The Astrophysical Journal, 406:407–419, 1993 April 1

MAGNETIC FIELD STRENGTHS IN HIGH-REDSHIFT GALAXIES: CAN THE GALACTIC DYNAMO BE TESTED?

Judith J. Perry
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
Alan M. Watson
Department of Astronomy, University of Wisconsin–Madison, 475 North Charter Street, Madison, WI 53706
and
Philipp P. Kronberg
Department of Astronomy, University of Toronto, 60 St. George Street, Toronto, Ontario, Canada M5S 1A7
Received 1992 February 18; accepted 1992 September 30

ABSTRACT

We examine the hypothesis that the population of strong H I absorption systems is responsible for a significant excess Faraday rotation measure in quasars, and conclude that the case is unproved, in contrast to a recent analysis by Wolfe, Lanzetta, & Oren (1991). We discuss the limitations and pitfalls inherent in attempts to derive firm magnetic field strengths from the existing *integrated* rotation measures of quasars, and we show that although it is premature to use integrated quasar rotation measures to either confirm or rule out particular mechanisms of magnetic field amplification in galaxy disks, our observations *may* call for reexamination of current theories of large-scale magnetic field generation. We discuss the sources of rotation measure in the double quasar 0957+561. Because of the uncertainties in the determination of the magnetoionic properties of high-redshift systems which we discuss, it is important that preliminary results should not be over- or misinterpreted and that caution should be exercised before attempting to tie these results to fundamental physical processes connected with galaxy formation and the early universe.

Subject headings: galaxies: ISM — ISM: magnetic fields — quasars: general

1. INTRODUCTION

Magnetic fields are widely recognized to have essential roles in the evolution of supernova remnants, star formation, the overall structure of the interstellar medium (ISM), cosmic-ray confinement, nonthermal radio emission, and the inhibition of conduction in clusters of galaxies, to name but a few examples. In addition to the importance of magnetic fields in the astrophysics of many objects in the local universe, and their possible effects on galaxy formation, their origin has an important bearing on the physics of the early universe.

In the past decade, the first detections and estimates of magnetic fields on galactic and intergalactic scales at the present and earlier epochs have focused attention on mechanisms by which weak, primordial seed fields can be amplified. Such amplification might arise during the formation of galaxies because of anisotropic and/or turbulent infall (Piddington 1972; Pudritz & Silk 1989) or by the action of a large-scale dynamo (Steenbeck, Krause, & Rädler 1966; Parker 1971). The magnetic field strength attained depends on the strength of the preexisting seed field, and some recent theoretical work has explored various mechanisms to create seed fields (Turner & Widrow 1988; Ratra 1992; Tajima et al. 1992). So far, direct observational measurement of the present-day remnant of the seed field in intergalactic space has been impossible, preventing a strong *direct* constraint on the strength of the seed field. This is unfortunate, since predicted seed fields (which are both model- and parameter-dependent) range over more than 10 orders of magnitude. This underlines the importance of *indirect* constraints, such as ones derived from the evolution of magnetic fields in galaxies.

However, the observational determination of the strength, order, and configuration of galactic-scale fields is difficult, and field values, essential for testing theory, can be erroneously inferred if the data are not analyzed in an appropriate way. We feel it is important, at this time of rapid progress in the subject, to understand the limitations in our current ability to determine observationally *actual field strengths.*

The discovery that the strength of the observed rotation measure (RM) of high-redshift quasars (after subtraction of the contribution of the Galaxy) appears to be correlated with the presence of optically detected absorption-line systems on the line of sight (Kronberg & Perry 1982, hereafter KP) led to the first estimates of high-redshift fields and to the hope that some of the outstanding questions about their origin and role could soon be answered. The importance of this result was that it implied that the absorption-line systems could be used to *locate* the Faraday rotating magnetoionic plasma, allowing the first estimates of magnetic fields in high-redshift systems to be made.

When plane-polarized radiation passes though a magnetized plasma, the plane of polarization is rotated by an amount proportional to the square of the wavelength, λ^2. The constant of proportionality, or RM, can be calculated using basic electrodynamics, and is the integral along the entire line of sight of the product of the parallel component of the field and the electron density. The RM is a signed measure and is positive if the magnetic field points toward the *observer* and negative if it points away. Therefore, for sources oriented at random, the RM *distribution* is expected to be centered on zero.

The observed RM of a column of electrons *localized* at a redshift z is (KP)

$$\mathrm{RM} = 2.63 N_{19} \langle B_{\parallel} \rangle (1+z)^{-2}\ \mathrm{rad\ m^{-2}}\,, \tag{1}$$

where N_{19} is the electron column density measured in units of

10^{19} cm^{-2} and $\langle B_{\parallel} \rangle$ is the mean (electron-density–weighted) line-of-sight component of the magnetic field measured in microgauss and is positive if the field is directed toward the observer:

$$\langle B_{\parallel} \rangle \equiv \frac{\int n_e B_{\parallel} \, dl}{\int n_e \, dl} . \tag{2}$$

The strong $(1 + z)^{-2}$ dependence on redshift comes from the fact that the observed rotation of the plane of polarization is proportional to λ^2. Integrated RM is a limited kind of measurement, since it adds in a signed sense and is averaged both along the line of sight from the quasar and across the telescope beam. Nevertheless, it has the potential to measure magnetic fields in ordinary galaxies far beyond the range of other techniques, and for this reason it has become the focus of efforts to determine magnetic fields in galaxies at high redshifts.

