

Summary, conclusion and future prospects

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5.1 Introduction

In this chapter a summary is given of the project followed by a few concluding thoughts, and the closes with suggestions for future research projects. The goal of this study was to conduct an optical analysis of the high mass star forming region RCW 34, motivated by the NIR study of de Villiers (2009).

The study by de Villiers (2009) was the first NIR photometric study of the region surrounding RCW 34. The NIR study revealed a large number of embedded stars. The number of objects that showed excess emission characteristic of CTTs, was a strong motivation to conduct an optical study.

Performing an optical study of such embedded objects is risky, especially when observations were previously taken by someone else who was not aware of what the data would be used for. One factor that could have had a negative impact on the outcome of the photometric results is that of the NIR sources not being detectable in optical filters. This would result in photometric results only for field stars.

Spectroscopic observations for the first 2002 data set were conducted to learn how long slit spectra are obtained and reduced. The 24 brightest stars in the region were selected for this task.

The second data set of spectroscopic observations was based on careful planning using the results from the previous data sets. Planning was based on the list of stars that matched between the *R* and *I* filters, and choosing those that were brighter than 16.5 magnitude. These were then matched to

their corresponding NIR magnitudes and prioritised according to their $J - H$ colours. A list of 76 was compiled from which 38 emerged from the spectroscopic observations as very noisy SEDs and three were found to show $H\alpha$ emission.

5.2 Summary of this research project

5.2.1 Spectroscopy

5.2.1.1 Spectra of the stars observed in 2002

The two stars that showed $H\alpha$ emission each had additional emission lines that were characteristic of heated gas emission. For star C it was a Na-I emission line and for star D an S-II emission line. Each of these emission lines suggests that the star's spectrum was contaminated by nebular emission and not by circumstellar matter. It is the most likely case for both stars that nebular emission was included with the spectra from these stars.

If one looks considers spectra in appendix D, the majority of the stars in the blue part of the spectrum show strong hydrogen absorption, suggesting that they are MS stars. In the set of blue observations numbers 2, 9 and 16 have spikes in the spectra that stretch across one or two pixels. This is most likely cosmic ray contamination.

If one considers that most of the spectra for this dataset displays the characteristics of MS stars, and that they are the brightest in the field of view, it may be safe to say that they are field stars. This raises the suspicion that star C and D may also be field stars with gas contamination.

5.2.1.2 SEDs of the stars observed in 2011

The SEDs for star A and E are very similar differing by the increased number of features displayed by A. Both show relatively featureless SEDs with weak $H\alpha$ emission lines and subtle increases towards the longer wavelength side of the SED. One reason could for this be that the sky subtraction was incorrect or that the stacking of the spectra was erroneous or that the equipment was not sensitive enough causing the majority of the SED to be filled with noise. Star B's continuum was the only one that had a structure similar to that of a MS star and weak molecular absorption lines, which are only found in low mass stars.

If one looks at the dataset of observations obtained in 2011 it is clear that the majority of the stars show an increase in their emission towards the longer wavelengths. From this it is evident that almost all of them are low mass stars or have excess emission from circumstellar matter.

The quality of the observations taken in 2011 was influenced by the 5\AA grating that was used. The trade-off between the lower resolution for the larger wavelength range was not ideal. This is because

the blue part of the spectrum that was included was so noisy that spectral identification was not possible. It would have been a wiser decision to use a grating with a shorter wavelength range but a higher resolution. Another shortcoming was that the two stars that exhibited $H\alpha$ emission in 2002 were not re-observed during the observations of 2011.

At the time of observation it was not known that the spectra of T Tauri stars are time-variant. It would have been useful if star A or star B could have been observed during one night at different time lapses. Another shortcoming is that it was not possible to obtain a velocity profile for the $H\alpha$ emission line. If the velocity profile of the $H\alpha$ emission line could have been determined, it would have been possible to say if the emission came from an accretion disk, circumstellar matter or nebular contamination.

5.2.2 Photometry

5.2.2.1 Colour-colour diagrams

The evaluation of $V - R$ against $R - I$ colour-colour diagram played a crucial role in determining the nature of the stars that matched in the V , R and I filters. With the help of the spectra it was possible to see that these stars were not reddened, but that they had excess blue emission.

