ON THE MAGNETIC FIELD THROUGH THE UPPER CENTAURUS–LUPUS SUPER BUBBLE IN THE VICINITY OF THE SOUTHERN COALSACK

N. D. R. BHAT\textsuperscript{1} and B-G ANDERSSON\textsuperscript{2}
\textsuperscript{1} Centre for Astrophysics \& Supercomputing, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia
\textsuperscript{2} SOFIA Science Center/USRA, NASA Ames Research Center, M.S. N211-3, Moffett Field, CA 94035, USA

Received 2010 June 18; accepted 2010 December 7; published 2011 February 8

ABSTRACT

The Southern Coalsack is located in the interior of the Upper Centaurus–Lupus (UCL) super bubble and shows many traits that point to a much more energetic environment than might be expected from a dark, starless molecular cloud. A hot, X-ray emitting envelope surrounds the cloud, it has a very strong internal magnetic field, and its darkest core seems to be on astronomical timescales “just about” to start forming stars. In order to probe the magnetic environment of the cloud and to compare with the optical/near-infrared polarimetry-based field estimates for the cloud, we have acquired Faraday rotation measurements toward the pulsar PSR J1210−6550, probing the magnetic field in the vicinity of the cloud, and a comparison target, PSR J1435−5954, at a similar line-of-sight distance but several degrees from the cloud. Both lines of sight hence primarily probe the UCL super bubble. The earlier estimates of the magnetic field inside the Coalsack, using the Chandrasekhar–Fermi method on optical and near-infrared polarimetry, yield $B_{\perp} = 64$–93 $\mu$G. However, even though PSR J1210−6550 is located only $\sim$30 arcmin from the (CO) edge of the cloud, the measured field strength is only $B_{\perp} = -1.1 \pm 0.2$ $\mu$G. While thus yielding a very high field contrast to the cloud we argue that this might be understood as due to the effects on the cloud by the super bubble.

Key words: ISM: individual objects (Southern Coalsack) – ISM: magnetic fields – pulsars: general – pulsars: individual (PSR J1047−6709, PSR J1210−6550, PSR J1435−5954)

Online-only material: color figures

1. INTRODUCTION

The Southern Coalsack provides one of the most spectacular sights on the southern night sky—at least for any interstellar medium (ISM) astronomer—with its very dark nebulosity contrasted by the Southern Cross and the Jewell Box cluster (NGC 4755). Beyond its naked eye attractiveness, it is a well-studied dark cloud that due to its relative proximity (high spatial resolution) and location in the Galactic plane (abundance of background stars suitable for optical and UV spectroscopy) provides one of the best test cases for the study of starless molecular clouds. (For a thorough introduction to the cloud, see the remarks by de Geus (1992), the cloud is located inside the Upper Centaurus–Lupus (UCL) super bubble. de Geus (1992) estimated that the super bubble has a radius of $R = 110 \pm 10$ pc, an estimated age of about 11 Myr, an estimated total energy input of $\sim 0.9 \times 10^{51}$ erg, and depending on the adopted distance to the Coalsack, the shell would have overtaken the cloud between about 2–5 Myr ago.

Andersson et al. (2004) found that the extended envelope of the cloud contained the high-ionization state O\textsc{vi} ion, characteristic of a gas temperature of $\sim 300,000$ K (Shapiro & Moore 1976). Because O\textsc{v} has an ionization potential of $\sim 113$ eV, O\textsc{vi} is generally expected to be produced by collisional ionization in the ISM. They also found that the cloud envelope could be seen in soft X-rays from the ROSAT PSPC observations. Based on these observations, Andersson et al. (2004) proposed that the hot cloud envelope was due to the cloud’s envelopment by the UCL super bubble. Duncan et al. (1995) noted the existence of a 2.4 GHz continuum emission arc around the cloud, which they designated as G303.5+0, and the data from Duncan et al. (1997) show that this emission is polarized (see Figure 2). Walker & Zealey (1998) identified this radio feature with an H\textalpha{} shell that they named “The Coalsack Loop.”