Since *all* magnetoionic plasma along the line of sight contributes to the net RM, magnetic field strengths can be derived only if *independent* information is available which both locates the *dominant* contributor to the observed RM and measures its local electron density and field reversal scale or, minimally, the local electron column density. (Where more than one line-of-sight object contributes, field cancellations and reinforcements broaden the expected RM distribution.) As we discuss below, precise decomposition of the contributions from the various contributors to quasar RM—the quasar itself, the halo and disks of individual intervening galaxies, and/or inter- and intracluster and intragroup media lying on the line of sight—is difficult. Such decomposition depends on a combination of different kinds of statistical studies and high-resolution study of individual objects in the local and distant universe. The two essentially different statistical treatments of the quasar data are (1) a statistical comparison of RM properties of the small sample for which independent additional information is available, such as absorption-line spectra, and (2) a statistical study of the redshift distribution of the larger sample of residual, or extragalactic, RMs (RRMs; see eq. [3]) for which other relevant information is lacking. These two methods are complementary and, until more uniform high-resolution optical spectra become available for the larger sample, *both* methods are required to draw even *tentative* conclusions about magnetoionic properties at high redshift.

There is direct evidence in the local universe (reviewed in § 2) that individual galaxies and the intracluster gas of groups and clusters have RMs of similar magnitude. For this reason, the assignment of RM at high redshift to particular objects, or classes of objects, is complicated and fraught with difficulty at this stage.

Watson & Perry (1991, hereafter WP) in their study of the most recent RM and absorption-line data, concluded that the data are consistent with a picture in which the low intrinsic integrated RRMs typically found in low-z quasars are due to the quasars having gas-poor elliptical galaxy hosts. They suggested that, *in general*, those few intervening systems which cause large RRMs are associated with spirals whose interstellar RMs are expected to be large. However the *high-z* absorbers, which contribute to excess RRM, may have a variety of causes which, at this point, remain to be clarified.

Recently, Wolfe, Lanzetta, & Oren (1992, hereafter WLO) claimed to have *statistically separated* and *quantified* the signature of strong H I or "damped Lyα" absorption systems in the quasar RM sample of Welter, Perry, & Kronberg (1984, hereafter WPK). They claim to show that a quasar which has a strong H I absorber on the line of sight is significantly more likely to have a "detectable" RRM than a quasar drawn from the general population. The strong H I absorption systems have a large column density of neutral hydrogen ($N_{\rm H\,I} \gtrsim 2 \times 10^{20}$ cm^{-2}). These systems have usually been taken to be the forebears of the disks of H I seen in spiral galaxies in the local universe (Wolfe et al. 1986; Lanzetta et al. 1991).

This interpretation of the H I systems has been questioned by Pettini, Boksenberg, & Hunstead (1990), Hunstead, Pettini, & Fletcher (1990), and Pettini & Hunstead (1990), who argue that the properties of these systems are remarkably similar to those of present-day H II galaxies, and that the strong H I absorption systems may be high-redshift examples of these H II galaxies.

WLO's set of quasars with strong H I absorption consists of five objects, only one of which has a high-redshift H I system (the absorber in front of 1331+170 at $z_a = 1.775$); three have systems with $z_a \lesssim 0.7$, and one has $z_a = 1.39$. WLO assume that observed quasar RRM is independent of redshift and that the magnetoionic properties of the strong H I systems are also redshift-independent. On the basis both of their assignment of the RM detected in the one high-redshift quasar known to have a strong "damped Lyα" absorption system to that system alone, and of their interpretation of such systems as progenitors of disk galaxies, WLO estimated the strength of magnetic fields in high-redshift protodisks. They then used this estimate as a test for the dynamo theory of magnetic field amplification in galaxies, and concluded that their estimated fields are too large to have been generated by the conventional galactic dynamo amplifying small cosmological seed fields ($B_{\rm seed} \sim 10^{-21}$ G).

However, WLO's conclusion about high-redshift systems depends critically on their assertion that the RRM distribution of their set of five H I objects (in itself potentially disparate) is distinct from that of the parent population of quasars and that conclusions about low-redshift H I systems can be extrapolated to high redshift.

In view of the astrophysical importance of the origin and evolution of magnetic field strengths at earlier cosmological epochs, this paper discusses in some detail how RM data need to be interpreted to infer actual magnetic field *strengths*. We use virtually the same data as WLO—namely, those published and discussed by WPK—to show that as a class strong H I systems do *not* give rise to a signficant contribution to quasar RMs.

This result differs from that of WLO for reasons which we discuss in the following sections. In particular, (1) the sample of strong H I absorbers is biased—it has significantly higher redshifts than the control sample. In fact, its RRM distribution is indistinguishable from that of the "high-z" population from which it is drawn. Furthermore, (2) the standard errors in *individual* RRMs, central to WLO's definition of a "detection" and thus to their statistical analysis, cannot be reliably determined at this stage. These factors remove the foundation both from WLO's conclusions about magnetic field strengths in disk systems at earlier epochs and also from their conclusions on the efficacy of the dynamo mechanism. A further key fact, ignored by WLO, is that their statistic is strongly affected by the $(1 + z)^{-2}$ dilution of RRM.

However, we have shown (WPK; WP) that the observed RRM(z) distribution almost certainly requires extensive magnetoionic systems at high redshift. It is necessary to establish observationally the properties of these systems before trying to understand the origin of their magnetic fields.

In § 2 we briefly review the current state of knowledge of extragalactic systems which are known to generate detectable Faraday rotation measures. In § 3 we describe the determination of RRM and its error. In § 4 we deal with the failings and weaknesses of WLO's statistical test, before showing in § 5 that there is no evidence that high-redshift H I absorbers contribute to quasar RRM. In § 6 we discuss the uncertainties in the determination of actual magnetic field strengths using integrated RRMs with particular reference to the systems present on the line of sight to the double quasar 0957 + 561. In § 7 we evaluate the current status of the competing theories for the generation of galactic magnetic fields. Finally, in § 8 we summarize and discuss our results.

