RADIO OBSERVATIONS OF NOVA REMNANTS

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Abstract

This thesis presents the analysis of radio observations of the nova KT Eri that was discovered on November 25\textsuperscript{th}, 2009. Five epochs of radio observations are studied, covering 126 days after the nova outburst. The data were obtained by the Australia Telescope Compact Array (ATCA) at the frequencies of 5.5, 9, 17 and 19 GHz and are reduced here using the radio interferometry data reduction package MIRIAD.

Radio emission has the advantage of not being subject to extinction by dust, compared to optical emission. Thus, it is a very useful tool for probing the physical parameters of nova eruptions. In this work, the radio observations of KT Eri are used to produce radio light curves at the aforementioned frequencies and derive conclusions about the physical properties of the nova shell.

Following a review of novae and a description of radio interferometry and data reduction, the ATCA data on KT Eri are reduced and the flux densities are derived. The standard Hubble flow model for thermal radio emission from novae is then described and used to generate model light curves in an attempt to fit the observations to the model. For an electron temperature of $10^4$ K and a distance of 5 kpc, plausible fits can be obtained to a single frequency, 5.5 GHz, leading to estimates for the values of the model parameters of a shell mass of $\sim 10^{-4}$ $M_\odot$, an ejection velocity of $\sim 4000$ km sec\textsuperscript{-1} and a ratio of inner to outer velocity of 0.01. However, the results show that at higher frequencies this model is not consistent with the observations. A comparison with the nova V1723 Aql is noted, since this is another example of a classical nova that does not follow the Hubble flow model.

Examination of the spectral indices reveals that the evolution of the KT Eri remnant over time does not agree with what is expected for a typical classical nova. Some characteristics of the light curves suggest that the emission from KT Eri could include a synchrotron component besides the thermal one. It is therefore discussed whether KT Eri is a recurrent nova after all.

The University of Manchester
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Master of Science by Research (MSc)
\textit{Radio Observations of Nova Remnants}
5\textsuperscript{th} September 2011
Declaration

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The author was born in Thessaloniki, Greece. She obtained an undergraduate degree in Physics at the Aristotle University of Thessaloniki, with a specialization in Astronomy, in 2010. She then came to Manchester, UK to attend a MSc programme at the University of Manchester, Jodrell Bank Centre for Astrophysics. The results of these studies are presented in this thesis.
Dedicated to that little girl,

who always wanted to explore the Universe,

forever fascinated by the mysteries of the Cosmos.
As for me, all I know is that I know nothing.

~ Socrates ~

...per aspera ad astra!
(...through difficulties to the stars!)

~ Latin Quote ~
CHAPTER 1
INTRODUCTION TO NOVAE

1.1 Historical References

An excellent and thorough review on the subject of novae is given in the work “Classical Novae” (Bode & Evans, 2008), where various authors contributed in their corresponding areas of interest. A nova is a star that ejects material into space and during this process it becomes more luminous. The name “nova” itself is an abbreviation from "stella nova", which means “new star”. The Merriam – Webster dictionary defines a nova as “a star that suddenly increases its light output tremendously and then fades away to its former obscurity in a few months or years”.

Observations of these celestial objects are recorded in Far Eastern writings over 3000 years ago, but it was after 1572 that novae caught the attention of astronomers in the western world; the year when the first supernova was observed by Tycho Brahe. The first true nova that was studied in Europe was a “new star” in the constellation of Vulpecula, observed by the monk P.D. Anthelme in 1670. Throughout the 19th century, more detections of novae were made possible with the progress in instrumentation. The first nova of the 20th century, visible to the naked eye, was Nova Persei 1901 (GK Per).

In the 18th century, a definition was given in Newton’s “Principia Mathematica” as:

*Of this kind are such fixed stars as appear on a sudden, and shine with a wonderful brightness at first, and after vanish by little and little.* (Duerbeck, 2008)

The definition remains almost the same at the beginning of the 20th century (Newcomb, 1901, p.127):

*A distinguishing feature of a star of this class [of new or temporary stars] is that it blazes up, so far as is known, only once in the period of its history, and gradually fades away to its former magnitude, which it commonly retains with ... little or no subsequent variation.*

According to modern understanding, the sudden spectacular brightening of the nova is thought to be the result of a cataclysmic nuclear explosion that happens upon the surface of a white dwarf (WD) star, caused by the accretion of material from a secondary companion. The accretion of hydrogen onto the WD leads to nuclear fusion in a runaway manner. This current understanding of novae originates from Kraft’s articles, where he
showed that binarity is a common characteristic of cataclysmic variables, particularly novae. He proposed that hydrogen burns explosively on the surface of the degenerate blue component (Kraft, 1963), and this idea was revived by Paczynski (1965).

### 1.2 The Nova Outburst

Novae belong in the family of cataclysmic variable stars, but for a long time they were not regarded as such, as it can be seen in review articles in the Handbuch der Astrophysik (Ludendorff, 1928; Stratton, 1928). However, some years earlier Shapley (1921) had already argued that there are not big differences between novae and other variable stars. His paradigms were the recurrent novae RS Oph, V1017 Sgr and T Pyx, along with the symbiotic stars RX Pup and Z And, which have photometric and/or spectroscopic properties similar to novae.

Our current understanding of novae is that they are interacting binary stars, the primary typically being a WD with a surface rich in nitrogen, carbon and oxygen. Its secondary companion is generally a main sequence star. The distance between the two stars is sufficient for the secondary to fill its Roche lobe and send matter to its companion through the inner-Lagrangian point. Hydrogen and other material flows to form an accretion disk around the WD, and then a layer of accreted material is formed onto its surface. The WD has burnt most of its hydrogen during its evolution, but this accretion layer is rich in hydrogen. In the case where the Roche lobe of the secondary is not filled, then material is being transferred to the WD via a wind.

As hydrogen plus some helium accumulates at the layer's base, it compresses and heats the material underneath it. Matter at the base becomes degenerate due to the increasing pressure. At a critical temperature of about 10 million K and a critical pressure of \( \sim 10^{19} \text{ N m}^{-2} \), nuclear fusion reactions begin. The accreted layer ignites leading to a thermonuclear runaway (TNR), since in degenerate matter the pressure is independent of the temperature, leading to rapid increasing of the burning process. As the TNR goes on, an explosion thrusts the surface envelope away in the form of an expanding shell (Starrfield, 1989). During this violent outburst, \( \sim 10^{-4} \text{ M}_\odot \) of accreted material is ejected into the interstellar medium (ISM) reaching speeds of several hundred to several thousand km sec\(^{-1}\).
In the beginning, the energy of the outburst is generated by the proton-proton chain. The CNO reactions follow when the temperature doubles to \( \sim 2 \times 10^7 \) K. These reactions and the energy they produce are mainly responsible for the expansion of the shell and the increase of the nova's luminosity by a factor of 2000 – 50000.

Most novae are overabundant in C,N or O by factors of \( \sim 100 \) compared to solar values, and in most cases He is enhanced too. However, some novae have been discovered showing very large overabundances of Ne (Smits, 1991). Two examples are novae QU Vul and V1307 Aql, which also present higher than solar abundances of Al, Mg or Si. The high values of these heavy-element abundances are best explained by the assumption that these nova outbursts occurred on ONeMg white dwarfs, rather than on the more common CO degenerate stars. Furthermore, the ejection velocities of novae with ONeMg progenitors appear to be more extreme than those of novae occurring on CO white dwarfs (Smits, 1991). V1500 Cyg has an abundance of Ne that is ten times larger than the solar value, and it is an example of a fast nova. Thus, it was proposed that neon enhancements are a prerequisite for fast novae.

### 1.3 Types of Novae

Novae are categorized by how often they occur, in addition to the behavioural details of each individual nova. There are three main varieties: classical novae, recurrent novae and dwarf novae.

**Classical Novae (CNe)**

A nova of this category brightens by a factor of 8 to 15 magnitudes. One of the defining characteristics is that the primary star ejects an expanding shell of matter. Classical novae are further categorized into 3 main varieties, due to differences in their light curves, according to modern catalogs and compilations (e.g. Downes & Shara, 1993):

- Fast novae (NA): they rise very abruptly to maximum, where they stay for a few days. Their brightness declines by a factor of 3 magnitudes within three months. There may be a series of fluctuations during this fading. A typical example of this type is Nova Persei 1901.
• Slow novae (NB): their increase in brightness is gradual. They remain at their maximum brightness for a few weeks or months before fading. They tend to fade slowly at first with fluctuations, after which the rate of fading quickens. Nova Herculis 1934 is a typical example of this type.

• Very slow novae (NC): these novae fade very slowly, remaining at their maximum brightness for a period of years. The following decline also occurs at a very slow pace. The main bulk of them are symbiotic novae. Stars of this type also display features of Wolf–Rayet stars and are referred to as RR Telescopii stars. NC novae show many physical differences from classic novae, thus they might be different objects, like planetary nebulae in formation. The first observed example was RT Serpentis in 1915, which remained at maximum magnitude of 10.5 for almost a decade.

Further discussion about the light curves of novae is given in Section 1.4.

**Recurrent Novae (RNe)**

Recurrent novae display brightness levels similar to those of classical novae, sometimes lower, but the difference is that they have exhibited more than one outburst during the period in which they were observed. It is speculated that all novae may in fact be recurrent; it is just that they have not been monitored long enough in order to detect a second outburst. This means that for most classical novae \( t_r \geq 10^3 \text{ yr} \), where \( t_r \) is the interval between eruptions, whereas for RNe the timescales in which eruptions recur are as short as 10 years. There are ten known examples of RNe (Schaefer, 2010), displaying increases of luminosity of 5 to 9 magnitudes. A well-known example is RS Ophiuchi (RS Oph), with a minimum 12.5 magnitude to a maximum 4.8. It has exploded six times, the most recent being in 2006, providing the opportunity for observation at different wavelengths.

Type Ia Supernovae (SN Ia) act like standardized candles in the universe, used to indicate relative distances. However, the identity of their progenitor system is yet to be revealed. The modern theoretical model claims that a donor secondary star provides its accompanying CO WD with accreting material; the WD’s mass reaches the Chandrasekhar limit and a thermonuclear explosion occurs, resulting in the Ia SNe phenomena (Kotak, 2008). It is not yet confirmed that binary systems similar to RS Oph are capable of leading to SN Ia, though observations show that various white dwarfs with red giant donor stars
have turned out to explode as SN Ia. This is the presumed fate of the system of RS Oph; it would be a certain fate if the composition of its WD was known (Justham & Podsiadlowski, 2008). Only a CO WD may explode, while in the case of an ONeMg WD a collapse is expected when it approaches the Chandrasekhar limit, caused by accretion. However, theoretical models of RS Oph-like systems failed to produce any SN-type explosions (Justham & Podsiadlowski, 2008).

**Dwarf Novae**

Some of the novae of this last category are also known by the specific name “U Geminorum stars”. Their increase in brightness is smaller compared to the other categories, only 2 to 6 magnitudes, and they reach maximum during a single day. They finally become quiescent after several days or weeks. Dwarf novae are different types of objects compared to CNe and RNe. Here, the outburst appears to be driven by an instability within the accretion disk, rather than by a TNR.

### 1.4 Optical Properties and Light Curves

Novae in our Galaxy concentrate towards the galactic disk and the bulge. The present nova detection rate is around 34 per year (Darnley et al., 2006). Fast novae are found closer to the galactic plane than slow novae, which tend to occupy the bulge (Figure 1.1). Observations of nova eruptions are now made in the whole range of the electromagnetic spectrum, from radio to gamma-rays.

With regard to nova light curves, novae were initially classified by Duerbeck (1981) based upon their speed and the structure of the curves. Until recently, nova outbursts were observed to have bolometric luminosities at the Eddington limit or above it. Duerbeck noticed that only rapid novae with smooth light curves exhibit super-Eddington luminosities. Novae of the rest of his types emit radiation near the Eddington limit; variations in their photospheric radius, i.e. mass loss irregularities, are responsible for the observed fluctuations in their light curves. The total amount of emitted energy falls in the range of $10^{45} - 10^{46}$ erg.

McLaughlin (1945) studied how the absolute magnitudes of novae at maximum are
related to the rates of decline. This maximum magnitude/rate of decline (MMRD) relationship provides the main tool for the use of novae as distance indicators, best calibrated via the method of nebular parallaxes. Livio (1992) also suggested that the plateau luminosity of novae in the constant bolometric phase is the best nova-related means to determine the extra-galactic distance scale. McLaughlin (1960) also found that the light curves of all the novae tend to look alike, if their time-scales are compressed (Warner, 2008). The resulting idealized light curve is shown in Figure 1.2.