Andersson & Potter (2005) used optical polarimetry and a Chandrasekhar–Fermi (CF) analysis (Chandrasekhar & Fermi 1953) to estimate the plane-of-the-sky magnetic field strength in the cloud and found a surprisingly large field of $B_{\perp} = 93 \pm 23$ $\mu$G, but one which is consistent, in equipartition, with the thermal pressure of the X-ray emitting gas seen by Andersson et al. (2004). Lada et al. (2004) used the $H$-band polarimetry of Jones et al. (1984) and results from their own C\textsuperscript{18}O ($J = 2–1$) observations to perform a CF analysis to estimate the magnetic field strength in Tapia’s Globule 2, the darkest of the cores in the cloud. They estimate a polarization angle dispersion...
of $\sigma_0 = 0.68 \text{ rad} \left( \approx 39^\circ \right)$ and hence derive a plane-of-the-sky magnetic field strength of $B_\perp \approx 24 \mu \text{G}$. We will argue below, in Section 3.2, that separating the polarization data probing Tapia’s Globule 2 from the surrounding cloud material, a narrower dispersion of polarization angles is found and hence a higher magnetic field estimate for the globule of $B_\perp \approx 65 \mu \text{G}$, consistent with the optical polarimetry estimate.

Lada et al. (2004) also used near-infrared photometry to map the density structure in Tapia’s Globule 2. They detect a ring-like column density enhancement that they interpret as a contracting shell of enhanced space density. Hennebelle et al. (2006) modeled the structure seen by Lada et al. (2004) and concluded that it is indeed due to a contracting shell, which they predict will lead to an onset of star formation about $10^4$ yr from now. They further show that the structure requires an external pressure transient to have passed over the cloud about $1.2 \times 10^6$ yr ago to trigger the cloud collapse. They speculate that the triggering event might have been the collision of two cloud fragments, giving rise to Tapia’s Globule 2. Models of cloud compression and collapse for magnetized clouds (Li & Waga 2002) can provide a similar column density pattern, cloud compression and collapse for magnetized clouds (Li & Waga 2002), the gray area in the lower part of the figure represents the Carina spiral arm with a pitch angle of $11^\circ$ (Vallée 2005) and a distance, in the direction of the Coalsack, of 1.3 kpc based on the results from Seidensticker & Schmidt-Kaler (1989). The H I shell detected by McClure-Griffiths et al. (2001) is indicated by a dashed circle.

Figure 1. Sketch of the relevant Galactic features is shown, with the Sun in the upper right. The UCL and the Coalsack are located based on the observations in de Geus (1992) and Crawford (1991). The pulsar distances are based on the NE2001 electron density model (Cordes & Lazio 2002). The gray area in the lower part of the figure represents the Carina spiral arm with a pitch angle of $11^\circ$ (Vallée 2005) and a distance, in the direction of the Coalsack, of 1.3 kpc based on the results from Seidensticker & Schmidt-Kaler (1989). The H I shell detected by McClure-Griffiths et al. (2001) is indicated by a dashed circle.

The location of the Coalsack relative to the UCL super bubble, the hot envelope, the strong magnetic field in the cloud, and the presence of a possibly contracting core in Tapia’s Globule 2 therefore seems to lead to a coherent picture of the Southern Coalsack as a cloud overtaken, compressed, and heated by the envelopment into a super bubble and thence as a nearby example of star formation triggered over large distances.

To further probe this scenario we have acquired Faraday rotations measurements toward the pulsars PSR J1210$-$6550 and PSR J1435$-$5954. The pulsar PSR J1210$-$6550 is located only about $30^\prime$ from the lowest $^{12}\text{CO}$ contour in the southwest-most cloudlet in the map of Nyman et al. (1989). The pulsar is at an estimated distance of $d = 1.15$ kpc, based on the NE2001 electron density model (Cordes & Lazio 2002) and hence on the near-side of the Carina arm and should primarily be probing the material associated with the UCL super bubble and the Coalsack envelope (Seidensticker & Schmidt-Kaler 1989). For comparison, we also observed the pulsar PSR J1435$-$5954, located about $17^\circ$ further along the Galactic plane, but at a similar distance of $d = 1.18$ kpc. Figure 1 shows the sketch of the geometry of the objects. Of course, it is important to remember the inherent dichotomy between the magnetic field components probed by polarimetry and the CF analysis on the one hand (plane-of-the-sky component) and Faraday rotation measurements (line-of-sight component) on the other.

