

Introduction

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1.1 About this project

This project is an optical study on the Southern high mass star forming region RCW 34 and was conducted for the completion of the masters degree of the author. Photometric and spectroscopic data were used to investigate the nature of stars in a $7' \times 7'$ field of view which is centred on RCW 34. The data consisted of three data sets composed of a photometric data set and two spectroscopic data sets.

The photometric and first spectroscopic data sets were collected in 2002 and provided to the author by the supervisor of this project. The second set of spectroscopic observations was gathered by means of telescope observations conducted by the author in 2011 with the knowledge of the results from previous observations.

During this project the author acquired essential skills in the reduction of the data given to him. Additionally the author was taught how to write an application for astronomical observations at the SAAO and how to independently use their facilities.

Three examination based subjects Independent of this study were completed to satisfy the requirements of this degree. These subjects covered transport theory, general relativity and the properties of the interstellar medium.

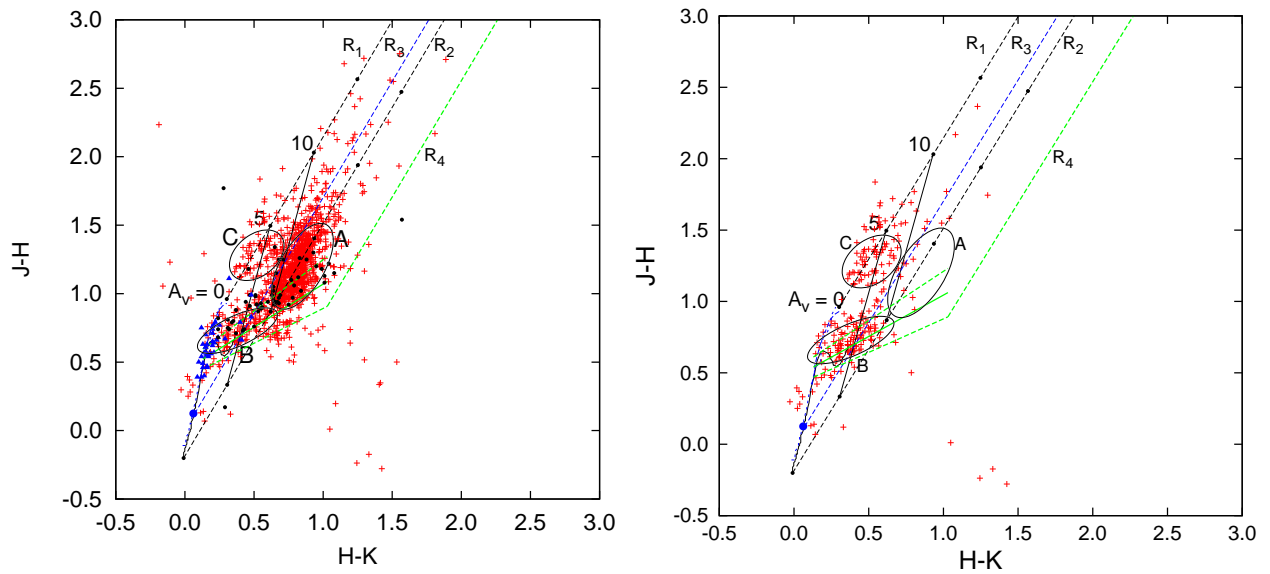
1.2 Rationale and aim of this project

The evolutionary cycle of stars has been thoroughly studied and most of the phases are well understood and documented. One phase in the evolutionary cycle that is not yet fully understood is that of star formation. The best way to gain a better understanding of star formation is to conduct studies on very young stars and their environments. This project was conducted with the aim of gaining knowledge of young stars and of the environment in which they form.

Some of the questions about star formation that have not yet been fully answered are how it occurs, what triggers it, what happens after formation has been triggered and what happens before the star becomes detectable with telescopes, *etc.* Understanding how star formation occurs will improve our understanding of how the solar system formed and how abundant exo-planets are.