![Figure 1.1 The distribution of classical novae in Galactic coordinates. The Galactic Centre is at the centre of the diagram, with increasing galactic longitude towards the left. Filled circles mark 132 fast novae; 40 slow novae are plotted as open circles; the crosses mark 58 uncategorized novae and the small dots correspond to 58 uncertain novae. All data are from the Downes et al. CV catalogue. [Bode & Evans, 2008; p.17]
Figure 1.2 Morphology of an idealized nova light curve. [Bode & Evans, 2008; p.19]

The initial rise to maximum is the first thing to observe on a light curve, because there is no way of knowing which stars will enter the category of novae. How long this rise lasts depends on the speed of each nova. The nova light curves typically display a flattening before the peak, known as the pre-maximum halt. After reaching the maximum brightness, where the system will remain for a few days, the decline begins. Differences between individual nova light curves are mainly apparent in the transition phase that follows the early decline. Some novae decline smoothly, while others display oscillations. A number of them exhibit a steep minimum, named 'DQ Her–type dip'. This minimum is associated with the beginning of dust formation procedures in novae where a CO-type WD is present; the result is that visual brightness is diminished, whilst the infrared emission rises (Evans et al., 2005).

Finally, the light curve displays a recovery from the minimum or a cessation of the oscillations, and in the last stage the brightness declines smoothly back to pre-nova levels. The whole system generally returns to pre-eruption luminosity after 1-10 years. The stages before and after the nova outburst are known as quiescence.

In relation to the classification of novae according to speed, five classes of novae were recognized: very fast, fast, moderately fast, slow and very slow (identified by Payne–
Gaposchkin, 1957). These “speed classes” are shown in Table 1.1. Nowadays it is clear though that these classes do not represent physically different classes of novae.

Table 1.1 Speed classification of nova light curves.
[Bode & Evans, 2008; p.18]

<table>
<thead>
<tr>
<th>Speed class</th>
<th>( t_2 ) (days)</th>
<th>( \dot{m}_V ) (mag d(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very fast</td>
<td>&lt; 10</td>
<td>&gt; 0.20</td>
</tr>
<tr>
<td>Fast</td>
<td>11–25</td>
<td>0.18–0.08</td>
</tr>
<tr>
<td>Moderately fast</td>
<td>26–80</td>
<td>0.07–0.025</td>
</tr>
<tr>
<td>Slow</td>
<td>81–150</td>
<td>0.024–0.013</td>
</tr>
<tr>
<td>Very slow</td>
<td>151–250</td>
<td>0.013–0.008</td>
</tr>
</tbody>
</table>

A final definition is repeated by Warner (1995), where relations are derived between the light curve decay times \( t_2 \) and \( t_3 \) (the time required to decay by 2 and 3 magnitudes from visual maximum correspondingly). The parameter \( t_3 \) may sometimes be used to classify a nova. For very fast and fast novae, the relation \( t_3 = 2.10 \times t_2 \) holds, while for moderately fast and slow objects the observed relation changes to \( t_3 = 1.75 \times t_2 \). The light curves used for the classification are based on both visual and blue/photographic bands. The crucial parameter for the categorization according to speed is the initial rate at which energy is generated; this rate itself is dependent on the mass of the white dwarf.

Two examples of optical light curves of classical novae are shown in Figure 1.3 and Figure 1.4. The former corresponds to the two fast novae V1500 Cyg and V1491 Aql, while the latter shows the moderately fast V705 Cas nova, where a classic DQ Her–type dip is observed, and the unusually slow nova V723 Cas (Heywood, 2004).

Duerbeck (1990), della Valle et al. (1992, 1994) and Williams (1992) classified Galactic novae in two groups which are characterized by different spectroscopic and photometric properties. The first group consists of fast and bright novae found in the solar neighborhood, whereas the slow and dim novae are located in the Galactic bulge.

Using the nebular expansion parallax method, it was found that the absolute maximum magnitudes of novae correlate with their height above the Galactic plane: the fast and bright novae (\( M_V \leq -9 \)) are not at high positions above the plane (height \( z \leq 100 \) pc).
and they possibly originate from massive progenitors (Livio, 1992). Thus, the WD is of relatively high mass, taking into account that the progenitor belongs to the stellar Population I. Light curves of fast novae exhibit a fast decline of \( t_3 \leq 20 \) days. Slow novae on the other hand, with magnitudes about two times fainter than the disk novae (\( M_V \leq -7.5 \)), have bigger values of \( z \) (up to 1kpc). Slow novae possibly evolve from less massive progenitors (Iben & Tutukov, 1996), since the WDs here appear to be members of the stellar Population II. They decline at a rate of \( t_3 \geq 20-25 \) days.

Della Valle & Livio (1995), based on studies of Galactic novae as well as novae in the Large Magellanic Cloud, expressed mathematically the aforementioned MMRD relationship in the form

\[
M_V = -7.92 - 0.81 \times \tan^{-1} \left[ \frac{1.32 - \log_{10} t_2}{0.23} \right]
\]  

(1.1)

where \( M_V \) is the absolute peak magnitude.
Figure 1.3  Visual light curves for the fast novae V1500 Cyg (top) and V1494 Aql (bottom). V1500 Cyg undergoes a smooth decline whereas V1494 Aql exhibits oscillations in the transition phase. Created using data from the AAVSO. [Heywood, 2004; p.34]
Figure 1.4 Visual light curves for the moderately fast nova V705 Cas (top) and the unusually slow nova V723 Cas (bottom). V705 Cas exhibits a DQ Her-type dip and V723 Cas exhibits additional peaks post-maximum. Created using data from the AAVSO. [Heywood, 2004; p.34]
Recently the USAF/NASA Solar Mass Ejection Imager (SMEI), located on the Coriolis satellite, has been used to obtain high-cadence light curves of novae (Hounsell et al., 2010). Latest results indicate that approximately 5 CNe per year are potentially detectable by SMEI. Near complete sky-map coverage was achieved with this instrument, providing the best sampled light curves of unprecedented temporal resolution. The obtained light curves clearly revealed nova features such as the duration of the pre-maximum halt; a phase of the outburst that usually is not monitored by ground-based observations. Studying of SMEI images enabled the detection of secondary maxima and the determination of the speed of decline. Also, parameters such as the bolometric luminosity, the WD mass and the distance of the novae were estimated using the obtained information regarding the beginning of dust formation.

Figure 1.5 and Figure 1.6 show examples of novae that were observed with SMEI. In the case of RS Oph, hard X-ray data from its latest outburst combined with the SMEI results lead to the conclusion that when the explosion occurred, extensive mass loss took place at high velocities. For V1280 Scorpii, a plateau located earlier in the light curve was found, along with two incidents of re-brightening peaks that were not recorded previously. This evidence shows the amount of detail that SMEI can provide for observations of novae.
Figure 1.5 SMEI light curve of RS Oph (black squares) in terms of “SMEI magnitude” (see Buffington et al., 2007) vs. time. Gray data are the Swift BAT 14–25 keV data from Bode et al. (2006), right-hand y-axis, the gray dashed line indicates zero flux on the right-hand y-axis. The star represents the discovery magnitude of the nova taken from Narumi et al. (2006). The triangle is the peak magnitude listed by the AAVSO. The arrow points the latest observed magnitude of the nova before rise. The inset shows the rising portion of the light curve with an expanded time scale. [Hounsell et al., 2010; p.482]
Figure 1.6 SMEI light curve of V1280 Sco (black squares). The superimposed gray stars are data taken from the “π of the Sky” project (see http://grb.fuw.edu.pl/pi/index.html). The difference between the late time SMEI light curve and the “π of the Sky” point might reflect the uncertainties with SMEI data at such faint magnitudes. The inset shows the region around the light curve break which is associated with the onset of dust formation. [Hounsell et al., 2010; p.483]
1.5 Spectroscopic Evolution

Individual novae present different spectral line configurations. This is a fact that makes the task of categorizing novae according to this aspect a difficult one. Generally, spectral lines appear and fade at different stages during the evolution of the novae.

Williams (1992) divided novae (his sample of novae taken from our Galaxy and from the LMC) into two spectroscopic classes: the FeII and the He/N novae. The former evolve slowly and display FeII lines as the strongest non-Balmer lines in their early emission spectra. The latter are characterized by fast spectroscopic evolution and their emission spectra contain He and N lines as the strongest non-Balmer lines. Finally, there are hybrid objects like nova Cyg 1975 (V1500 Cyg), which first belong to the FeII class but later evolve to the He/N one. These novae are classified as FeIIb (broad). Basic data of some well-studied novae are shown in Table 1.2.

Initially, X-rays dominate the spectrum of a nova eruption, but as the envelope expands, lines of longer wavelengths appear. Before the maximum is reached, optical spectra resemble those of early type stars; as the maximum gets closer the resemblance shifts to late type stars. In the beginning, permitted transitions dominate the spectra, caused by high gas densities (Williams, 1992).

As the expansion of the shell continues the light curve turns over, the temperature of the ejecta lowers and iron emission lines dominate the ultraviolet spectrum to the point of appearing as a continuum (“iron curtain phase” – Hauschildt, Wehrse, Starrfield & Shaviv, 1992).

The next phase of the nova decline is the “Orion” phase, where the spectrum is similar to that of an O–type star. At this stage, characteristic forbidden lines ([NII], [OIII]) make an appearance alongside permitted lines in the ultraviolet as the continuum fades. Possible initiation of dust formation may result in the decrease of optical and UV brightness, whereas the re-radiation of photons causes an increase in the infra-red emission.

The last stages of the nova phenomenon are optically thin and the spectrum is similar to that of a planetary nebula.
Table 1.2 Basic data.
[della Valle & Livio, 1998; p.821]

<table>
<thead>
<tr>
<th>Nova</th>
<th>$z$ (pc)</th>
<th>$t_2$ (days)</th>
<th>Spectral Class</th>
<th>$v$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T Aur</td>
<td>39</td>
<td>80</td>
<td>Fe II</td>
<td>1200</td>
</tr>
<tr>
<td>GK Per</td>
<td>85</td>
<td>6</td>
<td>He/N</td>
<td>4000</td>
</tr>
<tr>
<td>V 603 Aql</td>
<td>6.5</td>
<td>4</td>
<td>Fe IIb</td>
<td>4000</td>
</tr>
<tr>
<td>V 476 Cyg</td>
<td>380</td>
<td>7</td>
<td>Fe II</td>
<td>2500</td>
</tr>
<tr>
<td>RR Pic</td>
<td>200</td>
<td>80</td>
<td>Fe II</td>
<td>1600</td>
</tr>
<tr>
<td>XX Tau</td>
<td>2720</td>
<td>24</td>
<td>Fe II?</td>
<td>?</td>
</tr>
<tr>
<td>DQ Her</td>
<td>135</td>
<td>67</td>
<td>Fe II</td>
<td>1000</td>
</tr>
<tr>
<td>CP Lac</td>
<td>23</td>
<td>5</td>
<td>He/N ?</td>
<td>4200</td>
</tr>
<tr>
<td>CP Pup</td>
<td>15</td>
<td>5</td>
<td>He/N</td>
<td>2000</td>
</tr>
<tr>
<td>V500 Aql</td>
<td>900</td>
<td>20</td>
<td>He/N ?</td>
<td>2800</td>
</tr>
<tr>
<td>DK Lac</td>
<td>370</td>
<td>19</td>
<td>Fe II</td>
<td>2500</td>
</tr>
<tr>
<td>RW UMi</td>
<td>2500</td>
<td>200</td>
<td>Fe II?</td>
<td>?</td>
</tr>
<tr>
<td>V446 Her</td>
<td>100</td>
<td>5</td>
<td>He/N</td>
<td>2400</td>
</tr>
<tr>
<td>V533 Her</td>
<td>540</td>
<td>26</td>
<td>Fe II</td>
<td>1600</td>
</tr>
<tr>
<td>HR Del</td>
<td>205</td>
<td>$\geq 150$</td>
<td>Fe II</td>
<td>1700</td>
</tr>
<tr>
<td>LV Vul</td>
<td>35</td>
<td>21</td>
<td>Fe II</td>
<td>2700</td>
</tr>
<tr>
<td>FH Ser</td>
<td>90</td>
<td>42</td>
<td>Fe II</td>
<td>2100</td>
</tr>
<tr>
<td>V1229 Aql</td>
<td>225</td>
<td>18</td>
<td>Fe II</td>
<td>2200</td>
</tr>
<tr>
<td>V1500 Cyg</td>
<td>0</td>
<td>2.4</td>
<td>Fe IIb</td>
<td>5000</td>
</tr>
<tr>
<td>QU Vul</td>
<td>302</td>
<td>22</td>
<td>Fe II</td>
<td>1700</td>
</tr>
<tr>
<td>V838 Her</td>
<td>141</td>
<td>2</td>
<td>He/N or Fe IIb</td>
<td>3300</td>
</tr>
<tr>
<td>V1974 Cyg</td>
<td>330</td>
<td>23</td>
<td>Fe II</td>
<td>2300</td>
</tr>
</tbody>
</table>

### 1.6 Multi-wavelength Observations of Classical Novae

#### 1.6.1 Radio Emission

Radio emission from novae is either thermal or non-thermal (synchrotron). Thermal emission is typically present in spectra of classical novae, while non-thermal radiation is mainly observed in RNe and specifically in the case of RS Oph. In general it is expected that every nova emits both types of radiation, just in different proportions.

