CONFIRMATION OF A FARADAY ROTATION MEASURE ANOMALY IN CYGNUS

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ABSTRACT

We confirm the reality of a reversal of the sign of the Faraday rotation measure in the Galactic plane in Cygnus (Lazio et al. 1990), possibly associated with the Cygnus OB1 association. The rotation measure changes by several hundred rad m$^{-2}$ over an angular scale of 2$\degree$–5$\degree$. We show that a simple model of an expanding plasma shell with an enhanced density and magnetic field can account for the magnitude and angular scale of this feature. This model is consistent with observations of H$\alpha$ emission as well as other observations in this part of sky. We suggest that this structure is physically associated with a superbubble produced by the Cygnus OB1 association.

Key words: ISM: bubbles – H II regions – ISM: magnetic fields

1. INTRODUCTION

Faraday rotation is one of the best diagnostics of the plasma properties of the interstellar medium (ISM), in particular the strength and direction of the interstellar magnetic field (e.g., Clegg et al. 1992; Minter & Spangler 1996; Frick et al. 2001; Haverkorn et al. 2004; Vallee 2004; Haverkorn et al. 2006). When radio emission from a source of polarized radio waves propagates through a plasma, such as the ISM, the measured polarization position angle $\chi$ is given by

$$\chi = \chi_0 + \left[ \left( \frac{e^3}{2\pi m_e c^2} \right) \int n\vec{B} \cdot d\vec{s} \right] \lambda^2, \quad (1)$$

where $\chi_0$ is the intrinsic polarization position angle assumed independent of wavelength ($\lambda$), $n$ is the plasma density, $\vec{B}$ is the vector magnetic field, and $d\vec{s}$ is an incremental pathlength interval along the line of sight. The quantities $e$, $m_e$, and $c$ are the usual fundamental physical constants of the elementary electrical charge, the mass of an electron, and the speed of light. The quantity within square brackets is termed the rotation measure (RM) and is the quantity which constitutes a plasma diagnostic of the ISM. Equation (1) is in the cgs system of units. Conversion of the rotation measure to the more common SI units of rad m$^{-2}$ is done by multiplying the cgs value by a factor of $10^4$.

The rotation measure is a signed quantity, dependent on the density-weighted line of sight component of the magnetic field. The sign of the RM is of physical interest because it diagnoses the net polarity of the magnetic field along the line of sight. As seen in Equation (1), an increase in $\chi$ with increasing $\lambda$ indicates that RM, and thus the path-averaged magnetic field, is positive.

Measurements of rotation measure have been made along hundreds of lines of sight through the galaxy using many radio telescopes. These observations have been used to determine the large-scale structure of the Galactic magnetic field (e.g., Clegg et al. 1992; Vallee 2004) as well as properties of turbulence in the ISM (Lazio et al. 1990; Minter & Spangler 1996; Haverkorn et al. 2004).

This paper is particularly concerned with results reported by Lazio et al. (1990). Polarization measurements at three frequencies were made with the Very Large Array (VLA)4 of eight extended radio sources observed through the Galactic plane in Cygnus, in the vicinity of the Cygnus OB1 association. Previous radio observations had shown this region to be one of strong radio wave scattering, presumably due to plasma turbulence associated with the Cygnus OB1 association (Spangler & Cordes 1988; Fey et al. 1989; Spangler & Cordes 1998, see Section 2 below). The main goal of the observations of Lazio et al. (1990) was to determine properties of the plasma turbulence on large spatial scales, manifest by differences $\Delta$RM in the rotation measures on adjacent lines of sight to different parts of a background extragalactic radio source, and between lines of sight to different sources. The observations of Lazio et al. (1990) were consistent with a Kolmogorov spectrum of irregularities in the plasma around the Cygnus OB1 association.

The magnitude of Faraday rotation in this part of the Galactic plane was found to be sufficiently large to cause difficulty in extracting RM values from the observations at frequencies of 1.44, 1.65, and 4.88 GHz made by Lazio et al. (1990). The basic problem is that for RMs of several hundred rad m$^{-2}$, there can be several turns of the position angle between 1.65 and 4.88 GHz, and even a turn (or more) between 1.44 and 1.65 GHz. This is illustrated graphically in Figure 3 of Lazio et al. (1990). A technique was employed whereby the optimum set of values of RM consistent, in a least-squares sense, with the position angle measurements was retrieved. In the cases of four sources, 2004 + 369, 2005 + 368, 2007 + 365, and 2011 + 360, secure enough values for the average RM to the source were obtained to permit “unambiguous” rotation measures reported in Table 3 of Lazio et al. (1990). The RM values reported were all positive with values between 228 and 850 rad m$^{-2}$.

Clegg et al. (1992) presented polarization observations yielding RM for 56 extragalactic radio sources viewed through the Galactic plane, of which 4 were in the vicinity of the Cygnus OB1 association. The RM values reported were large (absolute magnitudes of several hundred rad m$^{-2}$), and negative. There were no sources in common between the samples of Lazio et al. (1990) and Clegg et al. (1992). This apparent large change in the RM (from several hundred rad m$^{-2}$ positive to a similar magnitude, but negative) within a small angular distance suggested

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4 The Very Large Array is an instrument of the National Radio Astronomy Observatory. The NRAO is a facility of the National Science Foundation, operated under cooperative agreement with Associated Universities, Inc.
either (1) an error in the observations and/or data reduction procedure by Lazio et al. (1990), so that the sign change did not exist, or (2) the existence of a remarkable plasma structure in the Galactic plane in this region, which could cause such a large gradient in RM. We refer to this large change in the Galactic Faraday rotation measure over a small angular scale as a Rotation Measure Anomaly. A partial argument against possibility (1) was available even at the time of Clegg et al. (1992). Processing of the polarization position angle measurements made and published by Lazio et al. (1990) through the RM algorithm of Clegg et al. (1992) yielded the RM values given in Table 3 of Lazio et al. (1990).

