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MAGNETIC FIELD STRENGTHS IN THE H II REGIONS S117, S119, AND S264

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ABSTRACT

We estimate the magnetic field strengths in three H II regions from VLA measurements of the Faraday rotation of extragalactic radio sources that lie behind the H II regions. Two of the extragalactic sources are double, with components separated by angles of 9″ and 26″; in each case, the rotation measures of the two components are identical. Field strengths for S117 (the North America Nebula) and S264 (the H II region surrounding the star λ Ori) are probably 1 or 2 microgauss. In the molecular cloud associated with S117, the magnetic field strength may have been as high as 50 microgauss.

S119 is part of an elongated shell and has a line-of-sight field of about 20 microgauss. The lower limit on the magnetic energy density is about half the thermal energy density, and magnetic forces seem to have played some role in producing the morphology of S119.

Subject headings: interstellar: magnetic fields — nebulae: H II regions — radio sources: general

I. INTRODUCTION AND OBSERVATIONS

In this *Letter* we derive magnetic field strengths in three H II regions from the Faraday rotation measures (RMs) of linearly polarized extragalactic radio sources that lie behind the H II regions. The observations were obtained with the Very Large Array (VLA),[1] using the technique of Heiles and Chu (1980) and a bandwidth of 3.125 MHz. The array consisted of 13 functioning antennas on all three arms, with distances ranging up to 10.5, 13.6, and 4.7 km for the east, west, and north arms, respectively.

Table 1 lists the observed parameters. As in Heiles and Chu (1980), errors are estimated maximum errors. 4C 43.52 and 4C 09.21 are double; the positions given are midway between the two components.

II. DERIVATION OF MAGNETIC PARAMETERS

Table 2 lists the derived parameters for these H II regions. For S117 (the North America Nebula) and S264 (the H II region surrounding λ Ori), the emission measures (EM), diameters, densities, and distances are from Wendker (1968) and Reich (1978), respectively. Wendker (1971) gives a distance and a 1400 MHz map for S119 but does not derive either the EM or the density. The peak of his map is coincident with 4C 43.52, the extragalactic source we observed; we derive the peak EM for S119 by assuming that 4C 43.52 contributes 1 K in brightness temperature to his map. S119 is part of an elongated shell, and S119 itself is elongated, roughly in the north-south direction. We derive its electron density by assuming that the distance along the line of sight is the same as that subtended by the short dimension of S119 across the line of sight.

Each measured RM has three contributors: the extragalactic source itself, the Galaxy, and the H II region. Since we wish to know the contribution from the H II region alone, we must estimate the other two contributions.

First, consider the contributions from the extragalactic sources. Kronberg and Simard-Normandin (1976) have presented the statistics of RMs for extragalactic sources located at $|b| > 5°$, where the galactic contribution is negligible. Their statistics indicate that the *a priori* probabilities that our RMs of -580, -1690, and 209 rad m^{-2} are produced by the sources themselves are 6%, 0%, and 30%, respectively.

Thus, for the first two regions, S117 and S119, we assume that the RMs come exclusively from the Galaxy and the H II regions. For the last region, S264, we can only regard the measured RM of 209 rad m^{-2} as an indication of the contribution from the Galaxy and the H II region. The measured RM cannot be regarded as an upper limit to these galactic contributions because of the possibility that the signs of RMs in the source and in the Galaxy are different, leading to cancellation. However, it is a likely upper limit.

Next, consider the galactic contributions for S117 and S119. These are difficult to estimate because the galactic contribution changes very rapidly near longitude 86° where these sources are located. The most extensive compilation of extragalactic RMs is that of Simard-Normandin, Kronberg, and Button (1981); in addition,

[1]The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 1

OBSERVED PARAMETERS

Source	4C 44.37	4C 43.52	4C 09.21
$\alpha(1950)$[a]	$20^h56^m42\overset{s}{.}0$	$21^h19^m24\overset{s}{.}7$	$05^h32^m05\overset{s}{.}4$
$\delta(1950)$[a]	44°34′24″	43°33′36″	10°02′34″
RM (rad m^{-2})	− 700 to −460	− 1740 to − 1640	160 to 260
Flux (Jy)	0.45	0.19	0.32
Polarization (%)	2.3	8.3	8.1
Galactic long.	85°.8	87°.8	194°.9
Galactic lat.	− 0°.7	− 4°.3	− 12°.0
H II region	S117	S119	S264

[a]4C 43.52 and 4C 09.21 are double; the positions given are midway between the two components.

