Probing the Rosette Nebula stellar bubble with Faraday rotation

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PROBING THE ROSETTE NEBULA STELLAR BUBBLE WITH FARADAY ROTATION

by

Allison Hainline Savage

A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Astronomy in the Graduate College of The University of Iowa

May 2013

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CHAPTER 1
INTRODUCTION

1.1 Introduction

Stars alter the surrounding interstellar medium (ISM) in a variety of ways. Over stellar lifetimes, stars can inject energy and material into their surroundings through winds, which can redistribute gas in stellar nurseries and create wind blown bubbles. Massive stars can also form HII regions by photoionizing the gas around the cluster. For both structures that can form around an OB association, the influence of the magnetic fields in these regions is very important to the formation of these objects because magnetic fields can impact the size, energy distribution, and appearance, among other aspects, of HII regions and stellar bubbles. It is difficult to constrain properties like the magnitude and the direction of the magnetic field. One technique that is used in observational astronomy to obtain measurements of the magnetic field is Faraday rotation, which is discussed in more detail in Section 2.1.1.

This paper is a contribution towards understanding how magnetic fields affects wind blown bubbles and HII regions and also towards the larger picture of understanding how massive stars like those in OB associations interact with the ISM. In Chapter 1 of this paper, Section 1.2 and 1.3 will detail the structure of HII regions and stellar bubbles, respectively. These two sections will discuss the theory associated with the formation and properties of these types of structures. Section 1.4 discusses properties of HII regions and stellar bubbles in the context of magnetic fields and dust, and it will compare the theory of such formations to the observations.

Chapter 2 is from the published work of Savage et al. (2013). Savage et al. (2013) was published in the Astrophysical Journal, Volume 765, Issue 1, article 42, in March 2013. The title of the published paper is “Probing the Rosette Nebula Stellar Bubble with Faraday Rotation.” The second chapter will narrow the focus from general HII regions and stellar bubbles to the specific case of the Rosette Nebula, which is a prominent HII region
with an associated stellar bubble. This paper employs Faraday rotation as a diagnostic tool for probing the structure of the bubble. Chapter 2 includes details of the observations conducted, data analysis, and discusses a simple model for the structure of the stellar bubble with an amplified magnetic field in the shell of the bubble of the Rosette Nebula.

1.2 The Structure of HII Regions

Stars form in dense clouds composed of mainly molecular gas and dust, which act as nurseries for star formation. The most massive stars, O and B stars, born in these clouds strongly interact with and affect the stellar nurseries by radiating photons in the ultra-violet spectrum with energies in excess of 13.6 eV. The photons ionize the surrounding HI gas, creating an HII region around the star. As the neutral hydrogen is ionized by these photons, the ionizing photons are able to propagate further out from the star into the surrounding ISM, creating a sphere of HII gas (Spitzer, 1968). The expanding HII region eventually reaches equilibrium, balancing the ionization rate with the recombination rate of free electrons and protons, which forms neutral atoms. Strömgren (1939) determined the extent of HII regions around an ionizing star, known as a Strömgren sphere. For a Strömgren sphere, which is the characteristic extent of an HII region, the star is assumed to be radiating isotropically, with spherical symmetry, and all of the free electrons are a product of the ionized hydrogen,

\[ N_{\text{ion}} = N_e. \]

The equation that characterizes the degree of ionization at a distance \( r \) from the star is

\[ \alpha n_e^2 \frac{4\pi}{3} r^3 = Q, \]

where \( Q \) is the rate of photons per second from the star, \( n_e \) is the electron density, \( r \) is the radius of the sphere, and \( \alpha \) is the recombination coefficient (McCullough, 2000; Strömgren, 1939).

The boundary between the HI and HII regions is an ionization front, which is a sharp transition from the fully ionized gas to the almost completely neutral gas (Yorke, 1986).
Kahn (1954) determined four different types of propagation for ionization fronts:

1. The ionization front is supersonic relative to the neutral gas into which it is propagating (R-type),

2. The ionization front is subsonic relative to the neutral gas into which it is propagating (D-type),

3. The ionization front progresses at speeds supersonic (or subsonic) relative to both the neutral gas in front and the ionized gas behind it (weak R-type or D-type, respectively),

4. The flow through the ionization front changes from supersonic to subsonic (or subsonic to supersonic) (strong R-type or D-type, respectively).

There are three phases to the evolution of HII regions: 1) the formation phase, 2) the expansion phase, and 3) the recombination phase (Yorke, 1986). In the formation phase when the star begins ionizing, an ionization front propagates at supersonic speeds through the surrounding gas until it approaches the Strömgren radius (Yorke, 1986). At the Strömgren radius, the propagating front transitions to a subsonic flow and a shock front forms, which then detaches from the ionization front (Yorke, 1986). The energy from the star is sufficient to ionize the gas and heat it by a factor of 100 higher than the neutral gas (Spitzer, 1968; Strömgren, 1939). In the expansion phase, the heated, ionized sphere of gas expands into the neutral gas surrounding the star (Yorke, 1986). The sphere is bound by the ionization front and its shock, which are separated by a thin shell of shocked, neutral gas (Yorke, 1986). During this phase, the expansion decreases the density within the sphere, allowing more photons to propagate out and ionize the gas until the end of the expansion phase when pressure equilibrium is established between the ionized and neutral regions (Yorke, 1986). The recombination phase occurs when a star evolves off of the main sequence (MS), where the ionizing flux decreases. This causes the ionization front to shrink even as the recombined gas continues to propagate forward with a momentum-driven shock front due to its inertia; in observations, this corresponds to a sphere of ionized
gas surrounded by thick shell of neutral gas, which is also expanding (Yorke, 1986). These three phases are the basic evolutionary stages of an HII region though there are deviations from these idealized stages in the presence of magnetic fields, dust, or when assumptions like spherical symmetry break down.

### 1.3 The Structure of Stellar Bubbles

Massive stars in OB associations can affect the surrounding ISM by photoionizing gas in the nearby vicinity and by their powerful stellar winds inflating a bubble around the stars; however, HII regions and wind blown bubbles can form independently of one another (Arthur, 2007). The structure of a wind blown bubble caused by a single star was modeled by Weaver et al. (1977), which consists of four primary regions as seen in Figure 1.1: in region (a), which is closest to the star, the hypersonic winds expand outwards; in region (b), the wind inflates a bubble with an interior cavity of hot, low density gas; in region (c), a thin shell of shocked interstellar gas, which was swept up by the winds, surrounds the cavity; in region (d), which is exterior to the bubble structure, the bubble is expanding into the ambient interstellar gas. Between regions (b) and (c), there is a contact discontinuity and a shock between regions (a) and (b) as well as (c) and (d) (Weaver et al., 1977). These regions of the stellar bubble shown in Figure 1.1 will expand coherently in time because the radius of the regions, and the whole structure, is a function of time, \( R(t) \).

The wind luminosity depends on the mass loss rate, \( \frac{dM}{dt} = \dot{M} \), and the terminal wind velocity, \( V_\infty \), where

\[
L_{\text{wind}} = \frac{1}{2} \frac{dM}{dt} V_\infty^2.
\]  

(1.2)

The governing equations for the Weaver et al. (1977) bubble due to a single star are as follows

\[
\frac{\delta v}{dt} + v \frac{\delta v}{dr} + \frac{1}{\rho} \frac{\delta p}{dr} = 0,
\]

(1.3)

\[
\frac{\delta \rho}{dt} + v \frac{\delta \rho}{dr} + \rho \frac{\delta v}{dr} + 2 \frac{\rho v}{r} = 0,
\]
Figure 1.1: From Weaver et al. (1977) illustrating the regions of a stellar bubble surrounding a point like source.

\[ \frac{D}{Dt}(pp^{-\gamma}) = 0, \]

which are the equations of motion, continuity, and energy conservation for an adiabatic flow, respectively. Weaver et al. (1977) modeled each region of a wind blown bubble using the hydrodynamical equations, all of which is worked out in detail in his paper.

The Weaver et al. (1977) model is a good approximation of the evolution of stellar bubbles due to a single star during the main sequence phase. In the MS, O stars have luminous winds with fast terminal wind velocities, \( V_\infty \sim 10^3 \text{ km s}^{-1} \), and large mass loss rates, \( \dot{M} \sim 10^{-6} \text{ M}_\odot \text{ yr}^{-1} \) (Massey et al., 1995). The powerful stellar wind of an O star expands into the surrounding medium, sweeping up HI and ionized gas as it flows, which inflates a bubble around the exciting star. The Weaver et al. (1977) model breaks down for later evolutionary stages of an O star, such as red super giant (RSG), luminous blue variable (LBV), and Wolf-Rayet (WR) stages. During the later periods of an O star’s life, the winds from the evolved star can form subsequent bubbles, which are inherently different than the MS bubble because of changes in the terminal velocity and the wind density of the evolved star.

For RSG stars, the winds are slow and dense, with \( V_\infty \sim 10–20 \text{ km s}^{-1} \) and \( \dot{M} \sim 10^{-4}–10^{-5} \text{ M}_\odot \text{ yr}^{-1} \) (Humphreys, 1991; Garcia-Segura & Mac Low, 1995). The RSG
winds form a second thin, dense shell behind the MS bubble (Toalá & Arthur, 2011); however during the RSG phase, the HII region is diminished due to the low population of ionizing photons (van Marle et al., 2005). A RSG evolves into a WR star if it has a mass $> 20$ M$_\odot$ (Massey, 2003). For a post-RSG WR star, the very fast, dense WR winds expand into the RSG shell, forming a WR shell. When the WR shell reaches the RSG shell, the two shells collide and then fragment (van Marle et al., 2005; Garcia-Segura & Mac Low, 1995). Due to both the WR and RSG winds being of similar density, the fragmented shells expand together, and there is a drastic increase in the number of ionizing photons, which reestablishes the previous HII region from the MS phase (van Marle et al., 2005).

