The Magnetic Field of the H II Region NGC 6334A from Faraday Rotation

L. F. Rodríguez1,2*, Y. Gómez1 and D. Tafoya3

1 Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Apdo. Postal 3-72, Morelia, Michoacán 58089, México
2 Astronomy Department, Faculty of Science, King Abdulaziz University, P.O. Box 80203, Jeddah 21589, Saudi Arabia
3 Department of Physics and Astronomy, Graduate School of Science and Engineering, Kagoshima University, 1-21-35 Kormoto, Kagoshima 890-0065, Japan

Accepted 2011 December 15. Received 2011 December 14; in original form 2011 October 11

ABSTRACT
We have studied the polarization characteristics and Faraday rotation of the extragalactic radio source J17204−3554, that appears projected on the north lobe of the galactic H II region NGC 6334A. From observations made with the Very Large Array at 6.0 and 3.6 cm in three different epochs (1994, 1997, and 2006), we estimate a rotation measure of \( +5100 \pm 900 \) rad m\(^{-2}\) for the extragalactic source. This large rotation measure implies a line-of-sight average magnetic field of \( B_\parallel \approx +3.6 \pm 0.6 \) \( \mu \)G, the largest obtained by this method for an H II region. NGC 6334A is significantly denser than other H II regions studied and this larger magnetic field is expected on the grounds of magnetic flux conservation. The ratio of thermal to magnetic pressure is \( \sim 5 \), in the range of values determined for more diffuse H II regions.

Key words: ISM: H II Regions – ISM: NGC 6334A – polarization – galaxies: quasars: J17204-3554.

1 INTRODUCTION
The magnetic field of astronomical sources is an important but in general difficult parameter to measure. In their pioneering work, Heiles & Chu (1980) and Heiles, Chu, & Troland (1981) used the Faraday rotation of extragalactic background sources behind four diffuse H II regions (S232, S117, S119, and S264) to determine rotation measures with absolute values in the order of \( 10^2 - 10^3 \) rad m\(^{-2}\). These rotation measures were then used to estimate the strength of the ordered magnetic field along the line of sight, \( B_\parallel \), to have values in the range of \( |B_\parallel| \approx 1 \) to 20 \( \mu \)G for regions with electron densities in the range of 2 to 14 \( \text{cm}^{-3} \). As part of their polarization survey of the Galactic plane, Sun et al. (2007) also used Faraday rotation to estimate the strength of the ordered magnetic field along the line of sight to two diffuse H II regions, G124.9+0.1 and G125.6-1.8. In the case of G124.9+0.1 (with an estimated electron density of 1.6 \( \text{cm}^{-3} \)), this magnetic field was found to be +3.9 \( \mu \)G, while in the case of G125.6-1.8 (with an upper limit to the electron density of 0.84 \( \text{cm}^{-3} \)) a lower limit of +6.4 \( \mu \)G was obtained. More recently, Harvey-Smith et al. (2011) studied the line-of-sight magnetic fields in five large-diameter Galactic H II regions (Sh 2-27, Sh 2-264, Sivan 3, Sh 2-171, and Sh 2-220), with electron densities in the range of 0.8 – 30 \( \text{cm}^{-3} \). Using the Faraday rotation technique, they find \( |B_\parallel| \) values in the range from 2 to 6 \( \mu \)G, which are similar to the typical magnetic field strength in the diffuse interstellar medium. The Faraday rotation method has not been used for more compact and denser H II regions since the probability of having a bright, linearly polarized background source behind a small solid angle is low.

In this paper we present determinations of the rotation measure at different epochs and frequencies in the direction of the AGN J17204-3554 (Bykov et al. 2006; Krivonos et al. 2007; Feigelson et al. 2009). This extragalactic object (\( \alpha(2000) = 17^{h} 20^{m} 21^{s}.81, \delta(2000) = -35^{\circ} 52^{\prime}.48^{\prime\prime}; l = 351^{\circ}.277, b = +00^{\circ}.678 \)) is a bright radio source (Rodríguez et al. 1980) and was originally believed to be embedded in the molecular cloud that contains the NGC 6334 galactic star-forming complex. It is located in the direction of the northern lobe of the bipolar H II region NGC 6334B (Moran et al. 1990) and it is known to be heavily scattered by the intervening plasma (Trotter et al. 1998).

Moran et al. (1990) estimate an emission measure of \( 6 \times 10^4 \text{ cm}^{-6} \text{ pc} \) for the H II region NGC 6334A along the line of sight to J17204-3554. Assuming that the depth of the ionized volume is comparable to the width of NGC 6334A in the plane of the sky (about 1' or 0.5 pc at a distance of 1.7 kpc) and a homogeneous medium, we estimate an electron
density of \( \sim 350 \, \text{cm}^{-3} \) for the intervening H II region. Since this electron density is much larger than the values in the lines of sight sampled by Heiles & Chu (1980), Heiles, Chu, & Troland (1981), Sun et al. (2007), and Harvey-Smith et al. (2011) we expected a larger magnetic field strength determination from the Faraday rotation measurements.