TABLE 2

DERIVED PARAMETERS

H II region	S117	S119	S264
EM (cm^{-6} pc)	2600	1470	250
$n(e)$ (cm^{-3})	9	14	2
RM of H II region	− 1100 to −60	− 2140 to − 1240	0 to 260[a]
B (par)/$n(e)$	0.03 to 0.52	1.04 to 1.80	0 to 1.3
B (par) (microgauss)	0.3 to 4.7	14.6 to 25.2	0 to 2.6
U (mag)/U (thermal)[b]	0.009 to 0.03	0.18 to 0.54	0 to 0.04

[a]A likely, but not definite, upper limit; see text.
[b]Lower limits only; see text.

Simard-Normandin and Kronberg (1981) have interpreted the data in terms of galactic rotation measures. The latter work defines three large regions of sky which contain consistent RM patterns. S117 and S119 are situated close to the boundary of "region A," which is characterized by large negative RMs, and fairly close to "region C" which has large positive RMs. The boundary between these two regions is sharp, in the sense that there is no intermediate region where small RMs of both signs are mixed together. This curious behavior is reflected in the RMs of their three extragalactic sources that lie closest to S117 and S119: 3C 418, at $(l, b) = (88\overset{\circ}{.}8, 6\overset{\circ}{.}0)$, has RM = −258 rad m^{-2}; 3C 428, at $(90\overset{\circ}{.}5, 1\overset{\circ}{.}3)$, has RM = −359; and 3C 431, at $(91\overset{\circ}{.}7, 0\overset{\circ}{.}1)$ has RM = +347. The reversal of RM in sign, and change in value by about 700 rad m^{-2}, over the $1\overset{\circ}{.}7$ distance between 3C 428 and 3C 431 epitomizes Simard-Normandin and Kronberg's description of the boundary between regions A and C. A search of the Palomar Sky Survey reveals no H II regions in this area which might lie in front of the extragalactic sources and be responsible for this behavior.

Our only recourse is to regard the galactic contribution for S117 and S119 as uncertain, lying between −400 and +400 rad m^{-2}. Our generous bounds on the RMs of S117 and S119 in Table 2 reflect this large uncertainty.

As noted by Heiles and Chu (1980), the ratio $B(\mathrm{par})/n(e)$, where B(par) is the line-of-sight component of the magnetic field and $n(e)$ is the electron density in the H II region, is proportional to the ratio of the observed quantities RM/EM. A physical quantity of considerable interest is the ratio of magnetic to thermal energy density,

$$\frac{U(\mathrm{mag})}{U(\mathrm{thermal})} = \frac{(B^2/8\pi)}{3n(e)kT} = 146\frac{n(e)}{T}\left(\frac{\mathrm{RM}}{\mathrm{EM}}\right)^2. \quad (1)$$

Here the units are: RM, rad m^{-2}; EM, cm^{-6} pc; $n(e)$, cm^{-3}; T, kelvins. Of course, the RM samples only the parallel component of B so that ratios of magnetic to thermal energy densities derived from equation (1) are lower limits only. These limits are listed in Table 2 for an assumed gas temperature of 8000 K.

III. DISCUSSION

a) S117: The North America Nebula

This large, evolved H II region has recently been discussed in detail by Bally and Scoville (1980). They model this region as the result of star formation inside a molecular cloud. Long ago the stars ionized the cloud, increasing the pressure by a large factor, and the ensuing expansion eventually reached the surface of the molecular cloud. The North America Nebula consists of gas which flowed out of the hole punched through the surface. By now the gas has expanded 20 pc away from the molecular cloud, implying an age of some 10^6 yr or more.