2. STUDIES OF EXTRAGALACTIC ROTATION MEASURE

KP separated the measured RM of quasars into two conceptual components:

$$\mathrm{RM} \equiv \mathrm{GRM} + \mathrm{RRM} , \tag{3}$$

where GRM (the Galactic RM) is the contribution of our Galaxy, and RRM (the residual RM) includes any contribution from the quasar itself (intrinsic RM) and from magnetized gas along the line of sight (intervening RM).

RM values add algebraically, so the final observed RRM can *potentially* be due to contributions from several sources. The elucidation of the relative contributions of different sources is complex, both because of the intrinsic nature of the problem and because the data available are limited. The RM contributed by intervenors can arise in a variety of objects between the immediate environment of the quasar and our own Galaxy, including the halos and disks of galaxies and protogalaxies, the clouds in the Lyα forest, the intracluster medium in clusters or the intragroup medium in groups of galaxies, and even a widespread intergalactic medium. Potential sources of the intrinsic RM of a quasar include the emitting volume itself (which by necessity contains a magnetized plasma) and gas in the cluster in which the quasar might be embedded (cf. Yee & Green 1987).

The observed quasar RRM distribution must be symmetric about zero if there is no preferred cosmological orientation of magnetic field direction. However, we note that the method used by WPK to determine the RRM will automatically remove the effect of a local coherent cosmological contribution out to a redshift of a few tenths.

The width (that is, the variance) of the distribution results from the convolution of the spatial distribution of the contributing RMs with their magnetoionic properties, and is observed to be strongly redshift-dependent (see Fig. 1 below).

2.1. *Statistical Studies of Quasar RRMs*

The contribution from a widespread intergalactic medium was demonstrated to be small by Kronberg & Simard-Normandin (1976) and Kronberg, Reinhardt, & Simard-Normandin (1977). Their conclusion was based primarily on the fact that too substantial a fraction of high-redshift quasars have small RRMs.

The Lyα forest clouds were ruled out as sources of observable RRMs initially by KP and later by WP on the basis of a more detailed analysis. To account for the observed RRMs, the Lyα forest clouds would have to have magnetic fields stronger than the equipartition value by more than an order of magnitude. (The equipartition field strength is estimated by equating the magnetic energy density with the thermal energy density inferred from absorption-line characteristics.)

KP analyzed a sample of 37 quasars for which both accurate RRMs and good absorption-line data were available. They concluded that there is a correlation between the width of the RRM distribution and the presence of strong C IV, H I, and/or Mg II absorption systems (although it was impossible to be sure that all intervenors had been detected—a point to which we return later). Their conclusion was subsequently supported by a more sophisticated approach taken by WP, which included analysis of possible selection effects. (We discuss the statistical tests used by WP and their reliability and robustness in § 3.)

A different approach to the data was taken by WPK, who developed simple, nonspecific parameterizations of the data in a study of the entire sample of 116 quasar RRMs. These analyses are independent of whether or not the line of sight to the quasar had been examined for the presence of absorption. Since their models do not depend explicitly on the source of the RRM, other than in the most general sense of whether it occurs along the line of sight or only at the quasar, their work is applicable to the study of many different, hypothetical sources of RRM, including the local environment of the quasar, galactic disks or halos, intracluster/intragroup gas, and the Lyα forest. They concluded that the redshift-dependent *distribution* of RRM was best fitted by models in which the Faraday rotating plasma was located in intervening systems rather than in the quasars themselves. The data are not extensive enough to allow a distinction to be made, say, between intervenors whose distributions are the same as those of either galactic halos or intracluster or intragroup gas. Nevertheless, in either case WPK estimated that the RM distribution of the intervening population—at source—must evolve approximately as $(1 + z)$, and have characteristic (present-epoch) magnetic fields $\langle B_{\|} \rangle$ of about 2–10 μG, with cell sizes ≈ 45 kpc. It is this sample which WLO recently reanalyzed in their attempt to separate the various contributors to foreground RRM.

In addition to their statistical analyses, KP, WPK, and WP estimated the magnetic fields in a number of individual absorption-line systems up to $z \approx 2$, obtaining *average* uniform components $\langle B_{\|} \rangle$ of several microgauss in each case, comparable to fields observed in the local universe. However, and as we shall discuss in § 6, these estimates are uncertain by an order of magnitude or more, not least because of uncertainties in the electron column densities N_e of the systems.

Those results are exciting, since they offer the hope that the magnetic fields at high redshift may now be accessible to measurement; however, we must emphasize that all of these studies have used relatively limited and inhomogeneous samples. Hence the use of formal statistical methods is unlikely, in itself, to lead to clear conclusions about magnetic field strengths at this stage, and the preceding discussion illustrates some pitfalls in trying to extract clear conclusions from limited samples of integrated rotation measure. Thus, it is important that our own and other's results should not be over- or misinterpreted, and that caution should be exercised before attempting to tie these results to fundamental physical processes connected to galaxy formation and the early universe.

One particularly successful aspect of the statistical work has been its ability to identify individual objects which, when studied in further detail, yield important new information on the RM intervenor. These results, in turn, encourage us to continue to work to strengthen the significance of the statistical studies. It is to these individual studies that we now turn.

2.2. *Individual Sources of RRM*

An important development has been detailed two-dimensional mapping of RRM in individual systems. These detailed studies of single objects are an ideal complement to the statistical analyses, since they provide information on the transverse structure and scale length of the magnetic field. Such structural information is required to further develop models for statistical analysis of the larger body of low-resolution RRMs. More important, the individual objects studied so far reveal the *diversity of sources of significant RRM*. They also provide more reliable estimates of magnetic field strengths than have been possible to date using statistical techniques.