To understand how star formation occurs in the Milky Way, star forming regions close to the Sun have to be thoroughly studied. The star forming regions close to our solar system have not been fully investigated, so more experimental work on them may be justified. For example, a recent study by Jeffries et al. (2011) found that there is not a wide spread of stellar ages in the Orion Cluster - suggesting that if the mean age of the cluster is 2.5×10^6 years then 95% of the elements have an age ranging from $1.3 \times 10^6 - 4.8 \times 10^6$ years. They discovered that the spread of the age for the cluster was shorter than the average age of a formation disk, suggesting that the epoch of star formation for this cluster did not last longer than a few million years. To name a few of these regions: the Taurus-Auriga-Perseus dark cloud complex region studied by Cernicharo et al. (1985); the dense Rho-Oph cloud which has an excess emission related to the neutral Hydrogen column density discovered by Bohlin et al. (1978) and the Vela R2 association, which is a cluster of young stellar objects studied in detail by Herbst (1975). The closest star forming region to Earth which has high mass stars is the Orion cluster (OC), as explained by Palla & Stahler (2005). This region has been thoroughly studied and has given us a good idea on how star formation occurs and on the properties of young stars. Hillenbrand (1997) covers a highly detailed optical study of 1600 stars in the cluster and discusses the spectrum of stellar masses, making it possible to construct a star formation history of the cluster. In a study by Herbst et al. (2001) a relation between the rotation rates and stellar masses were determined for 404 stars in the OC, giving a good guide to the angular momentum of pre-main sequence stars and proto-stars. A spectral study by Sicilia-Aguilar et al. (2005) on 237 stars in the OC revealed a new distinction between the angular momentum of classical T Tauri stars and weak-line T Tauri stars. The region continues to be studied and analysed so that the gaps in star formation theory can be filled.

A star forming region not as close as the other four is RCW 34, which will be the subject for this study. The reason for this lies in a 2009 deep near-infrared (NIR) study performed on RCW 34 by de Villiers (2009). In the NIR study a group of deeply embedded objects was discovered, which is uncommon for other star forming regions. The deepest study that has been performed on the region surrounding RCW 34 is by 2MASS, which had a limiting J magnitude of 16.12. This study is described by Van der Walt et al. (2012) and all further referencing will be to this paper.



(a) The NIR colour-colour diagram from the study by de Villiers (2009).

(b) The sources that were brighter than $J = 16.21$.

Figure 1.1: Reproductions of the colour-colour diagrams in Van der Walt et al. (2012). The green solid line is the classical T Tauri locus. The dashed green lines are the upper and lower limit of the T Tauri locus. The blue solid line is the main-sequence. The blue triangles are weak line T Tauris and the black dots are classical T Tauris from Strom et al. (1989).

A reproduction of a $J - H$ versus $H - K$ colour-colour diagram from the paper is shown in Fig 1.1a. The sources that were brighter than $J = 16.12$ are shown in Fig 1.1b. Three groupings of clustered objects were identified and are indicated by A, B and C. In group A in Fig 1.1a are approximately 700 sources, suspected to be reddened classical T Tauris. Group B lies along the classical T Tauri locus and probably contains unreddened classical T Tauri stars, and group C probably contains reddened weak line T Tauri stars. The strong clustering in group A has not yet been seen in any other star forming region described in the literature. This type of clustering makes RCW 34 unique and justifies further investigation.

This optical study was conducted independently to test the results of the NIR. This study also expands into a multi-wavelength photometric investigation while the spectroscopic part of this study would confirm the suspicions derived from the results of the NIR study if a star with $H\alpha$ emission can be discovered.

This project consists of two parts: The first, to conduct a photometric study and see if it agrees with the results from the NIR study; and the second, to conduct a spectroscopic study of stars in the region previously showing signs of pre-main sequence stars, specifically an $H\alpha$ emission line.

Now that the motivation and aim of this project have been given, the environment in which this study was performed will be discussed next. The discussion will commence with the constellation

in which RCW 34 is located, followed by a treatment of the most prominent molecular cloud in the constellation. This is followed by a discussion of the details of RCW 34 and its immediate surroundings and components.

1.3 Vela and RCW 34

1.3.1 Vela

Vela is a constellation in the Southern hemisphere that resembles and is named after a ship's sails. This constellation is sometimes mistaken for the Southern cross and is also known as the false cross. The part of the galaxy which lies in Vela is rich in molecular clouds, of which many are close to the Sun and was fully mapped for the first time by Bronfman et al. (1988) in a CO survey of the southern part of the Galaxy. The molecular clouds in Vela are collectively called the Vela molecular cloud complex. Murphy & May (1991) did an analysis on the velocities of the gas in the cloud complex and discovered that in many parts of the complex the clouds are contracting in on themselves. This is suggestive evidence of stars forming in the molecular cloud.