Both these pulsars were among later discoveries by the Parkes multibeam survey (Hobbs et al. 2004). PSR J1210$-$6550 is a very faint, long-period (4.3 s) pulsar with a very small duty cycle ($\sim 0.1\%$), with a period-averaged flux density at $1400 \text{ MHz}$ ($S_{1400}$) of $\sim 0.1 \text{ mJy}$, whereas PSR J1435$-$5954 is a relatively bright pulsar. Little is known about their properties apart from what has been deduced from their discovery and initial timing observations. Additionally, we observed PSR J1047$-$6709 in each observing session, a bright pulsar with a well-known rotation measure (RM), to serve as a “control pulsar” for validating polarimetric calibration and RM determination. The basic parameters of all three pulsars are listed in Table 1, along with the measurements of RM and the estimates of magnetic field strength derived from our data. We note that even in the best available pulsar surveys, no further observable targets are available meeting our requirements of (1) on-the-sky proximity to the Coalsack and (2) a distance less than that of the next spiral arm (Carina).

The locations of PSR J1210$-$6550 and PSR J1435$-$5954 on the sky and their relation to the known features around the Coalsack region are further illustrated in Figure 2, which shows an X-ray map in that area (from ROSAT data) along with the detections of CO ($J = 1\to 0$) from Nyman et al. (1989) and the polarized 2.4 GHz emission from Duncan et al. (1997).
1.1. Magnetic Fields from Rotation Measure Observations

Rotation Measure (RM) quantifies the degree of Faraday rotation that electromagnetic waves undergo as they propagate through the interstellar medium (ISM) from the pulsar to the Earth. This rotation is caused by the interaction of the electromagnetic waves with the magnetized plasma of the ISM and more specifically along the line of sight to the pulsar. For a pulsar located at distance $D$, the RM is given by

$$\text{RM} = \frac{e^3}{2\pi m_e^2 c^4} \int_0^D n_e(l) B(l) \, dl,$$

where $dl$ is the path vector element in the direction of wave propagation, $e$ and $m_e$ are the charge and mass of electron, respectively, $n_e$ is the free electron density, $B$ is the magnetic field vector, and $c$ is the speed of light. The above equation can be simplified to

$$\text{RM} = 0.812 \int_0^D n_e(l) B(l) \, dl,$$

where $D$ is in parsecs, $n_e$ is in per cubic centimeter, $B$ is in microgauss, and RM is in radians per square meter. The integral of $n_e$ along the line of sight is the dispersion measure (DM) and is given by

$$\text{DM} = \int_0^D n_e(l)dl,$$

and is usually expressed in units of parsecs per cubic centimeter ($\text{pc cm}^{-3}$, i.e., $D$ in pc and $n_e$ in cm$^{-3}$).

The quantity DM can easily be determined from the arrival time delays measured at different frequencies across the observing band (e.g., Lorimer & Kramer 2004) and, consequently, for all catalogued pulsars which are observable in radio, this is a well-known quantity. Thus, a measurement of RM enables a direct estimation of the magnetic field strength weighted by the free electron density. The mean value of the line-of-sight component of $B$ is thus given by

$$\langle B_l \rangle = \frac{\int_0^D n_e(l) B(l) \, dl}{\int_0^D n_e(l)dl} = 1.232 \frac{\text{RM}}{\text{DM}}.$$ 

The rest of this paper is organized as follows. We briefly describe our observations and data reduction in Section 2, determination of RMs in Section 3.1, and a reanalysis of the polarization data in Section 3.2. In the later sections (Sections 4 and 5) we present our main results and discuss their implications for the related physical models. Our conclusions are presented in Section 6.
as discussed in van Straten (2004) is not critical for the RM determination and therefore not considered in our analysis. The position angles were then computed for each phase bin from the Stokes $Q$ and $U$ parameters and the flux-density scale was determined from the observations of the Hydra calibration observations.