Though the HI gas is re-ionized during the WR phase, the density of the WR winds hinders the ionizing photons from penetrating much further than the WR shell, which eventually causes the Strömgren radius to coincide with the WR shell radius and forms one bubble for both the HII region and the stellar wind (van Marle et al., 2005). Eventually, an HII region may be formed outside of the WR shell, but it is narrow compared to the extent of other coexisting wind blown bubbles and HII regions (van Marle et al., 2005, 2007).

An O star that is very massive ($M > 85$ M$_\odot$ (Humphreys, 1991)) evolves into a LBV star, which has intermediate wind velocities of order $V_\infty \sim 200$ km s$^{-1}$ but extremely large mass loss rates of order $\dot{M} \sim 10^{-4}$ M$_\odot$ yr$^{-1}$ (van Marle & Keppens, 2012). LBV stars have irregular mass ejections, which can have mass loss rates up to $\dot{M} \sim 10^{-3}$ M$_\odot$ yr$^{-1}$ (van Marle et al., 2007). Though the LBV winds are slower than MS winds, the LBV winds can form a secondary shell inside of the MS bubble. If a LBV star looses sufficient mass for it to evolve into a WR star, the bubble formed by the post-LBV WR winds is different than the post-RSG WR bubble. During the WR phase of a post-LBV star, the WR wind sweeps up and absorbs most of the LBV shell because the LBV shell is a factor of 10 less dense than the WR wind (van Marle et al., 2007). The post-LBV WR structure consists of two bubbles: one supported by the HII region that extends out past the WR shell and into the original MS bubble, and a second bubble supported by the WR wind (van Marle et al., 2007). The dual bubbles are caused by the dense WR winds blowing out of the less
dense LBV shell, which allows for more ionizing photons to permeate out past the WR wind blown shell (van Marle et al., 2007).

1.4 Stellar Bubbles and HII Regions in Observations

The Weaver et al. (1977) model can approximate the structure and evolution of a MS stellar bubble, but it fails to accurately describe the subsequent bubbles formed during later evolutionary stages of an O star. Specifically, an ambient, homogeneous medium into which the bubble is forming cannot be assumed for RSG, LBV, and WR bubbles, as the previous winds drastically altered the surrounding medium. Another simplification that is also violated is spherical symmetry, as most observed bubbles and HII regions are not strictly spherical. In the process of forming a bubble, other structures can form in the HII region such as spokes, fingers, and chimneys. These formations are named for their visual appearance in observations as well as the method of formation. Spokes are dense, neutral formations that extend into the HII region and are formed by the winds sweeping up the clumpy material into the shell (Freyer et al., 2003). These clumps shadow parts of the HII region, which lead to pressure gradients and recombination in the shadowed region, as fewer ionizing photons penetrate through the clumpy shell (Freyer et al., 2003). Fingers are elongated HII regions caused by instabilities in the ionization front due to fragmentation of the shell (Garcia-Segura & Franco, 1996), and they are amplified by the stellar wind redistributing mass as it expands (Freyer et al., 2003). Chimneys are a particular pillar formation where the bubble blows out of the Galactic plane and funnels material from the disk of a galaxy into the halo (West et al., 2007; Norman & Ikeuchi, 1989). These formations indicate that the density is not homogeneous in the medium around a bubble or within it and that spherical symmetry assumptions are usually an oversimplification for these regions.

The structure of the wind blown bubble and HII region is also affected by magnetic fields. HII regions are plasmas, and they are strongly affected by magnetic fields because the field lines are “frozen” into plasmas. Stars can transport magnetic field lines out into
the surrounding medium through stellar winds. The Weaver et al. (1977) model does not take into account magnetic fields; however, Ferriere et al. (1991) modeled wind blown bubbles with magnetic fields and found that magnetized shells are thicker than unmagnetized shells and are elongated in the direction of the field lines. The structure of wind-blown bubbles can also deviate from spherical symmetry in the presence of magnetic fields, creating “dimples” in the sphere at magnetic poles (Ferriere et al., 1991), though simulations by Stil et al. (2009) did not find “dimples”. Stil et al. (2009) note that the vertical size of the bubble cavity decreases as magnetic pressure increases, whereas the size of the cavity along the field line increases with increasing magnetic pressure.

In wind blown bubble models, dust is also often neglected. Dust can absorb ionizing radiation from a star, which cools the shell and decreases the energy density of the expanding bubble (Everett & Churchwell, 2010). In simulations, Everett & Churchwell (2010) found that dust can survive in a wind blown bubble environment, and small amounts of dust can significantly alter the size and mass of the bubble. The energy within a dusty stellar bubble is approximately a factor of 8 less than the energy in a bubble without dust, and dusty stellar bubbles are generally smaller in size than bubbles without dust (Everett & Churchwell, 2010).

Though stellar bubbles have been laboriously studied, there are remaining features that are still not well understood. The growth rate discrepancy, also discussed as the missing wind luminosity problem, is when the age of a wind blown bubble is significantly younger than the responsible stellar cluster (Bruhweiler et al., 2010; Oey & Garcia-Segura, 2004). Oey & Garcia-Segura (2004) discuss the well-known result that most wind blown bubbles are smaller than models predict and that the growth rate discrepancy problem has been observed in nebulae associated with OB associations, when the stars are active within the shell structure (Oey, 1996). As discussed above, dust can significantly impact the size of a bubble, which is used to determine the age of the bubble. Stil et al. (2009) note that because magnetic fields can cause the bubble to elongate preferentially in the direction of the field lines, there may also be significant errors in determining the age
of the bubble, and the discrepancy in age due to this effect can be up to a factor of $\sim 4$. Another source for the age discrepancy in bubbles surrounding OB stars is that the wind luminosities have been overestimated, which could reduce mass loss rates (Muijres et al., 2011; Puls et al., 2008). Puls et al. (2008) discuss that if clumping is a factor of $\sim 4$, then mass loss rates are reduced by a factor of $\sim 2$; however, a factor of 10 or more for clumping would significantly alter mass loss rates, which in turn would affect models for the age of the bubbles.
CHAPTER 2
PROBING THE ROSETTE NEBULA STELLAR BUBBLE WITH FARADAY ROTATION

2.1 Introduction

Luminous young stars interact with and alter the interstellar medium (ISM) from which they form. They interact by photoionizing gas in their vicinity, leading to a propagating ionization front (Spitzer, 1968), and by the powerful stellar winds formed by hot, luminous stars. Over the course of a stellar lifetime, stellar winds modify the ISM by inflating a bubble of hot gas surrounding a star cluster. The Weaver et al. (1977) solution for the bubble due to a single star consists of an inner termination shock, a surrounding bubble of hot, low density stellar gas, a contact discontinuity, ISM gas that is photoionized, and finally, an outer shock through which the interstellar gas has passed. A diagram illustrating this structure is given in Figure 1 of Freyer et al. (2003). Within this picture, the visible HII region corresponds to the annular shell of shocked, photoionized gas. Whether a bubble structure exists, or instead a less dynamic structure corresponding to an ionization front, depends on the mechanical luminosity of the wind or winds in the star cluster. The long term goal of our research program is to better understand how stars in OB associations modify the ISM. In this paper, we present results on Faraday rotation measurements (a diagnostic of plasma properties) on lines of sight through the ionized “bubble” produced by one OB association, and interpret the measurements in the context of models of young clusters.

HII regions are plasmas, and principles of plasma physics determine how these structures evolve and impact the surrounding ISM. One of the most important properties of an astrophysical plasma is the magnetic field. The magnetic field in an HII region or stellar bubble can strongly impact the evolution of the HII region or bubble. At the same time, modification of the magnetic field in the vicinity of an HII region could have consequences for subsequent star formation, properties of interstellar turbulence, and heat flow, among
other processes. Measurement of magnetic fields in the ISM is notoriously difficult. One of the best available techniques, and the one utilized in this paper, is Faraday rotation of linearly polarized radio waves from extragalactic radio sources (described in Section 2.1.1 below; see Minter & Spangler (1996); Havercorn et al. (2004, 2006); Brown et al. (2003, 2007); Vallée (1993, 2004), among others, for prior uses of this technique). An attractive aspect of Faraday rotation is that it can also be measured for lines of sight that pass through the solar corona, and thus provide information on the coronal magnetic field (Mancuso & Spangler, 2000; Ingleby et al., 2007). The fact that the same diagnostic technique can be used in these two media may facilitate comparison between plasma processes in the corona and solar wind, and those in the ISM.

The specific object for study in this paper is the Rosette Nebula, which is a prominent HII region featuring an obvious shell structure and a central cavity (see Figure 2.1). It is located on the edge of a molecular cloud in the constellation Monoceros. We adopt as its center that of the NGC 2244 star cluster (which is responsible for the Rosette), which is given by Berghöfer & Christian (2002) as R.A.(J2000)= 06h 31m 55s, decl.(J2000)=04° 56′ 34″ (l=206.5, b= –2.1). The distance to the Rosette is 1600 pc and its age is estimated to be 3 ± 1 Myr old (Román-Zúñiga & Lada, 2008). Menon (1962) concluded that the Rosette Nebula is an ionization-bounded Strömgren sphere on the basis of radio continuum observations and that its structure is that of an annular shell. This structure is consistent with that of a wind-blown bubble, as mentioned above.