2 VLA ARCHIVE OBSERVATIONS

We searched in the archive of the Very Large Array (VLA) for continuum data sets with the following characteristics. They should have been obtained in the high-angular resolution A or B configurations to minimize the effect of the strong extended emission in the region. The observations were also required to have been taken over several hours and to include a phase calibrator observed over a wide range of parallactic angles, to correct for instrumental polarization.

We found three adequate data sets, whose parameters are summarized in Table 1. The data were edited and calibrated in amplitude, phase and polarization using the Astronomical Image Processing System (AIPS) package of the US National Radio Astronomy Observatory (NRAO), following the standard VLA procedures. The polarization calibration was performed using the observations of the amplitude calibrator to determine the absolute polarization angle, while the observations of the phase calibrator were used to determine and correct the antenna-based leakage terms that produce instrumental polarization.

We determined the Stokes parameters I, Q, and U of the sources observed by fitting directly the images with Gaussian functions using the task JMFIT of AIPS. The errors in the Stokes parameters are estimated from the intensity and angular dimensions of the sources and from the noise in the images following Condon (1997). These parameters, as well as the derived percentages and position angles of the linear polarization are given in Tables 2 to 4. The errors in the percentages and the position angles come from the propagation of the errors on the Stokes parameters. We list separately these parameters for the two IFs available at the VLA (separated by 50 MHz) at each band.

We searched for significantly different position angles in the two IFs of the data at each observed wavelength and epoch. Only in the case of the source of interest J17204–3554 (epochs 1994 and 1997 at 6.0 cm and epoch 1997 and 2006 at 3.6 cm) and the phase calibrator 1744−3554 (epoch 1994 April 28 and 1997 February 02) we find significant differences. We determined the rotation measures (RM) from these observations using

\[
RM = -\frac{\Delta \theta \nu}{2 \lambda^2 \Delta \nu} \text{rad m}^{-2},
\]

where \( \Delta \theta \) is the difference in position angles given in radians, \( \nu \) is the central frequency in MHz, \( \lambda \) is the central wavelength in meters, and \( \Delta \nu \) is the frequency difference in MHz (that in general, can be given in the same units used for \( \nu \)). With this definition, positive and negative RMs indicate average magnetic fields pointed towards and away from the observer, respectively.

For the 1994 observations of 1744–312 at 6 cm, we derive \( \text{RM} = +1500 \pm 600 \, \text{rad m}^{-2} \), in agreement with the much more accurate value of \( +1883 \pm 3 \, \text{rad m}^{-2} \) derived by Roy et al. (2005) from observations made from 4.8 to 8.5 GHz. Our technique is insensitive to small rotation measures and the upper limits for the rotation measure derived from the 1997 observations of 1733–130 at 6.0 cm, \( |\text{RM}| \leq 1000 \, \text{rad m}^{-2} \) (3-\( \sigma \) upper limit) are also consistent with the value of \( \sim 60 \, \text{rad m}^{-2} \) reported in the rotation measure catalog of Taylor et al. (2009) and previously by Rusk (1988).

In Table 5 we report our main result: the rotation measures derived for J17204–3554. We note that the two 6.0 cm determinations are consistent among them and the same happens for the two 3.6 cm determinations. However, the 3.6 cm determinations appear to be \( \sim 40\% \) larger than those at 6.0 cm and this effect deserves further attention. Law et al. (2011) have compared observations made in the 1 to 2 GHz range with the Allen Telescope Array and in the 5 to 22 GHz range with the Very Long Baseline Array and conclude that, as observed for J17204–3554, the rotation measure values and the fractional polarization are generally larger at higher frequencies. In the case of J17204–3554 this effect could be related to the fact that plasma scattering makes the source larger at the lower frequencies (Trotter et al. 1998). We may then be averaging over a larger volume at the lower frequencies and obtaining a lower value for the line-of-sight magnetic field. In any case, given the modest signal-to-noise ratio of our results, we will adopt as the rotation measure for J17204–3554 the value of \( +5100 \pm 900 \, \text{rad m}^{-2} \), the weighted average of the four determinations.

The absolute position angles of the linear polarization for J17204–3554 at a given frequency change significantly from one epoch to the other (compare, for example, the position angles at 4.8351 or 4.8551 GHz for 1994 April 28 and 1997 February 02). It is known that the absolute position angles of quasars at a given frequency can change by as much as several tens of degrees over timescales of months (see Zavala & Taylor 2001 and also The VLA/VLBA Polarization Calibration Page [http://www.aoc.nrao.edu/~smyers/calibration/]). In the case of a source with a large rotation measure such as J17204–3554, these variations most probably come from small changes in the parameters of the Faraday screen with time. For a rotation measure of \( +5100 \, \text{rad m}^{-2} \), a variation of only \( \sim 2\% \) in its value will produce a change of \( \sim 20^\circ \) in the position angle at 4.8 GHz.

