Chapter 5

Conclusions

5.1 Summary and Results

The original goal of this project was to detect polarization by selective extinction caused by elongated dust grain statistically aligned with the magnetic field around shells and supernova remnants in Cygnus and Monoceros. The light from stars as well as Hα emission from these objects was studied in order to determine the direction of polarization. By measuring polarization caused by selective extinction, the direction of polarization vectors reveal information about the direction of the magnetic field around these objects. However, detection of polarization by selective extinction is difficult since the degree of polarization is low.

In the images of the Cygnus and Monoceros region, polarization of starlight was detected for only 12 stars in one of the Cygnus images. All of these stars had previously measured values of polarization recorded in the catalogs of Hiltner (1951) and Axon and Ellis (1976). One of the stars, HD 198478 (55 Cygnus), is a standard polarimetric reference star listed by Sekowski (1974) as have an accepted degree of polarization of 2.8% and position angle 3° with respect to the line of constant right ascension measured at the star's location. When corrected for wavelength dependence, the polarization at the Hα wavelength is 2.7%.

The importance of having a standard star is that it is a reference upon which a comparison can be made. The degree of polarization obtained using the method to detect polarization in this disseration was found to be 2.7% with a 68% confidence interval of [2.1%, 3.3%]. The position angle was 6° with a 68% confidence interval of [3°, 9°]. These values were calculated using the γ-trimmed mean to determine the averages Stoke's parameters $\overline{q}$ and $\overline{u}$. The degree of polarization and position angle are in agreement with the accepted value of the reference star. The position angle measurement of 6° shows that the reference axis of the polarizer is probably off of alignment by only few degrees, however, the reference value does fall within the limits of the 68% confidence interval.

Eight other stars which had high degrees of polarization were measured as well. However, four of these stars had estimated degrees of polarization that were zero. Since three of these stars had a degree of polarization comparable to the degree of polarization of the reference star 55 Cyg, it was surprising that the polarization was estimated to be zero by the Wardle-Kronberg estimator. Upon inspection, outliers were seen in the histograms of each of these four stars. These outliers had the effect of inflating the standard deviation. When this inflated value was used in the Wardle-Kronberg estimator, its value was larger than the measured polarization, hence, by definition, the estimate of the degree of polarization is zero. Therefore, a means of handling the outliers was found in the use of the γ-trimmed mean. This method gives more weight to the central portion of the distribution, thus reducing the standard deviation. Upon applying this method, (as discussed in Chapter 3), the four stars, whose polarizations were previously set to zero, yielded degree of polarization and position angles consistent with published values.

I checked to see what effect the use of the γ-trimmed mean method had on the other stars which had degrees of polarization and position angles that were already in agreement with the published values. The program which determines the degree of polarization and position angle using the γ-trimmed mean was run on these stars and the results were, again, in agreement with the published values. All nine stars are in agreement with their published values as can be see by the last six columns of Table 3.4. These results demonstrated that the γ-trimmed mean method works to reduce the effect of outliers. Also importantly, is the fact that the γ-trimmed mean method does not alter the previous polarization results which are already in agreement with published values.

Therefore, I used this method to try to detect polarization from other stars in the images.

Some of the stars around the periphery of the supernova remnants and shell like structures were measured using the γ-trimmed mean method. However, none showed any sign of polarization. Unlike the stars measured above, most stars around the remnants and shell structures were faint. Typically around 8 to 9 magnitude, these stars had very low signal-to-noise ratios. The average magnitude of the nine detected stars was around 6 to 7 however. I conclude that the additional stars around these supernova remnants were too faint to have detectable polarizations by this method. This does not mean to imply that they have no polarization, simply that the method used here is limited in its ability to detect low levels of polarization from faint stars. Secondly, the polarization of the nine stars that were measurable had polarizations typically higher that 1%. From this I also concluded that unless a star had a high ($>$ 1%) degree of polarization, it would most likely go undetected by this method.

However, the information the nine measured stars did provide was invaluable to the rest of the project. First and foremost, it demonstrated that the method does indeed reproducibly measure polarization. Secondly, the nine stars showed that the alignment of the polarizer axis was quite good. The reference star's position angle reported with both the regular and γ-trimmed mean showed that the initial alignment was not off by more than 3°. The stars also showed that the γ-trimmed mean is an easy and effective method of handling data which has a large standard deviation due to outliers. I felt comfortable using this method in creating the polarization maps. Finally, the confidence intervals indicate that the degree of polarization could be measured to within $\sim$ 3% and the position angle to within $\sim$ 6°. Discouraged by the starlight results, but confident in the approach, I then made the polarization maps of the regions I had imaged.