According to Table 2, B(par) in S117 lies between 0.3 and 4.7 microgauss. The lower limit on the ratio of magnetic to gas pressure lies between 0.009 and 0.03. Thus, gas pressure dominates unless the geometry is extremely unfavorable. Following Heiles and Chu (1980), during the expansion $B \propto n^x$, with $x = 1/3$ if magnetic pressure dominates and $x = 2/3$ if gas pressure dominates. Since gas pressure dominates, $x = 2/3$.

According to Bally and Scoville (1980), the present density of the molecular cloud is 500 cm^{-3}; in the past it might have been greater, perhaps 1000 cm^{-3}. The present electron density in S117 is 9 cm^{-3}; thus, the density has decreased by a factor of about 100, and the magnetic field has decreased in strength by a factor of 20. If the present field strength in the ionized region is 2.5 microgauss, the average of our limits in Table 2, the field strength in the original molecular cloud when its density was 1000 cm^{-3} was about 50 microgauss.

A magnetic field strength of 50 microgauss in a molecular cloud of density 1000 cm^{-3} is quite consistent with the existing meager knowledge of magnetic field strengths in molecular clouds. The only direct information comes from attempts to measure Zeeman splitting of 18 cm OH lines in dust clouds, both in emission (Crutcher *et al.* 1975) and in absorption (Crutcher, Troland, and Heiles 1981). The emission line observations set 3 σ limits on the field strengths in three dust clouds of about 60 microgauss. The absorption line measurements are more sensitive, reaching limits as low as 16 microgauss; however, the clouds to which they refer have smaller densities because the clouds were selected by the presence of a strong extragalactic radio continuum source instead of the existence of high gas densities. Since the field strength in the present molecular cloud may well have been less than 50 microgauss, there is certainly no conflict with existing observational data.

A 50 microgauss field corresponds to a magnetic pressure that was 9 times higher than the gas pressure of the molecular cloud, if its temperature was 80 K. This circumstance is not necessarily surprising since the molecular region was sufficiently massive to have confined the magnetic field by gravity. The present mass of the molecular cloud is about 5×10^4 $M_\odot$; the gravitational energy of such a mass, confined to a sphere with density 1000 cm^{-3}, is about 2×10^{49} ergs. The corresponding magnetic energy, if the field strength was 50 microgauss, is 0.6×10^{49} ergs. Gravity dominates by a factor of 3; indeed, without the magnetic field the gravitational forces would have considerably exceeded the gas pressure.

Thus, the molecular cloud might have been a case in which self-gravity was balanced by magnetic pressure. Equally well, the field strength in the present ionized region could be much weaker than our adopted value of 2.5 microgauss, in which case the original cloud might have been supported by its own internal motions—or, for that matter, never have been in equilibrium at all, but formed the stars that have produced today's H II regions during its initial collapse.

b) *S264*: *The* H II *Region surrounding* λ *Orionis*

This region has recently been studied and reviewed by Murdin and Penston (1977) and by Coulson *et al.* (1978). It is widely regarded as a classical evolved Strömgren sphere with an associated H I shell (Wade 1957). The neutral shell is visible at several velocities in the photographic presentations of H I column densities of Colomb, Poppel, and Heiles (1980). S264 also has three associated dust shells (Coulson *et al.* 1978). S264 is well described by a theoretical model in which the initial density was about 10 cm^{-3} and the age is 10^6 yr (Lasker 1966). Recent work by Lada and Wilking (1980) shows that the bright-rimmed molecular cloud B35 lies on the periphery. B35 has an unusually high temperature for a dust cloud, which these authors ascribe to heating by an ionization-driven shock from S264 or by magnetic dissipation.

