the white dwarf is known as the outburst and is the one that is commonly observed by astronomers. This occurs until such time that the mass of the accretion disc becomes stable again, where the system returns to its quiescent stage. During this stage, the system remains silent until the hot spot is seen again, and the process of the system repeats all over again. The next section would discuss how the outbursts occur and describe the factors influencing it.

Shears et.al (2010) provides a more detailed description of the system of SU UMa type. According to their findings, “the light curve of a SU UMa system is characterised by superhumps, [which] are modulations in the light curve [and] are a few [percentage] longer than the orbital period, [which] are thought to [be caused by] the interaction of the secondary star with [the] eccentric accretion disc” (p.155). For example, if the orbital period is 6 magnitudes and the modulation is 10 magnitudes, then the latter is considered a superhump. There are other behaviours of the types of the dwarf novae, which have already been discussed in the opening section of this chapter. As a review, there are different distinct behaviours of the systems depending on their system, and these types are: UGSS, UGZ, UGSU, and the very rare UGWZ.
2.2 Evaluation of The System to Outburst

Fig 2.8 shows a scatterplot diagram of the number of days observed between the peaks of the outbursts of a dwarf nova identified as BV Centauri, which has been under observation for more than 54 years (Plummer et.al, 2009). As illustrated in the figure, the peak number of days lasts for more than 1800 days while the minimum can go up to less than 100 days. This phenomenon is very common with the different types of the dwarf novae.

The variability of the outbursts is interesting, and the best way to describe the reason behind it is through describing the process that results in outburst. There are two models which discuss the process as to how the systems have outbursts. It has already been previously established.
that there are two main factors which cause an outburst – the instability of the accretion disc and the nova outburst, resulting from the sudden transfer of material to the white dwarf (Cosmos, n.d.a).

Previous discussions provide the fact that dwarf novae have an interacting binary system that is closely related to a CV. This means that it has a primary star and a secondary star. When the orbital period, or the distance between the two stars becomes too narrow, the mass of the secondary star (main sequence star) fills out its Roche Lobe. This causes the transfer of the mass towards the primary star. Recall that the Roche lobe is the space to which the secondary star has its gravitational pull. Once the mass exceeds this region, it flows towards the white dwarf.

Unlike the CVs, the white dwarf would be engulfed by an accretion disc, a disc formed by materials diffused from a star. There is a constant flow of mass towards the accretion disc, which causes the disc to become denser every time the mass flows to it. Due to the nature of the correlation between the density of gases and their viscosity, the higher the density, the more viscous the gas becomes. When the accretion disc reaches a certain density, it would have also reached a “critical” viscosity (Wargau, 1999, p. 7).

The mass of the disc would fall towards the white dwarf, which causes a rapid increase in gravitational energy, to which the radiation increases as well, usually going up to as high as $10^{45}$ ergs (Wargau, 1999). When this happens, the hydrogen on the white dwarf burns. This causes the sudden increase in brightness of the white dwarf and is more commonly termed as an outburst. As the accretion disc gradually loses mass, its density and viscosity also decreases, gradually decreasing it back to its normal levels. When this happens, the radiation emitted
would be lessened, and the brightness would return back to its average levels. This becomes the end of the outburst. The mass flow to the accretion disc would return back to normal levels, and the system returns to its quiescence stage.

Fig. 2.8 shows a common system of dwarf novae; where there are variances in the period between the outbursts. Because of the nature of its process as a cycle, it only repeats over and over again. BV Cen., under the observation of astronomers for more than 54 years, is a perfect example showing the cycle from the evolution of the system to the outburst, and gradually returning back to its quiescent stage.

2.3 Photometric Behaviour of Dwarf Novae

Shears et.al (2010) reports the discovery of a new dwarf nova and confirms its most recent superoutburst in 2009. It was discovered in the course of a systematic search for dwarf novae in archival images. The method used for searching systematically is through the use of photometry. This subsection would discuss the behaviour of two systems that have been identified through the use of photometry.