The WD, after the outburst, causes photo-ionization of the ejecta. This results in thermal free-free emission from gas, which has been heated up to 10000 K (Seaquist, 1989). Radio emission from a nova nebula reaches a maximum later than in the optical light
curve because the optical depths of the radio wavelengths are higher. Therefore, the radio light curve of the nova remnant is obtained at a moment when the evolution of the optical curve is at its declining phase. The emitting gas stays optically thick for a long period after the maximum is reached, so the radio emission appears in a prolonged time-scale.

Classical novae were first studied in radio wavelengths by Hjellming and Wade in 1970 (Hjellming et al., 1979). The NRAO interferometer was used at $\lambda=3.7$ cm and $\lambda=11.1$ cm to detect nova HR Del and nova FH Ser. Figure 1.7 shows the radio light curves of these objects. The nova remnant of Vulpeculae 1984 was the first to be radio-mapped via use of the VLA at $\lambda=2$ cm (Taylor et al., 1988). Observed soon after the nova outburst, the shell exhibited non-spherical symmetry, followed by a shift to a more spherical shape in the next days. At present, radio maps of more nova shells are obtained. Through the analysis of these maps we gain insight into the structure of the shells; a non-spheroidal morphology is evident. Table 1.3 (Seaquist & Bode, 2008) shows classical novae detected at radio wavelengths.

Figure 1.7  The radio data for the novae HR Delphini 1967, FH Serpentis 1970 and V1500 Cygni 1975. Plots are a function of time since initial optical outburst. The plotted lines show the power laws indicated for the rising and decaying portions of the radio light curves. [Hjellming et al., 1979; p.1622]
Table 1.3 Classical novae detected at radio wavelengths.
[Bode & Evans, 2008; p.143]

<table>
<thead>
<tr>
<th>Name</th>
<th>Refs. to radio measurements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>GK Per</td>
<td>Reynolds &amp; Chevelier (1984); Seaquist et al. (1989)</td>
<td>Non-thermal emission detected from resolved remnant in 1983</td>
</tr>
<tr>
<td>HR Del</td>
<td>Hjellming &amp; Wade (1970); Hjellming &amp; Wade (1971)</td>
<td>Multi-frequency data</td>
</tr>
<tr>
<td>F11 Ser</td>
<td>Hjellming &amp; Wade (1970); Hjellming &amp; Wade (1971)</td>
<td>Multi-frequency data</td>
</tr>
<tr>
<td>V368 Sct</td>
<td>Herrero, Hjellming &amp; Wade (1971)</td>
<td>Detection, but no radio light curve</td>
</tr>
<tr>
<td>V1500 Cyg</td>
<td>Hjellming (1975); Hjellming et al. (1979); Seaquist et al. (1980);</td>
<td>Very detailed multi-frequency light curves</td>
</tr>
<tr>
<td>V1370 Aql</td>
<td>Turner (1985); Snijders et al. (1987)</td>
<td>Sparsely sampled declining radio light curve</td>
</tr>
<tr>
<td>PW Vul</td>
<td>Hjellming (1990)</td>
<td>Only observed during optically thin decay</td>
</tr>
<tr>
<td>QU Vul</td>
<td>Taylor et al. (1987)</td>
<td>Intense, very steeply rising radio spectrum initially. Radio image</td>
</tr>
<tr>
<td>V1819 Cyg</td>
<td>Hjellming (1996b)</td>
<td>Unpublished data</td>
</tr>
<tr>
<td>V827 Her</td>
<td>Hjellming (1996b)</td>
<td>Unpublished data</td>
</tr>
<tr>
<td>V838 Her</td>
<td>Hjellming (1991, 1996b)</td>
<td>Multi-frequency detections at one epoch</td>
</tr>
<tr>
<td>V351 Pup</td>
<td>Hjellming (1992, 1996b)</td>
<td>Multi-frequency detections at one epoch published; more data unpublished</td>
</tr>
<tr>
<td>V1974 Cyg</td>
<td>Ivison et al. (1993); Hjellming (1995, 1996a,b); Eyres, Davis &amp; Bode (1996)</td>
<td>Detailed multi-frequency images and light curves</td>
</tr>
<tr>
<td>V705 Cas</td>
<td>Eyres et al. (2000)</td>
<td>Multi-frequency images and light curves</td>
</tr>
<tr>
<td>V723 Cas</td>
<td>Heywood et al. (2002, 2005)</td>
<td>5 GHz MERLIN images and light curve</td>
</tr>
<tr>
<td>V1494 Aql</td>
<td>Eyres et al. (2005)</td>
<td>Multi-frequency light curves and MERLIN image</td>
</tr>
</tbody>
</table>

The qualitative characteristics of the light curves appear to be the same for all the studied radio novae, pointing to thermal radio emitters. However, a strong exception to this rule is the case of GK Persei, where non-thermal (synchrotron) emission dominates the
spectrum of the spatially resolved nebula. Seaquist et al. (1989) make the case that due to resemblance to young supernova remnants, GK Per can be perceived as a planetary nebula composed of neutral material. This claim is supported by other unusual characteristics it displays, like the fast deceleration of its ejected material and a considerably long orbital period.

GK Per was the first astronomical object to present expanding motions apparently at super-light velocities. Bode et al. (2004) made multi-frequency observations of this unusual remnant, confirming the existence of an old planetary nebula with an hourglass morphology into which the ejecta of the 1901 explosion are moving. Due to these interesting facts, it was claimed that GK Per will play an important role in understanding how binary stars interact and how planetary nebulae and SN remnants evolve. Images of GK Per are displayed in Figure 1.8.

The flux densities of radio novae are very weak; even the brightest sources emit at maximum densities of less than 100 mJy at the cm region of their spectra (Seaquist & Bode, 2008). Consequently, telescopes larger than optical ones are necessary to obtain accurate radio light curves. Most of the radio studies in the last years have been made with the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands, the Very Large Array (VLA) in New Mexico and the Multi-Element-Radio-Linked Interferometer Network (MERLIN) at Jodrell Bank in UK.

Systematic radio studies of classical novae in quiescence were carried out by Bode, Seaquist & Evans (1987); from the absence of non-thermal emission, except for the synchrotron radiation from GK Per, they concluded that classical novae provide the Galaxy with <1% of the electron energy contained in cosmic rays compared with supernovae. More about the subject of measuring radio flux densities from novae will be discussed in chapters 3 and 4.

Another well-studied nova that shows non-thermal emission is the recurrent nova RS Oph. In this case, the synchrotron emission comes from an expanding shock wave. The latest explosion of RS Oph was monitored in radio wavelengths with MERLIN, VLBA and the European VLBI Network (EVN) by O'Brien et al. (2006) at 6, 5 and 1.7 GHz. Figure 1.9 shows the radiation from the forward shock, which is radio-mapped for the first time. A model was suggested to describe the morphology of the expanding remnant. This model depicts a bipolar shell, inclined to the line-of-sight, and it is presented in Figure 1.10.
Figure 1.8 Images of the expanding ejecta of GK Per. (a) Optical image taken on 1917 November by G. W. Ritchey. (b) William Herschel Telescope Hα [NII] image taken 1993 September (Slavin, O’Brien & Dunlop, 1995). (c) 5 GHz radio image taken with the VLA in 1997 August showing non-thermal emission (Seaquist, 2003). (d) Chandra observations from 2000 February showing X-ray emission (Balman, 2002). [Bode et al., 2004; p.L64]
Figure 1.9 First detection of the shock wave in RS Oph. Image taken with VLBA at 6 cm. [O'Brien et al., 2006, PoS, 8th European VLBI network Symposium, 052]

Figure 1.10 A simple model for the RS Oph shell. A bipolar structure of gas, heated by the shock and swept up by the ejecta, is embedded within the sphere of the red giant wind. [O'Brien et al., 2006, http://www.astro.keele.ac.uk/rsoph/pdfs/obrien.pdf]
1.6.2 X-rays from Novae

In the recent years, the number of novae that have been observed systematically in the X-ray regime has increased. The results from carried out studies have been significant as well as totally unexpected in some cases (Krautter, 2008). GQ Mus was the first classical nova to be observed to emit X-rays shortly after its eruption, during observations which were conducted with the EXOSAT satellite in 1984. The recorded count rate indicated an increase of the X-ray flux at the beginning, followed by a nearly steady X-ray flux. The X-rays were interpreted as radiation caused by the collision of the nova shell with material emitted from the secondary. At that time, the detectors had no energy resolution, therefore there were no spectral data.

According to the TNR models, X-ray emission originates from the WD’s surface after the outburst, with a soft spectral energy distribution of a hot stellar atmosphere. It is in the nova phase of constant bolometric luminosity that we observe super-soft radiation, due to hydrogen burning in the envelope of the remaining ejected material surrounding the binary system, via the CNO cycle (Krautter, 2008). The nova is seen as a super-soft source (SSS-phase) even after the end of the hydrogen burning, until the temperature of the primary drops significantly. X-ray emission also occurs in the environment where the expanding shell meets the nova wind, resulting in strong shocks.

Observations made with ROSAT after 1996 showed the two components that comprise the X-ray spectrum of a nova outburst. The soft one, that puts novae in the category of super-soft X-ray sources, was ~0.5 keV; the second was the hard component of ~1 keV. In the beginning of our century, facilities like Chandra and XMM-Newton, with high spectral resolutions and sensitivities, allowed for obtaining data of high qualities.

Swift is a recently constructed multi-wavelength observatory that is part of NASA's medium explorer (MIDEX) program and was launched in 2004. Swift is dedicated to the studying of gamma-ray bursts and consists of three instruments which observe sources in the gamma-ray, X-ray and ultraviolet spectral regimes. Swift is proving to be a very useful tool for studying the residual nuclear burning after nova outbursts (Schwarz et al., 2011). It has revealed that when the SSS phase ends in RNe, the optical plateau due to fading ejecta also ends. This can be seen in Figure 1.11 for the recurrent nova U Sco and KT Eri. Also, Swift observations are appropriate for studying high velocity shocks and re-established accretion after the eruptions, which is a source of X-ray emission.
Figure 1.11 X-ray and optical light curves of KT Eri (top) and U Sco (bottom), revealing the ending of the optical plateau when the nuclear burning (SSS phase) ends. The upper panel shows count rates with the Swift XRT, the middle panel shows the hardness ratio and the lower panel shows the $m_V$. [Schwarz et al., 2011]
RS Oph exhibits both SSS X-rays and X-rays originating from shocks. It was observed with Swift during its super-soft phase that lasted 60 days (Ness et al., 2008). In the first month after the outburst, the spectrum is dominated by the radiation originating from the shock (Bode et al., 2006). Afterwards, the spectrum becomes softer as the SSS emission increases. This emission is coming from the environment close to the WD and subsequently penetrates the expanding ejecta. Figure 1.12 shows the X-ray light curve of RS Oph and indicates the extreme variability in the beginning of the SSS phase, likely due to variable, ionized absorption or as a result of intrinsic WD temperature variations (Osborne et al., 2011). After one month, a steady decline in count rate was noticed. It is shown that during the days following the first month, the bolometric luminosity had a constant value close to Eddington and later declined, possibly because the extensive nuclear burning on the WD had reached a stop. These Swift observations show that the mass of the WD is close to the Chandrasekhar limit and RS Oph is once again claimed to be a strong candidate for a future SN explosion.

![X-ray light curve of RS Oph from Swift data](image)

Figure 1.12 Entire 0.3–10 keV X-ray light curve of RS Oph from Swift data. The count rate as a function of the number of days since outburst is plotted on log-log scales. The super-soft phase is prominent between days 29 and 100. [Osborne et al., 2011]
1.6.3 Gamma-rays

It has been suggested that novae could produce gamma-rays via electron-positron annihilation after decays of radioactive isotopes and de-excitation reactions in the expanding nova envelope (Hernanz, 2008). Observations of the latest RS Oph eruption in 2006 showed that the soft gamma-rays produced could not originate from radioactive decays in the nova envelope, due to the spectral shape of the emission and the insignificant quantity of radioactive nuclei (Hernanz & José, 2008). After considering the results of nucleosynthesis studies and combining them with the TNR model for classical novae, it was claimed that gamma-rays from novae are the product of radioactive nucleosynthesis during the outburst, by interaction between the ejected material and the dense stellar wind (Hernanz, 2008). Senziani et al. (2008) proposed that gamma-ray emission in this case is the result of shocks in the ejected material.

The symbiotic star V407 Cyg is the first nova outburst to be observed to emit high-energy gamma-rays, in the range of 0.1 to 10 billion eV (Abdo et al., 2010). It was detected via the Fermi Large Area Telescope in March 2010. Figure 1.13 shows light curves of V407 Cyg in various wavelengths. The scenario for the gamma-ray emission demands that a red giant is the donor to the WD, i.e. a symbiotic system. The correlation between the fact that some of the symbiotic stars are RNe and the fact that RNe are potential progenitors of thermonuclear supernovae is interesting, and points to the possibility that V407 Cyg belongs to this category of binary systems.
1.7 This Dissertation

Nowadays, as the sensitivity of modern radio telescope networks increases, it will be feasible to detect more of the newly discovered Galactic classical novae as radio sources; though this requires more systematic projects in the radio frequencies. Radio observations of novae are useful in probing the physical characteristics and parameters of the expanding nova shells. This can be done for the whole time-scale beginning with the nova outburst and continuing to a few years after it; especially because radio observations are not affected by interstellar extinction.