There are two HII regions in Vela: RCW 34 and RCW 36. These regions were first documented by Rodgers et al. (1960) in a survey of H α emission nebulae of the Southern part of the Milky Way. In a deep NIR study by Baba et al. (2004) it was discovered that RCW 36 has at least one O8 or two O9 type stars that act as excitation stars. A study by Heydari-Malayeri (1988) suggested that RCW 34 is excited by one O8.5V type star.



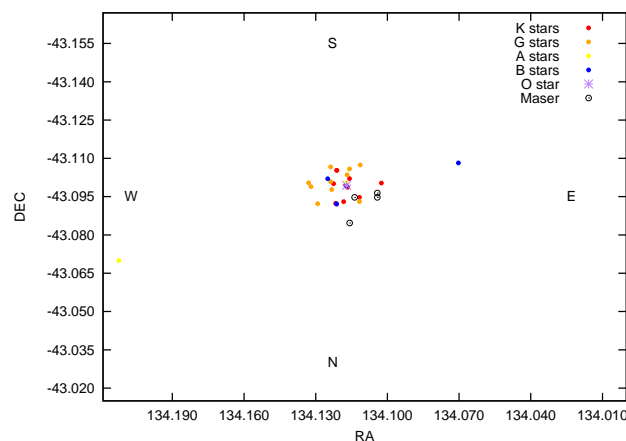
Figure 1.2: Figure 1 from Hill et al. (2011) is shown as a composite of three micrometer filter bands for the Vela star forming region. The red is 250 μm , the green is 160 μm and the blue is 70 μm . The central region is the HII region RCW 36 and the one at the bottom towards the right side is RCW 34. The blue shows the warmer gas in the HII regions and the red shows colder gas in dense filaments that are contracting in on themselves. In the filamentary structures there are embedded emission sources which are probably protostars.

1.3.2 The Vela molecular cloud complex and RCW 36

A more recent study by Hill et al. (2011) on the Vela molecular cloud complex included observations with the Herschel space observatory. Hill et al. (2011) give an in-depth description of the the central high-mass star region for RCW 36, where it is suspected that high mass star formation is still active. The column density and temperature maps were constructed by using pixel-by-pixel based spectral profile fitting. The visual extinction at the centre of RCW 36 is inff the order of 100 visual magnitudes. This high concentration of gas and dust is a result of the cloud contracting under its own gravitational field. The HII region which is of interest to this study, however, is RCW 34.

1.3.3 RCW 34

To better describe RCW 34 and its immediately surroundings, a layout of the region is presented and discussed here. A $7' \times 7'$ field of view is shown because that field of view was investigated by the NIR study and by this optical study. In Fig 1.3a a plot of all notable objects in the field of RCW34 is



(a) The objects in the $7' \times 7'$ field of view around RCW 34. These objects were taken from the SIMBAD astrophysical database system.



(b) A DSS image which is centred at RCW 34 and spans $8' \times 8'$

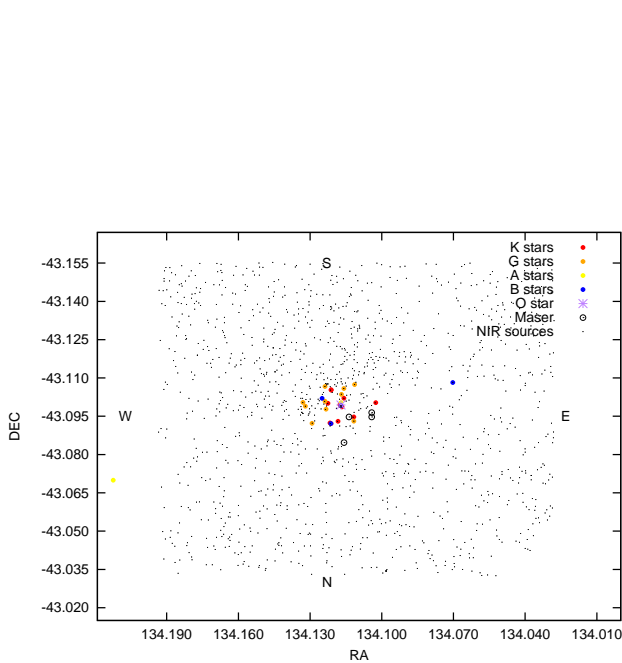
Figure 1.3: SIMBAD objects and DSS diagrams of the $7' \times 7'$ field of view around RCW 34.

shown. There are masers, 2MASS objects, objects with infrared excess, an HII region, massive stars and a cluster of low mass stars. It is quite unique to find so many masers - an indication of high mass star formation close to an HII region with a cluster of low mass stars in the same vicinity also.