The basic method done by the astronomers is as follows: blue objects were selected from the GALEX survey data release 3 (Shears et al., 2010) and were matched to objects in the USNO-B1.0 catalogue. Those showing large magnitude variations were flagged and verified with the U.S. Naval Observatory Flagstaff Section, which include the original photometric images from which the catalogue was originally created in order to verify the existence of the found objects. One of these objects was USNO-B1.0 0981-0723427, which was identified to be an out-
burst. Further outbursts were identified where the identified object was declared as a dwarf nova with the identity of ASAS J224349+0809.5.

Once the photometric images were made available, the behaviour of the observed system was further studied. The overall light curve of the outburst is shown in Fig 2.9 wherein it was observed that the star is brightest at V=12.8 in the ASAS-3 discovery image, and the Period after V=18.7. This implies that the outburst amplitude is about 6 magnitudes above the mean quiescence.

![Light curve of the outburst of ASAS J224349+0809.5 (Shears et.al, 2010)](image)

Fig 2.9 Light curve of the outburst of ASAS J224349+0809.5 (Shears et.al, 2010)

Further observations of the system lead to more discoveries. Time series photometry led to discovering that some three days after the first outburst was observed; there is some evidence that the star was brightening, which indicates that the first observation was only a precursor outburst. A plateau phase followed during which the star gradually faded at a mean rate of 0.11
magnitudes per day, which then followed a more rapid decline of approximately 0.98 magnitude/day. Then over the next few days, it reached a magnitude of 17.8. This was observed about 17 days after the first outburst. This was the minimum observed, which lasted for four days to which it brightened again to 14 magnitude. It lasted for approximately three days before returning to its quiescent magnitude at 18.7. The total outburst cycle lasted for more than 26 days.

What is intriguing about this outburst is that it was: 1) a superoutburst, and 2) followed by post outburst brightening. The explanation for this behaviour is that it was still part of the first outburst and should not be considered as a second normal outburst, primarily because of three reasons: 1) The star was at a magnitude above its quiescent stage (at 17.8 compared to the average of 18.7) between the first outburst and the second brightening; 2) There were superhumps identified during the temporary minimum; and 3) It occurred too soon after the first outburst, only approximately four days.

The researchers concluded that because of these behaviors, and based on the observations, it is classified under SU UMa type. Furthermore, based on available data, outbursts have been observed in October 2005, June 2006, and June 2007, leading to the researchers estimating an average period between outbursts to be 450 days.

Dwarf Novae SDSS J094002.56+274942.0 (Krajci et.al, 2010)

The CV J094002.56+274942.0 was discovered in 2007 by Szkody (2012) and was observed only once by SDSS at a magnitude of 19.10. Fig 2.10 shows the light curve of the aforementioned CV, and upon calculations made by the researchers, it was identified that a magnitude of 13.8 was sufficient to be used as a basis for the brightness for the system.
It was observed in November 2009 that on the 26th, the object was half a magnitude above its normal brightness (as seen above the value of 183 on the y axis), which is about 18 magnitude. And just two days afterwards, returned to its quiescence magnitude. Near the maximum of the outburst, the light curve was fairly featureless, and after a couple of days, there was a “double wave observed with a period of 0.16352 day” (Krajci et al., 2010) and constantly growing in amplitude. At quiescence stage, these waves were identified to have a period of 0.3 days, meaning that it has become more visible. The interpretation of this behavior is that these periodic variations are at the later stages of the outbursts and at quiescence because of the changing aspect angle of the shape of the dwarf. This change causes the light to increase as the system fades.