The primary focus of this project is the radio imaging of the recent classical nova KT Eri. The radio data which have been reduced in this work were obtained by ATCA, although data taken by MERLIN and VLA are also used. In Chapter 2, an overview of the basics of radio interferometry is presented, along with the methods of data reduction and
radio imaging. Chapter 3 shows the analysis of the observations of the KT Eri nova and presents its flux density measurements. Following this, the flux density values are used to produce the radio light curves of KT Eri at several frequencies, which are compared to model light curves presented in Chapter 4. Chapter 5 contains the final conclusions and the proposed future work to be taken in order to take the studying of nova remnants a step further.
2.1 Theory

A general review on the principles of interferometry is given by Thompson, Moran & Swenson (2001). Interferometry is based on the Young's slits fringe pattern. When a single point source emits coherent radiation, this results in the observation of interference fringes with a separation of \( \frac{\lambda}{d} \), where \( \lambda \) is the observed wavelength and \( d \) is the separation of the slits.

Modern radio interferometry uses the principles of aperture synthesis or synthesis imaging, which basically combines signals from a number of telescopes to produce images which will have the same angular resolution as a single antenna having the size of the whole array. This significantly increases the resolution. The aperture synthesis technique relies on interfering the signal waves from each antenna, given that coinciding waves of the same phase will add to each other while waves with opposite phases will cancel each other out. The first astronomers who applied the principles of aperture synthesis to radio wavelengths were Martin Ryle and his coworkers at the Cambridge University. In radio interferometers, the separated antennas are connected together using coaxial cables, waveguides, optical fibres and other types of transmission lines. For every separation and orientation of the telescope pairs, the lobe-pattern of the interferometer produces a component of the Fourier transform of the spatial distribution of the observed source's brightness. The sum of the measurements gives the final image of the object.

A source that emits in radio wavelengths forms a brightness distribution \( I(\theta) \) in the sky, where \( \theta \) is the position angle on the sky. The emitted radiation is collected by a single radio telescope from many directions. \( I(\theta) \) undergoes attenuation by a factor \( A(\theta) \), resulting in a modified sky brightness distribution given by \( I'(\theta) = I(\theta) \cdot A(\theta) \). \( A(\theta) \) is known as the primary beam. If the radiation comes from a direction close to the pointing centre, then \( I'(\theta) \) is approximately the same as the true brightness distribution of the source. However, if \( \theta \gg \frac{\lambda}{D} \), where \( \lambda \) is the observing wavelength and \( D \) is the diameter of
the antenna, then there is virtually no signal.

In a two element interferometer, the voltage outputs of the two antennas are inserted in a correlator which multiplies the signals and integrates over a time interval. Thus, high resolution is achieved. For a given pair of telescopes and a non-variable source, the correlator gives an output equal to a Fourier component of $I' (\theta)$, known as a visibility. This measured visibility is defined by the baseline projected onto the plane which is formed by the wave fronts of the observed emission. Each point on this plane, called the uv-plane, is specified by the coordinates $u$ and $v$ that point east and north respectively.

In the case where more than one interferometer pair are present, many simultaneous measurements can be obtained in the uv-plane. A synthesis array consists of $N$ telescopes which are linked to form $N (N - 1)/2$ baselines. The rotation of the array with the Earth causes each baseline to draw elliptical tracks in the uv-plane, as presented in Figure 2.1. This results in the Fourier component of the source varying with time and the array is able to sample the visibilities for a range of points in the uv-plane. The more complete the uv-coverage of the Fourier plane, the more faithful the reproduction of the sky intensity distribution will be in an image. Finally, the inverse Fourier transform of the visibility data will give the best approximation to the real brightness distribution of the source.
Figure 2.1  MERLIN uv-coverage for sources at six different declinations: 80°, 60°, 40°, 20°, 0° and -20°. [Heywood, 2004]

2.2 ATCA

The Australian Telescope Compact Array, located at the Paul Wild Observatory outside of the town of Narrabri in rural NSW (about 500 km north-west of Sydney), is the most important long-wavelength interferometer in the southern hemisphere (http://www.narrabri.atnf.csiro.au/). It consists of six 22-m antennas, forming baselines up to 6 km, and operates well at high frequencies. Telescopes of the ATCA array are shown in Figure 2.2.

ATCA was used to obtain the radio observations of KT Eri that are presented in Chapter 3. For any given array, the properties that affect the achieved resolution are maximum baseline length and observing wavelength, since resolution is given by the expression
\[ \theta = 1.22 \times \frac{\lambda}{D} \]  \hspace{1cm} (2.1)

in radians, and

\[ \theta'' = 206265 \times \theta \]  \hspace{1cm} (2.2)

in arcseconds. Inserting the respective values for ATCA in the aforementioned expression, we get the resolution of this array for the observed frequencies used in this work. Table 2.1 shows the calculated resolution values.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Resolution (arcseconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>2.27</td>
</tr>
<tr>
<td>9.0</td>
<td>1.38</td>
</tr>
<tr>
<td>17.0</td>
<td>0.71</td>
</tr>
<tr>
<td>19.0</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Table 2.1  ATCA resolution values for radio wavelengths

If any structure of the observed target is smaller than the interferometer beam, then it cannot be resolved. In this case, the only measurable quantity is the flux density of the object. The size of the remnant of KT Eri is discussed in the following chapter, in order to determine whether it should be treated as a point source in the analysis. On the other hand, interferometers of longer baselines lose the capability of detecting larger scale structures.
2.3 MERLIN and VLA

**MERLIN**

The Multi-Element Radio Linked Interferometer Network (MERLIN) is an aperture synthesis radio telescope which consists of up to 7 individual antennas, spread around the UK as shown in Figure 2.3. The array performs at frequencies between 151 MHz and 24 GHz and is operated by Jodrell Bank Observatory. The maximum baseline length is 217 km and the minimum is 6.4 km. The diameters of the antennas range between 25 m and 76 m, which is the Lovell telescope at Jodrell Bank.

Due to the limited number of the antennas, the rotation of the Earth plays a significant role in providing satisfying uv-coverage. Thus, a typical observation will take around twelve hours. MERLIN was updated to e-MERLIN with an addition of a new optical fibre network that connects the telescopes to Jodrell Bank Observatory, achieving a sensitivity of ~1 μJy.
Figure 2.3 Locations of MERLIN telescopes around the UK. [Image taken from http://www.merlin.ac.uk]

**VLA**

The VLA (Very Large Array) is located at New Mexico, U.S.A., and consists of twenty seven 25-m diameter radio telescopes, providing high sensitivity. The antennas are situated in a Y-shape configuration, which in turn can be arranged into 4 different configurations, A to D, depending on the distance between the telescopes. The maximum baseline length is ~36 km and the length of the most compact arrangement is ~1 km.

The VLA is undergoing an expansion, the EVLA project, which includes upgrades with modern receivers and electronics. This will provide astronomers with an instrument of very high sensitivity, higher resolution and improved spectral and imaging capability.

An aerial photograph of the VLA with the telescopes in their closest configuration is shown in Figure 2.4. In this dissertation no data were reduced using this instrument,
however radio flux density measurements taken by the VLA have been included in the models described in a following chapter.

![Aerial photograph of the VLA antennas.](image)

**Figure 2.4** Aerial photograph of the VLA antennas. [Image courtesy of NRAO/AUI]

### 2.4 Data Reduction and Radio Imaging

**Data Reduction**

The radio interferometry data reduction package used in this work is MIRIAD, which was developed specifically by ATNF (Australia Telescope National Facility) in order to process most ATCA synthesis data.

Data reduction of a visibility set starts with examining the data for each baseline and detecting any bad points. Such points are discontinuities in the amplitude or noisy peaks in the phase plot. In addition, a baseline may have produced inconsistent data due to interference from nearby radio sources, or a telescope may have recorded off-source visibilities. The MIRIAD task BLFLAG allows the user to flag bad data that could affect the
subsequent calibration steps.

Calibration of the data is carried out in order to minimize atmospheric and instrumental effects. Variations in the amplitude are caused by fluctuations in the receivers, while the atmosphere is responsible for the phase errors. At low frequencies under 5 GHz, the signals are delayed by the ionosphere, while at higher frequencies tropospheric effects are dominant. For each baseline, the visibilities given by the corresponding correlator are complex numbers including amplitude and phase components. These are connected to the true visibilities by a multiplying factor consisting of the complex gains of each individual antenna and baseline.

Determining the absolute flux density scale for an observation requires the interferometer to make a short observation (5 to 15 min) of a point-source. This source is of well-known flux density and it is called the primary calibrator. 1934-638 is the primary calibrator for nearly all the ATCA observations and it was used for calibrating most of the data in this work.

The task MFCAL determines the bandpass using the primary calibrator and actually solves for two antenna-based gain-terms; a frequency-dependent, time-independent bandpass, and frequency-independent, time-dependent gains. The interval parameter is the time-step for the gains. It must be set at a lower value than the ATCA integration time of 10 seconds, in order for MFCAL to solve for the gains once per integration. The following task is GPCAL, and it is performed upon the primary calibrator data so as to correct any X-polarized radiation leaking into the Y-polarized feed and vice-versa. This task solves for time-independent leakages and time-dependent gains. Both MFCAL and GPCAL know the flux of 1934-638, so the absolute flux density calibration is done automatically in MIRIAD.

The gains determined by the short observations of the primary calibrator are useless for determining the atmospheric phase variations for a synthesis observation that may last as long as 12 hours. Thus, it is necessary to make use of a secondary calibrator which is chosen specifically for each experiment. The secondary calibrator (known as the phase calibrator) is a strong compact source located only a few degrees away from the target object, and it is usually observed for 1-2 minutes every 15-60 minutes. After copying the bandpass, the polarization leakages and the absolute flux scale from the primary to the secondary calibrator, GPCAL is once again performed on the visibility set of the secondary calibrator to determine time-variable gains.

Finally, the calibration tables from the secondary calibrator are copied to the
visibility set of the observed source. Now, the source visibilities are ready for Fourier transformation and subsequently an image can be reconstructed.

**Radio Imaging**

The measured brightness distribution from the interferometer is $I^D(u,v)$ which corresponds to the dirty map in the uv-plane. The uv-coverage is not complete, therefore the Fourier transform of $I^D(u,v)$ will be the Fourier transform of the true brightness distribution $I(u,v)$ multiplied by a sampling function $S(u,v)$ which relates to the uv-coverage of the array. If the convolution theorem is applied to this relationship, the result is that the measured function $I^D(x,y)$ is given by the Fourier transform of $I(u,v)$ convolved with the Fourier transform of $S(u,v)$:

$$I^D(x,y) \leftrightarrow I(u,v) \times S(u,v) \quad (2.3)$$

where $\leftrightarrow$ means Fourier transform.

$I^D(x,y)$ is known as the dirty map, while the Fourier transform of $S(u,v)$ is known as the dirty beam, DB:

$$DB \leftrightarrow S(u,v) \quad (2.4)$$

Therefore, the de-convolution of the dirty beam from the dirty map will allow us to reconstruct the true sky brightness distribution, as expressed in the relationship

$$I^D(x,y) \leftrightarrow I(x,y) \odot DB \quad (2.5)$$

where $\odot$ stands for convolution. In essence, de-convolution algorithms attempt to remove the side-lobes around strong sources by filling in the uv-plane.

The most common procedure for restoring images from a radio interferometer data-set is an algorithm developed by Högbom (1974) called CLEAN. This is an iterative scheme, which proceeds by finding the pixel with the brightest component in the dirty map to be de-convolved and subtracting a fraction (the loop gain) of a given point spread function (PSF) from that location. The image frame with the subtracted fraction is stored as
a residual frame for the following iteration. The total subtracted flux is then added to an output frame with the form of a delta function in the same position as the peak of the subtracted PSF. Then, the code iterates through this scheme by finding the new location of the brightest component, subtracting the loop gain of the PSF from the residual frame and placing it into the output frame. The process is repeated until the criteria set in the beginning are fulfilled. This usually means that the flux of the clean components that are being extracted from the dirty map reach a specific threshold before the iterations stop.

The task RESTOR subtracts the clean-component model output from the original dirty map, after convolving it with the dirty beam. Examination of the residual data-set indicates if there is still any emission left to clean, in which case a bigger number of iterations would be needed. Finally, the restored image is produced by convolving the clean-component image with a Gaussian and adding in the residual image.

Besides the frequency and the maximum baseline length, other factors affect the resolution, such as the declination of the observed source as well as the weighting option that we used during the data reduction. The choice of the weighting option depends on what aspect of the radio map one wants to study. Weighting of the visibilities may be done by the correlator or by using software schemes. The most common weighting options are natural and uniform weighting. The former takes into consideration the variance of the measurements in each grid cell, which is affected by the sensitivities of the different telescopes of the array. The latter performs the Fourier transform of the uv data-set giving the same weighting to all visibilities, regardless of the variance. The difference is that maps which are produced using uniform weighting have better resolution than naturally weighted maps, which in comparison have better signal to noise ratio.
CHAPTER 3
RADIO OBSERVATIONS OF NOVA KT ERI

3.1 Introduction

KT Eridani (or Nova Eri 2009) is a recent nova that was discovered at an unfiltered CCD magnitude of 8.1 in the constellation of Eridanus on 2009 November 25.536 UT by Itagaki (2009). However, its outburst was already recorded on images taken on November 14th of the same year, at RA: 04:47:54.21, Dec: −10:10:43.1, J2000 (Yamaoka et al., 2009). The peak magnitude, determined by the amplitude in these pre-discovery images, was 5.4. Upon its discovery KT Eri was classified as a He/N nova after spectroscopic observations from several teams. Through photometry between 2009 November 1.13 UT and 2009 November 30.62 UT, the original spectrum of the progenitor revealed a hot star with circumstellar material surrounding it.