The process used to make the maps are discussed in Chapter 4 and all involved the γ-trimmed mean for determining $\overline{q}$ and $\overline{u}$. While all images show polarization, only the Monoceros region is analyzed in this thesis. The complexity of the Cygnus region precludes a simple examination of the polarization observed. An analysis of the polarization in the Cygnus images is left for future work. The Monoceros region has three objects which were targeted for study; a curved filament of Hα emission which is part of a larger shell structure, the Monoceros supernova remnant, and the Rosette Nebula. Both the curved filament and the Monoceros supernova remnant show only a patchy appearance of polarization. While some of the polarization observed may be real, I believe most of it is caused by: 1) an incomplete subtraction of the background polarization, 2) faint stars remaining in the image, 3) residual polarization from stars which were removed from the image. While it may be that some vectors are caused by selective extinction, there are no vectors in any type of circular pattern that is correlated with the circular appearance of Hα in either the curved filament or the supernova remnant. The lack of any significant polarization associated with the curved filament or the Monoceros supernova remnant shows that a mapping of the magnetic field using selective extinction of Hα by aligned dust grains is not possible for these two objects with the method used in this project.

The Rosette Nebula, on the other hand, does show a significant amount of polarization in a circular pattern, which at first I thought might be taken to be indicative of the direction of the magnetic field around it. However, upon closer examination, the explanation of the origin of the polarization is found to be not in selective extinction, but rather scattering. The first interesting thing to note is that the degree of polarization is higher than usually associated with polarization by selective extinction. From observations of the stellar polarization and reddening, Serkowski et al. (1975) showed that an empirical relationship holds between the maximum degree of polarization and the amount of color excess (or reddening). I used this empirical relationship to show that the maximum observed degree of polarization was only on the order of 3% to 4% at the Hα wavelength based on extinction measurements of the Rosette Nebula by Celnik (1986). Even the average polarization seen in the region of high polarization is on the order of 6%, which is still higher than the maximum that should be observed.

I determined that the polarization was not caused by scattered continuum light in the Hα bandpass from the central star cluster NGC 2244, but rather was scattered Hα light from the Rosette Nebula. Using the images from the Hα survey, photometry was performed on the central star cluster and in the region of highest polarization in both Hα and continuum light. From this, I showed that the number of counts per pixel in the region of high polarization due to Hα light from the star cluster were too few to account for the observed polarization in that region.

Considering the scattering case further, the circular pattern is an indicator of polarization by scattering when dust particles are illuminated by a central source. In this case the central source is the Rosette Nebula itself. These two considerations suggest that the polarization is not due to selective extinction, but rather scattering. The polarization image of the North America Nebula (NGC 7000) lent credence to the argument for polarization by scattering. The polarization vectors in that image show such an arrangement as to lead to the conclusion that *if* selective extinction is the cause, then the magnetic field is highly irregular in this region. Scattering is the more simple, and hence believable explanation.

A single scattering model was developed to try and predict the degree of polarization expected as a function of radial distance from the edge of the HII region. This model only assumes single scattering and spherical symmetry of the Rosette Nebula, and parameters were reasonably chosen based on 21 cm observations of Kuchar and Bania (1993) which showed the existence of an HI shell surrounding the HII region. The interior of the shell is very close to the point where the curved polarization starts in the region of high polarization. This was interpreted as indicating a relationship between the HI shell and the region of high polarization. The thickness of the shell varies, but the larger radius implied by the thicker shell matches closely the southern 3σ contour line of the Hα image. Using these reasonable values as input parameters (the only other parameter being the distance from the HII region) the program gave results which were inconsistent with the observed degree of polarization. While the degree of polarization observed varies slightly with distance from the nebula, it hardly ever exceed a value of 10%. The model yields values from 20% to 80% over the region of interest. This is much too high and I found the model to be inadequate at predicting the observed polarization.

Observations of the Rosette Nebula were made by Celnik (1985) who mapped the spatial extent of free-free emission in the Rosette Nebula. The map by Celnik shows that, while the continuum emission in the southeastern and southern boundary of the Rosette Nebula matches the 3σ contour of the Hα total intensity image, the western part of the region does not. In particular, the radio continuum emission ends before the Hα does.

Comparing the IRAS 12μm emission with Celnik's 4750 MHz continuum map, Cox et al. (1990) find that, with the exception between the 9 to 12 o'clock positions of the Rosette Nebula, the 12μm emission is mainly distributed around the Rosette Nebula outside the ionization front. Thus the small dust particles believed to be the cause of the 12μm emission are located where polarization is seen. We showed in section 4.5.3 that in all four of the IRAS wavebands, there was a positive correlation between infrared emission and Hα intensity in the region of high polarization between the 1 and 3 o'clock positions of the Rosette Nebula. (This is the same region where the 4750 MHz radio continuum emission mapped by Celnik (1985) was seen to end before the Hα.) Thus it was concluded that dust is the likely scattering agent for the Hα seen in the region of high polarization.