It was further observed that a small dip corresponding to the phase of one of the minimum variations occurred during the brightest stage of the outbursts. A possible explanation for
this one is that the dwarf was partially eclipsing the accretion disk or the hot spot. Data was conclusive and the researchers have categorized the system as a dwarf nova with an orbital period of 3.92 hours, with a 0.3 magnitude variability in its quiescent stage, which is due to the ellipsoidal shape of the main sequence star. There were also observed eclipses on the hot spot of the disc, causing the drop in magnitude. The outburst frequency was also observed to be about once per year or less though the researchers highly recommend that this be further evaluated and verified. If this assumption is correct, then it fits the explanation of the process of outbursts and the Disk-Instability Model, which is influenced by the period when the disc collapses. Since that the orbital period is very fast, it is evident that the mass transfer would be relatively fast as well, which then leads to more often outbursts or less period between outbursts.
Chapter 3

DETECTORS AND DATA

3.1 Rotse-IIIB

The ROTSE-IIIB telescope (as seen in Fig. 3.1) is one of the four (4) telescopes finished in 2003, which were developed alongside other ROTSE III telescopes located in different parts of the world, to gather optical variability data like fast optical transients. The other three (3) ROTSE-III were named as ROTSE-IIIA (Siding Spring Observatory near Coonabarabran, New South Wales, Australia), ROTSE-IIIC (High Energy Stereoscopic System site in the Gamsberg Mountains, Namibia), and ROTSE-IIID (TUBITAK National Observatory in Bakirlitepe, Turkey). Their locations are intentionally selected to have a continuous observation of sources near the equator and provide full-north coverage. In fact, ROTSE-IIIB is identical to the other ROTSE-III in terms of their system designed specifically for their identified components such as its CCD camera, data acquisition, enclosure, environmental sensing and protection, optics, the optical tube assembly, and telescope mount.
Rotse-IIIB is an automated robotic telescope which captures fast responses with \(~5\text{-}7\) s to GRB triggers from HETE-2, INTEGRAL, Fermi, and Swift satellites. Its telescope’s primary mirror is a Cassegrain with 0.45 m f/1.8. At the back of the primary with a corrector lens at the secondary is a mounted back illuminated thinned 2028 x 2048 Marconi CCD. For a 1.85\(^0\) x 1.85\(^0\) FOV, the 13.5 \(\mu\)m pixels subtend 3.28\(^\prime\). A single filter slot positioned in fix is available. However, only unfiltered data has been acquired to date. The unfiltered open CCD transmission ranges from \(~3000\) Å to \(~10000\) Å with the highest quantum efficiency at \(~5500\) Å. Also, the ROTSE-IIIB “can slew from horizon to horizon in just over 8 seconds” from a typical alert slew time of less than 4 seconds from the standby position at zenith because its mount takes a maximum slew acceleration of 16.4\(^0\)/s\(^2\) along the RA axis and 20.6\(^0\)/s\(^2\) along the Dec axis in which both axes can proceed to a maximum slew of 35.0\(^0\)/s\(^2\)” (Akerlof et al., 2003, p. 7).
For the operation of the Rotse-IIIB robotic telescope system, the enclosure houses three desktop computers in which the primary computer is responsible for running the data acquisition (DAQ) software system connected to a fiber optic link by an Ethernet cable. To manually test and control the system, this primary computer consists of monitor and keyboard for use by on-site operator (Akerlof et al., 2003, p. 8). The control computer serves as a firewall for the second computer wherein the main concern is to run the CCD and store the images used by the data reduction pipeline (Akerlof et al., 2003, p. 8). Moreover, these two computers use the Red Hat distribution in which the operating system is a LINUX (Akerlof et al., 2003, p. 8). On the other hand, the function of the third computer is to run the mount control code which is written in C++ and compiled under the operating system of Microsoft Windows NT 4.0 (Akerlof et al., 2003, p. 8). Through the RS-232 serial line, the third computer receives commands from the control computer.

3.2 Rotse-III Operation

The telescope features a rapid response system. The information is analyzed using pre-established values from the Gamma ray Coordinates Network (GCN). ROTSE consists of a dynamic scheduler with a target file for night detections. The scheduler can also carry out sky patrols and determine number of exposures and cadence. All operations by the ROTSE III are usually given a gamma ray detection alert from a computer that determines the location where an observation was made (Akerlof et al., 2003).
3.3 Rotse-III Optical Design

The recommended maximum swing radius of the ROTSE III should be 29 inches wide.

The telescope required the inclusion of a band-pass glass filter and a pro-magnetic shutter. Also, the design allowed for the inclusion of a vacuum silica window and a backside focal distance of at least 7.7mm. The quality of the image received by the observer was approximately 70% of the ray obtained from the incidence energy.