3 INTERPRETATION

The rotation measure estimated for J17204–3554 is quite large. The largest rotation measures known are usually found for extragalactic sources with a similar location to that of J17204–3554, that is, in the galactic plane toward the centre of the Galaxy. Brown et al. (2007) presented Faraday...
The value of the rotation measure is 

In the surroundings of J17204−G296.90+0.14 and behind the southern Galactic plane (253 day rotation measures for 148 extragalactic radio sources. Of these 148 sources, only two have absolute rotation measures in excess of 1000 rad m$^{-2}$ defined by Roy et al. (2005; 2008) determined the rotation measure toward J17204−3554 the typical absolute value of the rotation measure is $\sim 300$ rad m$^{-2}$. We can then propose that most of the rotation measure seen toward J17204−3554 is produced by the H II region NGC 6334A. Roy et al. (2005; 2008) determined the rotation measure toward 60 background extragalactic components in the region defined by $-6^\circ \leq l \leq 6^\circ$, $-3^\circ \leq b \leq 2^\circ$, that surrounds the galactic centre, where the largest rotation measures are expected. In this extreme sample, there is only one source with a rotation measure comparable with J17204−3554 (the source G358.917+0.072, about one degree away from Sgr A*, with a rotation measure of $\sim 4800$ rad m$^{-2}$).

If we then assume that practically all the Faraday rotation observed toward J17204−3554 is produced by the H II region NGC 6334A we can estimate the line-of-sight magnetic field of this last source. The rotation measure is given by

$$RM = 0.81 \int n_e B_\| dl \, \text{rad} \, m^{-2}$$

(2)

where $n_e$ is the electron density in the medium producing the Faraday rotation, given in cm$^{-3}$, $B_\|$ is the parallel component of the magnetic field in $\mu G$, and $dl$ is the differential of path length along the line of sight, given in pc.

Assuming a homogeneous medium and the values estimated by Moran et al. (1990) of $n_e \approx 350$ cm$^{-3}$ and $l = 0.5$ pc, we obtain $B_\| \approx +36 \pm 6$ $\mu G$, with this average magnetic field pointing toward us. This is the largest value of $B_\|$ obtained from Faraday rotation across an H II region. Harvey-Smith et al. (2011) present a compilation of values determined with this technique and find them to be typically located in the ranges of 0.6 $\mu G \leq B_\| \leq 10$ $\mu G$ and 1 cm$^{-3} \leq n_e \leq 20$ cm$^{-3}$. Harvey-Smith et al. (2011) have combined the H II Faraday rotation data with HI Zeeman effect observations to discuss line-of-sight magnetic fields for densities (electron or atomic) in the range of $1$ cm$^{-3} \leq n \leq 200$ cm$^{-3}$. They conclude that the slope of magnetic field versus density in this low-density regime is quite flat. A value of $|B_\|| \approx 3 \pm 3$ $\mu G$ could fit most of the available data. However, the value of $B_\|$ for NGC 6334A is substantially larger and indicates that it is very important to extend the Faraday rotation technique to denser H II regions, with $n_e > 100$ cm$^{-3}$.

Unfortunately, denser H II regions are typically smaller and this makes the probability of finding a bright polarized background source in their line of sight practically negligible. Fortunately, with the advent of ultrasensitive radio interferometers such as the EVLA and eMERLIN, one will soon be able to detect and study much weaker background sources, extending the Faraday rotation technique to higher electron densities.

Finally, following Harvey-Smith et al. (2011), we estimate the ratio of thermal to magnetic pressure, $\beta_\text{th}$, for NGC 6334A. This ratio is given by

$$\beta_\text{th} = \frac{16\pi n_e k T_e}{B^2}$$

(3)

where $k$ is Boltzmann’s constant, $T_e$ is the electron temper-

---

Table 1. VLA Archive Observations of J17204−3554 Used in This Paper

| Epoch          | VLA Configuration | Project | Wavelength (cm) | Amplitude Calibrator | Phase Calibrator | Parallactic Angle Range (°) | Time On-source (minutes) |
|----------------|-------------------|---------|-----------------|----------------------|-----------------|-----------------------------|--------------------------|
| 1994 Apr 28    | A                 | AM447   | 6.0             | 1331+305            | 1744−312       | 23                          | 50                       |
| 1997 Feb 02    | BnA               | AT202   | 6.0             | 1331+305            | 1733−130       | 43                          | 39                       |
| 1997 Feb 02    | BnA               | AT202   | 3.6             | 1331+305            | 1733−130       | 47                          | 60                       |
| 2006 Aug 17    | B                 | S7810   | 3.6             | 0137+331            | 1832−105       | 63                          | 100                      |

*a* For these observations 1832−105 was used to correct for instrumental polarization and J17204−3554, now included in the list of VLA calibrators, was self-calibrated.