3. ANALYSIS

3.1. Determination of Rotation Measures

Polarimetric profiles obtained from our analysis are shown in Figures 3 and 4. While PSR J1210–6550 is very faint, it shows a substantial degree of linear polarization (~35% of the total intensity). PSR J1435–5954 is relatively bright in comparison (see Table 1); however, the degree of polarization is much lower (linear and circular polarizations are ~8% and ~3% of the total intensity, respectively). The signal-to-noise ratios (S/Ns) of the linearly polarized intensities are therefore not very large and limit the significance achievable in the RM estimates. Flux densities of both pulsars show significant variations with time, presumably due to long-term interstellar scintillation effects expected at such moderate DMs (e.g., Bhat et al. 1999), and the quoted numbers are mean values from multiple measurements made over time spans of several months.

Our initial estimates of RM were determined using the standard procedure, where we searched for a peak in the total linearly polarized intensity $L = (Q^2 + U^2)^{1/2}$ obtained by summing the calibrated data in frequency (e.g., Han et al. 2006). This search is carried out over a large range of RM, ±1000 rad m$^{-2}$, in steps of 1 rad m$^{-2}$. Further, using the RM value corresponding to the peak, we summed the data to form the upper and lower band profiles. These were then used to refine the RM estimate by taking the weighted mean of the position-angle differences between the upper and lower bands across the profile, with the weight inversely proportional to the square of the error in position-angle difference for each pulse phase bin. The RM is then recomputed and the procedure is iterated until convergence.

In order to confirm and cross-check our initial estimates, as well as to obtain more robust RM measurements, we applied the RM determination method as developed by Noutsos et al. (2008), where a quadratic function was fitted to the PA versus frequency across the full observation band. These position angles are computed from the Stokes $Q$ and $U$ that are summed across the phase bins corresponding to the on pulse. This quadratic fitting algorithm finds the best fit by means of a Bayesian likelihood test, and uses a fitting function of the form, $PA = PA_0 + c^2RM(1/f_j^2 - 1/f_0^2)$, where $PA_0$ is the PA at frequency $f_0$ and $f_j$ is the frequency of channel $j$. The main advantage of this method is that it accounts for the 180° ambiguity inherent in the computation of the mean PAs from the Stokes $Q$ and $U$. The free parameters $PA_0$ and RM were stepped through the ranges $(0, \pi)$ rad and $\pi$ rad m$^{-2}$ in 1° and 1 rad m$^{-2}$, respectively. As demonstrated by Noutsos et al. (2008), this method is more robust and yields more reliable RM estimates. The main caveat however is that the S/N per frequency channel or sub-band needs to be sufficiently large for this method to yield meaningful results. While we were able to apply this method successfully to both PSRs J1047–6709 and
J1210–6550 (cf. Figure 5), such an estimation was not feasible in the case of PSR J1435–5954 owing to the very low signal to noise of its linearly polarized flux (cf. Figure 4). As a result, the RM estimate of this pulsar is derived from the standard method as discussed earlier in this section.

The final estimates of RM derived from our analysis are summarized in Table 1. For the control pulsar PSR J1047–6709, we obtained four independent measurements over a time span of four months, which are found to be consistent within their 1σ measurement uncertainties, with a mean value of $-84 \pm 3$ rad m$^{-2}$. For comparison, values from the published literature are $-73 \pm 3$ rad m$^{-2}$ (Han et al. 2006) and $-79 \pm 2$ rad m$^{-2}$ (Noutsos et al. 2008). Thus, our RM estimate is consistent (within 2σ) with the more recent measurement of Noutsos et al. (2008), though somewhat larger.