It was not known to the author that incorrect filters were used when comparing standard star data until late into the project. One thing that might have had an impact on the results is that the data for standard stars that were used for the conversion from instrumental to apparent magnitudes were given in Johnson-Cousins colours, not Johnson-Kron colours. The calibration was satisfactory for the results obtained in this study even though the conversion from Johnson-Kron to Johnson-Cousins colours increased the errors substantially. If the conversion between filter systems or calibration was incorrect, the increased errors would compensate for minute errors that arose from incorrect calibration.

The dereddened $V - R$ versus $V - I$ diagram in Fig 4.7d did not display the dereddened sources exactly on the MS as in the $V - R$ versus $R - I$ diagram. The dereddened source lay between the reddening line of the high mass end and the MS. This may be because the MS is broader than just the single line shown in these diagrams and because using a polynomial is a crude way to model the dereddening of stars. The stars that lay above the MS in both the colour-colour diagrams are most probably MS stars with very little reddening.

In this study it was not possible to evaluate the large number of sources that the NIR study delivered. The extinction estimated by de Villiers (2009) for the field of view was $A_V \approx 1 - 5$ and it was not known if any of these sources would be detectable in the optical filters. The only sources that were detectable in the U and B filters included the exciting star and the brightest field stars. From the V band towards longer wavelengths more sources were detectable.

5.2.2.2 Colour-magnitude diagrams

The colour-magnitude diagrams in Fig 4.8a and 4.9a both show clustering close to the low mass end of the MS. This could either have been reddened field stars or PMS stars that are above the MS. If the stars were correctly dereddened and they were mainly field stars, then it could be expected that they are distributed across the MS. This was the case, but the stars remain above the MS, meaning that these stars are more luminous than others in their corresponding spectral class in the MS, or that the dereddening was incorrect. It is not known to the author which of these possibilities is the correct one. A likely answer is that the stars are low-mass PMS stars still above the MS as the spectral observations done in 2011 showed that most of the stars are low-mass.

The R versus $R-I$ colour-magnitude diagrams for the sources that matched in the V , R and I filters shown in Fig 4.10 showed the same type of cluster as the V -based colour-magnitude diagrams. If the R versus $R-I$ colour-magnitude diagrams of the stars in Fig 4.10a and 4.11 are compared there are many more dim stars with colours that are redder in Fig 4.11 than in Fig 4.10a. These may be lower mass stars than those that were detected using the V , R and I filters. If the faint, low-mass stars that are shown only in Fig 4.11 are PMS stars, then they will be very young and will be embedded in the cloud. The majority of these stars will be late K type or M type stars. These stars lie far above the MS, implying that they are most likely very young.

The MS that is reddened to $A_V = 1.8$ in Fig 4.11 does not fit as well with the majority of the stars as in Fig 4.8a. This may be because the population used to construct the reddening model most likely consisted of field stars, and that the average reddening was for their extinction in the field. The extra stars detected only in the R and I filters have a much higher probability of being embedded young stars due to the high extinction found in the gas where they are embedded. If they were dereddened onto the MS, the average extinction would be much higher. This argument is reinforced by the high extinction calculated from the NIR stars by Van der Walt et al. (2012). The sources that were detected in filters with longer wavelengths show to what optical depth the cloud was probed with longer wavelengths.

5.2.2.3 NIR colour-colour diagrams

The NIR colour-colour diagrams in Figs 4.18, 4.19 and 4.20 show the small fraction of the 1283 sources that was visible in the optical and NIR filters. This is an indication of how many of the sources are embedded in the molecular cloud, and that it still holds much of its integrity.

Clustering is only seen in the colour-colour diagrams of Figs 4.19 and 4.20. Clustering for reddened WTTs above star E is seen as well as clustering between the reddening lines of the CTT locus and the reddening line of the high mass end of the MS. This clustering increases drastically in the colour-colour diagrams of only the NIR sources. No clustering is seen in any of the colour-colour diagrams for the optical sources as in the case of the ≈ 700 sources only seen in the NIR at the far-red part of the CTT locus. This can be because the sources that have the strongest excess NIR emission are embedded deepest. Alternatively if these sources are not deeply embedded they may be CTTs and have dust

envelopes absorbing all of the optical emission.

The three stars that displayed $H\alpha$ emission were shown in Fig 4.18 and an additional two in Fig 4.19. The fact that there are so few stars that showed $H\alpha$ emission of the 62 stars that were observed is consistent with the postulation of de Villiers (2009) that there is both a young and an old component in the cluster.