This technique has been applied to clusters at relatively low redshifts by Vallée, MacLeod, & Broten (1987) in Abell 2319; by Dreher, Carilli, & Perley (1987) and Taylor et al. (1990) in dense "cooling flow" clusters; and by Kim et al. (1989, 1990) and Kim, Tribble, & Kronberg (1991) in the Coma Cluster.

Kronberg, Perry, & Zukowski (1992, hereafter KPZ) mapped the RM of the radio jet in PKS 1229−021 ($z_e = 1.038$) with subarcsecond resolution and found that the structure in the map was best explained as being due to an ordered, bisymmetric field in an intervening foreground spiral galaxy at $z_a = 0.395$.

Recently the radio source 0218+357 has been mapped at milliarcsecond resolution and found to consist of two bright, flat-spectrum components separated by 335 mas (O'Dea et al. 1992; Patnaik et al. 1992). One of the components is near the center of a ring of steep-spectrum emission. Possibly a gravitationally lensed system, the ring has been interpreted as the smallest Einstein ring yet discovered. The two compact images have RMs which differ by approximately 870 rad m^{-2}. O'Dea et al. (1992), using detailed optical and radio observations, conclude that the RM *probably* arises in the lensing galaxy at a redshift of approximately 0.3. They show that the galaxy is most probably a compact, low-mass, elliptical system, with ISM properties consistent with those of giant (or possibly supergiant) H II regions or filaments of ionized gas. However, the lack of emission lines from the lens is then a mystery, and O'Dea et al. conclude that high-resolution optical observations are needed to resolve the outstanding puzzles associated with the high RM of this intervenor.

In addition, the existence of sources of RRM other than those associated with intervening galaxies and clusters is indicated by a combination of subarcsecond RM mapping of the radio jet of 3C 191 and analysis of its optical absorption-line spectrum (Kronberg, Perry, & Zukowski 1990; Perry & Dyson 1990). The data suggest that in this case the excess RRM is generated in the *local environment* of the quasar. Ordered magnetic fields with a strength of a few microgauss are likely to be present. This quasar ranks high on WPK's list of RRMs but does not possess a strong H I absorption system.

WPK's conclusion that intrinsic quasar RM was probably not responsible for the observed quasar RRM(z) was supported by the high-resolution study of RMs in the nuclei of quasars and BL Lac objects (O'Dea 1989), which found that their RMs are usually low, typically on a few tens of radians per square meter. However, extremely large RMs have been found to occur in some quasars (O'Dea, Baum, & Morris 1990; Kato et al. 1987).

3. THE RESIDUAL ROTATION MEASURE DATA SET

The RRM data set underlying both our previous work and that of WLO was published by WPK. A few revisions and additions are given in WP, and we present a further revision here. One of us (P. P. K.) is preparing an extensive new list of RRMs which should allow significant improvements in the statistics in future; currently the best reduced set remains that of WPK.

3.1. *Errors and Uncertainties in RRM*

Quasar RRM can be determined no more accurately than is allowed by the determination of the local Galactic RM. The GRM was estimated by KP and WPK by taking the average of approximately five nearby extragalactic sources within 30° of the quasar from the catalog of Simard-Normandin, Kronberg, & Button (1981). The procedure was outlined by WPK and described in detail by WP. The formal uncertainty in the GRM was estimated by taking the standard deviation of these objects about the GRM. Sources whose RM was more than 2 standard errors from the GRM were discarded and the process iterated. The RRM was then determined by subtracting the GRM from the RM (eq. [3]) and quadratically adding their errors to form the standard error ϵ. The errors in the GRM dominate in the determination of ϵ.

It is clear that this process will not lead to individual values of ϵ amenable to statistical analysis, because there is structure in the GRM on scales much smaller than those probed by this method and because the number of sources involved in determining RM is small—barely enough to determine the GRM in a region, let alone the higher moments of its distribution. The effects of small-scale substructure in GRM are likely to vary across the sky. However, ϵ provides a rough indication of the quality of an individual RM, and its distribution over the whole sample gives an indication of the typical error in RRM. Thus, its use in large statistical studies, such as that of WPK, is justifiable. However, each individual ϵ is most certainly not a reliable estimate of the standard error of its corresponding RRM. This point is vital, since WLO assume that the standard error in RRM is given by ϵ.

In addition, other *systematic* effects can sometimes dominate the error in RRM. The $n\pi$ ambiguity in position angle means that one must fit observations at several suitably spaced wavelengths to determine the RM, and these fits can be ambiguous when the object is faint or has low polarization, or when there is inadequate radio wavelength coverage in the polarization measurements. These effects, combined with variability in some cases (the measurements of polarization were not made simultaneously at all wavelengths) and the poor tolerance of the fitting process to errors in individual position angles, led Simard-Normandin et al. (1981) to estimate that up to 3% of their RMs could be seriously in error, by up to several tens of radians per square meter.

These considerations require that any analysis of this data set must be sufficiently robust that it can deal with occasional large errors in a small number of the RRMs, in addition to large but correct values of RRM. As we show below, WLO's analysis is more vulnerable to this misinterpretation of ϵ and occasional ill-determined RRMs than either the analyses of KP and WKP or most of the analysis of WP (as we discuss in

§ 5, we consider the *U*-test performed by WP to be robust but their *C*-test to be inadequate).

3.2. *The RRMs Used by WLO*

The quasar PKS 1229−021 has recently been reobserved (by KPZ), and the original RRM value reported by Simard-Normandin et al. (1981) was found to be in error due to an $n\pi$ ambiguity. The correct integrated RRM is +10 rad m^{-2}, rather than WPK's −56 rad m^{-2}. This changes this RRM from a "detection" to a "nondetection" in the terminology of WLO. (See § 4 for a definition and discussion of WLO's criterion for a "detection.") We emphasize that the vast majority of the values reported by WPK result from good fits to the radio polarization data and have repeatable RMs; only a small minority, estimated to be ~3% by Simard-Normandin et al. (1981) have RMs which are possibly seriously in error. WLO could not have been aware of this recent revision, but it does point out the danger of using small-number statistics with published rotation measures. Similar, or worse, problems would likely arise when any other RM list currently in the literature is used. The change in the status of PKS 1229−021 means that WLO now have three "detections," one "questionable detection," and one "nondetection" in their sample of quasars with strong H I absorption.