For both PSR J1210−6550 and PSR J1435−5954, we have obtained two to three independent measurements (with high significance) over a time span of three to four months. The resultant average values are $-32 \pm 4$ rad m$^{-2}$ and $-24 \pm 7$ rad m$^{-2}$ for PSR J1210−6550 and PSR J1435−5954, respectively. The relatively low significance on the RM estimate of the latter is primarily due to its low degree of polarization ($\sim 8\%$). In comparison, PSR J1210−6550 exhibits a moderately high linear polarization ($\sim 35\%$) and hence its RM is estimated with a relatively higher significance (Figure 5). However, due to its very narrow pulse (duty cycle of $\sim 1\%$), typically only four phase bins span the on pulse emission with our 512 bin resolution across the pulse period. The consistency between multiple measurements of each pulsar and the general agreement seen between the published and our measured RM estimates for the control pulsar give us confidence about the reliability of our RM measurements.

For the current analysis, the DMs toward each of the pulsars under consideration were taken from the ATNF Pulsar Catalog (Manchester et al. 2005); for both PSR J1210−6550 and PSR J1435−5954, the DM measurements ($37 \pm 6$ pc cm$^{-3}$ and $44.26 \pm 0.011$ pc cm$^{-3}$, respectively) are from Hobbs et al. (2004), who reported the original discoveries of these objects.

### 3.2. The Magnetic Field in Tapia’s Globule 2

As discussed in the introduction, Lada et al. (2004) used near-infrared polarimetry (NIR) from Jones et al. (1984) and their own deep CO observations of Tapia’s Globule 2 to estimate the magnetic field strength in this dark core. We here discuss this result in light of a reanalysis of the polarization data. Jones et al. (1984, p. 678) note about their H-band polarization map that:

“Immediately apparent in Figure 4 is a definite change in polarization angle between the northern block (block E [...] and the block centered on the globule (block D). Also the polarization within the 120” radius circle [the globule’s “half-extinction radius”] is about a factor of 2 higher than in block E.”

Figure 6 shows the distribution of polarization angles from Jones et al. (1984) where we have color coded the data from “block D” in blue (dark gray) and those from blocks E and F in yellow (light gray). The change in the average value of the polarization angles between the areas is clearly seen. A Student’s t-test analysis comparing the polarization angles of the “block D” sample versus the combined “block E” and “block F” samples yields a t-probability of $p = 0.0003$ and hence shows that the two populations are distinct. The position-angle dispersion for the full sample is $\sigma_0 = 39^\circ \pm 10^\circ$. However, if we follow Jones et al. (1984) and separate out only the “block D” polarization as tracing the field in Tapia’s Globule 2, we derive a position-angle dispersion of $\sigma_0 = 14^\circ \pm 2^\circ$. 

![Figure 5.](image-url) Position angle vs. frequency plots for PSR J1047–6709 and PSR J1210–6550, illustrating the RM estimation using the quadratic fit method (see Section 3.1 for details). The best-fit RM determined toward PSR J1210–6550 is $-32 \pm 4$ rad m$^{-2}$, which translates to $B_r = -1.1 \pm 0.2$ µG. These position angles are computed from the Stokes $Q$ and $U$. For PSR J1210–6550, they are summed over the four on-pulse phase bins that show polarized intensity above a 5σ threshold. The large errors on the position angles of this pulsar are thus due to its relatively low degree of polarization and a small number of on-pulse phase bins.
Figure 6. Distribution of H-band polarization angles from Jones et al. (1984) shows a distinctly bimodal distribution between the stars behind Tapia’s Globule 2 (“block D”) and the surrounding Coalsack material. For the full sample a position-angle dispersion of $\sigma_\theta \approx 39^\circ$ is deduced. If only the stars in “block D” are used, an angle dispersion of $\sigma_\theta \approx 14^\circ$ is found implying a magnetic field of $B_\perp \approx 64 \mu G$.

(A color version of this figure is available in the online journal.)

4. RESULTS

The estimates of $B_\perp$ derived from our RM measurements are summarized in Table 1. The measured field strength along the sight line toward PSR J1210−6550 is only $1.1 \pm 0.2 \mu G$, which is much lower than the plane-of-the-sky component ($B_\parallel \approx 93 \pm 23 \mu G$) estimated by Andersson & Potter (2005). The field strength estimated toward PSR J1435−5954 is somewhat lower, $B_\perp = -0.7 \pm 0.2 \mu G$, but again is directed away from us.