The purpose of this paper is to report observations made to confirm the large, positive RM values of Lazio et al. (1990). Observations were made with the VLA at two widely separated frequencies within the 5 GHz RF (radio frequency) bandpass. Observations were made at this frequency because RM values of the magnitude reported by Lazio et al. (1990) and Clegg et al. (1992) would cause measurable rotation of several degrees of position angle or more between the two bands, but there would be no “π” ambiguity.

There are two important results of this paper. The first is the confirmation of the large positive RMs reported by Lazio et al. (1990), and the corresponding pronounced rotation measure anomaly associated with the Cygnus OB1 association. The second result is that a simple, physically based model for this region of stellar interaction with the ISM can account for the magnitude and angular scale of the RM anomaly. The model describes the superbubble produced by the winds of a stellar association expanding in the magnetized plasma of the ISM. The existence of this bubble is indicated by H-Alpha spectroscopic observations made with the Wisconsin H Alpha Mapper (WHAM) and presented here, as well as previous results from the literature. These two results indicate that Faraday rotation observations and this model, in its present or a more sophisticated form, can be useful in exploring other locations where massive young stars interact with the ISM.

The outline of this paper is as follows. In Section 2, we summarize what is known from the literature on the Cygnus OB1 association and its plasma environment. In Section 3, we describe the polarimetric observations made with the VLA at 5 GHz (C band), and optical observations made with WHAM to investigate the plasma along this line of sight. In Section 4, we compare the RM values obtained here with the values of Lazio et al. (1990), and see that they are consistent. In Section 5, we develop a simple model for the plasma structure of an expanding plasma shell, presumably a stellar bubble, associated with the winds and UV radiation of the Cygnus OB1 association, and show that this model is capable of reproducing the magnitude and angular scale of the observed RM anomaly. Finally, Section 6 summarizes and concludes.

2. PLASMA ENVIRONMENT OF THE CYGNUS OB1 ASSOCIATION

The radio sources studied in this paper are in the Galactic plane, viewed through the vicinity of the Cygnus OB1 association. Cygnus OB1 is one of several OB associations in this part of the sky which are responsible for enhanced Hα, thermal radio, and x-ray emission relative to other directions in the Galactic plane (Bochkarev & Sitnik 1985).

Saken et al. (1992) and Nichols-Bohlin & Fesen (1993) discussed an apparent physical connection between the stars of Cygnus OB1 and an ionized shell of gas visible in infrared imagery and Hα and ultraviolet spectroscopy. Although its existence and nature are by no means certain, this feature may correspond to the dense shell of shocked and photoionized interstellar gas associated with the bubble (or superbubble) produced by the Cygnus OB1 association and approximately described by the theory of Weaver et al. (1977). A projection of the positions of the O and B stars in the Cygnus OB1 association (taken from Humphreys 1978) on the Hα image shows that most of the stars fall within, or slightly beyond, the possible shell, which mildly corroborates our interpretation of it as the swept-up plasma of an interstellar superbubble. This point was also made in Nichols-Bohlin & Fesen (1993).

The superbubble associated with Cygnus OB1 is seen as a roughly circular arc with an angular radius of ≃ 2', centered on l = 75:0 and b = 1:0. Lozinskaya & Sitnik (1988) and Pravdikova (1995) have also discussed the relationship between this structure of ionized gas and the spectral class O and Wolf–Rayet stars in the Cyg OB1 star cluster. There is spectroscopic evidence for an expanding shell of gas associated with the association. This expanding shell includes both ionized gas (Nichols-Bohlin & Fesen 1993; Sitnik et al. 1995) and neutral gas (Dewdney & Lozinskaya 1994), which presumably lies outside the ionized shell. These observations indicate that the shell of gas is expanding in our direction at a speed of 50–70 km s⁻¹ (Sitnik et al. 1995). This last observation partially motivated the superbubble model developed in Section 5. Results published in the literature do not show as clear observational evidence for the redshifted, far side of the bubble. This issue is discussed further in Section 5.

The best estimate for the distance to Cygnus OB1 is 1.8 kpc. The basis for this distance (also adopted in Spangler & Cordes 1998) is the set of results presented in Section 2.4 of Nichols-Bohlin & Fesen (1993, see Table 3 of that paper). At this distance and with the aforementioned angular radius of 2', the physical radius of the shell is of order 72 parsec. Furthermore, properties of the Cygnus OB1 superbubble are developed in Section 5.1 as part of our physical model for the RM anomaly.

3. OBSERVATIONS

3.1. VLA Polarimetric Observations

Radio polarization measurements of four sources from the sample of Lazio et al. (1990) were made on 1999 December, 13–14. The observations were made between UT 19:46 on December 13 to UT 3:42 on December 14. The sources observed are given in Table 1. Column 1 gives the J2000 name of the source, and column 2 gives the B1950 name used in Lazio et al. (1990). The remaining columns are described at the end of this section.

Three of the sources listed in Table 1, 2007 + 369, 2009 + 367, and 2013 + 361, had rotation measures listed as “unambiguous” by Lazio et al. (1990). The fourth source, 2015+364, was not so listed but was observed in the present project because of the high polarized intensity, which facilitated a comparison of our observations and results with those of Lazio et al. (1990).

Observations were made at two frequencies, 4585 and 4885 MHz within the C band RF bandpass. At both frequencies, a 50 MHz intermediate frequency (IF) bandwidth was received and correlated. The 300 MHz separation between the two bands is about the maximum possible within the overall C band front-end bandpass for the original pre-EVLA receivers, while still

5 The Expanded Very Large Array (EVLA) is a project, currently underway, to upgrade the receivers and other systems of the VLA.
having similar gain and acceptable system temperature. For the purposes of this project, we consider polarization measurements at two frequencies as adequate for measuring Faraday rotation, rather than three frequencies as conventionally prescribed. As discussed in the preceding section, given the rotation measure values published by Lazio et al. (1990), the Faraday rotation between the closely spaced frequencies of 4585 and 4885 MHz should be a small fraction of 180°. In this case, there is no possibility of the polarization position angle rotating through 180° or more between the two frequencies of observation (the "\(n\pi\) ambiguity"). At the time of the observations, the VLA was in the B array.