The percent polarization was also graphed as a function of the 12μm emission for this same region. It is shown in Figure 4.31 that the degree of polarization rises as the 12μm brightness increases, but then reaches a maximum and then decreases while the 12μm emission continues to rise. This was interpreted as behavior due to multiple scattering. The failure of the single scattering model becomes more evident in the light of this fact. A more realistic model for this geometry would include multiple scattering.

Finally, I compared the ratio of [SII] to Hα intensity in the region of high polarization in order to show that light from this region results from scattering. A check of consistency was made by comparing the ratio of [SII]/Hα from observations of two different regions. The North America Nebula (NGC 7000) and the California Nebula (NGC 1499) were imaged two months earlier than images of the Rosette Nebula (NGC 2237-9) and the California Nebula (NGC 1499). The ratio of [SII]/Hα yielded consistent values between the North America Nebula and the California Nebula. In the brightest regions, the ratio was typically ~ 0.1 in the images of the North America Nebula and the California Nebula. Comparing the same locations in both images of the California Nebula, the ratio was found to be practically the same for the observations made on two different nights.

The [SII]/Hα intensity ratio was then plotted radially for a wedge region from the center of the nebula to the outer edge of the high polarization region. The result showed the behavior expected: an increase in the [SII]/Hα ratio up to where the edge of the HII region ends and the high polarization begins. The end of the increase in [SII]$/$Hα ratio also corresponds well to the end of the radio continuum emission in the map of Celnik (1985) and the interior of the HI shell mapped by Kuchar and Bania (1993). Beyond this border, the [SII]$/$Hα ratio flattens up to a radius of about $60'$. This $60'$ limit corresponds well to the greatest radius implied by the thicker HI shell radius in the region of high polarization. The fact that the ratio of [SII]$/$Hα remains relatively flat in the region of high polarization is, I believe, strongly indicative of scattering by dust in that region. The fingerprint of the [SII] and Hα light which last left the region is reflected in the leveling off behavior of their ratio. The light which last left the actual HII region would remain unchanged as it traveled along a ray from the nebula to the scattering point. Therefore, upon scattering, the [SII] and Hα light should have the same ratio as that which last left the nebula as observed.

From all the evidence gathered and presented in this disseration, I believe that scattering by dust is the explanation of the Hα intensity seen in the Rosette Nebula between the 1 and 3 o'clock positions beyond a radius of $\sim 40'$. Around the southern and southeastern regions there is evidence that Hα emission is real, as evidenced in the free-free continuum map at 4750 MHz by Celnik (1985). However, the presence of dust in these regions, particularly small particles which are thought to be responsible for the 12μm emission, leads to the conclusion that the polarization observed here is also due to scattering. How much of the observed Hα in the southeastern and southern regions is due to scattering and not emission by recombination has not been determined.

The fact that some of the Hα intensity is actually scattered and not emission might relate to the question of the warm ionized medium. The source(s) of ionization have not been readily identified. Observations of the [SII]$/$Hα ratio by Reynolds (1985, 1988) have shown that scattered light from HII regions is not the *dominant* source of the background emission. However, as I have shown in the case of the Rosette Nebula, scattering by Hα plays a role in interpreting the sizes of such regions, i.e. extending the apparent region slightly into the interstellar medium. If the argument applied here can be extended to other HII regions, then scattering can play an important factor in interpreting the size of other regions and possibly may account for part of the warm ionized medium as well.

5.2 Future Work

The method of imaging polarization presented in this dissertation has been shown to be useful for detecting polarization by scattering. Therefore, the extension of this work to other HII regions would be useful in determining the role played by scattered Hα in those regions. The geometry of the Rosette Nebula made an interpretation of the scattering more direct than would be possible in the Cygnus region. The next step would naturally then be to analyze the polarization seen in the Cygnus images.

Other regions can be imaged as well. In particular, a stellar wind blown shell of HII associated with the star forming region W4 was shown to be particularly bright in Hα from the images of the galactic Hα survey. The shell in W4 has roughly the same linear extent as the Rosette Nebula. This shell has about the same angular extent as the Rosette Nebula. The use of the 58 mm camera lens of the SLIC used to record large 10° diameter regions could be replaced by the 135 mm lens to record the W4 shell at a better resolution.

The single scattering model was shown to be inadequate at describing the polarization seen around the periphery of the Rosette Nebula. It predicted values of polarization on the order of 20% to 80% which were too high. A multiple scattering model would be more appropriate. A search through the astronomical literature found no suitable model which could be applied to the situation at hand. Therefore, the application of a multiple scattering model to the geometry of the Rosette Nebula would be a worthwhile endeavor. The creation of such a multiple scattering model was not undertaken in this dissertation due to the complexity of such a task.