The nova outburst was studied by Ragan et al. (2009), who obtained photometric and spectroscopic observations of KT Eri. They estimated the $t_2$ and $t_3$ times to be 8 and 15 days respectively. Wide emission lines, which are typical for a He/N nova, dominated the spectrum. Measurements of the Hα and Hβ lines yielded FWHM values of ~3000 km sec$^{-1}$ and ~2600 km sec$^{-1}$ respectively. The estimated E(B-V) colour excess value was ~0.08. Consequently, the distance of KT Eri was calculated at around 6.5 kpc. This group noted that "a distance of 6.5 kpc means that the 15 mag star observed at approximately the same coordinates before the outburst is too bright to be a progenitor of Nova Eri 2009." However, Drake et al. (2009) concluded that the highly variable 15$^{th}$ magnitude star, that shows evidence of pre-outburst circumstellar material, is related to KT Eri. They reported historical observations of the pre-nova source of KT Eri, studying the photometry of the source from 2005 to 2009 and finding a possible periodicity of ~210 days. They also noted similarities between KT Eri and the soft X-ray transient CSS081007:030559+054715.

Observations of the initial rise, peak and early decline were made with SMEI (Hounsell et al., 2010). The visual light curve, presented in Figure 3.1, shows a steep initial rise of the nova, rising 4.1 magnitudes over 2.7 days. A pre-maximum halt is indicated on 2009 November 13.90 UT, at m ~ 6. This halt would seem to have lasted only a few hours, which is in accordance with the speed of the nova. KT Eri reached an unfiltered SMEI...
maximum apparent magnitude of $5.42 \pm 0.02$ on 2009 November 14.67 UT. A subsequent rapid decline followed, with $t_2 = 6.6$ days. This value justifies KT Eri being placed under the category of very fast novae. The very fast decline, along with the relatively low amplitude of the eruption, associate KT Eri with RNe such as U Sco (Schaefer, 2010) rather than with CNe. KT Eri was reliably detected with SMEI for the last time on 2009 November 27.23 UT at $m = 8.3 \pm 0.1$. Figure 3.2 shows the SMEI light curve of KT Eri, compared with data from the Liverpool Telescope SkyCamT, which seem to be in good agreement with each other. From this image it is confirmed that this nova has more noticeable similarities to RNe rather than to CNe.

![Figure 3.1 The visual light curve of KT Eri.](http://www.astro.ljmu.ac.uk/archive/research/Light_curve.html)

Optical spectroscopy using the Liverpool Telescope and X-ray measurements were compared to connect the appearance of the HeII 4686Å line with the emergence of the super-soft source phase in the X-ray regime (Ribeiro, 2011). This connection could prove a
useful indicator for future X-ray observations. The SSS phase is important, as it samples the continued extensive nuclear burning on the surface of the WD after the explosion. Morphokinematical modelling showed that the KT Eri remnant resembled a dumbbell with a ratio between the major to minor axis of 4:1 and with an inclination of 58 degrees. The derived maximum expansion velocity was $V_{exp} = 2800 \pm 200$ km sec$^{-1}$. This value will be used later in a discussion about the physical characteristics of the KT Eri shell.

![Figure 3.2](image.png)

Figure 3.2  The visual light curve of KT Eri (black squares) derived from SMEI. Liverpool Telescope SkyCamT data (gray stars) are superimposed. The inset shows the rising portion of the light curve with an expanded time scale. [Hounsell et al., 2010]

KT Eri was detected as a bright soft X-ray source (Bode et al., 2010). It was monitored intensively with the Swift X-ray telescope during its SSS phase, which exhibited a high and rapid variability that resembles the one seen in RS Oph. Ness et al. (2010) also
observed KT Eri on day 70 with the Low Energy Transmission Grating onboard Chandra. They obtained a high resolution X-ray spectrum which once again indicated a bright super-soft source, and a high variability in the light curve was recorded. Finally, Beardmore et al. (2010) studied the previously mentioned X-ray light curves in search for variability on shorter timescales and found a ~35 sec oscillation. This was the second time that such an oscillation in the SSS emission was observed, first one being in RS Oph. It is yet unclear whether this quasi-periodic modulation occurs due to rotation of the WD or there is a nuclear burning instability (Schwarz et al., 2011).

3.2 Radio Observations

Observations at radio wavelengths provide the best method of estimating the ejected mass of nova outbursts and the morphology and geometry of their expanding remnants. At first, the radio light curve is optically thick and the flux density increases with time, as the nova remnant is expanding. Subsequently, the nova enters the optically thin region where the flux density decreases. The time when this turn-over occurs depends on the mass of the ejected material and the velocity at which the ejecta are moving.

KT Eri was detected as a radio source during the rising part of the radio light curve as reported by O’Brien et al. (2010). Several epochs of observations were made at radio frequencies, using ATCA, VLA, MERLIN and EVN. KT Eri was not detectable at a 3-sigma upper limit of 0.18 mJy during the first observations with MERLIN at 5 GHz, from 2009 December 4th to December 8th. The first detection was recorded at 5 GHz with VLA on the 28th of December, and the measured flux density was 0.21 mJy. At the same frequency, observations with MERLIN between days 60-65 resulted in a flux density value of ~0.33 mJy. Afterwards, two epochs of observations with ATCA took place and the recorded flux densities were 0.56 mJy at 5.5 GHz on day 71 after the outburst (January 1st) and an increased value of 0.74 mJy on day 81 (February 3rd). Also flux densities were measured for these last two days at 9 GHz and 17 GHz. The measured values are presented in Table 3.1. Day 1 corresponds to the day that the outburst of KT Eri was identified on radio images by Yamaoka et al. (2009), as mentioned before, i.e. November 14th, 2009.

The aforementioned flux density observations taken with VLA, MERLIN and EVN
are used in the following chapter during the modelling of the light curve of KT Eri. However, the data taken with ATCA for the epochs of 01/24/2010 (day 71) and 02/3/2010 (day 81), which appear in Table 3.1, were re-analysed consistently in this work and the reduction resulted in different values of the flux density. These last values are used in the discussion about the light curve of KT Eri in the following chapter.

Table 3.1 Radio observations of KT Eri with MERLIN, VLA and EVN (Days 22-88).

<table>
<thead>
<tr>
<th>Date</th>
<th>Day</th>
<th>Frequency (GHz)</th>
<th>Flux Density (mJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/4-8/2010</td>
<td>22</td>
<td>5.0</td>
<td>&lt; 0.18 – MERLIN</td>
</tr>
<tr>
<td>12/28/2010</td>
<td>44</td>
<td>4.8</td>
<td>0.21 – VLA</td>
</tr>
<tr>
<td>01/13-18/2010</td>
<td>62.5</td>
<td>5.0</td>
<td>0.33 – MERLIN</td>
</tr>
<tr>
<td>01/19-28/2010</td>
<td>71</td>
<td>5.0</td>
<td>0.35 – MERLIN</td>
</tr>
<tr>
<td>01/24/2010</td>
<td>71</td>
<td>5.5</td>
<td>0.56 – ATCA</td>
</tr>
<tr>
<td>01/24/2010</td>
<td>71</td>
<td>9.0</td>
<td>0.85 – ATCA</td>
</tr>
<tr>
<td>02/3/2010</td>
<td>81</td>
<td>5.5</td>
<td>0.74 – ATCA</td>
</tr>
<tr>
<td>02/3/2010</td>
<td>81</td>
<td>9.0</td>
<td>1.41 – ATCA</td>
</tr>
<tr>
<td>02/3/2010</td>
<td>81</td>
<td>17.0</td>
<td>2.27 – ATCA</td>
</tr>
<tr>
<td>02/10/2010</td>
<td>88</td>
<td>5.0</td>
<td>0.82 – EVN</td>
</tr>
</tbody>
</table>

3.3 Discussion of the Radio Maps

The restored radio images of KT Eri are presented here. The data reduction was done with the MIRIAD package and the epochs of the observations that were analysed are shown in Table 3.2. In the column where sources are listed, the first line refers to the flux calibrator (primary) and the second line is the phase calibrator (secondary). 1934-638 is normally the source used as the primary calibrator for ATCA observations. 0434-188 is used as a phase calibrator for the frequencies of 5.5 and 9 GHz, while 0458-020 was observed as the phase calibrator at the frequencies of 17 and 19 GHz. Figure 3.3 shows an example of a visibility data-set of KT Eri observed at 5.5 GHz on 2010, March 23rd (day 126), after the bandpass,
gain and polarization corrections were applied to the uv-visibilitys.

The process that was followed during the reduction is essentially the one described in section 2.4. Several CLEAN runs were done to the obtained dirty maps for each epoch and frequency, in order to determine the number of iterations that would produce the best clean-component images. The characteristics of the beam for each produced radio map are given in Table 3.3. Performing self-calibration on the data was deemed pointless, since KT Eri is a faint source. Examples of restored images of KT Eri are given in Figure 3.4 and Figure 3.5.

Table 3.2 Radio observations of KT Eri with ATCA (Days 71-126).

<table>
<thead>
<tr>
<th>Date</th>
<th>Day</th>
<th>Frequencies (GHz)</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-Jan-24</td>
<td>71</td>
<td>5.5, 9</td>
<td>0823-500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0434-188</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>KT Eri</td>
</tr>
<tr>
<td>2010-Feb-03</td>
<td>81</td>
<td>5.5, 9, 17, 19</td>
<td>1934-638</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0434-188, 0458-020</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>KT Eri</td>
</tr>
<tr>
<td>2010-Feb-09</td>
<td>87</td>
<td>5.5, 9, 17, 19</td>
<td>1934-638</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0434-188, 0458-020</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>KT Eri</td>
</tr>
<tr>
<td>2010-Feb-21</td>
<td>99</td>
<td>5.5, 9, 17, 19</td>
<td>1934-638</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0434-188, 0458-020</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>KT Eri</td>
</tr>
<tr>
<td>2010-Mar-20</td>
<td>126</td>
<td>5.5, 9, 17, 19</td>
<td>1934-638</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0434-188, 0458-020</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>KT Eri</td>
</tr>
</tbody>
</table>

In Figure 3.4 there appears another radio source at the 5.5 GHz frequency, which is not detected in the maps of the higher frequencies. The NASA Extragalactic Database (NED) revealed that this is the radio galaxy named NVSS J044802-100824. NVSS stands
for NRAO/VLA Sky Survey, which covers the sky north of J2000.0 DEC = -40° at 1.4 GHz, while the rest of the name indicates the coordinates of this galaxy; RA: 04:48:02.2, DEC: -10:08:24. This position is referenced by Condon et al. (1998). The measurement of the flux density of the radio galaxy gave the result of 21.4 mJy at 1.4 GHz. The structure of the galaxy, as seen in Figure 3.4, is consistent with the previous observations. Its flux density from the data reduction in this work at 5.5 GHz was estimated ~1.04 mJy. This is also broadly consistent with not detecting the galaxy at the higher frequencies, since it is a non-thermal source and therefore it is brighter at low frequencies.

Table 3.3 ATCA beam characteristics of the produced radio maps.

<table>
<thead>
<tr>
<th>Date</th>
<th>Day</th>
<th>Frequency (GHz)</th>
<th>Beam Major Axis (arcsec)</th>
<th>Beam Position Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-Jan-24</td>
<td>71</td>
<td>5.5</td>
<td>17.58</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>11.15</td>
<td></td>
<td>9.8</td>
</tr>
<tr>
<td>2010-Feb-03</td>
<td>81</td>
<td>5.5</td>
<td>10.63</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>6.65</td>
<td></td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>4.15</td>
<td></td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>3.72</td>
<td></td>
<td>3.4</td>
</tr>
<tr>
<td>2010-Feb-09</td>
<td>87</td>
<td>5.5</td>
<td>10.73</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>6.51</td>
<td></td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>3.90</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>3.49</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>2010-Feb-21</td>
<td>99</td>
<td>5.5</td>
<td>10.50</td>
<td>-7.3</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>6.48</td>
<td></td>
<td>-7.3</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>3.91</td>
<td></td>
<td>-4.9</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>3.48</td>
<td></td>
<td>-4.9</td>
</tr>
<tr>
<td>2010-Mar-20</td>
<td>126</td>
<td>5.5</td>
<td>6.91</td>
<td>-1.7</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>4.64</td>
<td></td>
<td>-0.9</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>2.47</td>
<td></td>
<td>-1.3</td>
</tr>
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<td></td>
<td>19</td>
<td>2.21</td>
<td></td>
<td>-1.2</td>
</tr>
</tbody>
</table>
Figure 3.3 Example of the calibrated visibilities of KT Eri at C-band from ATCA baselines, using the XX and YY linear polarization parameters.
Figure 3.4 Restored images of KT Eri at 5.5 GHz (top) and at 9 GHz (bottom). The flux density is reported in mJy.
Figure 3.5 Restored images of KT Eri at 17 GHz (top) and at 19 GHz (bottom). The flux density is reported in mJy.
3.4 Flux Density Measurements

ATCA was used to obtain the radio observations of KT Eri that are presented and analysed in this work. There are 5 epochs of data at C-band (5.5 GHz) as well as at the frequencies of 9, 17 and 19 GHz. These observations are listed in Table 3.4 along with the measured flux density values for each epoch. The RMS value for each reduction is also given. Each flux density with its corresponding error bar was integrated from the restored maps with the MIRIAD task IMFIT, after the dirty map was cleaned using 2000 CLEAN iterations. These are the flux density values that will be used in the following chapter.