Within the central cavity of the Rosette is the OB stellar association NGC 2244. Photometry and spectroscopy studies put the age of NGC 2244 at less than 4 Myr (Perez et al., 1989). Evolutionary models place the main-sequence turnoff age at 1.9 Myr (Román-Zúñiga & Lada, 2008). Despite this age discrepancy, both theoretical models and observations indicate that NGC 2244 is still forming stars (Román-Zúñiga & Lada, 2008). There are 21 confirmed pre-main sequence stars, and 113 confirmed stars belonging to NGC 2244, of which at least 7 are O type stars and 24 are B type stars (Román-Zúñiga & Lada, 2008; Park & Sung, 2002; Ogura & Ishida, 1981; Wang et al., 2008). The two brightest stars are
HD 46223, an O4V star, and HD 46150, an O5V star (Román-Zúñiga & Lada, 2008; Wang et al., 2008).

2.1.1 Faraday Rotation as a Diagnostic Technique for Stellar Bubbles

Faraday rotation is an excellent diagnostic tool for estimating properties of astrophysical plasmas such as the density of the general ISM and the large-scale structure of the Galactic magnetic field. Faraday rotation is the rotation in the plane of polarization of a radio wave as it propagates through a plasma that has a magnetic field. The polarization position angle $\chi$ of a source, or part of a source, whose radiation has propagated through the ISM is given by

$$\chi = \chi_0 + \left[ \left( \frac{e^3}{2\pi m_e^2 c^4} \right) \int_0^L n_e \vec{B} \cdot d\vec{s} \right] \lambda^2$$

where $\chi$ is the polarization position angle, $\chi_0$ is the intrinsic polarization position angle (i.e. that which would be measured in the absence of a medium), $e$ is the fundamental electric charge, $m_e$ is the mass of the electron, $c$ is the speed of light, $n_e$ is the electron density, $\vec{B}$ is the magnetic field, $d\vec{s}$ is the incremental pathlength interval along the line of sight, and $\lambda$ is the wavelength. The integral in Equation (1) is taken from the source at $s = 0$ to the observer at $s = L$. The variable $L$ represents the effective thickness of the plasma. With this convention, a positive value for the integral corresponds to the average magnetic field pointing from the source to observer, while a negative value represents a mean magnetic field pointing from the observer to the source. The quantity in square brackets is defined as the rotation measure (RM). The fundamental definition of Faraday rotation given in Equation (2.1) is in cgs units. Values of RM are conventionally given in SI units. This conversion can be accomplished by multiplying the cgs value of the RM by a factor of $10^4$ to obtain the SI value. Alternatively, an expression which gives an SI value for the RM
given mixed but convenient interstellar units is (Minter & Spangler, 1996)

\[ \text{RM} = 0.81 \int_0^L n_e (\text{cm}^{-3}) \vec{B} (\mu \text{G}) \cdot \vec{d}s \ (\text{pc}) \text{ rad m}^{-2} \]  

Equation (2.1) shows that if measurements of \( \chi(\lambda) \) are available at two or more wavelengths (preferably three or more), the RM can be measured as the slope of a line through the data on a plot of \( \chi \) versus \( \lambda^2 \),

\[ \text{RM} = \frac{\Delta \chi}{\Delta (\lambda^2)} \]  

The wavelengths of observation must be spaced closely enough that there is no possibility of a “wrap” of \( \pi \) radians between two adjacent frequencies of observation. This is referred to as the “n–\( \pi \)” ambiguity. A discussion of the constraints on spacing between observing frequencies, as well as an illustration of the difficulties if they are spaced too far apart, is given in Lazio et al. (1990) (see Figures 3 and 4 of that paper). Further details of how we extract RM values from our data are given in Section 2.3.2.

Among the many studies to have used Faraday rotation in the investigation of interstellar magnetic fields are Rand & Kulkarni (1989); Minter & Spangler (1996); Brown et al. (2003, 2007); Harvey-Smith et al. (2011); Van Eck et al. (2011). To extract information on the magnetic field, it is necessary to have information on the electron density, since the integrand in Equation (2.1) is the product of \( n_e \) and \( B_\parallel \), the parallel component of the interstellar magnetic field. The data sources we use for estimates of \( n_e \) are described in detail in Section 2.4.1 below.

2.1.2 The Rosette Nebula as a Candidate for Faraday Rotation Measurements

The Rosette Nebula is an excellent object for studies of stellar bubbles via the technique of Faraday rotation. Besides being a prominent HII region with a shell and cavity, the Rosette has other properties which make it an excellent choice for studies of the impact of a young stellar association on the surrounding ISM. The Rosette is in the rough direction of the Galactic anticenter (\( l=206.5^\circ \)). This gives it a number of advantages relative to HII
regions and young star clusters in the inner two quadrants of the Galactic plane. Since star formation regions are relatively rare beyond the solar circle, there is no confusion in the Rosette field with other star formation regions at different distances along the line of sight. By contrast, studies in the Cygnus Region (e.g., Whiting et al. (2009)) are complicated by numerous star formation regions at various distances. Extinction also is less heavy for most anticenter lines of sight. The star cluster responsible for the Rosette Nebula (NGC 2244) is clearly seen, and the spectral types of the stars have been determined.

Another advantage of the Rosette Nebula is its structural simplicity. It resembles the theoretical ideal of a photoionized interstellar bubble as described by the theory of Weaver et al. (1977). Furthermore, the parameters of the bubble structure have been determined by the radio continuum observations of Menon (1962), and later confirmed by Celnik (1983, 1985). Celnik (1985) determined that the Rosette Nebula is a spherical shell of ionized matter around NGC 2244 on the basis of radio continuum observations at 1.4 GHz and 4.7 GHz with the 100 m telescope at Effelsberg. Celnik also reported values for the inner and outer radius of the shell of gas and the density within the HII region (Celnik, 1985). We adopt Celnik’s parameters for the shell density and the structure in our analysis in Section 2.4.

2.1.3 Previous Results of Faraday Rotation Diagnostics of HII Regions

Whiting et al. (2009) presented a study of the Galactic plane region near the Cygnus OB1 association. The main purpose of Whiting et al. (2009) was to confirm the existence of a “Faraday Rotation Anomaly” in this part of the sky, i.e., a large change in RM over a small distance on the sky. Whiting et al. (2009) argued that this anomaly was due to the plasma bubble associated with the Cygnus OB1 association. Whiting et al. (2009) also developed a simple shell model that reproduced the observed magnitude and the change in RM in Cygnus. In Section 2.4, we will use this shell model to interpret our data on the Rosette Nebula.

See Celnik (1985), Section 5.1 for the details of those measurements.
Harvey-Smith et al. (2011) used Faraday rotation and Hα measurements with the WHAM spectrograph (Haffner et al., 2003) to measure the electron density and line of sight magnetic fields in several HII regions. Faraday rotation was measured for extragalactic radio sources viewed through the HII regions. They probed 93 lines of sight in five HII regions, and found that each HII region displays a coherent magnetic field, with a range of 2–6 μG for the parallel component (Harvey-Smith et al., 2011). Harvey-Smith et al. (2011) briefly compared their RM values with the model presented by Whiting et al. (2009) and concluded that there is no evidence for a shell with an amplified magnetic field in any of the HII regions. Whiting et al. (2009) and Harvey-Smith et al. (2011) thus come to different conclusions about the nature of the plasma shell that comprises an HII region. It should be noted that Whiting et al. (2009) claimed that the Faraday rotation anomaly was consistent with a wind-blown bubble, but did not claim that it was inconsistent with a shell without magnetic field amplification. Additional observations of the sort presented in Whiting et al. (2009) will help resolve this issue. Measurements of RM on a large number of lines of sight through an HII region (in the case of the present paper, the Rosette Nebula) will diagnose the plasma structure of the HII region, and determine if the HII region produces significant modification of the interstellar magnetic field. In time, we plan to carry out such observations on a set of HII regions associated with star clusters of different age, stellar luminosity, and wind power.

2.2 Observations

All observations were made with the Karl G. Jansky Very Large Array (VLA) radio telescope of the National Radio Astronomy Observatory during the first several months of commissioning of the upgraded VLA. Details of the observations and resultant data are given in Table 2.1. The VLA was in D array for all of the observations. We observed 23 extragalactic radio sources whose lines of sight pass through or close to the Rosette
Figure 2.1: Mosaic of the Rosette Nebula compiled from the Palomar Sky Survey II. The interior sources whose lines of sight pass through, or close to, the visible nebula are labeled with the prefix of “I”. The exterior sources whose lines of sight are well outside the visible nebula are labeled with the prefix of “O”. Sources with negative RMs are labeled with open circles and those with positive RMs have solid circles. Depolarized sources are marked with an “X”. The source symbols are scaled with the magnitude of the log $|\text{RM}|$. The Second Palomar Observatory Sky Survey (POSS-II) was made by the California Institute of Technology with funds from the National Science Foundation, the National Geographic Society, the Sloan Foundation, the Samuel Oschin Foundation, and the Eastman Kodak Corporation. The STScI Digitized Sky Survey can be found at http://stdatu.stsci.edu/cgi-bin/dss_form.

The sources were chosen from the NRAO VLA Sky Survey (NVSS), which covers the entire sky north of declination $-40^\circ$ at 1.4 GHz (Condon et al., 1998). We also observed four calibrators, 3C286, J0632+1022, J0643+0857, and 3C138. The calibrator 3C286 is commonly used for absolute calibration of the visibility amplitudes because it has a well-known flux density. It is also used to calibrate the origin of the polarization position angle. The source 3C138 was used for independent observations that could also set
the flux density scale and determine the origin of the polarization position angle. Specifically, we used our observations of 3C138 to independently confirm the value of the R–L phase difference (used to calibrate the polarization position angle) obtained from 3C286. The source J0632+1022 was the primary calibrator for the project, functioning as the gain calibrator, i.e., determining the complex gain of each antenna as a function of time. This source (J0632+1022) was also used to measure the instrumental polarization, described by the “D factors”, $D_R$ and $D_L$ (Bignell, 1982; Sakurai & Spangler, 1994). We also observed a second source, J0643+0857, to obtain a completely independent set of D factors which confirmed our instrumental polarization calibration.