According to Table 2, B(par) in S264 lies between 0 and 2.6 microgauss. As noted in § II, it is possible but unlikely that B(par) is greater than 2.6 microgauss; we shall assume that 2.6 microgauss is indeed an upper limit. The lower limit on the ratio of magnetic to thermal energy density is less than 0.04. As for S117, gas pressure dominates, and $x = 2/3$, unless the geometry is extremely unfavorable. From Lasker's models, the initial density was some 5 times the present density. Thus, during the expansion of the H II region the magnetic field strength has decreased by a factor of 3. If the present field strength is 1.3 microgauss, the field strength in the original cloud of density 10 cm^{-3} was 4 microgauss, and the magnetic pressure exceeded the gas pressure by a factor of about 6. However, the field could have been much weaker.

A magnetic field strength of 4 microgauss in an H I region of density 10 cm^{-3} is quite consistent with the existing meager knowledge of magnetic field strengths in diffuse H I clouds. The only direct information comes from attempts to measure Zeeman splitting of the 21 cm H I emission line (absorption measurements sample denser, colder regions). Typical limits for such regions are about 5 microgauss (Troland and Heiles 1981). The field strengths derived from Faraday rotation of pulsars and extragalactic radio sources are about 3 microgauss, a value which applies to regions of considerably lower density (see review by Heiles 1976).

c) *S119*: *A Region of High Magnetic Field*

S119 is the brightest part of a thick, ionized shell surrounding the O8 star 68 Cyg. The shell diameter is about 1°3, or 23 pc. Fabry-Perot observations by Treffers

(1980) show that expansion motions are very slow. Thus, this shell fits the picture of an evolved H II region. The shell is elongated by about 50% in the north-south direction, and parts of the shell contain smaller scale structures which are elongated in the same direction as the shell itself.

According to Table 2, B(par) in S119 is about 20 microgauss. The lower limit on the ratio of magnetic to thermal energy density lies between 0.18 and 0.54. Thus, the magnetic field should have had some effect on the gas dynamics throughout the expansion of the H II region. Since the shell is thick, the original density before ionization and expansion could not have been much higher than the present density of 14 cm^{-3}, and the magnetic pressure exceeded the gas pressure by a large factor. Expansion must have occurred preferentially along the field lines, a situation which leads to $x \approx 0$—that is, little change of magnetic field strength with density. The magnetic field in the original neutral region must have been roughly equal to its present value, 20 microgauss. In the direction perpendicular to the magnetic field, the pressure in the ionized gas exceeded the *total* pressure in the neutral region by only a factor of about 10—not the usual factor of 200, which would apply in the direction parallel to the field lines. This may well account for the elongated shape of the ionized shell.

The present neutral gas surrounding S119 may be similar to the original neutral gas in having a much larger magnetic than gas pressure. Containment of the magnetic field is a problem because there are no large dust clouds visible nearby, so no gravitational role can be played by massive clouds. Containment could occur by the stagnation pressure of an expanding shell. Heiles (1976) has cataloged large, expanding shells of H I gas in the galaxy. His Table 1 lists one such shell, GS 088−04+17, which encloses S119. The diameter of this shell is 6° and its expansion velocity is 8 km s^{-1}. With this velocity, the stagnation pressure is high enough to keep the magnetic pressure from blowing the H I gas apart within the shell. Perhaps the star that produced S119 was formed from, and S119 is currently enveloped by, the H I in this shell.

d) Homogeneity of Magnetic Fields in H II *Regions*

We know of three H II regions for which RMs have been sampled by double radio sources: S119, S232 (Heiles and Chu 1980), and S264. The component separations are about 26″, 33″, and 9″, respectively. Only for S232 might there exist a detectable difference in RM between the two components; if it is real, it amounts to about 14%. For S119 the difference is less than 6%, and for S264 it is less than 20%.

Gas pressure dominates magnetic pressure by large factors in S232 and S264. In these regions we might expect random gas motions to generate small-scale structure in the magnetic field. This might be responsible for the possible 14% difference in S232.

Magnetic pressure is not negligible in S119. The enhanced importance of magnetic pressure might prevent the generation of small-scale structure in the field and be responsible for the small RM difference between the two components of 4C 43.52.

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