In addition to the four program sources given in Table 1, we also observed the source 2007 + 404 as a phase and instrumental polarization calibrator, and 3C138 for purposes of calibrating the polarization position angles. The procedures of polarization calibration and mapping and analysis of the data are essentially identical to those in previous VLA polarization projects of ours such as Lazio et al. (1990).

In the previous investigations, the basic data products used were maps of the Stokes parameters \(Q\) and \(U\), and maps of the polarization position angle \(\chi\), and the polarized intensity \(L\),

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

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

Since the maps were made from 5 GHz data taken in the B array, the angular resolution of the maps is about 1.9 arcsec (FWHM of synthesized beam).

The procedure for measuring Faraday rotation from these observations was as follows. Maps of \(\chi\) and \(L\) were made at both frequencies. The maps of \(\chi\) at the two frequencies were subtracted from each other, giving a map of \(\Delta\chi\), where the definition and significance of \(\Delta\chi\) are

\[
\Delta\chi = \chi(4585) - \chi(4885) = RM \left[ \lambda_{4585}^2 - \lambda_{4885}^2 \right]
\]

\[
RM = \frac{\Delta\chi}{\lambda_{4585}^2 - \lambda_{4885}^2} = 34.3 \Delta\chi(\circ) \text{ rad m}^{-2}.
\]

In Equation (3), \(\chi(4585)\) is the polarization position angle measured at a frequency of 4585 MHz, \(\lambda_{4585}\) is the corresponding wavelength at that frequency, and \(\Delta\chi(\circ)\) is the difference in the polarization position angles at 4585 and 4885 MHz in degrees. In the first two lines of Equation (3), \(\chi\) and \(\Delta\chi\) are in radians and \(\lambda_{4585}\) and \(\lambda_{4885}\) are in meters, and RM has its conventional units of rad m\(^{-2}\). In the convenient formula of the third line of Equation (3), RM is also in rad m\(^{-2}\), and \(\Delta\chi(\circ)\) is in degrees.

Illustrations of our data reduction procedures are given in Figures 1 and 2 for the sources 2007 + 369 and 2015 + 364, respectively. In each figure, panel (a) shows the polarization position angle map with variations in \(\chi\) reflecting the intrinsic structure of the radio source. A comparison of these maps with the corresponding ones in Figure 2 of Lazio et al. (1990) shows entirely satisfactory agreement, even though the observations of Lazio et al. (1990) were made in the C array, and had lower
angular resolution (restoring beams roughly 3 times larger) than
the present maps. This statement is true for all four sources in
common between the present project and that of Lazio et al.
(1990).

The \( \Delta \chi \) maps in panel (b) of both figures show a rotation
between the two frequencies, which can be related to RM via
Equation (3). For both sources, \( \Delta \chi \) is nearly uniform across
the source being about 20\(^\circ\) for 2007 + 369, and nearly zero for
2015 + 364 (see Table 1 for exact values). The data in these
figures clearly indicate that large Faraday rotation variations
exist between these two sources, and thus across the Cygnus
OB1 region.

For each source we chose a number of regions (\( \geq 1 \)) in which
the polarized intensity was high enough for a reliable position
angle measurement. In each region, we made a measurement
of \( \Delta \chi \) at the position where \( L \) was locally a maximum. The
errors were calculated on the basis of the conventional standard
error in the polarization position angle measurement at a single
frequency, \( \sigma_{\chi} = \frac{1}{2} \sigma_Q \). These errors in the position angle
measurements at 4885 and 4585 MHz were propagated into
\( \Delta \chi \), and the RM measurement via Equation (3).

The results of these measurements are shown columns 3–
5 of Table 1. Column 3 gives the source subcomponent
for the measurement (e.g., Np for “north preceding,” Sf for
“south following,” and cc for “central component”), column 4
gives the \( \Delta \chi \) measurement for that component, and column 5
gives the rotation measure to that component, calculated with
Equation (3).

3.2. WHAM H\( \alpha \) Observations

We also used data from the University of Wisconsin H Alpha
Mapper (WHAM; Haffner et al. 2003) for this part of the
sky. The WHAM spectrometer measures H\( \alpha \) spectra at one
degree intervals on the sky. Integration of the H\( \alpha \) spectrum
over wavelength provides a measurement of the integrated H\( \alpha \)
intensity, which is directly related to the emission measure (EM
\( \equiv \int n_e^2 ds \)) of plasma along the line of sight (see Section 4.1).
These emission measure images can trace structures that could
be responsible for the RM anomaly. Maps of the spectra are
also useful for identifying different components along the line
of sight, distinguished by their line-of-sight velocities. For the
present project, we examined a map of normalized spectra on a

![Figure 2. Same as Figure 1, except for 2015 + 364. The peak intensity of the map is 7.11 mJy beam\(^{-1}\).](image)

![Figure 3. Comparison of the RM values emergent from this paper with those of Lazio et al. (1990).](image)

1\(^\circ\) grid in the region 65\(^\circ\) \( \leq l \leq 82\(^\circ\) \) and \( -4\(^\circ\) \leq b \leq 8\(^\circ\) \). The
velocity range of each spectrum is approximately \( \pm 100 \text{ km s}^{-1} \).

4. ROTATION MEASURES TO FOUR SOURCES
IN CYGNUS

In this section, we discuss the significance of the new
measurements of the four sources in Cygnus, as well as the
implications of the already published measurements of Lazio
et al. (1990).

4.1. Comparison with Observations from Lazio et al. (1990)

The RM values from this study (Column 5 of Table 1) are
compared with those of Lazio et al. (1990) in Figure 3. All
data from Table 1 are displayed with the exception of the
measurement of the central component of 2013 + 361 since
the polarization of this component was not measured by Lazio
et al. (1990). The values plotted on the abscissa of Figure 3 are
taken from Table 3 of Lazio et al. (1990) except for 2015 + 364.
This was not listed as a source with an “unambiguous rotation
measure” by Lazio et al. (1990). Given the small value of RM
from our measurements, it was clear that the Lazio et al. (1990)
measurements were not affected by the \( n \pi \) ambiguity,” so we fit the position angle measurements from Table 2 of Lazio et al. (1990) for the RM values. This was done for both components of the source.