A hyperbolic correction was deemed unnecessary since a parabolic mirror was used to ease the manufacturing and testing process. Also, the parabolic mirror ensured that the device did not require extra degrees of freedom from a secondary 30 mirror. Nonetheless, a secondary mirror was used to assist the optical system in avoiding any mechanical constraints.

As a result, Ohara S-FPL51Y was the most suitable lens element for the first optical glass, whereas Ohara BAlIII5Y was used for the subsequent lenses (Akerlof et al., 2003, p. 137). Schott BK7 (517642) was used as the color filter in the telescope.

3.4 Mechanical Fabrication and Design

The primary parabolic mirrors were designed by Tuscon. The pixel size of the CCD (Charge Coupled Device) camera was set at 13.5 micrometers to limit diffraction performance and relax optical tolerance. All the refractive components were coated for antireflection (Yost et al. 804).
3.4.1 CCD Camera

The CCD camera was designed by Marconi Applied Technologies using a back-illuminated sensor with a resolution of 2048 by 2048 and a pixel width of 13.8 micrometers. In addition, it had high quantum efficiency with low noise readout at 1 megahertz.

Due to the high quantum efficiency, the efficiency of the CCD camera was improved by 100% compared to the earlier ROTSE-I telescope. ROTSE-I had a thick CCD which lost about 50% of the quantum efficiency more than modern CCDs have, such as is used by ROTSE-III.

Also, various engineering problems were identified in the feasibility of the initial design when propylene glycol was used as the coolant (Akerlof et al., 2003, p. 138).

3.4.2 Telescope Mount

The telescope mount is a complex custom component of the ROTSE III telescope. The mount features an 18-inch aperture.

In addition, the steel component in the mount lowered the telescopes inertia and provided a slew platform. To achieve this positioning, the declination and ascension planes move until they reach the limits of the mount.

3.4.3 Telescope Enclosure

The ROTSE III telescopes demand a robust, strong, and simple enclosure. The enclosure for the telescopes consists of four pieces, which include a 90-inch diameter vertical cylinder, a foot skid measuring 8 by 12 feet, a motorized hatch cover, and 24-inch diameter telescope pier.

The entire model is welded together, except the hatch cover. When complete, the enclosure weighs about 6750 pounds (Rykoff et al., 2005, p. 1). The design of the hatch cover is crucial,
since it should allow easy observation of the sky. Therefore, the cover should be able to swing completely away from the telescope such that at least $2\pi$ steradians are visible always.

3.5 Environmental Sensing and Protection

The telescope contains environmental sensors that protect it from adverse environmental conditions. To avoid damage of its components, the telescopes enclosure usually locks itself when the wind speed is above 30 miles per hour. Also, It's equipped with precipitation and temperature sensors which initiate the closing sequence when the environmental conditions are unfavorable.

3.6 Automated Data Acquisition Software

The ROTSE III uses an automatic data acquisition system. The system includes various high-power computers, which communicate with the telescope’s devices using shared memory. The ROTSE III telescope represents an astronomical milestone in constructing high aperture, observatory equipment when there is a need to study and research fast optical transients.

In general, The primary goal of the ROTSE project is to study the prompt optical emission from Gamma-Ray Bursts (GRBs). Gamma-ray Bursts are, perhaps not surprisingly, bright flashes of gamma-ray radiation from outer space. High energy radiation does not penetrate the Earth's atmosphere so in order to see these flashes, we need to send detectors up into space on satellites and spacecraft. If you were in space, and could see high-energy radiation, you would see, roughly once a day; some random spot on the sky get very bright for perhaps only a fraction
of a second, perhaps for as long as a few minutes. That was a GRB. However, just seeing that flash does not tell you what caused the flash, or even how far away it was.

The ROTSE system used for the prompt optical flash from GRB 990123 convincingly demonstrated the value of autonomous robotic telescope systems. Pursuing a program of rapid follow up observation of gamma ray bursts. ROTSE has developed a next-generation instrument, ROTSE-III, that will continue the search for fast optical transients. The entire system was designed as an economical robotic facility to be installed at remote sites throughout the world (Akerlof et al., 2003).