However, an interesting twist is the recent discovery by KPZ that *substantial* RM variations on small linear scales *do* exist along the radio jet in PKS 1229−021 despite its modest integrated RRM. These variations are compatible with the RRM reversals arising in a strong H I galaxy disk intervenor at $z = 0.395$. The one case in which there is *independent* evidence that the RRM arises in an intervening disk system does not satisfy WLO's criterion for a "detection"!

The quasar 0458−020 was not included by WLO in the majority of their analysis but was used in their discussion of the galactic dynamo. Observations of 0458−020 since 1981 have shown that the linear polarizations vary, sometimes on short time scales. However, the multiwavelength observations required to measure RM were not made simultaneously but over a period of several months. For this reason, we consider its RM to be effectively undetermined at present; therefore its RM should be removed from studies of intervening systems at this time.

4. A CRITICAL EVALUATION OF WLO's STATISTICAL TEST

WLO define "statistically significant Faraday rotation" or a "detection" as $\mathrm{RRM} \geq 3\,\sigma_{\mathrm{RRM}}$, where they take $\sigma_{\mathrm{RRM}} = \epsilon$. They then test the hypothesis that the subset of quasars having "damped Lyα" absorption systems is drawn from a different parent distribution than the remaining "undamped" quasars by comparing the relative frequency of "detection" of RRM. They claim, thereby, to show that "the QSOs most likely to exhibit Faraday rotation are the ones located behind damped Lyα systems."

In principle, such a test for the presence of a distinct contribution by H I absorbers to quasar Faraday rotation measures is quite straightforward. An unbiased sample of quasar RRM measurements is assumed to exist, a subset of which satisfies an independent criterion—i.e., strong H I absorption. If this subsample conforms to the general population in all other ways (e.g., it has the same redshift and error distribution), has real errors which are uniform and well defined, and is sufficiently large, then the statistical test performed by WLO would be formally correct and would reliably test whether the distribution of RRM in the subsamples is different from that of the general RRM population.

Unfortunately, the current data are not characterized this way. Not only are merely five RRMs associated with strong H I absorption (a marginal sample at best), but also the redshift range of these few sources is biased to higher redshifts relative to the general RRM population, and the errors are ill defined.

In § 4.1 below we briefly review the WLO test; in § 4.2 we describe the distribution of redshift and observed RRM of the WPK sample; and in (§ 4.3) we show that *the strong* H I *sample is biased to high redshift*. This redshift bias, combined with the fact that the standard deviation RRM is not well represented by the errors, ϵ (an assumption crucial to WLO's definition of a "detection"), which are themselves ill determined and dominated by the Galactic foreground, independently render invalid both WLO's statistical test and the conclusions they draw from it. In particular, WLO's binomial approach, assuming a unique, redshift-independent probability function for the "detection" of RRM, is incorrect. In the remainder of this section we explain the basis for our belief that WLO's fundamental test statistic has additional weaknesses which make it inappropriate for the study of current quasar RRM data.

4.1. *The Statistical Test Used by WLO*

WLO define three samples which they call the "statistical," "statistical—damped," and "statistical—not damped" samples (which they denote by S, Sd, and Snd), consisting of all 116 WPK objects, the subset for which strong H I absorption (observed as damped Lyα or strong 21 cm absorption) has been detected, and the subset for which such absorption has not been detected. The sample sizes are 116, 5, and 111.

WLO begin by noting that, by their criterion for detection, there are 40 of WPK's objects in the S sample with "detected" RRM, that all five objects in the Sd sample have "detected" RRM, and hence 35 objects in the Snd sample have "detected" RRM. They then *postulate* that the a priori probability of "detecting" RRM is given by the occurrence of "detected" RRM in the Snd sample, i.e., $35/111 = 0.315$, and thus they conclude that the probability of all five objects in the Sd sample having "significant" RRM is only $(0.315)^5 = 0.003$. However, as we discuss below, their sample of strong H I absorbers is biased to high redshift, and this simple approach is incorrect. They take this low probability as evidence that the two samples are drawn from different distributions, and conclude that the presence of strong H I absorption is correlated with the presence of "significant" RRM.

4.2. *The Distribution of Redshift and Observed RRMs*

In Figure 1 we combine and augment Figures 2, 3, and 4 of WPK to illustrate the difficulties in determining the significance of the observed RRMs of the H I sample of WLO. Figure 1*a* shows the redshift distribution of all of WPK's quasars (*hatched*) in comparison with the strong H I absorption sample (*solid*) and a fit to the data of the form $N(z) = 4(z - 0.1)\exp[-2(z - 0.1)]$. The lowest redshift in the strong H I sample is 0.849 (that of 1328+307), and there are no less than 44 quasars in the control sample of 111 with lower redshifts.