A comparison of the present measurements with those of Lazio et al. (1990) is also given in Table 2, which assembles all the RM data for this part of the sky. This table also includes the data from Clegg et al. (1992) which is used in the discussion of Section 5. Columns 1 and 2 give the J2000 and B1950 names of the sources, and columns 3 and 4 give the source Galactic longitude and latitude. Columns 5 and 6 give the measurement of RM reported in Lazio et al. (1990) or Clegg et al. (1992). Column 7 gives the RM reported in this paper taken from Lazio et al. (1990) to our measurement for these components; the ratios of the large range of rotation measures in this part of the sky, which produces a change from large positive RM to large negative RM, and thus the rotation measure anomaly described in the Introduction. In Section 5 we discuss its nature. The total change in RM can be seen to be at least 800 rad m\(^{-2}\).

Finally, both our data and the refit position angle data from Lazio et al. (1990) show a negative RM for 2015 + 364. The present investigation, utilizing data taken and reduced in the same way for all four sources, both confirms the large and positive RM values presented in Table 3 of Lazio et al. (1990), and also shows a source in the same region with a negative RM (2015 + 364). This is consistent with the results of Clegg et al. (1992) who find negative rotation measures in close angular proximity to the sources with positive RM of Lazio et al. (1990). The independent data from this paper confirm the RM gradient in this part of the sky, which produces a change from large positive RM to large negative RM, and thus the rotation measure anomaly described in the Introduction. In Section 5 we discuss its nature. The total change in RM can be seen to be at least 800 rad m\(^{-2}\).
the logarithm of the absolute magnitude of RM. Black symbols, both open and filled, represent measurements reported in this paper. White symbols show data published in Lazio et al. (1990) and Clegg et al. (1992). The RM measurements are plotted on a background representing the intensity of the integrated Hα emission in this part of the sky from the WHAM instrument.

As a final point, we note that Lazio et al. (1990) presented arguments that the RMs measured and discussed here are due to the ISM of the Milky Way, and are not intrinsic to the extragalactic sources (see Section 5 of Lazio et al. 1990).

5. THE SOURCE OF THE RM ANOMALY

In this section, we discuss the nature of the RM anomaly which has been confirmed by the present observations. We propose that the anomaly is caused by a superbubble formed by the stellar winds of the Cygnus OB1 association discussed in Section 2. The theory of Weaver et al. (1977) indicates that wind-formed stellar bubbles should have a shell of enhanced plasma density between the outer shock and the contact discontinuity which separates the shocked ISM from matter in the stellar wind. As discussed in Section 5.1, there should also be an enhancement of the magnetic field in the shell. For these reasons, a shell associated with a stellar superbubble is a good candidate for the source of an RM anomaly. In addition to the evidence for this bubble presented in Section 2, our WHAM data present suggestive evidence for its existence. The half arc of emission seen in Figure 4 (and Figure 7) is not inconsistent with a limb-brightened shell. The Hα emission shows a possible half arc of emission with an angular radius of 2.3 centered on $l = 75^\circ$ and $b = 1^\circ$. The lower half of this arc is obscured by heavy interstellar extinction in the “Aquila Rift.” Radio continuum and recombination line observations of this region, summarized in Figure 6 of Spangler & Cordes (1998), show evidence for ionized gas at and below the Galactic equator at $l = 76^\circ$, and extending to $b = 1^\circ$ at $l = 74^\circ$. Interstellar extinction obscures the emission from this plasma in the WHAM image.

Further evidence comes from the WHAM spectra shown in Figure 5. Each spectrum results from a WHAM pointing in the region of Cygnus OB1. For each spectrum, the ordinate has been independently scaled to illustrate the spectral line shape. The velocity range for each spectrum is approximately $\pm 100$ km s$^{-1}$. Figure 5 shows that the spectra on the periphery of the shell have a single, relatively narrow component. The spectra near the center of the shell, on the other hand, reveal asymmetry in some cases, and splitting into two components in others.

The presence and extent of asymmetries and splittings of the lines were examined quantitatively by fitting multiple Gaussian components to nine of the more interesting spectra. We do not claim that these fits are unique, but they do provide a quantitative measure of asymmetry or multiplicity of a line, including the sign and magnitude of Doppler shifts. A particularly clear example of a spectrum with a shifted component is that at $l \approx 75^\circ$, $b = 0^\circ$.8, which shows a blueshifted spectral component with a velocity of $-54$ km s$^{-1}$. The main component of the line is at $+3$ km s$^{-1}$. Another clear case of a dual-component spectrum is the adjacent spectrum at $l \approx 76^\circ$, $b = 0^\circ$.8. There is a redshifted component at $+39$ km s$^{-1}$ with the velocity of the main line being close to zero. The fitting of this line also indicates the possible presence of redshifted emission extending to higher positive velocities.

Of the nine spectra in the shell which were fit for multiple components, four show a blueshifted component or asymmetry, four show a redshifted component or asymmetry, and two near the periphery of the shell are consistent with a single line component with no evidence of asymmetry. One spectrum, at $l \approx 75^\circ$, $b = 1^\circ$.7, shows a redward shift in the line center and a blueshifted line asymmetry.

The blueshifted components, which can be identified with the approaching wall of the plasma shell, have a typical velocity of $\approx -50$ km s$^{-1}$. The redshifted components, interpreted as the far side, receding wall of the bubble, have radial velocities in the range of $+20$ to $+40$ km s$^{-1}$, although a higher velocity emission is sometimes suggested by the fits.

The spectra in Figure 5 do not adhere to the perfect form of a uniform, expanding shell, in which both the redshifted and blueshifted components would be seen in every spectrum near the center of the shell with a velocity separation which decreased with distance from the shell center to the periphery. The data of Figure 5 would then seem to indicate that the shell is inhomogeneous with patches of higher emission measure dominating on certain lines of sight. Our results are broadly consistent with previous spectroscopic exploration of this region described in Section 2, although the present WHAM observations may show evidence for the far wall of the shell, which was not as clear in previous reports.