In addition to the calibrators, we observed 23 program sources. We had 12 sources whose lines of sight passed through the Rosette Nebula. The remaining 11 sources have lines of sight that pass near the Rosette Nebula but outside the obvious Hα-emitting shell. We observed these latter sources so we could establish a background RM value due to the Galactic plane. Figure 2.1 shows an image of the Rosette Nebula with the positions of our sources superposed.

We observed 128 MHz wide spectral windows centered on three frequencies: 4.436 GHz, 4.936 GHz, and 7.636 GHz. We had three sessions on the VLA (“scheduling blocks”) on 2010 March 20, July 4, and August 22. We also made observations at 4136 MHz for the March and July sources, which would have provided polarization measurements at four frequencies. However, we ultimately flagged all 4.1 GHz data due to overwhelming radio frequency interference (RFI). Table 2.1 presents a summary of the observations, which includes the date of observation, the duration of the sessions, the frequencies observed, the VLA array, the restoring beam used for each session, the number of scans per source per session, and the characteristic rms noise level in the $Q$ and $U$ maps. The sources for the March and July sessions were the same, and we observed those sources at all three frequencies. The August session observed additional sources. This new set of sources was observed at 4.4GHz and 4.9GHz only. The intent was to observe these sources at 7.6 GHz as well, but the D array observing season ended before a forth scheduling block.
was carried out. Table 2.2 lists all the sources with a project name in Column 1, the R.A. and decl. (J2000) in Columns 2 and 3, respectively, the galactic longitude and latitude in Columns 4 and 5, the angular distance between the line of sight and a line of sight passing through the center of the Rosette, $\xi$, in Column 6. The total Clean Flux at 4.9GHz is given in Column 7, and in Column 8, the number of frequencies observed for each source, where the number 3 corresponds to the set of frequencies of [4.4 GHz, 4.9 GHz, and 7.6 GHz] and the number 2 corresponds to the set [4.4GHz and 4.9GHz]. The range in frequency between 4.4 GHz and 7.6 GHz allows us to obtain RM values that are as low as a few tens of rad m$^{-2}$, given the errors in the polarization measurements (see Section 2.3.2 below). The shorter range between 4.4GHz and 4.9GHz allows for measurements of large RM values without being affected by the “$n-\pi$ ambiguity”.

### Table 2.1: Log of Observations

<table>
<thead>
<tr>
<th>Dates of observation</th>
<th>2010 March 20; 2010 July 4; 2010 August 22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of observing sessions (h)</td>
<td>5.95; 5.89; 5.94</td>
</tr>
<tr>
<td>Frequencies of observationsa (MHz)</td>
<td>4136; 4436; 4936; 7636</td>
</tr>
<tr>
<td>VLA array</td>
<td>D</td>
</tr>
<tr>
<td>Restoring beam (diameter)</td>
<td>12&quot;8; 19&quot;6b</td>
</tr>
<tr>
<td>Number of scans per source per session</td>
<td>5</td>
</tr>
<tr>
<td>rms noise level in Q and U maps (mJy beam$^{-1}$)</td>
<td>0.042; 0.048; 0.037c</td>
</tr>
</tbody>
</table>

a) The observations had 128MHz wide spectral windows centered on the frequencies listed. b) The March and July sessions were restored using a beam size of 12"8, and the August session was restored with a 19"6 beam size. c) Average rms noise levels for 4.4 GHz, 4.9 GHz, and 7.6 GHz, respectively.
<table>
<thead>
<tr>
<th>Source</th>
<th>$\alpha$(J2000)</th>
<th>$\delta$(J2000)</th>
<th>$l$</th>
<th>$b$</th>
<th>$\xi^a$</th>
<th>$S$(4.9GHz)$^b$</th>
<th>Number of f Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(h m s)</td>
<td>(° ' '')</td>
<td>(°)</td>
<td>(°)</td>
<td>(arcmin)</td>
<td>(Jy)</td>
<td></td>
</tr>
<tr>
<td>I1</td>
<td>06 28 39.50</td>
<td>04 47 08.0</td>
<td>206.1</td>
<td>-2.9</td>
<td>49.6</td>
<td>0.017</td>
<td>2</td>
</tr>
<tr>
<td>I2</td>
<td>06 29 56.26</td>
<td>04 26 33.0</td>
<td>206.5</td>
<td>-2.7</td>
<td>42.2</td>
<td>0.260</td>
<td>3</td>
</tr>
<tr>
<td>I3</td>
<td>06 29 57.30</td>
<td>04 47 45.5</td>
<td>206.2</td>
<td>-2.6</td>
<td>30.6</td>
<td>0.038</td>
<td>3</td>
</tr>
<tr>
<td>I6</td>
<td>06 30 50.04</td>
<td>05 29 26.6</td>
<td>205.7</td>
<td>-2.1</td>
<td>36.6</td>
<td>0.013</td>
<td>2</td>
</tr>
<tr>
<td>I7</td>
<td>06 31 24.28</td>
<td>05 02 50.8</td>
<td>206.2</td>
<td>-2.1</td>
<td>9.9</td>
<td>0.043</td>
<td>2</td>
</tr>
<tr>
<td>I8</td>
<td>06 31 34.31</td>
<td>04 22 34.4</td>
<td>206.8</td>
<td>-2.4</td>
<td>34.4</td>
<td>0.025</td>
<td>3</td>
</tr>
<tr>
<td>I10</td>
<td>06 32 31.12</td>
<td>05 30 32.7</td>
<td>205.9</td>
<td>-1.7</td>
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<td>0.024</td>
<td>2</td>
</tr>
<tr>
<td>I12</td>
<td>06 33 03.14</td>
<td>04 44 56.0</td>
<td>206.6</td>
<td>-1.9</td>
<td>20.6</td>
<td>0.047</td>
<td>3</td>
</tr>
<tr>
<td>I14</td>
<td>06 33 46.34</td>
<td>05 36 54.0</td>
<td>205.9</td>
<td>-1.4</td>
<td>48.9</td>
<td>0.070</td>
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<td>06 34 00.01</td>
<td>05 10 42.8</td>
<td>206.3</td>
<td>-1.5</td>
<td>34.2</td>
<td>0.021</td>
<td>3</td>
</tr>
<tr>
<td>I16</td>
<td>06 34 11.48</td>
<td>05 25 32.0</td>
<td>206.1</td>
<td>-1.3</td>
<td>44.7</td>
<td>0.020</td>
<td>2</td>
</tr>
<tr>
<td>I18</td>
<td>06 35 25.96</td>
<td>05 14 15.3</td>
<td>206.4</td>
<td>-1.2</td>
<td>55.4</td>
<td>0.028</td>
<td>2</td>
</tr>
<tr>
<td>O1</td>
<td>06 24 18.84</td>
<td>04 57 01.9</td>
<td>205.4</td>
<td>-3.7</td>
<td>113.6</td>
<td>0.150</td>
<td>2</td>
</tr>
<tr>
<td>O2</td>
<td>06 25 51.89</td>
<td>04 35 40.2</td>
<td>205.9</td>
<td>-3.6</td>
<td>92.8</td>
<td>0.340</td>
<td>3</td>
</tr>
<tr>
<td>O4</td>
<td>06 27 21.09</td>
<td>05 45 37.8</td>
<td>205.1</td>
<td>-2.7</td>
<td>84.0</td>
<td>0.090</td>
<td>3</td>
</tr>
<tr>
<td>O5</td>
<td>06 27 36.73</td>
<td>06 32 52.1</td>
<td>204.4</td>
<td>-2.3</td>
<td>115.7</td>
<td>0.066</td>
<td>3</td>
</tr>
<tr>
<td>O7</td>
<td>06 27 38.32</td>
<td>03 24 59.6</td>
<td>207.2</td>
<td>-3.7</td>
<td>111.7</td>
<td>0.220</td>
<td>2</td>
</tr>
<tr>
<td>O9</td>
<td>06 30 52.53</td>
<td>06 24 50.5</td>
<td>204.9</td>
<td>-1.6</td>
<td>89.6</td>
<td>0.050</td>
<td>3</td>
</tr>
<tr>
<td>O11</td>
<td>06 33 32.77</td>
<td>04 00 06.0</td>
<td>207.3</td>
<td>-2.1</td>
<td>61.5</td>
<td>0.110</td>
<td>2</td>
</tr>
<tr>
<td>O14</td>
<td>06 35 51.95</td>
<td>03 42 18.0</td>
<td>207.9</td>
<td>-1.8</td>
<td>94.9</td>
<td>0.029</td>
<td>2</td>
</tr>
<tr>
<td>O15</td>
<td>06 36 05.69</td>
<td>04 32 40.5</td>
<td>207.1</td>
<td>-1.3</td>
<td>66.9</td>
<td>0.410</td>
<td>3</td>
</tr>
<tr>
<td>O16</td>
<td>06 37 23.05</td>
<td>04 05 44.1</td>
<td>207.7</td>
<td>-1.3</td>
<td>96.3</td>
<td>0.029</td>
<td>3</td>
</tr>
<tr>
<td>O17</td>
<td>06 37 36.18</td>
<td>05 55 32.5</td>
<td>206.1</td>
<td>-0.4</td>
<td>103.4</td>
<td>0.038</td>
<td>2</td>
</tr>
</tbody>
</table>

a) Angular distance between the line of sight and a line of sight through the nebula. See Section 2.4.1. b) Total flux at 4.9GHz.
2.3 Data Reduction

All data reduction was performed with the Common Astronomy Software Applications (CASA) data reduction package. The calibration procedure is similar to that used in our prior Faraday rotation projects with the VLA, such as Whiting et al. (2009) and Minter & Spangler (1996). The procedure for reducing and calibrating the data was as follows.

