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VLBI OBSERVATIONS OF THE RADIO SOURCES 0552+398 AND 1848+283: MEASUREMENTS OF THE DEPARTURE FROM EQUIPARTITION

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ABSTRACT

Very Long Baseline Interferometer observations at 5 and 10.6 GHz, together with multi-frequency flux density measurements, are reported for the compact radio sources 0552+398 and 1848+283. Both sources are characterized by sharply peaked spectra with maxima in the 5–10 GHz range and are thus good approximations to the theoretical ideal of a homogeneous synchrotron source. Our data are used to determine the magnetic field strengths in these sources, which have been compared with the "equipartition magnetic field" estimates. In the source 0552+398, the field is weaker (by a factor of about 100) than the equipartition value. On the other hand, our observations of 1848+283 are consistent with this source possessing roughly equal energy densities in the magnetic field and relativistic electrons.

Subject headings: interferometry — magnetic fields — quasars — radio sources: general

I. INTRODUCTION

One of the quantities most commonly calculated from observations of nonthermal radio sources is the equipartition magnetic field, i.e., the value of the magnetic field in a synchrotron radiation source which has approximately equal energy densities of magnetic field and relativistic particles. The attraction of this observable is that it is rigorously defined, and its value is relatively insensitive to measured quantities or poorly constrained physical parameters. However, there is no *a priori* reason for believing that magnetic fields in radio sources are at the equipartition values, and it would be instructive if an independent estimate of the field strength could be obtained in even a restricted sample of sources.

In principle, an independent estimate of the magnetic field strength can be made in the case of opaque synchrotron sources. As is well known, the magnetic field of a source which becomes opaque to its own radiation is (Kellermann 1974)

$$B \sim 2.3 \times 10^{-5}(S_m/\theta^2)^{-2}\nu_m^{\,5}(1+z)^{-1} \text{ gauss}, \quad (1)$$

where S_m is the peak flux density (Jy), ν_m is the frequency of maximum flux density (GHz), and θ is the angular diameter (mas).

Studies based on equation (1) have led to divergent results. Scott and Readhead (1977) used the technique of interplanetary scintillations to measure the angular sizes of sources which become optically thick at frequencies of ~ 100 MHz. They contended that such sources were, in fact, very close to being "in equipartition," i.e., possessing equal energy densities of relativistic particles and magnetic field. However, it is generally believed that sources which show maxima in their spectra at frequencies of a few GHz are far from equipartition, in the sense that the relativistic particle energy density greatly exceeds that of the magnetic field (Kellermann and Pauliny-Toth 1981). One of the more compelling demonstrations that this inequality exists is to be found in Jones, O'Dell, and Stein (1974).

One possible reason for this discrepancy is apparent in equation (1). The inferred magnetic field is proportional to high powers of the observables. Uncertainties in measurement or convention can therefore lead to significant errors in the magnetic field estimate. By the same token, this estimate is quite sensitive to assumptions concerning the source geometry and structure.

In this paper we attempt to determine the magnetic field strength in the radio sources 0552+398 (DA 193) and 1848+283. The reason for considering this venerable topic again is that we feel these two sources are particularly well suited for an analysis of this sort. Both are characterized by rather sharply peaked radio spectra, with maxima in the frequency range 5–10 GHz. In fact, of 136 sources whose spectra were measured by Owen, Spangler, and Cotton (1980), 0552+398 had the steepest spectrum on the low frequency side of maximum, with an optically thick spectral index close to the value of 5/2 expected for a homogeneous synchrotron source.

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The spectral shapes of these two sources make them superior candidates for a magnetic field analysis for two reasons:

1. The occurrence of a sharply peaked radio spectrum, with optically thick spectral index close to 5/2, is an indication that a source is a reasonable approximation to the idealization used to derive equation (1), that of a homogeneous synchrotron source. As was noted above, such objects are relatively rare. Most compact radio sources have rather broad maxima, with optically thick spectral indices of 0.3–0.7 (Spangler 1980). Such spectra are characteristic of nonuniform sources.

2. The spectral shapes of objects such as 0552+398 and 1848+283 facilitate precise measurement of the quantities in equation (1) such as ν_m and S_m. This should permit a more precise determination of the magnetic field than is possible for a source with an ill-defined maximum.