Table 2. Linear Polarization Parameters of 1744−312 and J17204−3554 on 1994 April 28

| Source        | Frequency (GHz) | $I$ (Jy)$^a$ | $Q$ (mJy)$^a$ | $U$ (mJy)$^a$ | Polarization (%)$^b$ | P.A. (°)$^c$ |
|---------------|-----------------|--------------|--------------|--------------|----------------------|--------------|
| 1744−312      | 4.8351          | 0.386±0.001  | −5.4±0.2     | −1.3±0.2     | 1.44±0.05            | −83.2±2.1    |
| 1744−312      | 4.8851          | 0.387±0.001  | +5.7±0.2     | +0.0±0.1     | 1.47±0.05            | −90.0±1.5    |
| J17204−3554   | 4.8351          | 0.470±0.002  | −0.1±0.1     | −2.8±0.1     | 0.60±0.02            | −46.9±2.0    |
| J17204−3554   | 4.8851          | 0.473±0.002  | −2.4±0.1     | −2.1±0.1     | 0.67±0.02            | −69.4±1.8    |

*a* Stokes parameters $I$, $Q$, and $U$.

*b* Percentage of linear polarization.

*c* Position angle of the linear polarization.
Our main results can be summarized as follows.

(i) We studied the Faraday rotation of the extragalactic radio source J17204-3554, that appears projected on the north lobe of the galactic H II region NGC 6334A, estimating a rotation measure of $+5100 \pm 900$ rad m$^{-2}$. This is one of the largest rotation measures found for any type of source.

(ii) This rotation measure implies a line-of-sight magnetic field of $B_{\|} \approx +36 \pm 6 \mu$G for NGC 6334A, the largest obtained by this method for an H II region.

(iii) For the ratio of thermal to magnetic pressure we obtain $\beta_{th} \simeq 5$, in the range of $2 \leq \beta_{th} \leq 22$ obtained by Harvey-Smith et al. (2011) for the five large-diameter Galactic H II regions studied by them.

(iv) These results suggest that it is necessary to study much weaker background sources behind denser H II regions, extending the Faraday rotation technique to higher electron densities. This possibility will become feasible with the ultrasensitive arrays like eMERLIN and the EVLA.

ACKNOWLEDGMENTS

LFR acknowledges the financial support of DGAPA, UNAM and CONACyT, México.

REFERENCES

Brown, J. C., Haverkorn, M., Gaensler, B. M., Taylor, A. R., Bizunok, N. S., McClure-Griffiths, N. M., Dickey, J. M., & Green, A. J. 2007, ApJ, 663, 258
Bykov, A. M., et al. 2006, A&A, 449, 917
Condon, J. J. 1997, PASP, 109, 166
Feigelson, E. D., Martin, A. L., McNell, C. J., Broos, P. S., & Garmire, G. P. 2009, AJ, 138, 227
Harvey-Smith, L., Madsen, G. J., & Gaensler, B. M. 2011, ApJ, 736, 83
Heiles, C., & Chu, Y.-H. 1980, ApJ, 235, L105
Heiles, C., Chu, Y.-H., & Troland, T. H. 1981, ApJ, 247, L77
Krivonos, R., Revnivtsev, M., Lutovinov, A., Sazonov, S., Churazov, E., & Sunyaev, R. 2007, A&A, 475, 775
Law, C. J., et al. 2011, ApJ, 728, 57
Moran, J. M., Rodríguez, L. F., Greene, B., & Backer, D. C. 1990, ApJ, 348, 147
Rodríguez, L. F., Cantó, J., & Moran, J. M. 1982, ApJ, 255, 103
Roy, S., Rao, A. P., & Subrahmanyan, R. 2005, MNRAS, 360, 1305
Roy, S., Pramesh Rao, A., & Subrahmanyan, R. 2008, A&A, 478, 435
Rusk, R. E. 1998, Ph. D. thesis, Univ. of Toronto
Sun, X. H., Han, J. L., Reich, W., Reich, P., Shi, W. B., Wielebinski, R., Fürst, E. 2007, A&A, 463, 993
Taylor, A. R., Stil, J. M., & Sunstrum, C. 2009, ApJ, 702, 1230
Trotter, A. S., Moran, J. M., & Rodríguez, L. F. 1998, ApJ, 493, 666
Zavala, R. T., & Taylor, G. B. 2001, ApJ, 550, L147

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.