1. We flagged out measurements corrupted by RFI. For all sessions, some antennas were completely flagged because of corrupted or missing data. We also implemented position corrections for a number of antennas. As well as usual systematic flagging procedures (e.g., “Quack”), we visually inspected the data in order to manually remove RFI and other problems.

2. Calibration of the array, consisting of determination of the complex gains and instrumental polarization parameters (“D factors”), as well as the right-left phase difference for the entire array, was carried out following the online EVLA Continuum Tutorial and supplemented by the handbook for the CASA program.\(^3\)

3. Polarized images of the sources were made from the calibrated visibility data with the CASA task CLEAN. CLEAN is a task that Fourier transforms the data to form the “dirty map” and “dirty beam”, carries out the CLEAN deconvolution algorithm, and restores the image by convolving the CLEAN components with the restoring beam. We produced CLEANed maps of the Stokes parameters $I$, $Q$, $U$, and $V$. Different weighting schemes in the $(u, v)$ plane were used in the different sessions. The weighting was set to uniform for the March and July sources, but natural weighting was used for the August sources in order to obtain a better signal to noise ratio for the weaker sources observed in that session. The restoring beam for the March and July sources, across all frequency bands, was 12′′. For the August sources, the restoring beam was 19′′.6. The larger restoring beam in the 2010 August session is due to the

\(^3\)For further reference on data reduction, see the NRAO EVLA Tutorial “EVLA Continuum Tutorial 3C391”. [http://casaguides.nrao.edu/index.php?title=EVLAContinuumTutorial_3C391]
use of natural rather than uniform weighting in the \((u,v)\) plane. All maps presented utilized external calibration only. A single iteration of phase-only self calibration did not produce an improved signal-to-noise ratio for our maps.

### 2.3.1 Imaging the Sources

Having obtained the maps of the Stokes parameters \(I, Q, U,\) and \(V\) for each source at each frequency, we generated maps of the linear polarized intensity, \(L,\) and the polarization position angle, \(\chi\)

\[
L = \sqrt{Q^2 + U^2}
\]

\[
\chi = \frac{1}{2} \tan^{-1} \left( \frac{U}{Q} \right)
\]

For each source and frequency, we worked with images of \(I, L,\) and \(\chi.\) Examples of the images of two of our sources are shown in Figures 2.2 and 2.3. Figure 2.2 shows the \(I, L,\) and \(\chi\) maps of a point source (to the D array), I15, that was found to have a large RM \((633 \pm 14\) rad m\(^{-2}\)). Figure 2.3 shows a source, O2, which is resolved to the D array and possesses structure.

### 2.3.2 Determination of Rotation Measures

In this section, we describe how we obtained RMs from data of the sort shown in Figures 2.2 and 2.3. We first identified a local maximum in the polarized intensity in the 4.4GHz map. We then measured the polarization position angle \(\chi\) at this location for the two or three frequencies available for this source. Since the sources from the August scheduling block have only two data points, the RM was calculated from Equation (2.3). There are also larger errors associated with the sources from the August scheduling block due to having only two data points that are only slightly separated in frequency. There are three data points for the sources from the March and July scheduling blocks and the RM was calculated by plotting the polarization position angle, \(\chi,\) against \(\lambda^2\) and fitting a line to this relationship. An example of this is illustrated in Figure 2.4, for the source I15, and
Figure 2.5 for the source O2. All of our RM values were positive except for I18 and a component of O14. Two of the sources, I3 and O11, were depolarized, so we did not obtain a RM for them.

Figure 2.2: Maps of I15 at the three frequencies of observation. The vectors show the polarization position angle, $\chi$, the gray scale is the polarized intensity, $L$, and the contours are the intensity, $I$, with contour levels set to $-2, -1, 2, 10, 20, 40, 60$, and $80\%$ of the peak intensity, which is 19.0 mJy beam$^{-1}$ at 4.4GHz. The dashed contours indicate negative intensities, illustrating the level of noise and map imperfections. The circle in the lower left corner indicates the restoring beam.

The source I2 requires additional comments. I2 is an interior source from the March and July scheduling blocks. Usually, this would mean that we had polarization data at
Figure 2.3: Maps of O2 in the same format as Figure 2.2. The contours of total intensity are at –2, –1, 2, 10, 20, 40, 60, and 80% of the peak intensity, which is 10.2 mJy beam$^{-1}$ at 4.4GHz.

three frequencies. However, the 4.4GHz data for I2 were excluded from the calculation of the RM measurement. The 4.4GHz data failed a test for data quality that we applied to our observations, as follows. For each source and frequency, the data from each scan was mapped. As discussed in Section 2.2 above, each source was typically observed for 5 scans during the 6 hour observing session. These scan maps were made in all polarization parameters as well as the total intensity $I$. The purpose of this exercise was to make sure that no
Figure 2.4: Plot of the polarization position angle $\chi$ in radians against the square of the wavelength in m$^2$ for the interior source I15 (image shown in Figure 2.2). The value of the fit RM is $633 \pm 14$ rad m$^{-2}$. Error bars are contained within the plotted symbols.

Figure 2.5: Polarization position angle data for source O2, in the same format as Figure 2.4. The two sets of data points present measurements for the two components of the source seen in Figure 2.3. The solid black points represent the data for the north component (component (a) in Table 2.3), and the solid gray points are for the south component (component (b) in Table 2.3). The fit RM values are $80 \pm 8$ rad m$^{-2}$ for component (a) and RM= $64 \pm 6$ rad m$^{-2}$ for component (b). Error bars are contained within the plotted symbols.

systematic changes occurred during the observing session, due to incorrect correction for instrumental polarization, or similar effects. Once it was determined that the polarization
data were “stationary” during the observing session, and that no drastically flawed data were present, $I$, $Q$, and $U$ maps as well as maps of the derived quantities $L$ and $\chi$, were made with all available data. Unlike the other sources for which values of $\chi$ were within 1 $\sigma$ of the mean values, the $\chi$ time series for I2 showed scan-to-scan variations larger than noise. We examined I2 at 4.9GHz and 7.6 GHz, and determined that inconsistent polarization position angles were not present at the higher frequencies. Since we only used two frequencies in determining the RM value for I2, there is a larger error associated with this source. The degree of linear polarization for I2 was extremely low, 0.1% at 4.4GHz, and we attribute the variations of $\chi$ to residual instrumental polarization artifacts, which can appear with low values of the degree of linear polarization (Sakurai & Spangler, 1994). We retain I2 as one of the sources in our sample because we believe the data from the two higher frequencies are adequate to determine RM. The RM for I2 is consistent with the values for adjacent sources that we determined from measurements at three frequencies, indicating that $n-\pi$ ambiguities are not a problem.

The fits to the data shown in Figures 2.4 and 2.5 are sufficiently good to give us confidence that we have an accurate measure of the RM. Nonetheless, there can be a residual concern that the RM is larger than the value resulting from our fit, and that there is one or more rotations of $\pi$ radians between the frequencies observed. To exclude this possibility and demonstrate that the three frequency RM fits were accurate, we made a $\chi(\lambda^2)$ fit within the 4.4GHz bandpass for those sources with RM $\geq 500$ rad m$^2$. As described above, the 4.4GHz spectral window had 64 channels of 2MHz bandwidth. The end channels on both ends of the bandpass were discarded, and the remaining channels averaged to five sub-IF channels of 22 MHz each. A fit of $\chi(\lambda^2) = \chi_0 +$ RM$\lambda^2$ was then redone over the 4.4GHz spectral window. In all cases, the RM from this procedure agreed, within the errors, with the values obtained by fitting to two or three frequencies of 4.4, 4.9, and 7.6 GHz. A final check of the data set was to examine the degree of linear polarization,

$$m = \frac{L}{I},$$
where $I$ is the total intensity, for each source or source component at each of the frequencies of observation. If the degree of linear polarization is constant, this indicates that the Faraday rotation occurs in an external medium, such as the Galactic ISM. A case where $m$ is a function of frequency, with a smaller $m$ at lower frequencies, indicates internal Faraday rotation and depolarization within the synchrotron emitting source. The dependence of $\chi$ on $\lambda$ is then not proportional to $\lambda^2$, and a fit of the type we have done could yield an inaccurate estimate of the RM.

For each source or source component with measurements at three frequencies, the weighted mean degree of linear polarization $\bar{m}$ was calculated from the measurements of $m$ at each of the frequencies. The weighting was with the error on $m$, calculated from the noise level in the $Q$ and $U$ maps. We then calculated the reduced $\chi^2$ statistic for the 3 measurements about this mean (with $\nu = 2$ degrees of freedom), and chose as a flag threshold a value of $\chi^2_{\nu} = 3.9$, which corresponds to a 2% probability of constancy of $m$ with frequency, for three measurements (Bevington, 1969).

We considered the $\chi^2_{\nu}$ statistic as a screening operation rather than a definitive test, since the error in $m$ was calculated from the $Q$ and $U$ noise levels on blank portions of the image; such a procedure can underestimate the true error on a portion of the source where $L$ or $I$ is large. Of the 16 sources or source components (excluding I2) with observations at three frequencies, 9 passed this screening operation for $m$ being independent of frequency, and thus unaffected by depolarization.

We then carefully examined the data for the remaining sources in more detail. We found that in nearly every case, depolarization could be excluded, and we concluded that the blank field noise measurements underestimate the true errors in $m$. For example, for two source components (O2a and O5b) the excessive $\chi^2_{\nu}$ was due to $m$ at 7.6 GHz being slightly lower than at 4.4 and 4.9 GHz. This is the opposite of the behavior for Faraday depolarization, and shows that our measurements are not affected by depolarization.