For our reanalysis of the NIR polarimetry in Tapia’s Globule 2, if we retain the values of turbulent velocity ($v_t = 0.23 \text{ km s}^{-1}$) and space density ($n = 10^4 \text{ cm}^{-3}$) derived by Lada et al. (2004), but use the narrower position-angle dispersion ($\sigma_\theta = 14^\circ$), we estimate a plane-of-the-sky magnetic field strength for Tapia’s Globule 2 of $B_\parallel \approx 64 \mu G$. This higher value is consistent (within 1.5$\sigma$) with the field strength ($B_\parallel = 93 \pm 23 \mu G$) derived by Andersson & Potter (2005) using optical polarimetry of the full Coalsack cloud. It is, however, significantly higher than the value of $B_\perp \approx 25 \mu G$ derived by Lada et al. (2004) based on equipartition arguments between magnetic, gravitational, and kinetic energies, which is also very close to their CF-analysis-based value.

Rathborne et al. (2009) have used a detailed analysis of the $^{13}$CO ($J = 1\rightarrow 0$) emission to argue that the globule is in fact the confluence of two subsonic flows. They estimate the average space density of the globule to be $n \approx 2.7 \times 10^4 \text{ cm}^{-3}$. They, however, also detect CS emission from the inner parts of the globule. The CS molecule has a high critical density and is expected to trace high-density gas ($n \gtrsim 10^5 \text{ cm}^{-3}$). Finally, the spatial resolution of Jones et al.’s (1984) polarimetry data is not high enough to fully sample the magnetic field variations on the scale of the observations of Rathborne et al. (2009). Hence, a detailed understanding of the magnetic field in the core of the globule will require additional observations.

5. DISCUSSION

A number of theoretical studies have addressed the characteristics of super bubble evolution (Weaver et al. 1977; Tomisaka 1998; Stil et al. 2009) and of the effects of a magnetized interstellar cloud being overtaken by a supernova remnant (SNR; Mac Low et al. 1994; Melioli et al. 2005; Leão et al. 2009). While there are no detailed modeling studies specifically addressing a magnetized cloud enveloped in the relatively slowly expanding super bubble, we can gain some insights into the physics, and estimate the characteristics, of such a cloud by viewing it as a detached part of the inner surface of a super bubble wall or by comparing it to studies of a cloud enveloped by an SNR. As shown by most super bubble models starting with Weaver et al. (1977), the inside of the super bubble shell will reach temperatures in excess of $10^6$ K and should reach thermal pressures of $P \sim 10^9$ K cm$^{-3}$ (Tomisaka 1998). While the magnetic field is swept up and enhanced, only marginal magnification of the field strength is expected for the inside of the bubble shell (Tomisaka 1998). In contrast, Mac Low et al. (1994) find that the field comes into equipartition with the gas pressure for the cloud overtaken by an SNR and that the magnetic field protects the cloud from being shredded by the shock. Leão et al. (2009) have calculated the star formation efficiency for clouds enveloped by an SNR driven by an energy injection of $10^{51}$ erg, but only briefly discuss the results for SNR in the radiative phase, where the expansion velocity is more comparable to that for the UCL super bubble. Nonetheless, based on their Figure 9, the predicted imminent onset of star formation in the Coalsack (Hennebelle et al. 2006) is consistent with being triggered by the interaction with the UCL super bubble.

As shown by Tomisaka (1998) and Stil et al. (2009), an expanding super bubble will sweep up the ambient magnetic field, compressing it in the direction perpendicular to the undisturbed field direction and leaving an almost field-free bubble interior. Those calculations show a precipitous drop of the magnetic field at the inside of the bubble wall. Hence, by treating the cloud as a detached part of the wall, we expect that the magnetic field frozen into the cloud will also show an abrupt drop-off. As noted by Mac Low et al. (1994), the initial compression of a magnetized cloud is expected to reverse on timescales short compared to the lifetime of the bubble. Moreover, in the simulations of super bubbles the magnetic field leads to relatively thick shells—particularly in the direction perpendicular to the ambient field (Stil et al. 2009). However, Stil et al. (2009) point out that including realistic cooling functions leads to thinner shells and stronger magnetic fields than in adiabatic simulations. Since the average magnetic field, as traced by the optical polarimetry, runs NE–SW, such corrections would likely be particularly important for the location of PSR J1210−6550, where cooling flows from the dense cloud likely produces a much more efficient heating than in the locations where the cloud and surrounding hot gas are connected across the magnetic field lines.