The task IMFIT has several options with which it can measure the flux density of a specific region in the given radio map. The option “object: point” was applied to all the measurements, since KT Eri was treated as a point-source in the sky. This is justified by calculating the angle diameter of the nova remnant in arcseconds and comparing it with the ATCA beam. A time period of approximately 120 days is used in the calculation, given that the last observation in this analysis was made on 2010, March 20th (day 126).

For a distance of $d = 6.5$ kpc, an ejection velocity of $V = 2800$ km sec$^{-1}$ and $t = 120$ days, the angle diameter of KT Eri, $\theta_{KT}''$, is given by

$$\theta_{KT}'' = 2 \times 206265 \times \frac{V t}{d} \implies \theta_{KT}'' = 0.061 \ .$$

(3.1)

In Table 2.1 it is shown that the resolution of the ATCA beam varies between 2.27'' for the lowest frequency at which KT Eri was observed and 0.66'' for the highest frequency. Consequently, KT Eri is viewed by the ATCA beam as a point-source during all the observations at all frequencies.
Table 3.4 Flux densities with IMFIT at 2000 CLEAN iterations

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Day</th>
<th>Frequency (GHz)</th>
<th>Flux Density (mJy)</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-Jan-24</td>
<td>71</td>
<td>5.5</td>
<td>0.75 ± 0.04</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.0</td>
<td>1.42 ± 0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>2010-Feb-03</td>
<td>81</td>
<td>5.5</td>
<td>1.05 ± 0.08</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.0</td>
<td>1.97 ± 0.18</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.0</td>
<td>3.59 ± 0.23</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.0</td>
<td>3.76 ± 0.47</td>
<td>0.18</td>
</tr>
<tr>
<td>2010-Feb-09</td>
<td>87</td>
<td>5.5</td>
<td>1.12 ± 0.08</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.0</td>
<td>1.76 ± 0.20</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.0</td>
<td>2.03 ± 0.25</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.0</td>
<td>1.79 ± 0.26</td>
<td>0.15</td>
</tr>
<tr>
<td>2010-Feb-21</td>
<td>99</td>
<td>5.5</td>
<td>0.40 ± 0.12</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.0</td>
<td>0.94 ± 0.17</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.0</td>
<td>0.60 ± 0.45</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.0</td>
<td>1.03 ± 0.42</td>
<td>0.21</td>
</tr>
<tr>
<td>2010-Mar-20</td>
<td>126</td>
<td>5.5</td>
<td>1.07 ± 0.06</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.0</td>
<td>1.97 ± 0.20</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.0</td>
<td>0.98 ± 0.20</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.0</td>
<td>1.25 ± 0.20</td>
<td>0.12</td>
</tr>
</tbody>
</table>

In Table 3.5 (a)-(d) there are listed the IMFIT measurements of the flux density for 250 CLEAN iterations, along with the results for a greater number of iterations. However, a higher number of iterations does not result in a noticeable effect on the flux density, since the produced error bars of the new estimated values are still big. Also, there was not a significant difference in the RMS values of the residual maps either.
Table 3.5(a) Flux density (mJy) at 5.5 GHz.

<table>
<thead>
<tr>
<th>Date</th>
<th>Iterations</th>
<th>250</th>
<th>500</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-Jan-24</td>
<td>250</td>
<td>0.77 ± 0.06</td>
<td>0.74 ± 0.04</td>
<td>0.75 ± 0.04</td>
</tr>
<tr>
<td>2010-Feb-03</td>
<td>500</td>
<td>1.05 ± 0.08</td>
<td>1.04 ± 0.08</td>
<td>1.05 ± 0.08</td>
</tr>
<tr>
<td>2010-Feb-09</td>
<td>2000</td>
<td>1.13 ± 0.07</td>
<td>1.12 ± 0.07</td>
<td>1.12 ± 0.08</td>
</tr>
<tr>
<td>2010-Feb-21</td>
<td>250</td>
<td>0.51 ± 0.18</td>
<td>0.47 ± 0.15</td>
<td>0.40 ± 0.12</td>
</tr>
<tr>
<td>2010-Mar-20</td>
<td>500</td>
<td>1.15 ± 0.08</td>
<td>1.14 ± 0.07</td>
<td>1.07 ± 0.06</td>
</tr>
</tbody>
</table>

Table 3.5(b) Flux density (mJy) at 9 GHz.

<table>
<thead>
<tr>
<th>Date</th>
<th>Iterations</th>
<th>250</th>
<th>500</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-Jan-24</td>
<td>250</td>
<td>1.44 ± 0.07</td>
<td>1.43 ± 0.07</td>
<td>1.42 ± 0.06</td>
</tr>
<tr>
<td>2010-Feb-03</td>
<td>500</td>
<td>1.99 ± 0.19</td>
<td>2.09 ± 0.08</td>
<td>1.97 ± 0.18</td>
</tr>
<tr>
<td>2010-Feb-09</td>
<td>2000</td>
<td>1.82 ± 0.17</td>
<td>1.78 ± 0.20</td>
<td>1.76 ± 0.20</td>
</tr>
<tr>
<td>2010-Feb-21</td>
<td>250</td>
<td>0.79 ± 0.25</td>
<td>0.84 ± 0.26</td>
<td>0.94 ± 0.17</td>
</tr>
<tr>
<td>2010-Mar-20</td>
<td>500</td>
<td>2.13 ± 0.23</td>
<td>2.06 ± 0.21</td>
<td>1.97 ± 0.20</td>
</tr>
</tbody>
</table>

Table 3.5(c) Flux density (mJy) at 17 GHz.

<table>
<thead>
<tr>
<th>Date</th>
<th>Iterations</th>
<th>250</th>
<th>500</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-Feb-03</td>
<td>250</td>
<td>3.67 ± 0.25</td>
<td>3.64 ± 0.23</td>
<td>3.59 ± 0.23</td>
</tr>
<tr>
<td>2010-Feb-09</td>
<td>500</td>
<td>2.12 ± 0.30</td>
<td>2.00 ± 0.28</td>
<td>2.03 ± 0.25</td>
</tr>
<tr>
<td>2010-Feb-21</td>
<td>2000</td>
<td>0.75 ± 0.35</td>
<td>0.57 ± 0.38</td>
<td>0.60 ± 0.45</td>
</tr>
<tr>
<td>2010-Mar-20</td>
<td>250</td>
<td>1.19 ± 0.22</td>
<td>1.05 ± 0.21</td>
<td>0.98 ± 0.20</td>
</tr>
</tbody>
</table>
Table 3.5(d) Flux density (mJy) at 19 GHz.

<table>
<thead>
<tr>
<th>Date</th>
<th>Iterations</th>
<th>250</th>
<th>500</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-Feb-03</td>
<td>3.82 ± 0.33</td>
<td>3.84 ± 0.41</td>
<td>3.76 ± 0.47</td>
<td></td>
</tr>
<tr>
<td>2010-Feb-09</td>
<td>1.84 ± 0.32</td>
<td>1.81 ± 0.28</td>
<td>1.79 ± 0.26</td>
<td></td>
</tr>
<tr>
<td>2010-Feb-21</td>
<td>1.63 ± 0.29</td>
<td>1.62 ± 0.26</td>
<td>1.03 ± 0.42</td>
<td></td>
</tr>
<tr>
<td>2010-Mar-20</td>
<td>1.88 ± 0.28</td>
<td>1.23 ± 0.24</td>
<td>1.25 ± 0.20</td>
<td></td>
</tr>
</tbody>
</table>

Finally, a higher number of CLEAN iterations was tried in several observations which had big error bars to determine whether this would have an effect on the quality of the cleaned map and to check if the residual noise would be lower. The results are presented in Table 3.6. Apparently, the difference between the values with a low number of iterations and those with higher iteration numbers is insignificant. The respective maps did not present any big difference in their quality and levels of noise either.

Table 3.6 Examples of flux density values (mJy) from IMFIT with a varying number of CLEAN iterations.

<table>
<thead>
<tr>
<th>Date / Frequency</th>
<th>Iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>250</td>
</tr>
<tr>
<td>2010-Feb-03 5.5 GHz</td>
<td>1.05 ± 0.08</td>
</tr>
<tr>
<td>2010-Feb-03 19 GHz</td>
<td>3.82 ± 0.33</td>
</tr>
<tr>
<td>2010-Feb-09 17 GHz</td>
<td>2.12 ± 0.30</td>
</tr>
<tr>
<td>2010-Mar-20 9 GHz</td>
<td>2.13 ± 0.23</td>
</tr>
<tr>
<td>2010-Mar-20 19 GHz</td>
<td>1.88 ± 0.28</td>
</tr>
</tbody>
</table>
CHAPTER 4
MODELLING OF NOVA SHELLS

4.1 Introduction to Nova Shells

An expanding shell of $\sim 10^{-5}$ to $10^{-4}$ $M_\odot$ of ejected material is what accompanies a typical nova outburst. This shell expands at velocities of hundreds to thousands of km sec$^{-1}$. Nova shells exhibit a variety of morphological features, such as equatorial rings and polar caps (Gill, 1999). Observability of nova shells depends on the resolution of the modern large telescopes and the progress in high efficiency instruments; the shell needs to be spatially well-resolved from the bright central source. Since the brightness of the shell fades quickly, this imposes an extra limit on the number of luminous nova shells available for observation.

When the expanding ejecta engulfs the secondary, a common envelope is formed. As the expansion continues, the primary is exposed and its hot fast wind interacts with the density variations of the shell, giving it a non-spherical shape. Numerical models have been carried out to represent the structure of the nova shell in the common envelope stage. The effects of angular momentum in the remnant formation due to the rotation of the white dwarf envelope were first studied by Porter, O'Brien & Bode (1998). Their hydrodynamical simulations of the flows around a nova system show that nova shells become more prolate rather than oblate, as the envelope rotation increases. Furthermore, it could also be that in some novae the ejection takes the form of jets, also leading to a prolate shell structure (Sokoloski et al., 2008).

The shaping mechanisms cannot be directly observed, due to the optically thick ejecta at the time when the shell is formed. Magnetic fields are another factor that can also affect the morphology of nova shells, especially in the binary systems where the magnetic fields are strong. Slavin, O'Brien & Dunlop (1995) undertook a deep optical imaging survey of the nebular remnants of northern-sky classical novae; later the survey was extended to include southern-sky novae (Gill & O'Brien, 1998). The results of the surveys are important as they provide information on the shaping mechanisms at work.

Figure 4.1 shows examples of optical and radio images of resolved nova remnants.
Figure 4.1  Optical images of nova shells with scales shown in arcseconds (top) and MERLIN maps at 5 GHz showing the radio evolution of the remnant of V705 Cas. [O'Brien & Bode, 2008]
4.2 Models for Novae

In previous years some models have been developed in order to process the radio emission coming from expanding remnants of CNe. These simple models assuming Bremsstrahlung radiation can be used to estimate the physical properties of the nova shell from fits to the observed light curve. Some examples of novae that have been modelled in the past are FH Ser, HR Del and V1500 Cyg (Hjellming et al., 1979). Heywood (2004) also applied various models to CNe including V723 Cas, V1494 Aql and V1974 Cyg.

Each model gives solutions for the equations of radiative transfer through a region of gas for free-free emission, for a number of shell configurations. These solutions yield a value of the flux density. There follows a theoretical analysis about the radiative transfer process.

Optical Depth and Flux Density

In the Rayleigh-Jeans regime the approximation $h\nu \ll kT_e$ applies, therefore the Planck function is written as

$$B(\nu, T_e) = \frac{2kT_e}{c^2} \nu^2$$

where $T_e$ is the effective temperature and $\nu$ is the observed frequency. The optical depth $\tau$, along a line of sight $s$ through a spherical emitting region as shown in Figure 4.2, is given by

$$\tau = 2\int_{s_1}^{s_2} \kappa(\nu) \, ds$$

where $\kappa(\nu)$ is related to the emissivity $j(\nu)$ (Tucker, 1975) and to the Planck function $B(\nu, T_e)$ by the relation

$$\kappa(\nu) = \frac{j(\nu)}{B(\nu, T_e)} .$$
Combining the aforementioned relations and assuming we are dealing with a spherical shell of radius \( r_2 \) and diameter \( D \), the flux density is given by the expression

\[
S = \frac{2\pi B(v, T_e)}{D^2} \int_0^{r_2} (1 - e^{-\tau}) \alpha \, d\alpha
\]  

(4.4)

where \( \alpha \), as shown in the configuration in Figure 4.3, has dimensions of length and needs to be substituted by a dimensionless integration variable, \( x \), as given by \( \alpha = x \, r_2 \). The flux density is calculated by adding up the contributions from each concentric shell of radius \( \alpha \) and thickness \( d\alpha \).