Figure 1*b* shows the individual RRMs of the sample. Quasars in the control sample which satisfy $\mathrm{RRM} < 3\epsilon$ are shown as crosses, and those which satisfy $\mathrm{RRM} > 3\epsilon$ are

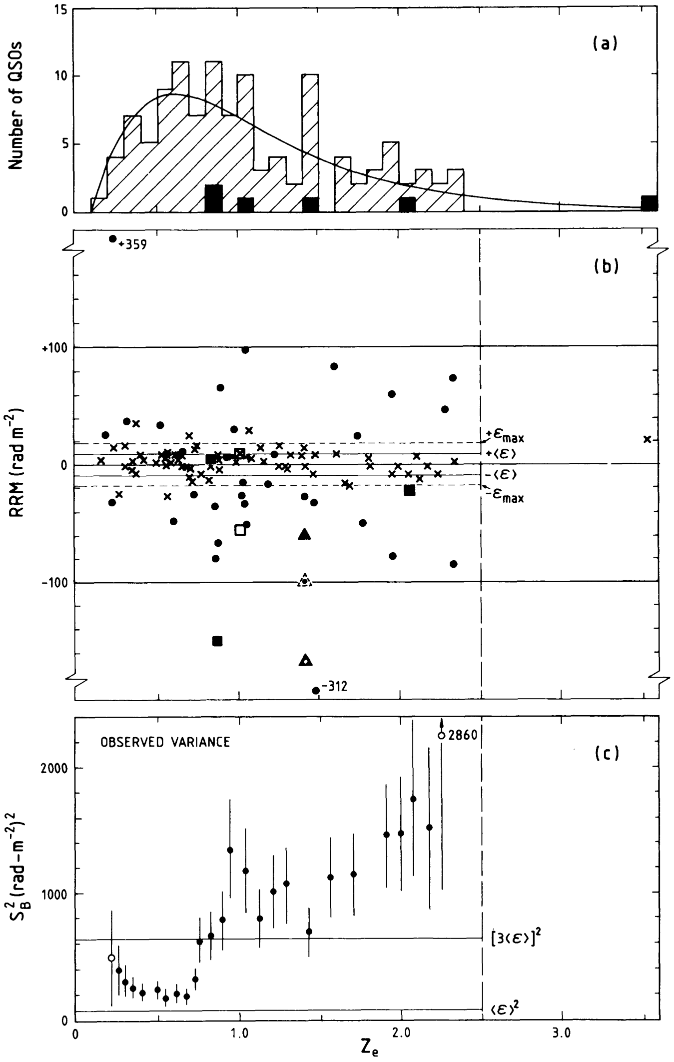

FIG. 1.—Distribution of redshift and observed RRM of the WPK sample of quasars. (*a*) $N(z_e)$ for the full sample (*hatched*) compared with the strong H I absorption sample (*solid*). The line is a fit to the data of the form $N(z_e) = 4(z_e - 0.1) \exp[-2(z_e - 0.1)]$ used by WPK in their statistical analysis of RRM(z). (*b*) Individual values of RRM(z_e). Quasar RRMs in the control sample (that without observed H I absorption) which satisfy WLO's criterion for a detection (RRM $> 3\epsilon$) are shown as filled circles, and those which do not as crosses. RRMs of the H I sample are shown as filled squares, except for those of PKS 1229−021 (shown as an open square [old RRM—a "detection"] and a crossed square [new RRM—not a "detection"]) and of the double quasar 0957+561 (shown as a solid triangle [image A], an open triangle [image B], and a dotted triangle [the assumed contribution of the lensing galaxy, the difference between the RRMs of images A and B; see § 7]). The average and largest values of ϵ for the whole sample (which are independent of z) are also shown. (*c*) Variance of the observed (uncorrected to source) distribution of RRM(z) for the 112 quasars studied statistically by WPK. (Their statistical analysis was restricted to quasars within the range $|\mathrm{RRM}| < 100$ rad m^{-2} and $0 < z_e < 2.4$ because of the small numbers outside this range.)

shown as filled circles. Quasars in the strong H I absorber sample are shown as filled squares, with the exceptions of PKS 1229−021, which is shown as an open square (old RRM—a "detection") and a crossed square (new RRM—not a "detection"), and the double quasar 0957+561, which is shown as a solid triangle (RRM of −63 rad m^{-2} for image A), an open triangle (RRM of −163 rad m^{-2} for image B), and a dotted triangle (the assumed contribution of the lensing galaxy of 100 rad m^{-2}, the difference between the RRMs of images A and B; see § 7). Also shown are the average and largest values of ϵ for the whole sample.

Figure 1*c* shows the variance of the observed (uncorrected to source) distribution of RRM as a function of redshift for the 112 quasars studied statistically by WPK. (Their sample was restricted to quasars with $|\mathrm{RRM}| < 100$ rad m^{-2} and $0 < z_e < 2.4$ because of the small numbers outside this range.) Note that the lowest redshift of the H I sample occurs where the variance of the entire sample becomes larger than the WLO criterion for a detection.

4.3. *The Redshift Bias of the "Damped Lyα" Subsample*

The redshift bias can be clearly seen from these figures: the strong H I sample is at a higher mean redshift (1.25 compared with 1.09) than the control sample, and consequently is drawn from a population with systematically higher values of RRM.

Conventionally, one investigates such an alleged bias by means of a Kolmogorov-Smirnov test (von Mises 1964). In this case, the most powerful discriminator is a one-sided two-sample test with sample sizes of 5 and 111. Unfortunately, there is no analytic expression for the distribution of the deviation in the two-sample case where one of the samples is small (the normal infinite-series solution asymptotically approaches the required probability in the limit where both samples are large). We have used the expression for the one-sided case, an approach which assumes that the normalized cumulative frequency distribution of the larger sample corresponds exactly to the true cumulative probability distribution. This assumption becomes more valid as the size of the larger sample increases, but leads one to *marginally* underestimate the probability that the samples are drawn from the same distribution. We calculate a maximum negative deviation of −0.414, which leads to a probability that the strong H I and control samples are drawn from the same distribution of less than 14%.[1]

The effects of the bias to higher emission redshift in the strong H I absorber sample are quite straightforward. WPK showed that the standard deviation of the observed RRM about zero increases roughly linearly with emission redshift (see Fig. 1). Thus, the strong H I sample is drawn from a population with systematically higher values of RRM than the control sample as a whole, whereas both samples have values of ϵ with similar distributions. The consequence of this is that high-redshift quasars, including those in the strong H I sample, are more likely to produce "detections" than are low-redshift quasars; this alone can explain the number of "detections" in the strong H I sample. This type of selection bias was extensively explored by WP (see their Fig. 6), who also suggested a simple bias-free solution (which we shall apply to this problem in § V).