In four of the five remaining cases, the decrease in $m$ from 7.6 to 4.9 GHz was very small (i.e., $\leq 13\%$), and we believe the high values of $\chi^2_{\nu}$ are due to the low estimate of
measurement errors on $m$. In all of the aforementioned cases, we feel that a fit of $\chi(\lambda^2)$ gives a good estimate of the RM due to the Galactic ISM, unaffected by the depolarization within the source. A point in support of this contention is the fact that three of these components were in double sources, and the RMs of the two components were in satisfactory agreement (see Table 2.3, described below).

The only source for which depolarization might be present is I14b. It was flagged by the $\chi^2$ screening criterion, and the degrees of linear polarization at 4.4, 4.9, and 7.6 GHz are $0.018 \pm 0.001$, $0.023 \pm 0.001$, and $0.031 \pm 0.001$, respectively. These measurements seem to show a progression in $m$ with increasing frequency, as well as a reduced $\chi^2$ value formally inconsistent with constancy. These data may indicate depolarization, in which case a source-associated rotation of the position angle, independent of the Galactic ISM, might occur. Furthermore, in this case there is a difference in RM between the two components of the source (see Table 2.3 below), although a linear fit to the $\chi$ versus $\lambda^2$ data was obtained. Although this difference in RM between two source components with a small angular separation could indicate a problem with depolarization, it could also be an interesting probe of small scale variations in the nebula, as discussed in Section 2.4.2 below. In the remainder of this paper, we will use the data for component I14b, with the recognition that the inferred RM might contain a component due to the source itself rather than the Galactic ISM.

A similar test was undertaken, with a corresponding reduction in the degrees of freedom, for the 12 sources or source components with observations at two frequencies. Only 1 source (O7) had a $\chi^2$ for 1 degree of freedom that exceeded the 2% probability threshold and therefore merited closer examination. We concluded that the large $\chi^2$ was due to small inferred errors on the $m$ values at the two frequencies; the $m$ values at 4.4 and 4.9 GHz are in good agreement, with $m_{4.4} > m_{4.9}$. Internal Faraday depolarization or depolarization by a plasma screen in front of the source cannot be occurring in this case.

To conclude, with the probable exception of I2, and the possible but not certain case of I14b, all of the RM values obtained from our sources and source components appear to
be measures of the Galactic ISM.

Our results on the polarization properties of our sources and the resultant RM values are shown in Table 2.3. The first column of Table 2.3 lists the source name. Duplication of sources in this column indicates that there were two components to the source for which we were able to obtain RM values. Each source has two or three associated rows in the table, and subsequent components of the same source also have two or three rows. These rows give data for the two or three frequencies of observation. Column 2 identifies the components of the duplicated source as either (a) or (b). There were nine sources that had two components. Column 3 lists the frequency associated with the data for the source, Column 4 lists the linear polarized intensity, $L$ (mJy beam$^{-1}$), and the associated error, Column 5 the degree of linear polarization, $m$. Column 6 is the polarization position angle $\chi$ and the associated error, and Column 7 has the RM with associated errors. Since the RM is obtained by fitting a line to the $\chi(\lambda^2)$ data for the March and July sources, and by Equation (2.3) for the August sources, Column 7 has one value per source component.

2.3.3 Comparison of RM Measurements with Taylor et al. (2009)

Taylor et al. (2009) re-analyzed data from the NVSS in order to obtain RMs for 37,543 radio sources. That study provided RMs for the sky north of $-40^\circ$ in declination. We can compare our RM values with the previously derived RM values by Taylor et al. (2009) for seven of our sources in common with Taylor et al. (2009). There are two reasons for carrying out this comparison. First, it serves as a check on our data and method of data analysis. Second, there are inconsistent reports in the literature regarding the accuracy of the Taylor et al. (2009) results. In a study of the magnetic field in the direction of the Galactic poles, Mao et al. (2010) found discrepancies between their RM measurements and those of Taylor et al. (2009). A comparison of RM values from Taylor et al. (2009) and independent measurements was also made by Van Eck et al. (2011), with the VLA. Van Eck et al. (2011) found generally satisfactory agreement, although there was a population
Figure 2.6: Comparison of RM values from Taylor et al. (2009) and the present study. The lighter solid line represents the case of perfect agreement, and the heavy solid line represents a weighted least-squares fit to the data.

of outliers as well as an apparent systematic bias at RM $\simeq 50$–$100$ rad m$^{-2}$ (see Figure 4 of Van Eck et al. (2011)). A full discussion of the comparison between independent RM measurements and the RM values from Taylor et al. (2009) is given in Section 4.2 of Harvey-Smith et al. (2011). We think it worthwhile to make additional comparisons between Taylor et al. (2009) and independent measurements made specifically for the purpose of measuring Faraday rotation. Figure 2.6 illustrates the comparison of our RM measurements with those of Taylor et al. (2009). The sources that are in common are all exterior sources, O1, O2, O4, O7, O9, O15, and O17. None of our interior sources were contained in the catalog of Taylor et al. (2009). Our RM values compare favorably with those of Taylor et al. (2009). The light solid line in Figure 2.6 shows the case of perfect agreement between the two sets of measurements, and this is clearly a satisfactory representation of the data. A weighted least squares linear fit to the data shown in Figure 2.6 gives a slope of $m = 1.04 \pm 0.04$ and an intercept of $b = -14.1 \pm 8.1$ rad m$^{-2}$ (heavy solid line). The good agreement between the two sets of measurements is consistent with the assessment of Van Eck et al. (2011), and gives confidence in our RM measurements. We note that this does
not address the question of the systematic error in some of Taylor et al. (2009) RMs that was pointed out by Van Eck et al. (2011).

2.4 Observational Results and Modeling in Terms of the Interaction of an HII Region with the Interstellar Medium

The first question in the analysis is whether the RM data from Table 2.3 show evidence for an RM enhancement associated with the Rosette Nebula. Such an enhancement is illustrated and clearly seen in Figure 2.7. In Figure 2.7, we plot the measured RM versus angular distance from the center of the Rosette Nebula, which we take to be the center of the NGC 2244 star cluster as given by Berghöfer & Christian (2002) (see Introduction). A very clear signature of a Faraday rotation enhancement is seen for the 6 lines of sight (nine sources and source components) with angular separation \( \leq 40' \) from the nebular center. The excess RM due to the Rosette Nebula is also visible in Figure 1, in which the size of the plotted symbol for each source is dependent on RM. Those sources viewed through the Rosette have larger RMs. The mean RM for sources seen through the Rosette Nebula is 675 rad m\(^{-2}\), with a range of 200 \( \leq \) RM \( \leq \) 900 rad m\(^{-2}\). Lines of sight that are more than 40' from the center of the nebula have a mean of 147 rad m\(^{-2}\), with a standard deviation of 77 rad m\(^{-2}\). In calculating the mean and standard deviation of the background, we have excluded the two sources in our sample with a negative RM (I18, RM=\(-270 \pm 54\) rad m\(^{-2}\) and O14(b), RM=\(-38 \pm 60\) rad m\(^{-2}\)). It is unclear whether the negative RMs have Galactic or extragalactic origins. The RM in both cases was obtained from measurements at only two frequencies. As presented in Table 2.3, both the polarized intensity and degree of linear polarization for those two sources are low. Although we include these sources in Table 2.3 because they passed our selection criteria, we do not include them in our calculation of the Galactic mean background. We interpret this mean background as due to the Galactic Faraday rotation in this part of the sky, which is independent of the Rosette Nebula. The data in Figure 2.7 show a “RM anomaly” of 50–750 rad m\(^{-2}\) associated with the Rosette Nebula. This is comparable to, and perhaps slightly smaller than that reported for the Cygnus OB1
association by Whiting et al. (2009). However, the Whiting et al. (2009) result is more ambiguous because of the angular proximity of other HII regions as well as other Galactic objects, which confuse measurements in that field.

Figure 2.7: RM (rad m$^{-2}$) for each source and source component in Table 2.3 vs. angular distance (arcminutes) from the center of the Rosette Nebula. All the sources, and components, are represented on the graph along with the associated error bars.
Table 2.3: Polarization Results

<table>
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<tr>
<th>Source</th>
<th>Component</th>
<th>( \nu ) (GHz)</th>
<th>( L ) (mJy beam(^{-1}))</th>
<th>( m ) (%)</th>
<th>( \chi ) (°)</th>
<th>RM (rad m(^{-2}))</th>
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<tr>
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</tr>
<tr>
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</tr>
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<td>$m$ (%)</td>
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Table 2.3 – Continued
Table 2.3 – Continued

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<td>4.9</td>
<td>20.80 ± 0.06</td>
<td>8</td>
<td>16.4 ± 0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.6</td>
<td>14.87 ± 0.11</td>
<td>8</td>
<td>6.6 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>O16</td>
<td>4.4</td>
<td>3.23 ± 0.05</td>
<td>13</td>
<td>−70.8 ± 0.4</td>
<td>199 ± 6</td>
</tr>
<tr>
<td></td>
<td>4.9</td>
<td>2.96 ± 0.04</td>
<td>13</td>
<td>−81.6 ± 0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.6</td>
<td>1.94 ± 0.05</td>
<td>13</td>
<td>−105.3 ± 0.7</td>
<td></td>
</tr>
<tr>
<td>O17</td>
<td>4.4</td>
<td>2.52 ± 0.03</td>
<td>10</td>
<td>−27.2 ± 0.4</td>
<td>149 ± 11</td>
</tr>
<tr>
<td></td>
<td>4.9</td>
<td>2.28 ± 0.03</td>
<td>10</td>
<td>−34.7 ± 0.4</td>
<td></td>
</tr>
</tbody>
</table>

2.4.1 Comparison of Observations to HII Region Shell Models

In this section, we compare our observations with mathematically simple expressions which describe the dynamics of an HII region interaction with the surrounding ISM. The first is the model presented in Whiting et al. (2009). The Whiting et al. (2009) model contains a simple parameterization of a stellar bubble, as described by the theory of Weaver et al. (1977). In that model, the HII region consists of an inner, low density cavity comprised of shocked stellar wind, and a contact discontinuity (assumed spherical) separating the shocked stellar wind from ISM material. This ISM material is shocked and photoionized interstellar gas which has passed through an outer shock. The last part of the bubble structure is the outer shock itself. The parameters of the model are \(R_0\), the outer radius of the shell; \(R_1\), the inner radius of the shell; \(n_e\), the plasma density within the shell; \(n_e = 0\) is assumed for \(r < R_1\); and \(\vec{B}_0\), the interstellar magnetic field outside the shell. A distinction

\(^4\)This model is described in more detail in Section 5.1 of Whiting et al. (2009), and illustrated in Figure 6 of that paper.
is made between the pristine magnetic field $\vec{B}_0$ upstream of the outer shock, and the down-
stream magnetic field inside the plasma shell, which has been modified by passage through the
shock.