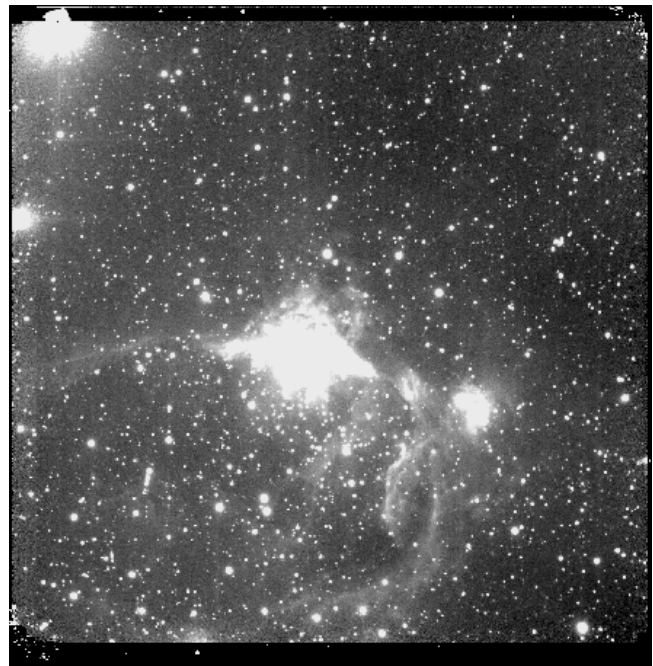
Figure 1.3b shows an image for the same field of view. The HII region is the white nebula in the centre of the image, masking the exciting star. In the top half of Fig 1.3b, there are not as many stars

as in the bottom. This is due to a molecular cloud that obscures the light emitted from stars in this part of the field of view. The HII region has an arched shape towards the bottom of the image. This is part of a bubble that has been cleared out of the molecular cloud by the exciting star and other stars. The bubble is much more prominent in the NIR image shown in the next subsection, Fig 1.4b.

1.3.3.1 NIR layout



(a) The NIR sources with those shown in Fig 1.3a.



(b) The K band image that was used in the photometric study by de Villiers (2009).

Figure 1.4: NIR images of the $7' \times 7'$ around RCW 34.

In the study by de Villiers (2009), many infrared sources with excess emission were detected at a significant distance from the HII region, shown in Fig 1.3a. Here the full effect of the deep study become clear due to the rich uniform distribution of objects which is not seen in the 2MASS survey because they are so deeply embedded. The bubble shape is much more apparent here than in the DSS image and should be kept in mind for the rest of this study.

The sources detected by de Villiers (2009) are plotted together with those shown in Fig 1.4a. Figure 1.4a shows a uniform distribution for the embedded sources that extends to the edge of the image, suggesting that the cluster extends beyond the field of view. In Fig 1.4b the Northern and Southern directions are opposite to that in Fig 1.4a. The uniform distribution of embedded objects is obscured by the nebulous emission from the hot gas.

1.3.3.2 Exciting star

The first detailed study on RCW 34 was done by Heydari-Malayeri (1988). And consisted of a photometric and spectroscopic analysis of the exciting star and its surrounding gas. Long slit spectra of the exciting star were observed and four spectral profiles of the gas N, S, E and W from the star were analysed. An average extinction of $A_V = 4.2$ was calculated for the region surrounding the exciting star. The spectra from the star and the gas indicated that the light from the exciting star is reddened by dust local to the HII region and also by interstellar dust between the exciting star and the Earth. An excess was discovered at wavelengths of $3.4\text{-}\mu\text{m}$ and $11.5\text{-}\mu\text{m}$ caused by circumstellar matter. The gas heated by the exciting star is moving at a velocity of ~ 28 km/s in the radial outward direction. Roughly 0.4 pc¹ towards the Western side of the exciting star, there is a change in the velocity showing that the gas starts moving at ~ 70 km/s in the opposite direction of the outward expanding gas.

There are three masers situated close to RCW 34. The first is an H₂O maser located at $l=264.29$, $b=1.46$ which was first catalogued by Braz & Scalise (1982). The second is also an H₂O maser, catalogued by Caswell et al. (1989) and is at $l=264.29$, $b=1.46$, roughly 26 arc seconds from the first maser. The third maser is a methanol maser located at $l=264.29$, $b=1.46$ and was first catalogued by Caswell et al. (1995). Masers are an indication of the formation of massive stars in a molecular cloud. The emission mechanisms for masers are similar to those for lasers except that the wavelengths at which the light is radiated are in the μm range.