4.4. *The Frail Nature of a "Detection"*

Redshift has a strong effect on the observed RRM, in that the RRM is diluted by $(1 + z)^{-2}$ between the source of the RRM and our own Galaxy. Thus, the "significance" of a given constant RM (at source) will decrease as the redshift of the

---

[1] Furthermore, if we use WLO's binomial approach to test the redshift distribution, we conclude that the probability of drawing 5 systems at random from the tail is only 7%. This follows from the fact that 65 out of the 111 nondamped quasars have $z_e > 0.84$, the minimum redshift of the strong H I sample. Thus, the probability of a single quasar satisfying this "high-redshift" criterion is $p(z > 0.84) = 0.58$, and the probability of drawing 5 systems at random from the tail is $(0.58)^5 = 0.069$. This is in disagreement with WLO's claim that the redshift distribution of the strong H I systems is not biased.

source increases. This is an additional reason that WLO's statistic is unsuitable for studies of intervening absorbers at large redshifts. For example, the average value of ϵ in the WPK sample is 8.3 rad m^{-2}, and so the value of an integrated RM at source required for a "detection" in an object at $z = 0.5$ is 56 rad m^{-2}. However, a "detection" of an object at $z = 2$ requires a RM *at the source* of 224 rad m^{-2}. In addition, the inclination of a disk system is likely to have a significant effect on the magnitude of its contribution to the RM. Finally, because of the additive nature of RRM, cancellations can occur if there is a significant chance of finding more than one source of (locally coherent) RM along the line of sight. Statistical methods for dealing with all these aspects of the RRM were developed in detail by WPK.

The uncertainties in the RRM, ϵ, are dominated by the errors in the GRM, which reflect the spacing of extragalactic sources on the sky and are redshift-independent. Therefore, if a quasar lies in a "clean" part of the sky, it can qualify as a detection by WLO's criterion even if its RRM is almost zero. For example, 3C 286, a strong H I quasar, is counted as a "detection" with an RRM of 3 rad m^{-2}, but it happens to be one of only two objects in the entire sample with $\epsilon \gtrsim 1$. Since the variance of the entire sample is strongly redshift-dependent (for reasons discussed at great length in WPK), WLO's statistic is inappropriate with these data. Every strong H I quasar has a redshift such that the measured standard deviation of the observed RRM distribution is greater than $3\langle\epsilon\rangle$ (see Fig. 1*c*). It is not remarkable that they are found, individually, to have "detectable" RRM.

Furthermore, as discussed by WP, the correlation of large RRM with an observable property of a quasar is not by itself proof that that property and RRM are directly, physically linked. For example, consider a model in which the RRM arises within the quasar itself and increases with redshift faster than $(1 + z)^2$. The probability of absorption is higher at large redshift, since the length of the line of sight increases with redshift. One would then expect larger redshift quasars to be observed to have both larger RRMs and a greater incidence of absorption, and might erroneously conclude that one is responsible for the other. This problem was addressed in detail by WP, and although the observations at that time were insufficient to allow definitive conclusions to be reached, details of an approach which can be used to resolve this uncertainty were presented. A further complication of inhomogeneous redshifts is that windows for the detection of specific lines are entered and left as redshift increases.

4.5. *The Probability of Detection*

WLO define a probability for the "detection" of RRM which is independent of the emission redshift, whereas the true probability depends on the emission redshift (i.e., the path length to the quasar). This is a fundamental problem with the design of their test, since RRM has been shown by WPK to be a strongly evolving function of redshift.

Two aspects of RRM make WLO's approach invalid. First, their criterion for a detection does not hold up well in the case where there is a significant chance of two or more sources lying on the line of sight, since RM adds in a signed sense, allowing two sources to *either* reinforce or cancel one another. Their test is applicable in cases where the detectability of a given property does not depend on the presence of other sources with the same property and is insensitive to redshift. Such a situation is commonly encountered in statistical studies of absorption lines in which the detectability of one absorption line of a given strength is not affected by the presence of a small number of other lines (although the problem of redshift windows for detection remains) and is not a strong function of redshift. This interference might be ignorable if the probability of getting two or more sources on the line of sight were small, but by WLO's own statistic (and under most simple physical models), the probability of a single "detection" is at least 30%—and could be much higher, particularly since cancellations might have occurred which would not be "detectable" under WLO's criterion.

WLO address concerns that their result may be due to contamination of the Snd sample by quasars possessing strong, but hitherto unobserved, H I absorption. However, as was pointed out in WP, contamination of the "control" sample only makes a given apparent correlation *more* striking, and therefore would not make a spurious positive result more likely.

4.6. *The Contribution of Sources Other than Strong* H I *Systems*

WLO use the statistics of strong H I absorbers (Lanzetta et al. 1991; Bosma 1981) to predict the level of the contamination in the Snd sample, and conclude that between three and 20 quasars in that sample will have as yet undetected strong H I absorption. If strong H I absorption systems were the only sources which produced a "detectable" RRM, one would only expect 3–20 "detections" in the Snd sample: in fact, one finds 35. Thus, there are of order 15–32 *additional* sight lines possessing "detected" RRM which cannot be attributed to strong H I absorption.