Because the field inside the super bubble in the Stil et al. (2009) simulations is weak and turbulent, most of the predicted RM will be due to the shell. On a large scale, Stil et al. (2009) therefore estimate the RM for a 10 Myr old bubble, seen for sight lines perpendicular to the undisturbed field, to be less than $\sim 20$ rad m$^{-2}$, dominated by asymmetries in the shell. For sight lines along the undisturbed field, relatively large RMs are seen close to the tangent of the shell while the RM in the projected
center of the bubble is significantly lower. These predictions are generally consistent with our observations through the UCL super bubble. Vallee & Bignell (1983) observed extragalactic background sources through the Gum Nebula and derive an average RM in the inner part of the Gum Nebula of \( \sim 130 \text{ rad m}^{-2} \). However, the Gum Nebula is located at \( l \sim 270^\circ \) and hence much closer to the projected direction of the Galactic magnetic field. Also, as Vallee & Bignell (1983) used extragalactic background sources, contributions from the rest of the Galaxy along the line of sight cannot be excluded. As the simulations by Stil et al. (2009) show, for this geometry a fairly large RM is expected.

The line of sight toward PSR J1435−5954 is located at larger Galactic longitude (\( l \sim 316^\circ \)) than that for PSR J1210−6550 and hence at a larger angle relative to the nominal undisturbed Galactic magnetic field. The lesser RM seen toward this pulsar, as compared to the one for PSR J1210−6550, is thus also in line with the models by Stil et al. (2009).

Based on the results from the CF analyses from optical (Andersson & Potter 2005) and NIR data (Jones et al. 1984; Lada et al. 2004; our Section 3.2), the results presented here thus seem to indicate that both the sight lines probed fall in the “diffuse” part of the super bubble, including the one toward PSR J1210−6550. This then suggests that the edge of the magnetized Coalsack cloud is quite sharp and located close to the lowest CO contour—at least in the direction of the magnetic field. This is consistent with models; however, it needs to be tested in detail. Further observations and models specifically targeted at simulating a magnetized cloud enveloped in a super bubble, with parameters tailored to those of the Coalsack and the UCL super bubble, are required to address the viability of this interpretation.

6. CONCLUSIONS

We have acquired RM data for two pulsars behind the UCL super bubble, one of which probes a sight line very close to the Southern Coalsack. While constituting a small sample, these two are the only readily observable pulsars to provide a specific probe of the Faraday rotation in the three-dimensional vicinity of the cloud. We find that the results for both lines of sight are consistent with predictions of models of a magnetized super bubble without internal clouds. Since earlier estimates of the magnetic field strength in the Coalsack indicate a strong field (at least in the plane of the sky), this indicates that the magnetized cloud is either very sharply bounded or that the field in the cloud is oriented almost completely in the plane of the sky.

We have shown that the observational data set available for the Coalsack is consistent with the hypothesis of a cloud relatively recently overtaken by a super bubble and therefore at the brink of star formation. Specific modeling of the interaction of the Coalsack and the UCL will be required to confirm this picture; the proximity of the cloud and the wealth of observational data are promising to provide important constraints on such models.

We are grateful to Willem van Straten and Aristeidis Noutsos for discussions on the polarimetric analysis, Ravi Sankrit and Tim Robishaw for discussions on the super bubble models and interstellar magnetic fields, and Matthew Bailes for his encouragement and support to this project. We thank an anonymous referee who provided useful comments that helped to improve the paper. The Parkes radio telescope is part of the Australia Telescope, which is funded by the Commonwealth of Australia for operation as a National Facility managed by the Commonwealth Scientific and Industrial Research Organization.