The difference between the number of sources detected in each filter set highlights the diversity of the population of objects in the cluster. This shows that there may be stars in different phases of formation, and that star formation is still actively occurring in the region.

5.2.3 Layout of the stars

A layout of all the sources that were detected in all the different filter sets and the objects that were logged in the SIMBAD database for the region is shown in Fig 5.1.

This diagram was constructed to provide an overall view of the $7' \times 7'$ field considered in this study. By plotting all of the matching sources for the different filters, the effectivity of the optical study in testing the NIR study's results can be shown. It is also possible to see structure in this region and get the "big picture".

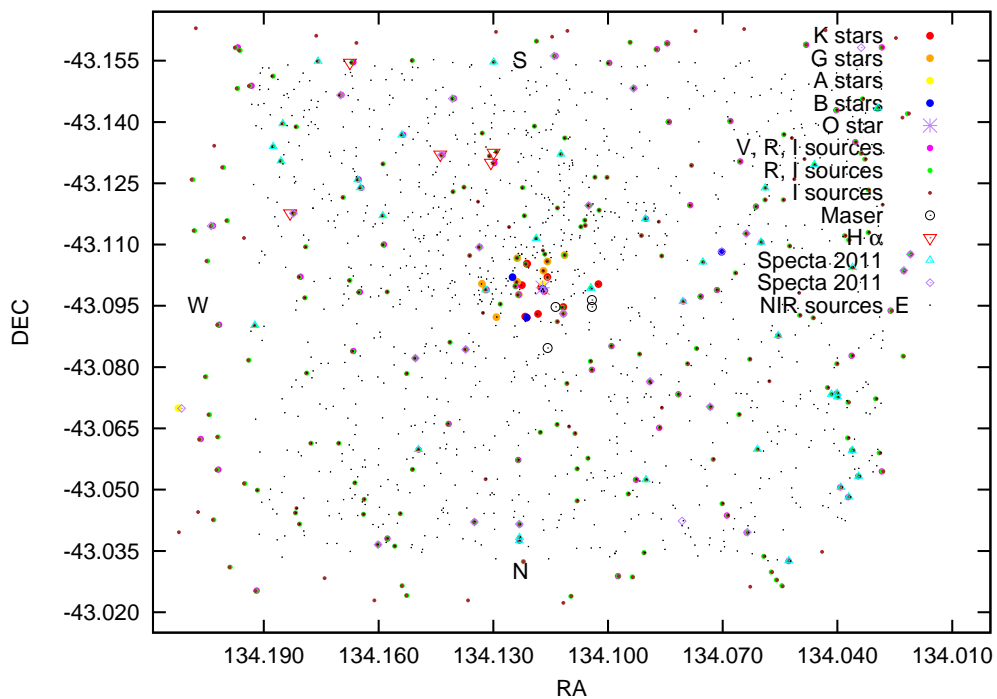


Figure 5.1: An overlay of all the objects that are shown in Figs 4.12, 4.14, 4.16, the stars that are catalogued on the SIMBAD database. Also the stars of which spectroscopic observations were obtained in 2002 and 2011. The stars that showed $H\alpha$ emission are also shown.

In Fig 5.1 the black points are the NIR sources; the red spots are the sources that match in the V , R and I ; the green crosses are the sources that match in the R and I ; and the blue circles are the sources in the I filter. The field of view for the optical telescope was larger than that of the NIR telescope, which is why Figs 4.12, 4.14 and 4.16 displayed a larger optical field of view than that of the near infrared images. There were 60 sources that matched in Fig 4.12 , 174 in Fig 4.14 and 189 in Fig 4.16.

The majority of the sources catalogued in the SIMBAD database are seen close to the exciting star. These sources were also detected in the 2MASS and other surveys because the exciting star has cleared the area surrounding it of dense gas. The sources evaluated in this optical study and in the NIR study were discovered because these studies probed deeper into the molecular cloud than automated surveys.

In Fig 5.1 the presence of masers suggest the active formation of massive stars. The stars that showed $H\alpha$ emission lines are most probably T Tauris, which adds weight to the argument that star formation continues in this region. The uniform distribution of stars detectable in the optical and NIR studies shows that the cluster is larger than the field of view that was studied. The South-Western quadrant of this image shows a clustering of many luminous objects and contains those that display $H\alpha$ emission. These are most likely very young stars the formation was triggered by the exciting star.