1.3.3.3 The star formation history

A more in-depth study on RCW 34 was conducted by Bik et al. (2010) with the VLT and Spitzer. Three star formation phases were identified, a trend of formation starting from the Southern part of the bubble region towards the North. A cluster was identified inside of the bubble shape in the gas, this bubble having been blown away by the stars associated with this cluster. The ionisation front towards the North, which is host to three OB type stars, was also identified. The distance to the region was measured as 2.5 ± 0.2 kpc and will be used for calculations in this study. The massive exciting stars are at the intersection of the bubble region and a denser molecular cloud. What most likely happened is that the low mass cluster initially formed and with the process of clearing out, the gas in the bubble region triggered contraction at the edge of the molecular cloud, causing the formation of the high mass stars.

Van der Walt et al. (2012) discovered that a small cluster of very luminous stars are in the bubble region. This is consistent with the results of Bik et al. (2010), who concluded that the most probable trigger for the formation of these luminous stars was the presence of exciting stars. The process would be triggered when they cleared out the bubble region.

¹The standard unit which is used to measure distance in astronomy is the **parsec** (*pc*). This is the distance at which a star would move 1 arc-sec when parallaxed by the Earth at opposite sides of the Sun, see the example in Tayler (1994). The distance of one parsec is: $1 \text{ pc} = 3.09 \times 10^{16} \text{ m} = 3.26 \text{ light years}$.

1.3.3.4 Optical layout

Figure 1.5 is a composite image of the images that were used in the photometric study for this dissertation. This large scale image is shown to illustrate the difference between the NIR shown in Fig 1.4b and the optical. Clearly, there are not as many sources visible in the optical, which make this research project more risky than the one by de Villiers (2009), because the deeply embedded objects that were detected in the NIR may be too faint and obscured to give good results in this photometric study. The bubble region is the least obscured part of the region and has the highest probability of delivering the desired result of finding a T Tauri star.



Figure 1.5: A colour stacked image of the B , V and R filters used for the blue, green and red colours respectively of the photometric images that were used in this study. The field shown is roughly $7.7' \times 7.7'$.

1.4 The outline of this dissertation

The following chapters of this dissertation will now be briefly summarised:

- **Chapter 2:** A theoretical background on which this study is based, is given. This chapter starts with a short summary on light, the Planck emission profile of stars, and how a star emits light similar to a black body. Because this study is about star formation and pre-main sequence stars, in a way the theory about the trigger mechanisms for star formation is covered, followed by the stages through which a pre-main sequence star progresses up to a zero-age main sequence star. One of these stages is called the T Tauri phase. This is the stage wherein most of the stars that were discovered by de Villiers (2009) are suspected to be, and searching for these types of stars

in an independent study is the goal of this dissertation. To understand the nature and properties of T Tauri stars, a thorough description of their properties is given. T Tauri stars are found in gaseous environments in different phases of the interstellar medium. A few short sections are given to describe these different phases. The chapter ends with a description of the tools for photometry and spectroscopy used in this study.

- **Chapter 3:** The acquisition and reduction process of the data used in this study is described in this chapter. Three data sets were employed: Photometric and spectroscopic sets that were obtained in 2002, and a third data set obtained in 2011 by telescope observations after careful planning based on the prior data. A description is given of the equipment that was used for the acquisition of the data. Then each step in the reduction process is described. This is followed by the techniques that were used to calibrate the images and perform measurements to yield usable results.
- **Chapter 4:** In this chapter, the results from the spectroscopic and photometric studies are presented and discussed. It starts with the stars that show an $H\alpha$ emission line and explains how a simple method was used to identify the spectral class of each star. Then it is followed by a set of colour-colour diagrams which were used to deredden a set of stars onto the main-sequence that matched in the V , R and I filters. Substantially, colour-magnitude diagrams showing the reddened and unreddened stars, and a colour-magnitude diagram for the sources that matched in the R and I filter, are presented. NIR colour-colour diagrams are constructed for the stars that matched in the optical and NIR filters. Lastly, the locations of the stars for each matching filter set are plotted relative to the masers, the exciting star and the stars that showed $H\alpha$ emission.
- **Chapter 5:** The final chapter summarises this study and gives some concluding thoughts. All of the objects from the SIMBAD database, the NIR study and this study are plotted over each other and placed in a larger context. Lastly, thoughts and suggestions are given as to future research projects on RCW 34.