By associating an RM fluctuation with an identifiable astronomical object, our approach in this section differs from that of our previous papers, such as Lazio et al. (1990) and Minter & Spangler (1996). In those papers, fluctuations in RM from one line of sight to another were attributed to density and magnetic field fluctuations which arise naturally in magnetohydrodynamic (MHD) turbulence. An expression which gives the rotation measure structure function in terms of statistical descriptions of the turbulence is given in Equation (31) of Minter & Spangler (1996).
There are two motivations for this different approach in the present paper. First, as discussed in Section 2 and above, there is independent observational evidence for such a structure (the Cygnus OB1 association) on the lines of sight of interest, and it is desirable to calculate its effect on the Faraday rotation of distant sources. Second, the magnitude of the RM anomaly under consideration is large, and seems to require a more drastic RM change between adjacent lines of sight than could be provided by turbulence (e.g., compare with RM differences measured by Minter & Spangler 1996). Future research will be necessary to determine how much of the RM fluctuations seen in the Galactic plane is due to widely distributed turbulence, and how much is due to dense, magnetized plasma structures associated with H\textsc{ii} regions and supernova remnants.

5.1. Physical Model of the Interstellar Bubble

In this section, we explore a simple physical model for the superbubble shell associated with Cygnus OB1 and see if it can produce an RM anomaly of the sort observed and displayed in Figure 4. We make no claims as to the uniqueness of this model. Indeed, it is possible that the RM distribution in the sky is dominated by a random superposition of regions with different sign and magnitude of RM at different distances along the line of sight. However, in this section we will show that structures of the sort known to exist in the vicinity of OB associations (and particularly the Cygnus OB1 association) can produce a Faraday rotation anomaly with a magnitude and angular extent of the sort we observe.

Figure 6 shows a cartoon illustrating the bubble, which incorporates features from the model of Weaver et al. (1977). The radius $R_0$ defines the location of the outer shock. Inside $R_0$ is a shell of thickness $\Lambda$, which contains dense photoionized ISM material. It is this dense plasma which, in our model, produces the H\textsc{ii} shell seen in the WHAM image of Figure 4, and contributes to the enhanced rotation measure.
The interstellar magnetic field ($\vec{B}_0$) will also be modified by this shell, and it contributes to the enhanced RM. We assume that it is uniform across the region exterior to the bubble and modified in the standard way by an MHD shock, in which the component normal to the shock front $B_n$ is unchanged, while the component in the shock plane $B_\perp$ is amplified by a factor $X$, $B_{\perp 2} = XB_{\perp 1}$, where 1 and 2 refer to the upstream and downstream regions of the shock (Gurnett & Bhattacharjee 2005, p. 263, see their equation 7.3.23). In the case of a strong shock, $X$ equals the density compression ratio, which we take to be $X = 4$.

As indicated in Figure 6, the line of sight perforates the shell at two points, I (ingress) and E (egress). The normal vectors to the shock at these two points are

$$\vec{n}_I = \frac{\vec{r}_I}{R_0},$$

$$\vec{n}_E = \frac{\vec{r}_E}{R_0},$$

where $\vec{r}_I$ and $\vec{r}_E$ are the vectors from the center of the shell to the ingress and egress points.

The normal and perpendicular magnetic fields in the upstream regions at the ingress and egress points are

$$\vec{B}_{nI} = (\vec{n}_I \cdot \vec{B}_0)\vec{n}_I,$$

$$\vec{B}_{nE} = (\vec{n}_E \cdot \vec{B}_0)\vec{n}_E,$$

and

$$\vec{B}_{\perp I} = \vec{B}_0 - \vec{B}_{nI},$$

$$\vec{B}_{\perp E} = \vec{B}_0 - \vec{B}_{nE}.$$

The net magnetic fields in the shell (the downstream region) at the ingress and egress points are given by

$$\vec{B}_{I 2} = \vec{B}_{nI} + X\vec{B}_{\perp I},$$

$$\vec{B}_{E 2} = \vec{B}_{nE} + X\vec{B}_{\perp E}.$$

Finally, the $z$ components of the magnetic fields in the shell at the ingress and egress points, $B_{zI}$ and $B_{zE}$, which determine the Faraday rotation, are obtained by taking the dot product of Equation (9) with the unit vector in the $z$ direction (the direction from the source to the observer), $\hat{z}$.

As seen in Equation (1), the rotation measure is an integral along the line of sight. In a realistic model of a shell, the line-of-sight component of the magnetic field $B_z$, as well as the density would vary along the line of sight through the shell. Given the simplified nature of the model presented here, we approximate the RM as

$$RM(\xi) = \frac{CnL(\xi)}{2} [B_{z I} + B_{z E}],$$

where $C$ is the collection of atomic constants within the curved brackets in Equation (1), which has the value $2.631 \times 10^{-17}$ in cgs units, or 0.81 if $L$ is in parsec and $B_z$ in microGauss. The variable $n$ is the assumed uniform plasma density in the shell, $B_{z I}$ and $B_{z E}$ are the downstream (postshock) line-of-sight components of the magnetic field at the ingress and egress points, respectively. The length of the chord through the shell is denoted by $L(\xi)$, where $\xi$ is the distance of the line of sight from the center of the shell, as illustrated in Figure 6. Equation (10) assumes that all plasma characteristics are uniform in two branches of the line of sight, each of thickness $L/2$ as shown in Figure 6. The first branch is from the ingress point to an interior point, and the second branch extends from the interior point to the egress point. The values of these interior points depend on whether the parameter $\xi < R_I \equiv R_0 - \Delta$, or $\xi > R_I$. In the former case, the interior points are points where the line of sight intersects the inner surface of the shell. In the latter case, both interior points are the same as the midpoint of the chord through the shell. This definition is clarified by reference to Figure 6. It is relatively simple to show that

$$L(\xi) = 2R_0\sqrt{(1 - (\xi/R_0)^2)},$$

if $\xi \geq R_1$,

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

if $\xi \leq R_1$.