The source 0552+398 is a high-redshift quasar ($z = 2.365$). The object 1848+283 has been identified with a 17th magnitude blue stellar object (BSO) (Condon *et al.* 1983), indicating that it is also a quasar albeit one of unknown redshift.

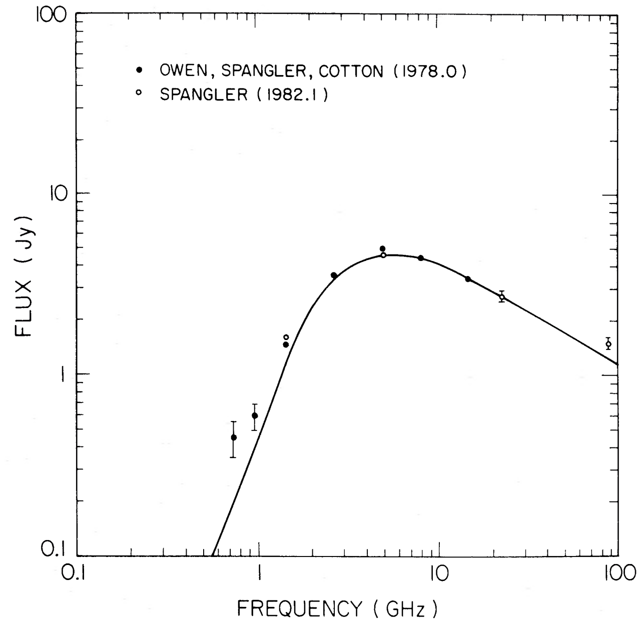

FIG. 1.—Spectrum of 0552+398 in the frequency range 750 MHz to 90 GHz. Different symbols indicate measurements made in early 1978 and early 1982, respectively. The solid curve represents a two-component model which is consistent with the VLBI observations.

II. OBSERVATIONS

a) *Flux Density Measurements*

For measurements of the integrated radio spectrum, we relied in large part on the broad-band measurements of Owen, Spangler, and Cotton (1980). However, these measurements were made circa 1978.0, whereas the VLBI observations which they are to complement (described below) were carried out in 1981 June and August. It was therefore necessary to determine the effects of source variability on the spectrum. To this end, additional flux density measurements were made in 1982 at 1.4, 4.9, 15.0, and 22.5 GHz using the Very Large Array, and (in the case of 0552+398) at 89.6 GHz with the NRAO 11 m millimeter-wavelength radio telescope. For 1848+283, we have also included measurements at 5 and 10.6 GHz, made by Richard Porcas with the Bonn 100 m telescope during the VLBI observations.

All of our flux density data are plotted in Figures 1 and 2. The curves represent models fit to the spectra, which are discussed below.

The observations of 0552+398 indicate that the spectrum of this source in 1982 was virtually identical to that measured by Owen, Spangler, and Cotton (1980) in early 1978. This fosters hope that the spectrum of 0552+398 was also as shown in Figure 1 at the time of our VLBI observations in mid-1981. This is not certain to be the case, as Altschuler and Wardle (1976) observed variability at the level of 20% in the time interval 1973–1975.

The observations of 1848+283 (Fig. 2) show evidence for variability in the interval 1978.0–1982.7, hardly surprising for such a compact source. However, at both epochs the spectrum above 3 GHz is well represented by a single homogeneous synchrotron component. The departure from the model spectrum at lower frequencies