There are seven major system components: optics, optical tube assembly, CCD camera, telescope mount, enclosure, environmental sensing and protection, and data acquisition. Each is described in turn in the hope that the techniques developed here will be useful in similar contexts elsewhere. The ROTSE-III fulfills a significant need in a relatively unexplored area of astronomy. Finally, the information is analyzed in this system using pre-established values from the Gamma ray Coordinates Network (GCN). ROTSE consists of a dynamic scheduler with a target file for night detections. The scheduler can also carry out sky patrols and determine number of exposures and cadence. All operations by the ROTSE III are usually given a gamma ray detection alert from a computer that determines the location where an observation was made (Akerlof et al., 2003).
CHAPTER 4

DATA REDUCTION

4.1 Clustering of Raw Images Using Source Extractor (SExtractor) Package:

4.1.1 Raw Images

ROTSE produces raw image files that include the two-dimensional arrangements of analog-to-digital (ADC) contents of (x,y) organization of the image which reveals the three-dimensional spread of visual light powers in the CCD level. Perfectly, the CCD level matches to the speculum focal level (Ferrante, 2015).

The image files also includes a header which is a roster of data from the camera (e.g. sequential number, CCD temperature), mount (e.g. RA and Dec main locations), climate (e.g. temperature, wind speed and course, moisture), and warned trigger data. This data includes comprehensive photograph of the system condition at the time of contact (Rykoff and Smith, 2003).

4.1.2 Dark Frame Subtraction

Dark-frame subtraction is a manner used to reduce image dark current. A dark frame is an image taken with the sensor in absence of light and the shutter locked, principally an image of noise in the sensor (Ferrante, 2015).

The dark frame is then subtracted from following images to correct for permanent-form noise as that’s due to dark current. Perceptible permanent-form noise is always produced by pixel sensors with dark current more than the usual and may look as sunny pixels on long contacts.
CCD sensors that seem as abnormally bright pixels are called "stuck" while sensors that only brighten up after long contacts are called "hot" (Rykoff and Smith, 2003).

4.1.3 Source Extraction Technique

Source Extractor (S Extractor) is a program that creates a collection of items from a large image (Bertin, 1996). Related features of S Extractor include its ability to work on large images with slight interference and to deal with a different object forms and levels. It is mainly helpful for the examination of large extragalactic studies but can also work efficiently on mildly crowded star domains. S Extractor employs automatically developed for new software that optimally detects, de-blends, measures, and classifies sources from astronomical images. The main functions are as follows (Bertin, 1996) Backing for extended FITS, 1 M pixel/s with a 2GHz processor, DE mixing of interlacing prolonged objects, Actual-time cleaning of images to increase detectability.

4.2 Standardization of star list to standard catalogs

The ROTSE image processing pipeline was established by the ROTSE collaboration to look for fleeting objects in images taken with the ROTSE-III telescope (Yuan and Akerlof, 2008). The pipeline benefits of cross-convolution-Figure 4.1 to do image subtraction which is an important technique in eliminating influences from fixed sources and to magnify any subtle changes. For example, image subtraction is essential to discover a source hidden inside a host galaxy. The complete ROTSE data analysis pipeline is explained in Figure 4.1.

The pipeline starts by analysis of images through S Extractor to achieve primary object recognition, scale central locations, and set opening magnitudes. S Extractor makes an object list using qualitative (x,y) units. A detached pipeline program written in IDL (idlpacman) links the
object with roster of shining stars more than magnitude 15 in the United States. The Marine Observatory (USNO) A2.0 catalog is used to determine the astrometric solution and the estimated magnitude zero-point for the field. It also produces a third-order polynomial warp mapping of \((x,y) \rightarrow (\alpha, \delta)\) so that the position of each object is stated in equatorial coordinates. Later this image used in image deduction to show how to array objects with accurate coordinates (Rykoff et al., 2005).