The rotation measure through a shell of the sort shown in Figure 6 is of order $RM_0 \equiv 2CnB_0R_0$, where $B_0$, is the upstream (preshock), line-of-sight component of the magnetic field. The maximum value of the rotation measure occurs for chords with $\xi > R_1$, and is $\frac{10}{7} RM_0$ for a compression factor $X = 4$. The difference $\Delta RM$ between the maximum rotation measure and the RM of the central chord depends on the ratio $\frac{R_1}{R_0}$, but is of order $\Delta RM \approx \frac{4}{5} RM_0$.

5.1.1. Estimating the Plasma Density in the Shell

Equation (10) takes as its input several properties of the plasma shell illustrated in Figure 6, and perhaps seen in the H$\alpha$ map of Figure 4. Obviously, one of the most important is the assumed constant plasma density $n$ in the shell. This parameter can be estimated from the measurements of the emission measure in column 8 of Table 2, and calculated using Equation (5). As seen in the data from Table 2, the resultant emission measures for the sources viewed through Cygnus OB1 showed modest variation from one line of sight to another with a total range of 192–360 cm$^{-6}$ pc.

It is obvious that interstellar extinction will reduce these emission measures below their true values with corresponding underestimates of the plasma density in the shell. We estimated the role of extinction and corrected it in the following manner.

Spangler & Cordes (1998) analyzed a number of lines of sight through the same part of the Cygnus OB1 association (compare the locations of the sources in Figure 4 of this paper with Figure 6 of Spangler & Cordes 1998), in that case studying the magnitude of interstellar scattering. As part of that analysis, values for the emission measure along a number of lines of sight to extragalactic radio sources were determined from radio continuum brightness temperatures, which are not subject to interstellar extinction. The values for the emission measure along those lines of sight are given in Table 2 of Spangler & Cordes (1998). We measured the H$\alpha$ intensity along these same lines of sight, and used them to obtain an estimate of the emission measure from the WHAM data, which was compared with the radio-based emission measures. For the five sources in Table 2 of Spangler & Cordes (1998), the ratio $A$ of the radio-based EM to the optically based one ranged from 1.4 to 4.2 with a mean of 2.6. The range in values of $A$ may well represent spatial variations in the extinction from one line of sight to another. Furthermore, since the beam of the radio telescope used for the radio continuum measurements (Max Planck Institut für Radioastronomie at Effelsburg) and WHAM are different, the effective extinction in the two beam solid angles may not be the same. Nonetheless, to obtain a first-order estimate of the effects
of extinction in this region, we corrected the WHAM emission measures by the mean value of $A = 2.6$.

This empirical correction factor is in good agreement with independent a priori estimates of extinction in this part of the sky. Previous investigations have also corrected emission measures derived from WHAM measurements using the interstellar reddening $E(B - V)$ along lines of sight of interest (Haffner et al. 1998; Berkhuijsen et al. 2006). Both of these studies utilized the correction factor contained in Equation (1) of Haffner et al. (1998)

$$A = e^{2.2E(B-V)},$$

where $A$ is the multiplicative correction factor applied to observed $H\alpha$ values, and $E(B - V)$ is the reddening in magnitudes. We follow Berkhuijsen et al. (2006) by employing the results of Diplas & Savage (1994), who obtained a value for the reddening per unit distance of $E(B-V)/r = 0.257$ mag kpc$^{-1}$, where $r$ is the distance to an object. This value refers to lines of sight in the Galactic plane. Since the lines of sight considered in the present study are very close to the Galactic plane, we assume this value along the entire line of sight to all parts of Cygnus OB1. Given the 1.8 kpc adopted distance to Cyg OB1, the independently estimated reddening is 0.46 mag, and the corresponding estimate for the extinction correction $A$ is 2.8, in obviously satisfactory agreement with the empirical factor described in the previous paragraph. The agreement between these two estimates supports the simplifying assumption used in this paper that most of the H$\alpha$ emission from the shell in Figure 4 originates in the vicinity of the Cygnus OB1 association.

Given all of this, our estimate for the density of the shell, calculated along each line of sight, is given by

$$n = \sqrt{\frac{2.25A H\alpha}{L(\xi)}}.$$

The density calculated in Equation (13) assumes the shell is a spherical annulus with uniform density. If the plasma is clumped with a filling factor less than unity, the density calculated in Equation (13) will be less than the density in the clumps. The rotation measure calculated under the assumption of a uniform shell with density given by Equation (13) will exceed the true rotation measure from a shell with a clumped density. It should be noted from Equation (13) that the derived density is rather weakly dependent (proportional to the square root) on the imperfectly known extinction parameter $A$.

For each line of sight, the source-specific value of $\xi$ was used. Calculation of $L(\xi)$ also requires knowledge of the distance to the shell or bubble (1.8 kpc; see Section 2) and the thickness of the shell. From the WHAM data shown in Figure 4, we estimated $R_0 = 71$ pc and $\Delta = 39$ pc. The values of $R_0$ and $\Delta$ were obtained in the following manner. We examined the WHAM H$\alpha$ intensity along the line of constant Galactic latitude at $b = 1^\circ$ and through the center of the shell (i.e., an intensity “slice” centered on the shell at constant Galactic latitude). The normalized intensity along this line was compared with a plot of $L(\xi)$ for various values of $R_0$ and $\Delta$. This simple approach is motivated by the fact that for a homogeneous spherical shell, $EM = n_\parallel L(\xi)$. Although by no means unique, a model shell with $R_0 = 71$ pc and $\Delta = 39$ pc does approximately reproduce the dependence of H$\alpha$ intensity along the line at constant $b$. A visual representation of this model on the sky and its correspondence with the WHAM data is shown in Figure 7. The coincidence of the circles representing $R_0$ and $R_0 - \Delta$ with the distribution of H$\alpha$ light hopefully indicates that the adopted values of $R_0$ and $R_0 - \Delta$ are reasonable. The values for the density which resulted from these calculations spanned a fairly narrow range of 2.3–3.9 cm$^{-3}$.