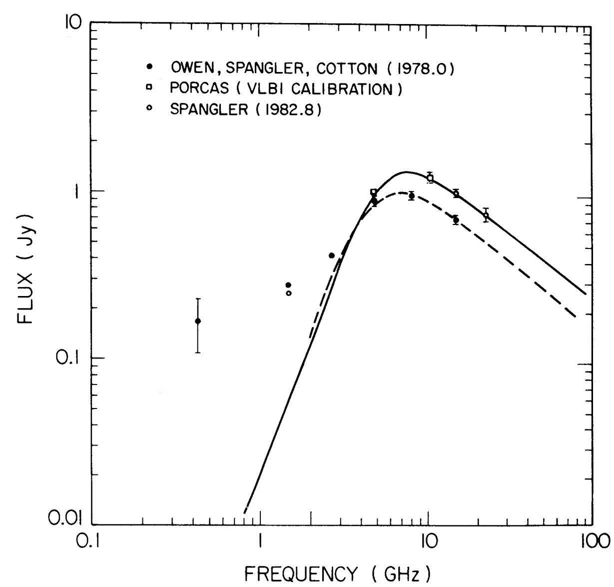

FIG. 2.—Spectrum of 1848+283 in the frequency range 430 MHz to 22.5 GHz. Different symbols indicate measurements made in early 1978, mid-1981, and mid-1982. The data show evidence of variability during the 4 year interval. The curves indicate single-component homogeneous synchrotron source models fit to the data. The solid curve represents a fit to the 1981–1982 spectrum, while the dashed curve represents the 1978.0 measurements. The models provide a good fit to the data except at low frequencies, where the departure is probably due to an extended component.

is probably due to an extended steep-spectrum component (Owen, Spangler, and Cotton 1980).

b) *VLBI Observations*

Observations with the United States VLBI Network, augmented by the 100 m telescope of the Max Planck Institut für Radioastronomie, were made at 2.8 cm in 1981 June, and 6 cm in 1981 August. The 2.8 cm interferometer consisted of antennas at Bonn, NRAO, Fort Davis, and Owens Valley. The 6 cm interferometer was comprised of these elements, and also the Haystack antenna and the Very Large Array in "phased array" mode. The video tapes were correlated with the NRAO processor in Charlottesville, Virginia.

The calibrated data (correlated flux densities and closure phases) were analyzed in three ways: (1) hybrid maps, (2) model fitting, and (3) study of plots of fringe amplitude versus baseline length. We now discuss these analyses for each of the sources.

i) *0552+398*

The hybrid map was made with three iterations of the Readhead-Wilkinson (1978) algorithm, plus an additional two iterations employing amplitude self-calibration as well. A contour plot of the 6 cm map is shown in Figure 3 (*top*). The map contains at least 90% of the entire single-dish flux of the source.

In view of the featureless nature of the map in Figure 3, we proceeded to fit a model to the visibility data. An attempt was made to make the model as simple as is consistent with the main features of the observations. For example, while the amplitudes alone may be reasonably fit by a single elliptical Gaussian component, small (~20° max) but significant closure phase excursions from zero require some asymmetry to the brightness distribution.

Accordingly, it was felt that the simplest model which could account for the main features of the data consisted of two components possessing circular Gaussian brightness distributions. A comparison of the least squares–fit model and the 6 cm data for selected baselines and closure phases is shown in Figure 4.

A model fit was also undertaken for the 2.8 cm observations. Since these data were more limited than the 6 cm observations, we incorporated the information obtained from the 6 cm model. The angular size of the extended component, the separation of the extended and compact components, and the position angle of the line joining the two components were taken from the 6 cm model. The model-fitting program was allowed to vary the ratio of the component flux densities and the angular size and ellipticity of the compact component. The position angle of the compact component was constrained to be along the axis of the double. A satisfactory fit to the 2.8 cm data was obtained.

The results of the model fitting are presented in Table 1. The errors quoted are empirical estimates determined from parameter ranges which gave equally good representations of the data.

Finally, as perhaps the simplest form of data analysis, we examined a plot of visibility amplitude versus projected baseline length $[(u^2 + v^2)^{1/2}]$. Such a plot allows one to compare the measured visibility function with that of an object possessing a circular Gaussian brightness distribution. The 6 cm observations conformed reasonably well with a Gaussian model of angular size (FWHM) of 0.7–0.8 mas. This value will serve as an estimate of the angular size of the source as a whole. At 2.8 cm, the shape of the visibility function is similar to that at 6 cm for baseline lengths less than about 1.5×10^8 wavelengths. For longer baselines ($2-3 \times 10^8$ wavelengths), however, we measure more correlated flux than would be expected for a 0.7 mas Gaussian, indicating that we are probing more compact structure in the source.