**ROTSE–III Data Analysis Pipeline**

![Flowchart](image)

**Figure 4.1.** Flowchart depicting the ROTSE-III data analysis pipeline as implemented in an automated real-time process (Rykoff and Smith, 2003).
4.3 RPHOT

RPHOT is a popular software package for computerized data acquisition and reduction of UBVRI aperture photometry. Also, it can manually acquire data from any aperture photometry and reduce "all-sky" and differential photometry to instrumental magnitudes. The visual transients related with gamma ray bursts (GRBs) can be relatively dim (m(t= 60s) > 18) and they naturally diminish as power-law (f ∝ t^α); so, to detect this visual degeneration, minor opening telescopes, as the ROTSE-III instruments, should react rapidly to satellite activators and start imaging the ray positional fault boxes immediately. This rush to identify GRB OTs is then displaced by the rush to declare the exact site of the OT and its illumination and deterioration rate to permit spectators on larger opening instruments to choose if further observation is required or even possible. When the monitoring is completed, there is then a last rush to publish this information to permit spectators to inform or review their science programs in time for the subsequent incident. In this chapter I will detail the interactive data reduction and study set, RPHOT, which was designed to pick up where the original ROTSE-III pipeline left off. RPHOT allows users to construct publication quality light curves from ROTSE-III data quickly; it is very easy to be run by exhausted astronomers at 4:30 am, yet flexible enough to control a variety of problems (Quimby, 2003)
Chapter 5

RESULTS

5.1 Photometry and Create a Light Curve by RPHOT

Photometry measures the amount of light in pictures of astronomy objects. Specifically, light emitted from stars and those in galaxies are quantified. The amount of light is variable with the change of time for certain stars or star systems. There are star systems which can change quite rapidly in a span of hours, or sometimes extendedly over a large number of years. The physical properties of these stars could then be determined based on the speed at which the amount of light changes. For certain variable stars or star systems, the change of the amount of light may be seen in the light curve plots.

To measure light from stars and galaxies, software applications and packages can be used such as RPHOT. We can take many images of the variable star system through a telescope over a period of time, typically a month. The changes of the brightness of a star system may be tracked over that period. In differential photometry, from an image full of stars, we can find one star whose brightness does not change with time and compare the difference in brightness with another star. In our plots, the differential brightness is what is measured and plotted over time. The software, RPHOT, provides information about how much of the image of our star, the Dwarf Nova, has taken up.

It provides the diameter of the star’s light and locates the center – the Point Spread Function (PSF). This PSF measures how the brightness of the star changes with how far our star’s
center is. PSF also determines the precise location of our star and how much light there is within the circular aperture of our star.

The light curve for the nova is created using a terminal program. The following procedures are used to do this:

First, we opened the terminal program then we created an image directory and prod directory. Then, we moved different files, as they should be, to the different directories. The initial steps were saved before exiting.

Next, I opened IDL and performed the analysis. It took some time for IDL to open up, as what may be expected. To assign the variable for the chosen data file based on the field name in rframes.txt, we used the command

\[ f = \text{findfile('image/080312_tss1231+1427–123225+142042_3b006-008_c.fit')} \]

Then using RPHOT, we entered

\[ rphot, data, imlist=f, refname=f, targetra=, targetdec=, /small \]

Then we clicked on the object tab again and clicked on Refstars. Then we changed the radius to 5 arcmins and the minimum S/N to 12. And then we clicked AutoSelect. This is to change the parameters which RPHOT uses to pick stars to calibrate dwarf nova. The change to 5 arcminutes allows RPHOT to consider reference stars for calibration that are very close to the subject. The change of the minimum S/N to 12 requires the reference objects to be bright so that the results is a good measurement of the calibration in the area of the image.