The external magnetic field $B_0$ was estimated as follows. We assumed that the magnitude of the ISM field is $|B_0| = 3–5$ $\mu$G, as indicated by numerous independent studies using Faraday rotation (e.g., Minter & Spangler 1996; Haverkorn et al. 2004; Haverkorn 2007). We adopted a value of $B_0 = 4.0$ $\mu$G. The orientation of the interstellar magnetic field with respect to the line of sight at the location of the Cygnus OB1 association bubble is unknown and was left as an adjustable free parameter.

To model the rotation measures for the sample of sources shown in Figure 4, we adopted values of $R_0$, $\Delta$, $n$, and $B_0$ as described above. Additional free parameters which affect the RMs are the angle $\theta$ between the interstellar magnetic field and the line of sight at the location of the Cygnus OB1 association, and an offset constant $RM_{off}$, which is the background rotation measure in this part of the Galactic plane. Values for the latter two parameters were chosen which gave an acceptable match to the observed rotation measures. The calculated model RMs used the specific value of $n$ for each line of sight as obtained from Equation (13). The model RMs thus incorporated available observational information, rather than a single mean value for $n$ as would be required by strict adherence to the model.

The parameters of this model for the shell associated with the Cygnus OB1 superbubble are given in Table 3 as “Model A.” The rotation measures emergent from this model are shown in Figure 8 and Figure 3 as “Model A.” The rotation measurements are given in Figure 8 in the same format as Figure 4. Figure 8 is qualitatively similar in appearance to the true measurements given in Figure 4. The range of model RMs is from $+665$ to $-359$ rad m$^{-2}$.

The densities calculated from Equation (13) and used in the subsequent analysis below utilize the full measured H$\alpha$ intensity in the shell structure. The values of $H\alpha$ were not corrected for a background level which would exist in the absence of the shell; we found that it was difficult to estimate such a level. To get a rough idea of the effect of such a background level, we also carried out a set of calculations in which the measured
I_{H\alpha} values were corrected by subtraction of a constant level of 50 Rayleighs before substitution into Equation (13). The resultant densities were slightly lower than those in Table 3. A similar set of rotation measures to those shown in Figure 8 was obtained, with the same range of RM, by use of a smaller value of the angle $\theta$ (36° instead of 59°). Observationally, we cannot distinguish between these two slightly different models. Model A as presented in Table 3 can be considered as presenting an upper limit to the plasma density $n$ and magnetic field tilt angle $\theta$.

We also carried out calculations for a model shell similar to that discussed by Spangler & Cordes (1998) and based on observations from the literature and theoretical arguments. This second model (“Model B”) has $R_0 = 94$ pc and $\Delta = 13$ pc. Model B has its own set of associated shell densities obtained from the emission-measure measurements, and the free parameters $RM_{off}$ and $\theta$ were adjusted to give a good representation of the observations. This model also satisfactorily represented the observed range of RM values with the model RM values ranging from $+784$ to $-274$ rad m$^{-2}$, although its inner and outer radii do not conform as well to the H$\alpha$ emission as Model A (Figure 7). The parameters for Model B are also given in Table 2.

The ability of these simplified shell models (with independently derived values of the shell parameters) to reproduce the magnitude and angular scale of the observed RM values is an important scientific result of this paper. Given the simplified nature of the model (spherical symmetry, uniform plasma density, etc.), it cannot be expected to reproduce the data set in detail. The observations show that the source 2015 + 364 has a small value for the absolute magnitude of the RM, whereas the model in Figure 8 shows a large negative RM. However, the model does account for a more fundamental property of the observations, which is the change from large positive to large negative RM over an angular scale of a couple of degrees. Furthermore, since the model can explain a transition from large positive to large negative RM, it can clearly produce values with small $|RM|$ (“null points”). Our model as constructed does not succeed in placing them exactly on the right place on the sky.

The models presented in Table 3 are clearly not unique as regards plasma parameters. It is obvious from Equation (10) that the plasma density, the magnitude of the upstream magnetic field, and the angle between the interstellar field and the line of sight are highly correlated. However, although correlated, these parameters have values which are bounded by measurements presented here (i.e., plasma density), independent observations (magnitude of the galactic magnetic field), or geometry (value of $\cos \theta$). Families of shell and ISM parameters which can reproduce our Faraday rotation observations are constrained by other information about the Cygnus OB1 region or the ISM in general.

To summarize this subsection, the calculations presented above are sufficient to demonstrate that a physical structure similar to the plasma shell associated with the Cygnus OB1 superbubble would produce a rotation measure anomaly similar to that which we observe. A more realistic model incorporating additional independent information on the geometry and other properties of the Cygnus OB1 association superbubble (Saken et al. 1992; Nichols-Bohlin & Fesen 1993; Spangler & Cordes 1998) as well as a more sophisticated theoretical expression would probably result in better agreement between model observables and observations.

### 5.2. Comparison with Other Anomalies Reported in the Literature

In this subsection, we discuss the evidence for other similar features in the sky which might be physically similar to the plasma shell around Cygnus OB1. Jacques Vallee has published many papers which report and discuss RM features on the sky (e.g., Vallee 1993, 2004), which he refers to as interstellar magnetic bubbles. In comparison with the object discussed here, the interstellar magnetic bubbles are larger in angular extent, are at higher Galactic latitudes, and induce smaller changes in the background RM. Although Vallee (1993, 2004) does not model these variations in the same way as we do, he does posit a connection with stellar OB associations. Further consideration of the similarity (and difference) of the objects discussed by Vallee, and the plasma shell associated with the Cygnus OB1 association would be worthwhile.

An object more similar to that described in this paper is the rotation measure anomaly in the Galactic plane at $l \approx 92^\circ$, discovered by Clegg et al. (1992), a point which was noted in that paper. The $l \approx 92^\circ$ anomaly has been mapped in more detail and with greater density of sources by Brown & Taylor (2001), who identified it as one of three similar anomalous regions (not including Cygnus OB1), although the feature at $l \approx 92^\circ$ is the clearest case in their sample. The change in RM due to this region is of the order of several hundred to 1000 rad m$^{-2}$, which is quite comparable to the Cygnus OB1 feature. The angular extent is also very similar with an angular diameter of 2-5 (Brown & Taylor 2001). However, in spite of these similarities between the two features, there are no obvious H II regions or interstellar bubbles similar to Cygnus.