REFERENCES

Andersson, B-G, Knauth, D. C., Snowden, S. L., Shelton, R. L., & Wannier, P. G. 2004, ApJ, 606, 341
Andersson, B-G, & Potter, S. B. 2005, MNRAS, 356, 1088
Bhat, N. D. R., Rao, A. P., & Gupta, Y. 1999, ApJS, 121, 483
Chandrasekhar, S., & Fermi, E. 1953, ApJ, 118, 113
Cordes, J. M., & Lazio, T. J. W. 2002, arXiv:astro-ph/0207156
Crawford, I. A. 1991, A&A, 247, 183
de Geus, E. J. 1992, A&A, 262, 258
Duncan, A. R., Haynes, R. F., Jones, K. L., & Stewart, R. T. 1997, MNRAS, 291, 279
Duncan, A. R., Stewart, R. T., Haynes, R. F., & Jones, K. L. 1995, MNRAS, 277, 36
Franco, G. A. P. 1989, A&A, 215, 119
Han, J. L., Manchester, R. N., Lyne, A. G., Qiao, G. J., & van Straten, W. 2006, ApJ, 642, 869
Hennebelle, P., Whitworth, A. P., & Goodwin, S. P. 2006, A&A, 451, 141
Hobbs, G., et al. 2004, MNRAS, 352, 1439
Hotan, A. W., van Straten, W., & Manchester, R. N. 2004, PASA, 21, 302
Jones, T. J., Hyland, A. R., & Bailey, J. 1984, ApJ, 282, 675
Kato, S., Mizuno, N., Asayama, S., Mizuno, A., Ogawa, H., & Fukui, Y. 1999, PASJ, 51, 883
Knude, J., & Hog, E. 1998, A&A, 338, 897
Lada, C. J., Huard, T. L., Crews, L. J., & Alves, J. F. 2004, ApJ, 610, 303
Leão, M. R. M., de Gouveia Dal Pino, E. M., Falceta-Gonçalves, D., Melioli, C., & Geraissate, F. G. 2009, MNRAS, 394, 157
Li, Z., & Nakamura, F. 2002, ApJ, 578, 256
Lorimer, D. R., & Kramer, M. 2004, Handbook of Pulsar Astronomy (Cambridge: Cambridge Univ. Press)
Mac Low, M., McKee, C. F., Klein, R. I., Stone, J. M., & Norman, M. L. 1994, ApJ, 433, 757
Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, AJ, 129, 1993
McClure-Griffiths, N. M., Dickey, J. M., Gaensler, B. M., & Green, A. J. 2001, ApJ, 562, 424
Melioli, C., de Gouveia Dal Pino, E. M., & Raga, A. 2005, A&A, 443, 495
Noutsos, A., Johnston, S., Kramer, M., & Karastergiou, A. 2008, MNRAS, 386, 1881
Nyman, L.-A., Bronfman, L., & Thaddeus, P. 1989, A&A, 216, 185
Rathborne, J. M., Lada, C. J., Walsh, W., Saul, M., & Butner, H. M. 2009, ApJ, 690, 1659
Seidensticker, K. J., & Schmidt-Kaler, T. 1989, A&A, 225, 192
Shapiro, P. R., & Moore, R. T. 1976, ApJ, 207, 460
Staveley-Smith, L., et al. 1996, PASA, 13, 243
Stil, J., Wityk, N., Ouyed, R., & Taylor, A. R. 2009, ApJ, 701, 330
Straizys, V., Claria, J. J., Piatti, A. E., & Kaslauskas, A. 1994, Balt. Astron., 3, 199
Tomisaka, K. 1998, MNRAS, 298, 797
Vallée, J. P. 2005, AJ, 130, 569
Vallee, J. P., & Bignell, R. C. 1983, ApJ, 272, 131
van Straten, W. 2004, ApJS, 152, 129
Walker, A., & Zealey, W. J. 1998, PASA, 15, 79
Weaver, R., McCray, R., Castor, J., Shapiro, P., & Moore, R. 1977, ApJ, 218, 377