Whiting et al. (2009) obtain the following formula for the RM through such a shell.

$$\text{RM}(\xi) = \frac{C n_e L(\xi)}{2} [B_{ZI} + B_{ZE}]$$ (2.6)

where $n_e$ is the plasma density (electron density) in the shell, $L(\xi)$ is the length of the
chord through the shell, and $B_{ZI}$ and $B_{ZE}$ are the downstream line of sight components of
the magnetic field at the points where the line of sight enters (ingress) and leaves (egress)
the shell respectively, given in Equations (7)–(9) of Whiting et al. (2009). The variable $\xi$ is
the transverse, linear distance between the line of sight and a line of sight passing through
the center of the shell (i.e., $\xi=0$ is a line of sight through the center of the shell and $\xi=R_0$
is a line of sight which is tangent to the outer edge of the shell.). The constant $C$ is the
collection of fundamental physical constants in curved brackets in Equation (2.1). The
constant $C$ has the value $2.631 \times 10^{-17}$ in cgs units, or 0.81 if “interstellar units” of cm$^{-3}$,
$\mu$G, and parsecs are chosen for $n_e$, $\vec{B}_0$, and $L$, respectively. $L(\xi)$ is given by

$$L(\xi) = 2R_0 \sqrt{1 - (\xi/R_0)^2}, \text{ if } \xi \geq R_1$$ (2.7)

$$L(\xi) = 2R_0 [\sqrt{1 - (\xi/R_0)^2} - (R_1/R_0) \sqrt{1 - (\xi/R_1)^2}], \text{ if } \xi \leq R_1$$

Exterior to the shell, we assume the magnetic field of the ISM is uniform, but it will
be modified in the shell. The theory of magnetohydrodynamic shock waves (e.g., Gurnett
& Bhattacharjee (2005)) shows that the magnetic field component in the shock plane is
amplified by a factor $X$, and the component normal to the shock front is unchanged. The
factor $X$, for the case of a strong shock, is equivalent to the density compression ratio.

We redefine the $B_{ZI}$ and $B_{ZE}$ components in terms of $B_{0Z}$, the upstream line of sight
component of the magnetic field. Employing these assumptions and definitions in Equation
(2.6), we have
\[
\text{RM}(\xi) = C n_e L(\xi) B_{0Z} \left[ 1 + (X - 1) \left( \frac{\xi}{R_0} \right)^2 \right].
\] (2.8)

It should be pointed out that our shell model, expressed in Equations (6)–(8), assumes that the post-shock field strength at the ingress or egress point applies everywhere along the half-chord connecting the ingress or egress point to the midpoint of the chord (see Figure 6 of Whiting et al. (2009) for an illustration). No attempt is made here to confront the physically complex question of the shell magnetic field as a function of position throughout the shell. Our approximation is presumably accurate for a thin shell, in which the chord extends only a short distance from the shock front before entering the bubble interior (again, see Figure 6 of Whiting et al. (2009)). However, in the case of a thick shell, this approximation must break down, and Equation (8) must be inaccurate. Other than recognizing this fact, further investigation is beyond the scope of this paper. This recognition should motivate further theoretical work to obtain analytic expressions which incorporate the results of MHD calculations such as Ferriere et al. (1991) and Stil et al. (2009). For our model of Equation (8), we adopt the shell parameters from Celnik (1985), where \( R_0 = 16.9 \) pc, \( R_1 = 6.2 \) parsecs, and \( n_e = 10.8–15.5 \) cm\(^{-3}\). These numbers refer to Celnik’s Model 1, which is the single shell model. For the calculations described below we utilize a density equal to the mean of Celnik’s values, \( n_e = 13.1 \) cm\(^{-3}\). The variable \( B_{0Z} \), the \( z \) component of the upstream ISM magnetic field, is
\[
B_{0Z} = B_0 \cos \theta,
\]
where \( B_0 \) is the magnitude of the general interstellar field. In the analysis of this paper, we assume \( B_0 \) to be a known constant, and \( \theta \) to be a variable with a wide range of possible values at a given point in the Galaxy. The justification for this choice is the rather well-established value for the magnitude of the magnetic field in the low density phases of the ISM (e.g., Rand & Kulkarni (1989); Minter & Spangler (1996); Haverkorn et al. (2006)). We choose \( B_0 = 4 \) \( \mu \)G in the calculations below. The angle \( \theta \) may have a well-defined expectation value for the location of the Rosette Nebula in the Galaxy, but the actual value
at a specific location and time presumably departs significantly from this expectation value due to turbulent fluctuations in the ISM. A meaningful analogy would be the interplanetary magnetic field at 1 AU. Although the average direction conforms to the Parker spiral, a measurement at a given time shows the field pointing in a wide range of directions.

It should be recognized that in reality, both $B_0$ and $\theta$ are random variables with mean values and probability density functions. As such, the true unknown variable is $B_{0z}$ which is formed from them. Again, observations of the solar wind prove instructive. Examination of several days of interplanetary magnetic field measurements show that the angles defining the direction of the interplanetary field show random variations, but the magnitude of the field does as well. The solar wind provides some support for our practice in the present case. Although the magnitude of the field does change with time, the fractional changes are usually relatively small in comparison with the large variations in the orientation of the interplanetary field. This statement is supported by the well-known observational result that the variance of the magnitude of the interplanetary field is much less than the variance in the components (Bruno & Carbone, 2005).

In comparing the model of Equation (8) with our data, we overlaid curves generated by Equation (2.8) on a plot of the RM versus the distance $\xi$ in parsecs from the center of the Rosette (Figure 2.8), and effectively used the free parameter $\theta$ as a “tuning knob” for the model. By doing so, we obtained a value of $\theta = 72^\circ$ such that the model reproduces the magnitude of the measured RMs, and their dependence on the distance from the center of the Rosette Nebula. The degree of agreement between the model and the data in Figure 2.8 is actually quite good, particularly since we have adopted the shell model parameters $R_0$, $R_1$, and $n_e$ directly from the data of Celnik (1985). We have not varied these parameters in an attempt to optimize the fit. Figure 2.9 presents the shell model with altered radii in order to obtain a better fit for the model Equation (2.8) to the data.

To fit the magnitudes of the RMs viewed through the nebula, our model requires that the interstellar magnetic field at the location of the Rosette Nebula (before modification by the bubble associated with the Rosette) be rather highly inclined to the line of sight.
Figure 2.8: Plot of RM vs. distance from center of the Rosette Nebula. This plot differs from Figure 2.7 in that the distance of the lines of sight from the nebular center have been converted from arcminutes to parsecs, and the model for Faraday rotation through a stellar bubble given by Equation (2.8), has been overplotted. This model utilizes the following shell parameters: $R_1=6.2$ pc, $R_0=16.9$ pc, and $n_e=13.1\ \text{cm}^{-3}$. Achieving this fit requires that the interstellar magnetic field at the location of the Rosette Nebula has a magnitude of 4 $\mu$G and is inclined at an angle $\theta=72^\circ$ with respect to our line of sight.

Figure 2.9: This plot is the same as Figure 2.8 except the inner radius of the shell has been changed to optimize the fit to the data, $R_1=4.2$ pc. The value of $\theta$ is $\theta = 72^\circ$. 
Interestingly, our value of \( \theta \) is roughly consistent with that expected for the mean Galactic field at the location of the Rosette Nebula. We use the galactic longitude of 206.5 for the Rosette, and assume a Galactocentric distance of the Sun of 8.5 kpc, and a distance to the Rosette of 1.6 kpc. In this case, the angle between the line of sight and an azimuthal magnetic field is 68°. This is obviously completely consistent (to a doubtlessly fortuitous degree) with our model value of \( \theta = 72° \).

Studies of the functional form of the Galactic magnetic field, while not conclusive at discriminating between an azimuthal field and one which follows the spiral arms, indicate that the field in the approximate neighborhood of the Sun has a pitch angle of \(-8°\) (Beck, 2001; Ferri`ere, 2011). Application of this pitch angle to an azimuthal field would then produce an expected angle of 60° between the mean Galactic field at the location of the Rosette and the line of sight. This value is also in acceptable agreement with our inferred value, in that it indicates a magnetic field that is oriented at a large angle with respect to the line of sight.