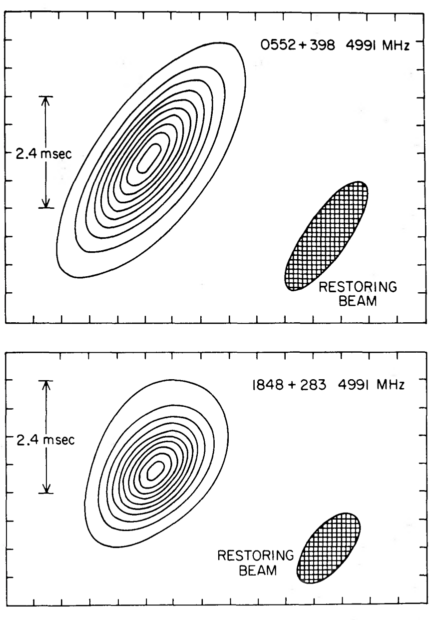

FIG. 3.—(*top*) Hybrid map of 0552+398 at 6 cm. The contours are at 5, 15, 25, 35, 45, 55, 65, 75, 85, and 95% of the peak intensity, which is 1.24×10^6 Jy arcsec^{-2}. The restoring beam is 2.80×0.90 mas at position angle −36°. (*bottom*) Hybrid map of 1848+283 at 6 cm. The contours are at the same levels as for 0552+398, and the peak intensity is 4.28×10^5 Jy arcsec^{-2}. The restoring beam is 1.80×0.90 mas at position angle −40°.

TABLE 1

STRUCTURE OF 0552+398: TWO-COMPONENT GAUSSIAN MODEL

Parameter	Comp 1	Comp 2
Flux density (5 GHz) (Jy).............	1.7 ± 0.2	3.0 ± 0.2
Flux density (10.6 GHz) (Jy)	2.0 ± 0.2	1.6 ± 0.3
Angular size ($\theta_{\rm FWHM}$) (mas)	0.30 ± 0.05	0.88 ± 0.02
Axial ratio	0.50 ± 0.2	1.0

NOTES.—Separation of components: 0.37 ± 0.05 mas. Position angle of line joining components: −80° ± 20°. Angular size of source as a whole: $\theta_{\rm FWHM}$ = 0.7–0.8 mas.

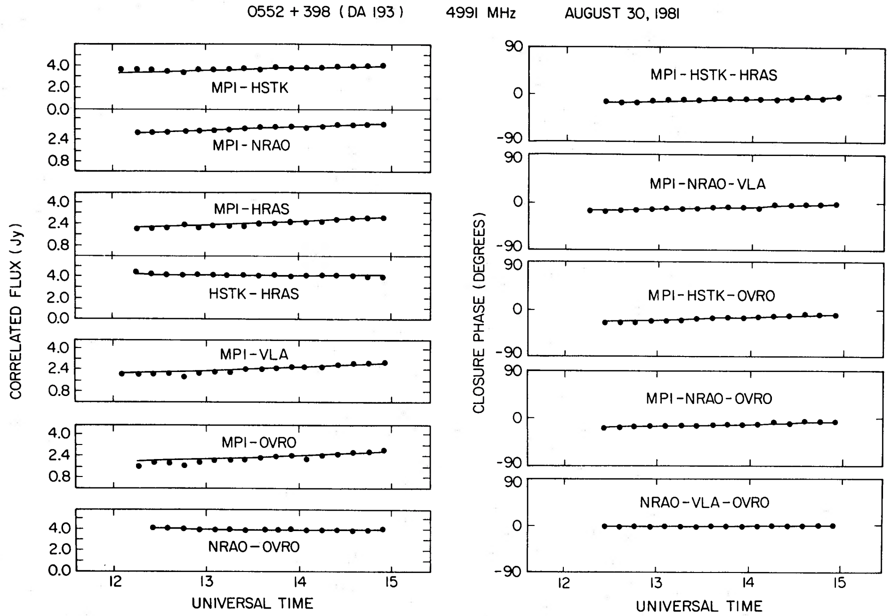

FIG. 4.—Comparison of the double model for 0552+398 (Table 1) with observed 6 cm amplitudes and closure phases on selected baselines. The measurement errors are comparable to the sizes of the data points.

ii) *1848+283*

The 6 cm hybrid map of 1848+283 is shown in Figure 3 (*bottom*). Once again, the map appears to contain at least 90% of the single-dish flux.

A model-fitting analysis showed that at 6 cm the source could be satisfactorily described by a single elliptical Gaussian, with angular size 0.76 mas, axial ratio = 0.60, and position angle 56°. The reason for the success of this relatively simple model is that the observed closure phases were remarkably small considering the degree to which the source is resolved. For no triangle of baselines were the closure phases systematically greater than 10°. Figure 5 compares this model with observed amplitudes on selected baselines.