Figure 4.2  Line of sight through a spherically symmetric emitting shell.
In this chapter the Hubble flow model is applied to the radio observations of KT Eri that were presented in Chapter 3.

### 4.3 The Hubble Flow Model

In the Hubble flow model it is assumed that mass is ejected instantaneously and forms a detached, isothermal and spherically symmetric shell through a difference in the velocities of the inner and outer shell boundaries (Seaquist & Palimaka, 1977). The model is named after this radial velocity gradient.

\[
S = \frac{2\pi B(v, T_e)}{D^2} \left( \frac{r^2}{r_z} \right) \int_0^1 (1 - e^{-\tau}) x \, dx
\]  

(4.5)
Figure 4.4 shows a schematic of the shell. The radii of the inner and outer boundaries are given by $r_1$ and $r_2$ respectively. The dashed line refers to the line of sight. The optical depth is integrated along the line of sight $s$. The distance from the centre, $r$, varies as the shell is expanding and $a$ is the projected distance.

![Diagram of the shell](image)

**Figure 4.4** Geometry of the shell for the Hubble flow model.

The density as a function of $r$ is expressed as

$$\rho(r) = \frac{M}{4\pi r^2 (r_2 - r_1)}$$  \hspace{1cm} (4.6)

Electron density, if we substitute the above equation in its definition, is consequently given by

$$N_e = \frac{\rho}{\mu m_H} = \frac{M}{4\pi r^2 \mu m_H (r_2 - r_1)}$$  \hspace{1cm} (4.7)
where $M$ is the ejected mass, $\mu$ is the mean molecular weight and $m_H$ is the mass of the hydrogen atom. For an emitting region of pure hydrogen, $\mu$ equals 1. For fully ionized pure hydrogen, the optical depth $\tau$ is given by

$$\tau = 3.52 \times 10^{-12} T_e^{-1.5} g_{ff}(\nu, T_e) \nu^{-2} \int_{s_1}^{s_2} N_e^2 ds$$

(4.8)

where $g_{ff}(\nu, T_e)$ is the Gaunt factor, which for radio wavelengths (Bekefi, 1966) is approximated by

$$g_{ff}(\nu, T_e) = \left( \frac{\sqrt{3}}{\pi} \right) \left[ 17.7 + \ln \left( \frac{T_e^{1.5}}{\nu} \right) \right].$$

(4.9)

Substitution of (4.7) into the expression of $\tau$ given by (4.8) results in the following relationship

$$\tau = 3.52 \times 10^{-12} \frac{M^2 g_{ff}(\nu, T_e)}{16\pi^2 \mu^2 m_H^2 T_e^{1.5} \nu^2 (r_2 - r_1)^2} \int_{s_1}^{s_2} \frac{1}{r^4} ds.$$

(4.10)

The parameter of the integral limits changes from the line of sight $s$ to the projected radius $\alpha$, which is related to $s$ and $r$ by the expression $r = (\alpha^2 + s^2)^{1/2}$, as displayed in Figure 4.4. It follows that there will be two optical depth functions, depending on the area, which are $\tau_1(\alpha)$ for $0 < \alpha \leq r_1$ and $\tau_2(\alpha)$ for $r_1 \leq \alpha \leq r_2$. These two functions are provided in Appendix A.

Finally, the flux density is given by the equation

$$S_\nu = \frac{2\pi B_\nu T_e}{R^2} \left[ \int_{0}^{r_1} \alpha (1 - e^{-\tau_1(\alpha)}) \, d\alpha + \int_{r_1}^{r_2} \alpha (1 - e^{-\tau_2(\alpha)}) \, d\alpha \right].$$

(4.11)

### 4.4 Hubble Flow Model Light Curves

Examples of model light curves, using the Hubble flow model for different parameter
values, are presented in this section. All the models assume free-free emission from an isothermal shell which emits radiation at a temperature of 10000 K. In Figure 4.5 the light curve varies for several ejected mass values, while the ejection velocity is fixed at 2900 km sec\(^{-1}\) and the distance to the nova is given the value of 5 kpc. These specific values are selected so as to be close to the assumed values for KT Eri, according to Ribeiro (2011). The ratio of inner to outer velocity is fixed at 0.03 and the mass values are of \(10^{-4}\), \(10^{-5}\), \(10^{-6}\) and \(10^{-7}\) M\(_{\odot}\).

In this plot it is shown that the increase of the ejected mass leads to an increase in the flux density, because there is more emitting material. It is also clear that during the optically thick part of the light curve the shell mass does not affect the shape of the curve. This happens because it is simply the size of the shell (i.e. the ejection velocity) that determines its brightness. However, when the curve turns over due to the ejecta becoming optically thin, the varying shell mass produces an evident effect.

Figure 4.5 Model light curves for varying values of ejected mass. From top to bottom, these are \(10^{-4}\), \(10^{-5}\), \(10^{-6}\) and \(10^{-7}\) M\(_{\odot}\). The y-axis is in logarithmic scale for this and all further plots.
Figure 4.6 shows the light curves that the Hubble model generates if the shell mass is fixed at $10^{-4} \, M_\odot$ and the ratio of inner to outer velocity is fixed at 0.25, while the ejection velocity varies between the values of 1000, 2900, 3900 and 5000 km sec$^{-1}$. It is obvious that the increase in the velocity does not affect the maximum flux density value reached by the nova, but it does affect the total emitted flux during large periods of time. For a fixed mass, the light curve rises faster with higher velocities before the optical depth turns over. Thus, the emission also fades quicker since with faster velocities the density of the ejecta becomes lower sooner.

![5.5 GHz light curves](image)

Figure 4.6  Model light curves for varying values of ejection velocity. From right to left, these are 1000, 2900, 3900 and 5000 km sec$^{-1}$.

In Figure 4.7 the light curve varies for different ratios of inner to outer velocity, for a fixed shell mass of $10^{-4} \, M_\odot$ and for a distance of 5 kpc. The velocity ratio is the parameter that determines how thick the nova shell is. Examination of the plot reveals that varying this parameter leaves the total flux unaffected during the optically thick phase. However,
after the curve has turned over, a larger emitting region is indicated by a lower velocity ratio. It is obvious that the flux density peaks at a higher value for thicker shells, hence for decreasing velocity ratios. Upon further examination of the last stage of the light curves it is also evident that the light curves expressing values of a velocity ratio close to 0 converge with those that represent values of ratio close to 1. For values that are in the middle of the ratio range, the respective light curves fade quicker.

Figure 4.7 Model light curves for varying values of the ratio of the inner to outer velocity. From top to bottom, these are 0.9, 0.7, 0.5, 0.3 and 0.1.

Finally, the dependence on the distance of the nova is investigated in Figure 4.8. The distance is successively given the values of 3.9, 5 and 6.5 kpc while the ejection velocity is fixed at 2900 km sec$^{-1}$, the ratio of the inner to outer velocity remains stable at 0.03 and the ejected mass is fixed at $10^{-4}$ M$_\odot$. The plot shows that high values of the distance result in lower values of the peak of the emission. This is explained by the fact that
the further away a nova shell of certain characteristics is, the fainter the emission recorded. However, the behaviour of the light curve in regard to the turn-over of the optical depth is the same for all distance values.

The programs that were used to produce the light curves and later perform the fitting to them were developed by Heywood & O'Brien (2004).

Figure 4.8 Model light curves for varying values of the distance of the nova. From top to bottom, these are 3.9, 5 and 6.5 kpc.

4.5 Applying the Model to KT Eri

Here the model described in the previous section is applied to the ATCA observations of KT Eri presented in Chapter 3. Present in some plots are also flux density values from observations taken with MERLIN, VLA and EVN which were reported by O'Brien et al. (2010).

Figure 4.9 shows the C-band light curve of KT Eri, using the 5.5 GHz data from
Table 3.4 for 2000 CLEAN iterations. The plot also shows four model light curves which were generated by the Hubble flow model. The distance is assumed to be 5 kpc, the high ejection velocity is fixed at 2900 km sec$^{-1}$ and the ratio of inner to outer velocity is 0.03. The shell mass is given the values of $10^{-4}$, $10^{-5}$, $10^{-6}$ and $10^{-7}$ M$_{\odot}$. Obviously, none of the modelled light curves fits the actual data well. However, further increase in the mass of the ejecta would be pointless, since this would only make a difference when it becomes optically thin.

It is also apparent that the ATCA point for the 2010-Feb-21 date (day 99) is considerably low compared to what would be expected from the evolution of the light curve. This was true for the rest of the frequencies too, as it can be seen from Table 3.4 and Table 3.5, therefore the flux density measurements of this date are excluded from further plots and fitting attempts. This discrepancy is probably contributed to the performance of the antennas being poor that particular day, due to unfavorable atmospheric conditions.

Furthermore, the flux density value measured with EVN is lower than the ATCA measurements, the reason being that EVN consists of larger baselines than ATCA. Consequently, EVN provides better resolution and KT Eri is not viewed as a point-source but as an extended shell. Thus, it may be that EVN underestimates the flux density because, at its high resolution, it is resolving the source. This EVN value is also left out of the next plots.
Figure 4.9 The light curve of KT Eri at 5.5 GHz. The model light curves are for varying values of ejected mass. From top to bottom, these are $10^{-4}$, $10^{-5}$, $10^{-6}$ and $10^{-7} \, M_\odot$.

In Figure 4.10 the 5.5 GHz data are presented along with three model light curves. The continuous curve represents a distance of 5 kpc and an outer ejection velocity of 2900 km sec$^{-1}$. The dashed curve shows how the light curve changes if the ejection velocity is increased to 3900 km sec$^{-1}$ while the dotted curve depicts a light curve where the assumed distance of the nova has decreased to 3.9 kpc. In all the cases the shell mass is fixed at $10^{-4} \, M_\odot$. Apparently, the last two model light curves fit the data better than in the previous plot.
Figure 4.10 The light curve of KT Eri at 5.5 GHz. The model light curves are for varying values of outer velocity and distance. Shell mass is fixed at $10^{-4} M_\odot$. Continuous curve: distance is 5 kpc and outer ejection velocity is 2900 km sec$^{-1}$. Dashed curve: distance is 5 kpc and outer ejection velocity is 3900 km sec$^{-1}$. Dotted curve: distance is 3.9 kpc and outer ejection velocity is 2900 km sec$^{-1}$.

A better fit to the data, for a distance of 5 kpc, occurs when the ejected mass is increased to $5 \cdot 10^{-4} M_\odot$, while the ejection velocity remains fixed at 3900 km sec$^{-1}$ and the velocity ratio is 0.03. This model light curve is represented by the green curve in Figure 4.11. The superimposed red curve assumes the same value for the shell mass and the same ejection velocity, but the difference is that the velocity ratio is now increased to 0.74. The EVN value and the result of the 2010-Feb-21 observation are left out of the plot. Even though these light curves are closer to the observed flux densities, there is still the case of the last observation that shows that the light curve of KT Eri declines faster than what is assumed by the modelled curves. A safe conclusion would be that the shell mass is
probably close to $5 \cdot 10^{-4} \, M_\odot$ and the distance of the nova is $\sim 5 \, \text{kpc}$.

Figure 4.11  The light curve of KT Eri at 5.5 GHz. The model light curves are for varying values of the shell mass and of the velocity ratio. Distance is fixed at 5 kpc. Orange curve: shell mass is $10^{-4} \, M_\odot$, outer ejection velocity is 2900 km sec$^{-1}$ and velocity ratio is 0.03. Red curve: shell mass is $5 \cdot 10^{-4} \, M_\odot$, outer ejection velocity is 3900 km sec$^{-1}$ and velocity ratio is 0.74. Green curve: shell mass is $5 \cdot 10^{-4} \, M_\odot$, outer ejection velocity is 3900 km sec$^{-1}$ and velocity ratio is 0.03.

Figure 4.12 shows the light curve of KT Eri at 9 GHz. The parameters used to produce the continuous, dashed and dotted model light curves are the same ones used in the plot in Figure 4.10. As it seems, in both these plots the data appear to be closer fitted to the dashed curve, which corresponds to a shell mass of $10^{-4} \, M_\odot$, an outer velocity of 3900 km sec$^{-1}$ and a distance of 5 kpc.
Figure 4.12 The light curve of KT Eri at 9 GHz. The model light curves are for varying values of outer velocity and distance. Shell mass is fixed at $10^{-4} M_\odot$. Continuous curve: distance is 5 kpc and outer ejection velocity is 2900 km sec$^{-1}$. Dashed curve: distance is 5 kpc and outer ejection velocity is 3900 km sec$^{-1}$. Dotted curve: distance is 3.9 kpc and outer ejection velocity is 2900 km sec$^{-1}$.