We now consider a quite different HII region model which has been discussed in the context of Faraday rotation “anomalies”, that of Harvey-Smith et al. (2011) discussed in Section 2.1.3 above. Harvey-Smith et al. (2011) concluded that the magnetic field was not amplified in the volume of the HII region. We have adjusted our Equation (2.6) to express the Harvey-Smith et al. (2011) assumption of no \( \vec{B} \) field amplification, giving the formula

\[
RM(\xi) = C n_e L(\xi) B_0 Z
\]  

(2.9)

where all parameters are defined following Equation (2.6). The difference between these two expressions is that Equation (2.9) does not include amplification of the “upstream” interstellar magnetic field by the outer shock of the stellar bubble. As before, \( \theta \) is the only free parameter and was varied to obtain a fit to the observed RM observations. By visual inspection, we obtained \( \theta = 54° \) for reasonable agreement between Equation (2.9) and the data. A comparison of the model given by Equation (2.9) with the data is shown in Figure 2.10. Although it produces the magnitude and angular scale of the RM anomaly, it arguably
does not do as well in reproducing the observed dependence of RM on distance from the center of the nebula. The smaller inclination of the interstellar magnetic field ($\theta=54^\circ$) is easily understood since in this latter model, there is no amplification of the perpendicular component of the interstellar magnetic field at the outer shock front (see Equation (9) of Whiting et al. (2009)). We suggest that the model of Whiting et al. (2009) provides a better fit to the observed dependence of RM on distance from the center of the nebula for the case of the Rosette Nebula. To distinguish between these two models will require more lines of sight which pass between the inner and outer radii of the bubble (6 and 17 pc in the case of the Rosette Nebula). For the shell models described by Equation (2.9), in which the pre-existing interstellar magnetic field is unaltered by the presence of the HII region, the RM should have a maximum near the inner radius, as shown in Figure 2.10. In the model of Whiting et al. (2009), on the other hand, the magnetic field is amplified and “refracted” into the shock plane. This has the potential of producing “RM limb brightening”, as might be present in the Rosette Nebula data, Figures 2.8 and 2.9. This situation might be clarified by RM measurements of an additional 11 sources that were made with the VLA in 2012 February, and are currently awaiting reduction and analysis.

The fit value for $\theta$ probably does not have much diagnostic ability, at least in the case of a single nebula. The values of $\theta$ for an azimuthal Galactic magnetic field ($68^\circ$), or a spiral field with a pitch angle of $8^\circ$, $\theta = 60^\circ$ are more or less equally compatible with our shell model or the unmodified field model, Equation (2.9). However, all studies of the Galactic magnetic field show that the random component of the field is comparable to, if not larger than, the mean systematic component (e.g., Rand & Kulkarni (1989); Minter & Spangler (1996); Haverkorn et al. (2006)). Thus the interstellar magnetic field at the location of the Rosette is doubtlessly comprised of a mean, large scale component which is inclined at a large angle to the line of sight, and a random, turbulent component which is isotropic. As a result, the “local” interstellar magnetic field at the Rosette Nebula could point in virtually any direction.
Figure 2.10: This plot is the same as Figures 2.8 and 2.9 except the model that has been
overplotted is given by Equation (2.9) (interstellar magnetic field unmodified by HII re-
gion). This model curve requires that the interstellar magnetic field at the location of the
Rosette Nebula is inclined at an angle $\theta=54^\circ$ with respect to our line of sight.

There are some final and obvious remarks which should be made regarding a com-
parison between the results of the present study of the Rosette Nebula and those of Harvey-
Smith et al. (2011) on five other HII regions. The model of Whiting et al. (2009) assumes
that the plasma shell around the HII region is a bubble as described by the theory of Weaver
et al. (1977). The formation of a bubble on the scale of the Rosette Nebula requires stars
with very large wind luminosities, which can only be furnished by very early main sequence
stars or Wolf-Rayet stars. Such stars will only be found in very young stellar associations.
At a later time, stellar wind luminosities will subside and the wind-blown bubble or super-
bubble will cease to exist. As was discussed in the Introduction, the Rosette Nebula is an
excellent candidate for a stellar superbubble. The observations of Menon (1962) showed
that it has the annular shell structure expected of such a bubble, and it has been used as a
paradigmatic wind-blown structure in theoretical studies (e.g. Dorland et al. (1986); Dor-
land & Montmerle (1987)). It therefore would be expected, a priori, to show the plasma
structure expected for a bubble.
The HII regions studied by Harvey-Smith et al. (2011) could well be older clusters that are past the age when luminous stellar winds dominate their surroundings in the ISM. Resolution of this interesting question will require further observations of a sample of HII regions, with independent information on the ages of the star clusters and the wind luminosities of the constituent stars.

2.4.2 Differences in Rotation Measure between Closely Spaced Lines of Sight

The data in Table 2.3 show several cases in which RM is measurable for two components within the same source. This raises the possibility of measuring RM differences between closely-spaced lines of sight. Spangler (2007) uses the term *differential Faraday rotation* to describe such differences. In the case of the present observations, with a synthesized beam width (FWHM) of 12″8 and an assumed distance to the Rosette Nebula of 1600 pc, we can examine lines of sight separated by as little as 0.1 pc.

Differential Faraday rotation observations have been discussed by many authors (e.g., Minter & Spangler (1996); Haverkorn et al. (2008)). Measurements of the RM difference $\Delta$ RM on many pairs of lines of sight with a range of angular separations $\delta \theta$ can be used to construct the RM structure function $D_{RM}(\delta \theta)$. The RM structure function yields characteristics of interstellar plasma turbulence (Minter & Spangler, 1996; Haverkorn et al., 2008). Spangler (2007) also pointed out that a measurement of differential Faraday rotation could indicate the presence of an electrical current flowing between the lines of sight, and used a measurement of differential coronal Faraday rotation to deduce a model-dependent value for the magnitude of coronal currents. The same ideas could be applied to measurements of interstellar Faraday rotation.

In this subsection, we briefly discuss the status of differential Faraday rotation in our sample of sources. Nine of the sources in Table 2.3 have RM values for two source components. We restrict attention to those sources with $\chi$ measurements at three frequencies. Such observations provide more secure and precise RM values. These sources are I8, I14, O2, O4, O5, and O9. Obviously, with such a restricted set of data we cannot construct a
RM structure function, and our comments here will remain qualitative.

We first consider the four “exterior” sources O2, O4, O5, and O9. The RM values for these sources are presumably determined by the general ISM, with no contribution from the Rosette Nebula. The ∆ RM values for these sources range from ~ 7–25 rad m$^{−2}$, and in at least two cases (O5 and O9) seem consistent with zero, given the measurement errors. The other two exterior sources (O2 and O4) have ∆ RM values which appear slightly larger than expected for noise fluctuations about a zero expectation value.

The two “interior” sources I8 and I14 have ∆ RM values in excess of 100 rad m$^{−2}$, and larger than expected from our error estimates. This would seem to indicate enhanced differential Faraday rotation for lines of sight that pass through the interior of the Rosette Nebula, implying higher levels of plasma turbulence or electrical current systems flowing in the bubble associated with the Rosette. However, two caveats should be noted. First, as noted in Section 2.2, it is possible that component b of I14 is internally depolarized at the frequencies of observation, in which case neither the fit RM for component b nor the measured ∆ RM between the two components is a diagnostic of the ISM. Second, the small number of sources we are considering (two interior and four exterior sources) precludes any firm conclusions about the statistics of differential Faraday rotation inside and outside of the Rosette Nebula.

Given the data available in the present paper, a possible enhancement in ∆ RM for the interior source I8 (and perhaps I14) relative to the exterior sources is speculative. The statistics of differential Faraday rotation for lines of sight passing through the Rosette Nebula, and the comparison with the statistics for lines of sight which do not pass through the nebula, need to be determined by measurements for a larger number of sources. As mentioned in Section 2.4.1, multifrequency polarization measurements of an additional 11 sources with lines of sight through the nebula have been made and are awaiting reduction and analysis. Those data should determine if an enhancement in differential Faraday rotation due to the Rosette Nebula exists, and if it does exist, establish its properties.
2.5 Summary and Conclusions

The conclusions of this paper are as follows.

1. We observed 23 extragalactic radio sources whose lines of sight pass through or close to the Rosette Nebula and obtained Faraday rotation measurements for 21 of them. The interior sources, whose lines of sight pass through the Rosette, have an excess RM of 50–750 rad m$^{-2}$ with respect to a background due to this part of the galactic plane, which we determined to be +147 rad m$^{-2}$. We interpret this 50–750 rad m$^{-2}$ excess as the Faraday rotation measure of the plasma shell which comprises the Rosette Nebula.

2. We have compared our observations with a simplified analytic model for the plasma shell associated with a wind-driven, photoionized stellar bubble surrounding the NGC 2244 star cluster. This model was derived and presented in Whiting et al. (2009). We find the measurements adhere well to the model if the angle between the line of sight and the Galactic magnetic field at the location of the Rosette Nebula is $\theta=72^\circ$ (see Figure 2.8). This angle is compatible with that expected for the mean Galactic field at the location of the Rosette Nebula ($60^\circ$–$68^\circ$). Our observations support an interpretation in which the Rosette Nebula is a wind-blown bubble as described by the theory of Weaver et al. (1977).

3. We have also compared our observations with a simpler model in which the NGC 2244 star cluster photoionizes the surrounding gas without modifying the magnetic field, as proposed by Harvey-Smith et al. (2011). This model, unlike the stellar bubble model, does not naturally account for the observed, annular shell structure of the Rosette Nebula. This model can also reproduce the magnitude of the RMs measured through the Rosette Nebula, with a smaller angle between the line of sight and the interstellar field at the location of the Rosette ($\theta=54^\circ$). This model does not seem to account as well for the observed dependence of RM on the projected distance from the center of the nebula.
4. A determination of which of these models, if either, is better for the plasma structure of HII regions will require similar studies of more HII regions (with large numbers of lines of sight per HII region), spanning a range in age of the embedded star clusters.

5. We have compared our RM values with those of Taylor et al. (2009) for the 7 sources (with 10 source components) in common. Good agreement between the two sets of measurements was found. This comparison was principally undertaken as a check of the RMs resulting from our observations, but it also contributes to the literature on the accuracy of the large Taylor et al. (2009) RM data set. Our limited investigation supports the general accuracy of the Taylor et al. (2009) data, but does not contradict the finding of episodic inaccuracies or biases, as discussed in Van Eck et al. (2011).
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