A 6 cm visibility plot for 1848+283 shows a monotonic decrease of visibility with increasing baseline length, indicating that the angular size is of order 0.7–0.8 mas, which is consistent with the model fitting described above.

Our 2.8 cm observations were of very limited value. The source is sufficiently weak to render the baselines to Fort Davis useless, thus reducing the number of baselines to three. The long baselines (MPI-NRAO and MPI-OVRO) yielded visibilities equivalent to a Gaussian source of 0.4–0.5 mas, substantially less than that derived from the 6 cm observations, and the one closure phase was of order 20°. Again it appears that the higher resolution observations are probing finer structure within the source.

III. ANALYSIS OF OBSERVATIONS

In this section we consider models of the sources which can account for both the spectral and VLBI data and use these data to obtain estimates for the magnetic fields.

In analyzing these observations, we will model source subcomponents as uniform cylinders viewed parallel to

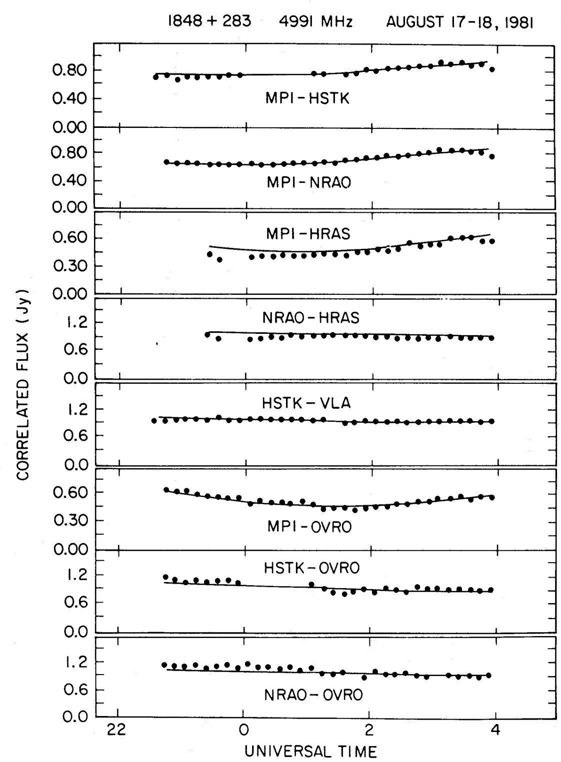

FIG. 5.—Comparison of an elliptical Gaussian model for the structure of 1848+283 with observed 6 cm amplitudes on selected baselines.

their axes. The spectrum of such a source is (Pacholczyk 1970)

$$F(\nu) = S_0 J(\nu/\nu_1, \gamma) , \qquad (2)$$

where

$$S_0 = \frac{\pi\theta^2(c_5/c_6)B^{-1/2}(\nu_1/2c_1)^{5/2}}{4(1+z)^{1/2}} . \qquad (3)$$

The variables in equations (2) and (3) are as follows. The frequency ν_1 is a fiducial frequency, roughly equivalent to the frequency of flux density maximum, and γ is the index of the (power law) energetic electron spectrum. The parameters c_5 and c_6 are functions of γ, and are tabulated in Pacholczyk (1970), as is the constant c_1 and the function $J(x, \gamma)$. The angular diameter of the source is given by θ and the redshift by z. Finally, B is the magnetic field strength, the quantity of interest to us. Actually, B is the component of the magnetic field perpendicular to the line of sight. Typically, this is considered to be quite close to the total field strength, and we shall adhere to this assumption. The consequences, should this not be the case, will be briefly discussed in § IV below.

We begin this analysis by considering the source 0552+398. As was noted above, the best model for the structure of this source consists of two components, the angular sizes and flux densities of which are given in Table 1. The spectrum of 0552+398 should therefore be described by two terms of the form of (2). Such a model, which is consistent with both our VLBI and spectral observations, is as follows:

$$\text{Comp 1: } S_0 = 3.29 \text{ Jy} \quad \nu_1 = 6.3 \text{ GHz} , \quad \gamma = 2$$

$$\text{Comp 2: } S_0 = 4.93 \text{ Jy} \quad \nu_1 = 2.7 \text{ GHz} , \quad \gamma = \tfrac{5}{2} .$$

The solid line in Figure 1 represents this model, which provides an excellent fit to the spectrum.