5.3 Conclusion and final thoughts

In conclusion, it can be said that RCW 34 displays all the signs of an active star forming region. The number of sources that were detected in different filters is a an indication of how deeply the sources are embedded in the molecular cloud.

The data used for this study were of low quality and therefore it would be expected that not many new stars would be discovered by optical photometry. The acquisition of the spectra was very time consuming, so the selection of which stars would be observed in 2011 was carefully planned and solely based on the priority in which they were ordered according to their $J - H$ colours. This ordering was correct because the three stars that show $H\alpha$ emission were amongst the first four stars in the group that were observed.

This project can be considered extensive due to the combined use of photometry and spectra used to hunt T Tauri stars in the region around RCW 34. It was fortunate that two stars that showed $H\alpha$ emission were discovered in the spectroscopic observations of 2002.

The most important result that emerged from this study was the discovery of the five stars that displayed $H\alpha$ emission. These stars confirmed the earlier photometric results and the suspicions of de Villiers (2009) that there were young stellar objects in the cluster of stars that surrounded RCW 34. Star B is by all the definitions in the literature a CTT and a late K type star. This star shows that there is one CTT in the region and a possible presence of other WTTs . The low quality of the data

gives enough reason to strongly suspect that there could be many more T Tauris or stars that display $H\alpha$ emission. The fact other stars observed in 2011 did not show $H\alpha$ emission indicates that a fraction of the stars are T Tauris and not the entire population. It is common for other star forming regions, such as NGC 2264, that only a fraction of stars in any cluster are T Tauris. Further research on RCW 34 is needed to understand the full extent of the cluster and how many members of this cluster are T Tauri stars.

In this study more was done than was initially planned and many refinements were performed on the data. For example the identification of the spectral star types for the stars that showed $H\alpha$ emission was performed afterwards to get an idea of the mass range in which these stars fell.

This project has gone beyond the objectives outlined in its title registration. It was necessary and in many cases essential to achieve closure between the photometric and spectroscopic studies.

5.4 Future prospects

This project tested the hypothesis of de Villiers (2009) that there are T Tauri stars in the region surrounding RCW 34. This study does raise questions, such as how many T Tauri stars there are in this region, what the extent of the cluster is, what the IMF of this region is and, what the density of the gas that embeds many young stellar objects is.

The answers to these questions may lie in a full multi-wavelength study of the region, ideas for such a project will now be listed:

- **Enlarging the extent of the NIR photometric study** will show how far the cluster extends. In both the NIR and optical photometric studies, the cluster extended beyond the extent of the images. NIR observations were performed by the author at the beginning of 2012 with a $24' \times 24'$ field of view, where eight panning $7' \times 7'$ images were taken around the initial field in the study by de Villiers (2009).
- **Dust mapping** of the $24' \times 24'$ region around RCW 34 would reveal the column density of the molecular cloud. By using the column density the visual extinction to all of the stars that were discovered in the initial NIR study and the conjoining fields of view can be calculated. Knowing the column density would make it possible to calculate the mass of the molecular cloud and the efficiency of star formation in the cloud.
- **Using SALT** very high quality optical photometry and spectroscopy can be performed on the $24' \times 24'$ field around RCW 34. SALT will be able to detect many more faint sources than was possible with the 1-m telescope. Photometry will be performed with SALTICAM, which also has an $H\alpha$ filter which will make it possible to detect any stars that display such emission. If time-lapsed observations can be done, the cluster can be tested for variable stars. A control field

will make it possible to easily distinguish field stars from the cluster members.

After photometry has been performed, the sources that are detectable in optical filters with SALT can be marked. Using the optical photometry to see which stars are bright enough to evaluate their spectra and which display H α emission, a mask can be constructed for the MOS device. By calculating the correct visual extinction for each of these stars, they can be correctly dereddened. If any of the stars are veiled by circumstellar matter they can be unveiled to see if there is anything substantially different to the T Tauris in the region around RCW 34 when compared to other star forming regions.

- **X-ray observations:** If the optical and NIR results show enough evidence of T Tauri stars, the region can be observed for X-ray emission. The strong magnetic fields of T Tauri stars make them good X-ray sources. X-ray emission from T Tauri stars is not yet fully understood, and observations similar to those of the Orion Ultradeep Project of Preibisch et al. (2005) can be suggested for the region.