At this point it would be worth doing a fit to the 5.5 GHz observations in order to get the best estimate of the parameter values for this nova shell. Inserting these observations in a Hubble fitting program resulted in the fitted light curve shown in Figure 4.13. The program reported the following parameters as the best fits:

Shell mass : $0.95 \times 10^{-4} M_\odot$
Ejection velocity : 4160 km sec$^{-1}$
Ratio of inner to outer velocity : 0.01
Inner velocity : 41.6 km sec$^{-1}$
Such a low value of the velocity ratio would indicate that the shell of nova KT Eri is a rather thick one.

Figure 4.13 The fitted light curve of KT Eri at 5.5 GHz.

**Performance of the Model at Higher Frequencies**

Figure 4.14 shows the flux density measurements of KT Eri at the frequencies of 17 and 19 GHz. Plotting the model light curves of KT Eri at these high frequencies while using the same parameter values as in the previous plots reveals that the data in this case do not fit even broadly with any of the curves.
Figure 4.14 Flux density measurements of KT Eri at 17 GHz (top) and at 19 GHz (bottom). Model light curves do not appear in accordance with the data. Continuous blue curve: shell mass is
$10^{-5} \, M_\odot$, distance is 5 kpc and outer ejection velocity is 2900 km sec$^{-1}$. Continuous orange curve: shell mass is $10^4 \, M_\odot$, distance is 5 kpc and outer ejection velocity is 2900 km sec$^{-1}$. Dashed curve: shell mass is $10^4 \, M_\odot$, distance is 5 kpc and outer ejection velocity is 3900 km sec$^{-1}$. Dotted curve: shell mass is $10^4 \, M_\odot$, distance is 3.9 kpc and outer ejection velocity is 2900 km sec$^{-1}$.

The Hubble fitting program was run on the 17 GHz data inserting once again the parameters of a shell mass of $10^{-4} \, M_\odot$, an outer velocity of 3900 km sec$^{-1}$ and a distance of 5 kpc. The produced fitted light curve is shown in Figure 4.15. In this case, the reported best fit characteristics were:

- Shell mass : $0.618 \times 10^{-4} \, M_\odot$
- Ejection velocity : 6000 km sec$^{-1}$
- Ratio of inner to outer velocity : 0.791
- Inner velocity : 4746 km sec$^{-1}$

In this case, the derived velocity ratio suggests that the nova shell is rather a thin one. Apart from the difference in the velocity ratio, the order of magnitude of the shell mass for both fits seems to be $10^{-4} \, M_\odot$ and the ejection velocity about a few thousand km sec$^{-1}$.

Obviously, the Hubble flow model does not seem to work consistently for both low and higher frequencies. The light curves do not follow a single model for all the observed wavelengths. Further discussion regarding this behaviour of the radio light curves follows in the next section.
4.6 Is KT Eri a Typical Classical Nova?

In this section, the relationship between flux density and frequency is investigated in order to discuss the evolution of KT Eri over time as a classical nova. The behaviour of the spectral index $\alpha$, as indicated by the relationship

$$S_\nu \propto \nu^\alpha,$$  \hspace{1cm} (4.12)

determines whether a source displays characteristics of thermal or non-thermal emission depending on the value of $\alpha$. Here, $S_\nu$ is the flux density at a specific frequency $\nu$. Thus, the determination of the spectral index helps in the evaluation and categorization of a certain nova as a classical or a recurrent one, since it is RNe that mainly display synchrotron radiation. (4.12) leads to the expression
\[ \log S_v = \alpha \log \nu \implies \alpha_{\nu_i}^{\nu_2} = \frac{\log(S_1/S_2)}{\log(\nu_1/\nu_2)} \]  

(4.13)

and the uncertainties of the values of the spectral indices are consequently given by the equation

\[ \delta \alpha_{\nu_i}^{\nu_2} = \frac{1}{\log(\nu_1/\nu_2) \cdot \ln 10} \sqrt{\left(\frac{\delta S_1}{S_1}\right)^2 + \left(\frac{\delta S_2}{S_2}\right)^2} \]  

(4.14)

In Table 4.1 the calculated spectral indices with their propagation errors are presented for the analysed observations in this work. The values of flux density that were used here, are obtained from Table 3.4.

Table 4.1 Spectral indices for the KT Eri observations.

<table>
<thead>
<tr>
<th>Date</th>
<th>Frequency (GHz)</th>
<th>Flux Density (mJy)</th>
<th>Spectral index (\alpha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-Jan-24</td>
<td>5.5 → 9</td>
<td>0.75 ± 0.04 → 1.42 ± 0.06</td>
<td>(\alpha_{5.5}^{9} = 1.29 ± 0.14)</td>
</tr>
<tr>
<td>2010-Feb-03</td>
<td>5.5 → 9</td>
<td>1.05 ± 0.08 → 1.97 ± 0.18</td>
<td>(\alpha_{5.5}^{9} = 1.27 ± 0.24)</td>
</tr>
<tr>
<td></td>
<td>9 → 17</td>
<td>1.97 ± 0.18 → 3.59 ± 0.23</td>
<td>(\alpha_{9}^{17} = 0.94 ± 0.17)</td>
</tr>
<tr>
<td>2010-Feb-09</td>
<td>5.5 → 9</td>
<td>1.12 ± 0.08 → 1.76 ± 0.20</td>
<td>(\alpha_{5.5}^{9} = 0.91 ± 0.27)</td>
</tr>
<tr>
<td></td>
<td>9 → 17</td>
<td>1.76 ± 0.20 → 2.03 ± 0.25</td>
<td>(\alpha_{9}^{17} = 0.22 ± 0.26)</td>
</tr>
<tr>
<td>2010-Mar-20</td>
<td>5.5 → 9</td>
<td>1.07 ± 0.06 → 1.97 ± 0.20</td>
<td>(\alpha_{5.5}^{9} = 1.23 ± 0.23)</td>
</tr>
<tr>
<td></td>
<td>9 → 17</td>
<td>1.97 ± 0.20 → 0.98 ± 0.20</td>
<td>(\alpha_{9}^{17} = -1.09 ± 0.36)</td>
</tr>
<tr>
<td>17 → 19</td>
<td>0.98 ± 0.20 → 1.25 ± 0.20</td>
<td>(\alpha_{17}^{9} = 2.18 ± 2.33)</td>
<td></td>
</tr>
</tbody>
</table>

The expected value of the spectral index for thermal emission in the Rayleigh-Jeans regime is \(\alpha \approx 2\), for optically thick emission. Therefore, a spectral index of 0 to 2 at radio frequencies is an indicator of thermal radiation. On the other hand, the definition of the spectral index leads to negative values of \(\alpha\) for non-thermal emission, such as synchrotron radiation.
At higher frequencies, the Rayleigh-Jeans approximation no longer applies and the spectral index departs from the $\alpha \approx 2$ value. The curve becomes optically thin as the flux density reaches a peak at a frequency given by Wien’s displacement law. After this point, $\alpha$ tends to be closer to zero. This turn-over happens sooner at higher frequencies than at lower ones. This is the typical behaviour of the light curves of other CNe but apparently it is not quite the case for the light curves of KT Eri.

As it can be noticed from Table 4.1, nearly all the values of the spectral index are positive and fall in the range of 0 to 2. The exceptions are $\alpha_{17}^{19} = -1.13$ for the 2010-Feb-09 epoch and $\alpha_{9}^{17} = -1.09$ for the 2010-Mar-20 epoch. These values would indicate non-thermal emission from KT Eri. One more indicator that KT Eri is not behaving as a typical classical nova is the fact that spectral indices at specific frequencies do not show a fast turn-over to zero, as it would be expected. For example, $\alpha_{3.5}^{9}$ remains at ~1.3 for the first two epochs, then it changes to 0.91 and then it rises again for the last observation. Another thing to be noticed is that the uncertainties in all the values of $\alpha_{17}^{19}$ are really high, compared to their corresponding values. This would indicate that the changes in the spectral index, for the high frequencies of 17 and 19 GHz, are not statistically significant.

Finally, V1723 Aql is another classical nova whose behaviour and spectra exhibit unusual characteristics (Krauss et al., 2011). Its radio light curves from 1 to 37 GHz, obtained with the EVLA, show that it does not follow the standard Hubble flow model either. The spectra always appear optically thin and the flux rises on faster timescales than can be reproduced with linear expansion. The suggested explanations include multiple emission components or ejected material originating from shocks. The idea about the possible presence of shock waves is encouraged by X-ray observations with Swift. Future modelling of both V1723 Aql and KT Eri would require more detailed handling of the featured parameters, in order to reach certain conclusions about this unusual observed behaviour at radio frequencies.
CHAPTER 5
CONCLUSIONS AND FUTURE WORK

In this thesis, radio observations of what was considered until recently a typical classical nova were reduced and analysed. At low frequencies, the shell of KT Eri displays some typical characteristics of a classical nova and the observations seem to fit the Hubble flow model at 5.5 and 9 GHz, for the physical parameters of a shell mass of $10^{-4} \, M_\odot$, an outer velocity of 3900 km sec$^{-1}$ and a distance of 5 kpc. However, this same model fails to reproduce the observed light curves at the higher frequencies of 17 and 19 GHz. This can be attributed to possible non-thermal emission from this nova remnant, as it can also be concluded from examination of the spectral indices.

Another possible explanation is that the Hubble flow model assumes radiation coming from a spherical shell, whereas the morphology of the actual remnant might be more complex. The Hubble flow model does not account for such morphological details. Considerations to be taken in future work considering the radio modelling of nova light curves include developing programs that take into account more complex shell structures, like the case of an asphericity of the shell, and details such as possible clumping of the ejected material. Additionally, the Hubble flow model assumes instantaneous mass ejection, while this could not always be true.

During the data reduction process, another way was tried to estimate the flux density values for each frequency and epoch by using the MIRIAD task UVFIT, which attempts to fit a given visibility data-set to point sources. The results showed that in certain cases the UVFIT values were somewhat high compared to the respective IMFIT ones. This could possibly be explained with the CLEAN bias effect, which introduces a systematic underestimate of point-source flux densities of $\sim 0.25 \, \text{mJy}$ and is more pronounced in extended objects (Becker et al., 1995). The CLEAN bias is currently evaluated for observations of the FIRST survey (Faint Images of the Radio Sky at Twenty centimeters) which is undertaken with the VLA. Therefore, it has not been measured yet for observations taken with ATCA, and no final conclusions can be drawn about its effect on the presented analysis. Future work should explore the possible effect of the CLEAN bias in these observations.

Finally, in regard to KT Eri, it is concluded that the observations that disagree with
the Hubble flow model point to the possibility of this object being a recurrent nova. Future observations of this source would show how the radio light curves have evolved until present time.
APPENDIX A

OPTICAL DEPTH

The optical depth functions, derived by (4.10) after the substitution of \( r = (\alpha^2 + s^2)^{1/2} \), are

\[
\tau_1(\alpha) = \frac{F(\nu, T_e, M)}{B_\nu} \cdot \frac{1}{\alpha^2 (r_2 - r_1)^2} \\
\times \left[ \frac{1}{\alpha} \cos^{-1} \left( \frac{\alpha}{r_2} \right) + \frac{1}{r_2} \left( 1 - \left( \frac{\alpha}{r_2} \right)^2 \right)^{1/2} \right] \\
- \left[ \frac{1}{\alpha} \cos^{-1} \left( \frac{\alpha}{r_1} \right) + \frac{1}{r_1} \left( 1 - \left( \frac{\alpha}{r_1} \right)^2 \right)^{1/2} \right]
\]

(A.1)

for \( 0 < \alpha \leq r_1 \) and

\[
\tau_2(\alpha) = \frac{F(\nu, T_e, M)}{B_\nu} \cdot \frac{1}{\alpha^2 (r_2 - r_1)^2} \\
\times \left[ \frac{1}{\alpha} \cos^{-1} \left( \frac{\alpha}{r_2} \right) + \frac{1}{r_2} \left( 1 - \left( \frac{\alpha}{r_2} \right)^2 \right)^{1/2} \right]
\]

(A.2)

for \( r_1 \leq \alpha \leq r_2 \).

The quantity \( F(\nu, T_e, M) \) stands for

\[
F(\nu, T_e, M) = 3.52 \times 10^{-12} \ \frac{M^2 \bar{g}_{ff}(\nu, T_e)}{16\pi^2 \mu^2 m_H^2 \tau_e^{1.5} \nu^2}.
\]

(A.3)
References


Drake A. J., Djorgovski S. G., Graham M. J. et al., 2009, ATel, 2331


Hernanz M. & José J., 2008, NewAR, 52, 386


Hounsell R. et al., 2010, ATel, 2558

Itagaki K., 2009, CBET, 2050

Justham S. & Podsiadlowski, 2008, ASPCS, 401, p.161

Kotak R., 2008, ASPCS, 401, p.150


Krautter J., 2008, ASPCS, 401, p.139


Ragan E., Brozek T., Suchomska K. et al., 2009, ATel, 2327


Schaefer B. E., 2009, AAS, 213, 491.04