A similarly good fit can be obtained with a single component, characterized by $S_0 = 7.0$ Jy, $\nu_1 = 3.2 \pm 0.2$ GHz, and $\gamma = 2$. This model, of course, cannot account for the structural detail of the two-component model and should be used in categorizing the source as a whole.

We now proceed to compute the magnetic field in 0552+398. We shall use equation (3), which is equivalent to equation (1), but somewhat superior in that the observables are more precisely defined. Use of equations (2) and (3) also allows use of all the flux density measurements rather than single-peak frequencies and flux densities determined by interpolation.

If we consider the source as a whole, i.e., adopt the single-component model for the structure and spectrum, equation (3) yields a magnetic field strength of 1.2×10^{-3} gauss, with an error of about 50%.

The same analysis carried out for the components of the two-component model yields values of 10^{-3} and 4×10^{-3} gauss for the extended and compact components, respectively, with about a 100% uncertainty. It is worth noting that the values yielded by the structurally more complex model do not differ drastically from the more crude single-component model.

The goal of this study has been to compare magnetic fields determined from turnover frequencies with equipartition magnetic fields. As noted above, this latter magnetic field estimate is relatively insensitive to the precise values of the observables. Our estimate of the equipartition magnetic field has been made in the usual way, using a formula similar to that of Miley (1980). Making standard assumptions, such as that there is equal energy density in relativistic protons and electrons, and that the minimum electron energy is 10 MeV, we obtain 0.13 gauss when the source is approximated by a single component. For the two-component model, we obtain 0.26 gauss and 9×10^{-2} gauss for the compact and extended component, respectively.

In the case of 1848+283, our analysis is somewhat complicated by the fact that the redshift of this source is unknown. The identification of Condon *et al.* (1983) indicates that this source is a quasar, so we have assumed a typical redshift of unity. This ignorance should not lead to drastic differences in the results quoted below. As may be seen in equation (1), the magnetic field deduced from the turnover frequency is proportional to $(1 + z)^{-1}$. Even if our guess for the redshift of this source is grossly in error, our magnetic field estimate would be within about a factor of 2 of the correct value. Calculation of the equipartition magnetic field requires knowledge of the linear size of the source, which naturally entails knowledge of the distance. However, two factors render our equipartition magnetic field estimate relatively insensitive to the source distance: (1) For most reasonable cosmological models, the relation between angular and linear size is only weakly dependent on redshift for $z \gtrsim 1$. (2) The equipartition magnetic field is proportional to a very low power of the linear size. For example, if 1848+283 is at a redshift of 0.1 rather than 1, the equipartition field given below would only be in error by about 40%.

Using a single-component model for this source, we obtain a magnetic field from equation (3) of 0.1–0.4 gauss. This value is appropriate to the 1982 spectrum. The equipartition field is 9×10^{-2} gauss.

Table 2 summarizes our results regarding magnetic field estimates for the two sources. Column (1) describes the nature of the model, and column (2) gives the Gaussian-equivalent angular size (FWHM) in milliarcsec. Column (3) gives the normalization constant S_0 in Jy; column (4) gives the fiducial frequency ν_1 in GHz; and column (5) lists γ, the spectral index of the energetic electron spectrum. Column (6) gives the magnetic field estimate and its estimated error. Column (7) gives the equipartition magnetic field value, and column (8) gives R, the ratio of equipartition to "actual" magnetic field strength.

IV. DISCUSSION

The main results of this paper are contained in Table 2. We see that 0552+398 departs from equipartition in the sense that particle energy dominates magnetic field

TABLE 2

MAGNETIC FIELD ESTIMATES IN 0552+398 AND 1848+283

Model (1)	θ_{FWHM} (mas) (2)	S_0 (Jy) (3)	ν_1 (GHz) (4)	γ (5)	B (gauss) (6)	B_{eq} (gauss) (7)	R (8)
			0552+398				
Single Comp.....	0.7–0.8	7.0	3.2	2	$(1.2 \pm 0.6) \times 10^{-3}$	0.13	112
Two Comp:							
Comp A	0.30	3.29	6.3	2	$(4 \pm 3) \times 10^{-3}$	0.26	64
Comp B	0.88	4.93	2.7	$\frac{5}{2}$	$(1 \pm 0.4) \times 10^{-3}$	9.0×10^{-2}	90
			1848+283				
Single Comp.....	0.6–0.8	2.09	6.1	$\frac{5}{2}$	0.1–0.4	9×10^{-2}	0.2–0.9