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**Table 3**

Models for Shell Associated with Cygnus OB1 Association  

| Shell parameter | Model A | Model B |
|-----------------|---------|---------|
| $R_0$ (parsec) | 71      | 94      |
| $\Delta$ (parsec) | 39 | 13 |
| $n$ (cm$^{-3}$) | 2.3-3.9 | 4.3-5.3 |
| $B_0$ ($\mu$G) | 4.0 | 4.0 |
| $RM_{off}$ (rad m$^{-2}$) | -723 | -676 |
| $\theta$ (deg) | 59 | 0 |

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*Figure 8.* Model rotation measures along the observed lines of sight in the same format as Figure 4. For this calculation, we used plasma shell densities of 2.3–3.9 cm$^{-3}$ and an external interstellar magnetic field of 4.0 $\mu$G oriented at an angle of 59° with respect to the line of sight (Model A from Table 3).
OB1 along the line of sight to the $l \simeq 92^\circ$ anomaly. Although further attention is clearly necessary, this simple qualitative astronomical observation would seem to preclude a plasma structure or stellar bubble of the sort we have discussed in Section 5.1. It may be the case that different types of objects can produce such RM anomalies, a conjecture supported by the catalog of Vallee (2004). Given the similarity in the Faraday rotation of the Cygnus OB1 and $l \simeq 92^\circ$ features, we cannot exclude the possibility that the bubble or plasma shell associated with the Cygnus OB1 association is not responsible for the strong Faraday rotation there.

However, an observational case for a strong effect of H$^\text{ii}$ regions on Faraday rotation was also made by Mitra et al. (2003), who reported two cases in which H$^\text{ii}$ regions produced what we would call a Rotation Measure Anomaly. Mitra et al. (2003) explored lines of sight to pulsars which were in the Galactic plane and beyond the solar circle. A particularly convincing case is presented for an RM anomaly associated with the H$^\text{ii}$ region S205. In this case, the H$^\text{ii}$ region appears to produce an anomaly of magnitude 300–400 rad m$^{-2}$ on an angular scale of $\sim 2^\circ$. This is comparable to, if somewhat smaller than, the anomaly discussed in the present paper. It is beyond the scope of this paper to compare the H$^\text{ii}$ region S205 and the plasma shell and stellar bubble associated with Cygnus OB1.

Possible RM anomalies may also be present in the results of Roy et al. (2008), who report RM measurements of 60 extragalactic radio sources in the direction of the Galactic center. Large fluctuations in RM are observed, superposed on a general background. Roy et al. (2008) interpret these variations in terms of turbulent fluctuations in the interstellar plasma, as was done by Minter & Spangler (1996). It would be difficult to determine the contribution of discrete H$^\text{ii}$ regions to the data of Roy et al. (2008) in view of the complicated nature of this region, the superposition of unrelated regions along the line of sight, and the heavy extinction which eliminates optical diagnostics.

Finally, the topic of RM anomalies is peripherally addressed in Sun et al. (2008), who include Faraday rotation as one of the diagnostics for a plasma and cosmic ray gas model of the Galaxy. They note the large variations in RM to extragalactic radio sources viewed through the Galactic plane, and recognize that H$^\text{ii}$ regions could make a contribution to this RM variance. They also conclude from RM and other data that magnetic and density fluctuations are correlated. This interesting result is naturally consistent with certain type of MHD turbulence models, but is equally consistent with an ensemble of shells or bubbles associated with OB associations as described in Section 5.1.

The best approach for further illuminating the role of stellar bubbles and H$^\text{ii}$ regions in producing RM anomalies (which indicate modification of the plasma environment of the ISM) will be to study OB associations in the direction of the Galactic anticenter where confusion of multiple objects along the line of sight is not an issue and interstellar extinction is less severe.

6. SUMMARY AND CONCLUSIONS

The conclusions of this paper are as follows.

1. Polarization observations at the closely spaced frequencies of 4585 and 4885 MHz with the VLA have confirmed the large positive Faraday rotation measures for the sources 2007+369, 2009+367, and 2013+361 reported by Lazio et al. (1990) on the basis of observations at different frequencies and analyzed independently.

2. The observations in this paper, together with those of Lazio et al. (1990) and Clegg et al. (1992), appear to show the presence of a “Faraday Rotation Anomaly,” in which the RM changes by several hundred rad m$^{-2}$ or more, over an angular scale of $2^\circ$–4°. The RM changes by about 800 rad m$^{-2}$ between the sources observed in this project separated by an angular distance of $\sim 2^\circ$. Inclusion of other sources observed by Lazio et al. (1990) and Clegg et al. (1992) leads to differences as large as 1300 rad m$^{-2}$ over angular separations which are only slightly larger.

3. The source 2015+364 is particularly important in demonstrating the reality of the anomaly and the consistency of the Lazio et al. (1990) and Clegg et al. (1992) measurements. This source has an RM which is negative and with a small absolute magnitude. It therefore functions as a link between the large positive RMs reported by Lazio et al. (1990) and the negative RMs with large $|\text{RM}|$ reported by Clegg et al. (1992).

4. This Rotation Measure Anomaly occurs for sources which are viewed through a part of the Galactic plane which contains the Cygnus OB1 association. Hα images from the University of Wisconsin H Alpha Mapper (WHAM) telescope show what may be a plasma shell caused by the stellar bubble or superbubble produced by the association. The WHAM spectral data support the presence of expansion of this shell as do a host of independent optical, ultraviolet, and radio studies.

5. We have developed a simple physical model of a plasma shell associated with a stellar bubble which appears to be present in Cygnus OB1. Using independent estimates of the shell size, thickness, and mean density, as well as the strength of the interstellar magnetic field outside the shell, we can reproduce RM gradients which are consistent with the observations.

6. The Rotation Measure Anomaly discussed here appears to be similar to a number of other anomalies reported in the literature. Future research could determine the degree of similarity and indicate the role of young star clusters in forming plasma shells and the associated RM anomalies. Such knowledge would illuminate the overall role of luminous stars in modifying the plasma state of the ISM.

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