To obtain the analysis, we entered

\[ usnoreadb, ra_coordinate, dec_coordinate, 0.1, \text{cat}, /rphot \]
This step gives the RA and Dec coordinates to the USNO catalog to get the measurement of the stars included in the said catalog. These measurements, which will be the basis of calibrating the reference stars in the ROTSE data, are saved in a .dat file generated. The .dat file is needed by RPHOT for the calibration. The next step is done to find files: we entered

\[ f = \text{findfile}(\text{prod/15\_cobj.fit}) \text{ was entered in followed by ss\_loop}\_f. \]

Only at this point that photometry could be made. We entered

\[ \text{runphot, prod/reference\_file\_cobj.fit, objname=’alcom’}. \]

The string of text – “reference\_file\_cobj.fit” is simply a reference file. What created the light curve is the reference image, which is

\[ 080312\_tss1231+1427–123225+142042\_3b006-008\_c.fit, \]

which can be seen in Figure 5.1.

5.2 Analysis of Light Curve

The light curve analysis is depicted in the plot. On the horizontal axis we can find the time. Since the reference time UT 30 September 2015, the scale is in days. This kind of source has a very high-frequency variability. We can certainly understand some general information on the source from this data.

The brightest magnitude reached during this period of time is approximately 13.9 while the faintest magnitude is approximately 17.1 mags.
Figure 5.1 Light Curve of Alcom

From this data, it is not clear if we detected two or three maxima. Assuming that the magnitude between $T=-180$ and $T=-175$ drops, then we have detected three maxima. The vertical dashed lines show the times of the maxima, at $T=-181$, $T=-175$, $T=-160$. It is important to note that there is a very large uncertainty during $T=-181$ since there is only one data point used. The five-day period from the reference time is indeterminate and there is a greater possibility that it will take less than five days.

Assuming we observed three maxima, so the period of time between the first two is 6 days, the period of time between the second two is 15 days.

Since the period should be theoretically the same, we have computed for the average number of days by adding $Per_1$ and $Per_2$ and dividing by 2. This procedure provided an average
of 10.5 days, that is, 6 days plus 15 days over 2. Furthermore, the standard deviation of the mean indicated +/- 4 days. Thus, Period = 10.5 days +/- 4 days.

As the period of the light curve variation is of order of days when we convert this into Hertz (cycles/second), the corresponding value in these units will be extremely low. The frequency is the inverse of the period (in seconds). The period is 10 days = 864000 seconds. Then the frequency is approximately $10^{-6}$ Hertz, or 1 millionth of an Hertz.

At the first maximum we have a magnitude 13.9; at the second maximum it decreased to 14.2, and at the last one it is approximately at 15.0 magnitudes. Then, the source is progressively becoming fainter with a higher magnitude. By a linear fit shown below, we can find the rate of dimming is approximately 0.05 magnitudes per day.

![Figure 5.2 Rate of Dimming Star Per Day](image-url)
5.3 Periodogram

A periodogram is one of the several mathematical tools used to detect and analyze periodic signals in light curves. Oftentimes, the eye would be able to determine repeated patterns present in a given light curve. However, the eye can be fooled into thinking that there is a periodic repetition where there is none. It can also be mistaken into dismissing a light curve as a noisy one, which may, in fact, be a series of repeated cycles of a periodic variation. Thus, one cannot rely on the naked eye alone, as it leaves itself open for errors, inaccuracies, or inconsistencies. In these cases it is best to make use of the given tools in order to achieve the correct measurements.

Given a time-series data, a periodogram is able to distinguish any existing intrinsic period signals. The periodogram calculates the significance of different frequencies in order to determine the signals accurately. While similar to the Fourier Transform, a periodogram is also optimized to take into account data accumulated over an uneven time sample. Different shapes in periodic signals are also accommodated by a periodogram.

This is highly useful in astronomical calculations, especially since the target objects might reposition itself over several nights. Furthermore, time constraints within spacecraft could cause irregular observation periods. Unevenly sampled data is common in such projects and therefore would prove a periodogram as a highly valuable and reliable method for computation.

A periodicity means that the data will show the same behaviour once in a period of time. In general, in a time series we can find several "periods", but the most important one is "the period" of data. This period will be the point at which the periodogram exhibits a maximum.
On the x-axis is the frequency, which is the inverse of the period, the frequency is measured in inverse days (1/days), and the period is thus measured in days. On the y-axis we have the non-normalized periodogram, the highest is the peak, the most important is that particular frequency. To go from the frequency to the related period, we just have to compute the inverse of the frequency. In this way, we will find the period in days.