energy. One important feature of Table 2 is that the value of the inferred magnetic field is not strongly dependent on whether one adopts a single-component model which describes the source *in toto*, or a more detailed two-component model. A plausible explanation of this may be found in equation (1). More detailed structural models will account for more compact components within a source (smaller θ). When one attempts to account for the radio spectrum with such a model, the compact component will furnish a larger proportion of the flux at higher frequencies, i.e., ν_{max} will be larger. Equation (1) shows that these two characteristics of a compact component (larger ν_{max}, smaller θ relative to a "global" model for the source) partially offset each other, so the magnetic field estimate might not differ greatly from that resulting from a more crude structural model. We also note that the amount by which the equipartition field exceeds the inferred one is of order 100 for both components of 0552+398, as well as the source as a whole (based on the single-component model). This result indicates that the particle energy density exceeds that in the magnetic field by about seven orders of magnitude.

The case of 1848+283 is interesting in that our magnetic field estimate appears to be consistent with its being in equipartition. The reason for this again appears clear from equation (1); the angular size of 1848+283 is almost identical to that of 0552+398, but the peak flux density is less than one-third that of the latter source, and the peak frequency is somewhat higher. The strong dependences of the magnetic field estimate on the observables then result in a stronger B field.

The results of this paper point to two directions for future inquiries:

1. How does one account for the departure from equipartition in the case of 0552+398 and (apparently) other strong, compact sources? A commonly voiced sentiment is that the compact sources, being close to the motive agent in the quasar or galaxy nucleus, are not "relaxed," i.e., have not reached equilibrium between the energetic particle and magnetic field energy densities. Such notions implicitly assume that the energetic particles furnish a free energy source for the eventual growth of the magnetic field, and that the process of coupling between these energy forms is still immature in most compact sources. These ideas should be quantified, and the measurements reported in this paper should assist in this regard.

2. Before such an undertaking progresses too far, however, it will be necessary to understand why a source such as 1848+283 (and presumably others) appears to be in equipartition, while objects like 0552+398 are dominated by energetic particles. Again invoking equation (1), we note that if weak ($S < 1$ Jy) compact sources have angular sizes and peak frequencies similar to the strong sources (as is the case for 1848+283), they will be closer to equipartition. VLBI observations of weak, compact components in bright E/S0 galaxies tend to support this statement (J. Wrobel, in preparation). The widely held belief that compact sources are strongly particle-dominated may therefore be partially a selection effect; the strongest sources are those which possess VLBI observations adequate to make a magnetic field estimate.

One possibility is that the difference between these two objects represents an orientation effect. We noted above that the quantity we measure in our analysis is the component of the magnetic field perpendicular to the line of sight. A situation which would be consistent with our observations is one in which both 0552+398 and 1848+283 are in equipartition, but there is a difference in the angle between the line of sight and the source magnetic field, this angle being large in the case of 1848+283, and small for 0552+398. The lack of significant circular polarization in sources like 0552+398 places constraints on the allowed angles, but such considerations typically preclude only extremely small angles between the field direction and the line of sight (Jones, O'Dell, and Stein 1974).

While attractive because of its simplicity, this explanation is probably untenable. Observations of this source by Altschuler and Wardle (1976) revealed fractional linear polarization of slightly less than a percent at 3.7 cm, and typically about one-half percent at 11.1 cm, with similar position angles at the two frequencies. These observations indicate significant geometric depolarization and suggest that the magnetic field of 0552+398 is highly random. It therefore seems unlikely that models which rely on a specific angle or range of angles between the line of sight and a large-scale magnetic field can account for our observations.

As a final point, our observations of 0552+398 indicate that a simple integrated spectrum does not necessarily imply that the source structure will be similarly simple. The spectrum of 0552+398 resembles a "textbook" case of a homogeneous, self-absorbed synchrotron source. Nonetheless, our VLBI observations, though resolution limited, indicate that the source structure must be modeled by at least two components. A core-jet structure doubtlessly would also suffice. The sources studied by Phillips and Mutel (1982) may be of a similar type. They have found several examples of compact doubles whose integrated spectra resemble that of a single homogeneous component. The conclusion to be drawn is that a sharply peaked radio spectrum does not ensure structural simplicity.

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