The two peaks are the most important frequencies of the periodogram. The first peak is the highest and corresponds to a value of 8 (it is between 1 and 10, closer to 8). The second peak is just after 10, so it is around 10 or 11. If the main frequency is 8, this means that the main period is 1/8 days, or about 3 hours. I have just computed the inverse. The second peak is the second most important frequency in this data set. Say it is 10, this means that the second most important period is 1/10 days, or about 2.4 hours. As the frequency of the measurements (once per day), and the number of measurements (25 nights) was limited, there are potentially large uncertainties if we extrapolate to very large frequencies. This can be addressed with additional data.
The periodogram technique hints that there may also be an additional variation at a shorter period (higher frequency) of 2 to 3 hours. Such a period is consistent with known rotational period of the accretion disk. However, this effect is at the edge of the resolution with the current data and would require further analysis to verify, validate, and identify the source of this contribution.

Therefore, from data we can say that there are some hints for a short timescale periodicity of about 3 hours. Subject to the above caveats According to Warner (1987), absolute magnitudes of dwarf novae can be computed using the equation:

\[ M_v(max) = 5.64 - 0.259 P(hr) \]

where \( M_v \) is the maximum light and \( P(hr) \) is the periodicity. Substituting the values:

\[ M = 5.64 - 0.259 \times 3(\text{hours}) \]

\[ M = 4.9 \]
Chapter 6

CONCLUSION

A Dwarf Nova is a type of cataclysmic variable star consisting of a close binary star system in which one of the components is a white dwarf that accretes matter from its companion. While observationally they are similar to standard novae, because they increase they luminosity over a short period of time, the physical mechanism leading to this variation in luminosity is different. Standard novae result from the fusion and detonation of accreted hydrogen on the primary's surface. For dwarf novae, the mechanism is radically different, being related to the accretion disk around of the binaries. The most updated theories suggest that dwarf novae result from instability in the accretion disk, when gas in the disk reaches a critical temperature that causes a change in viscosity, resulting in a temporary increase in mass flow through the disc, which heats the whole disc and hence increases its luminosity.

From an observational point of view, a dwarf nova shows several differences with respect to a nova and, even more importantly, to a supernova. The light curves of a dwarf nova, in the optical band, are characterized by a modest increase in brightness 2-5 magnitudes in the V band. The increase in luminosity of standard novae is much more important, while also a standard nova can exhibit a periodicity, like the dwarf nova.

The physical mechanism leading to a variation of the luminosity is due to instability in the accretion disk, when gas in the disk reaches a critical temperature that causes a change in viscosity, resulting in a temporary increase in mass flow through the disc, which heats the whole disc and hence increases its luminosity.
Within the dwarf nova family, we can classify our object to a SU UMa star, because it exhibits occasional super-outbursts which are typically 0.7 magnitudes brighter than normal outbursts. The outburst lifetime in these cases is on the order of 5 times the lifetime of a normal outburst.

Since the outbursts are generated by instabilities in the accretion disk, the outbursts will cease once the gas in the accretion disk is depleted. Hence, dwarf novae are in general expected to decrease their activity until depletion of gas in the accretion disk. This may require different times depending on the specifics of the system under investigation.

The increase and decrease of the brightness of this object is caused by the interaction of a star with the gas present in the accretion disk that surrounds it. Normal bursts are caused by the accretion disk becoming gravitationally unstable and losing material, which falls onto the star and heats up, increasing the overall luminosity of the star. When this gravitational instability ceases, then the star goes back to its normal level of luminosity. Super-outbursts are caused by the companion star interacting directly with the accretion disk of the star surrounded by the accretion disk. In fact, because these systems are binary, so there are two stars, one of them is embedded in an accretion disk. So when the companion star interacts with the accretion disk, a huge amount of material falls onto the couple of star, increasing once again the overall luminosity of the system, so-called a super-outburst.
BIBLIOGRAPHY