This throws their concept of a "detection" into question; even assuming that strong H I systems produce "detectable" RRM, there is no longer a simple correspondence between the presence of an H I system and a large RRM, given that RM adds in a signed sense. In this case, one can use the statistics developed by WPK which take into account the additive nature of RMs and allow for the possibility of augmentation and cancellation, or one can adopt the approach of WP and use large numbers of objects to beat down the cancellations which are likely to occur.

5. THE ROLE OF H I ABSORBERS IN QUASAR ROTATION MEASURE

Previous work has indicated that intervenors are *probably* the dominant source of quasar RRM. Strong H I absorption systems are clearly prime candidates as sources of quasar RRM. For example, PKS 1229−021 has RRM variations across its jet which *probably* arise in an intervening spiral galaxy, which also gives rise to the observed strong H I absorption. However, we must investigate further to decide whether H I absorbers—as a class—make any detectable contribution at high redshift, and whether their contribution is distinguishable from that of other classes of absorbers (such as Mg II and C IV absorbers). In this section we address the extent and detectability of the strong H I system contribution to RRM. We conclude that they *cannot* be the sole contributor to RRM and, furthermore, that they cannot be identified in the currently available extragalactic RM data as a distinct class of RRM intervenor.

5.1. *Are* H I *Systems the Only Source of RRM?*

A crucial test of the validity of the assumption that RRM is caused by a *single* population of intervenors is whether it is capable of reproducing the observed distribution of RRM as a function of redshift for the entire available sample. WLO calculate that between eight and 25 of the sight lines in the WPK sample of 116 quasars are likely to possess strong H I absorption. However, WPK produced lower bounds on the number of RRM intervenors required if intervenors dominate as a source of observed quasar RRM. They showed that, in order to reproduce the observed variance of the distribution, the probability of finding *some* Faraday rotating intervenor on the line of sight must exceed 0.5 by a redshift of 1 (see their Fig. 8). This is not compatible with strong H I systems being the *sole* source of quasar RM, and we are forced by the collective properties of the WPK sample to conclude that a large number of large RRMs cannot be attributed to strong H I absorption systems.

An alternative explanation might be that current studies of the number density and evolution of strong H I systems significantly underestimate their number at higher redshifts. However, we prefer to reject this alternative, for we have confidence in the excellent optical studies of strong H I systems performed by Wolfe, Lanzetta, and their collaborators (Wolfe et al. 1986; Lanzetta et al. 1991), and are aware that a plethora of other potential contributors to RRM exist (notably other metal-line systems and clusters; see § 2).

We conclude that H I systems cannot be the *sole* contributors to RRM, and may not even be the primary contributors in a population-weighted sense.

5.2. *A Test for Statistical Evidence for an RRM Contribution from* H I *Systems*

On the reasonable hypothesis that some H I systems will be RM intervenors at *some* level, we use the most recent version of the quasar RRM data in WPK's sample to test for an RM contribution from strong H I absorption systems. We shall apply a modification of the method developed by WP to test for an intervening origin of quasar RRM in the presence of data at different redshifts. We apply it to the current problem by pairing quasars with strong H I absorption sample with those from the general population which are closest in redshift (the "Sd" and "Snd" samples in WLO's notation). The pairings are shown in Table 1. We pair objects with known strong H I absorption with any object from the general population regardless of whether it has been searched for strong H I absorption, on the grounds that strong H I absorption in a given line of sight is unlikely (perhaps having a probability of 10%–20%). We have used the revised integrated RRM for PKS 1229−021 taken from KPZ.

Inspection of Table 1 shows that the RRMs of the quasars with known strong H I absorption are larger in three out of four cases, with the fifth being a tie. In borderline cases, like the tied pair, it is conventional either to ignore the pair or to average the results of two tests, counting it once "in" and once "out"; we have adopted the second approach. Applying a nonparametric Mann-Whitney *U*-test gives the probability of 0.34 that the two samples are drawn from the same distribution. This would not lead one to conclude that strong H I absorption is responsible for unusually large values of RRM. At this point, it is worth repeating that the possible presence of undetected absorption in the "control" sample does not bias the test in favor of finding that strong H I absorption is correlated with large RRM (see WP).

TABLE 1

PAIRED SAMPLE OF QUASARS

STRONG H I QUASAR			CONTROL QUASAR		
Name	z_e	RRM	Name	z_e	RRM
1328+307	0.849	+3	0336−019	0.852	−3
0809+483	0.871	−145	1252+119	0.871	−60
1229−021	1.038	+10	2230+114	1.037	−33
0957+561A	1.405	−63	2223−052	1.404	−27
1331+170	2.081	−23	0229+131	2.065	−7

As we mentioned in § 3, the only safe methods for analyzing RRMs must be robust to a small number of erroneous RRMs without excluding genuine but large RRMs. We feel that the test we have performed above satisfies this criterion, since the *U*-scores do not take into account the *magnitude* of the difference in RRM within a pair but only its sign. We feel that the *C*-test, used in addition to the *U*-test by WP, is unsafe in this context, and we will not be using it further in our analysis of these data. However with only *four* contributing data pairs, even the robust *U*-test becomes susceptible to one or two "rogue" RRMs.

5.3. *What Might the Magnitude of the Contribution of Strong* H I *Systems Be?*

There is as yet no positive evidence to suggest that high-redshift strong H I systems contribute in a special way to quasar RRM. However, we have not shown (indeed, we have not attempted to show) that they make no detectable contribution. In this light, it is worthwhile to discuss and constrain the magnitude of their possible contribution.

It is entirely possible that RRM arises in *both* strong H I absorption systems (putative disks) and Mg II systems (putative halos); disentangling their relative contributions will not be easy and, at the moment, is impossible, given the paucity of data and the lack of complete coverage along the line of sight. Perhaps the complete coverage which will be obtained with the HRS/FOS survey of bright quasars will alleviate this at relatively low redshifts. An additional complication is the discovery of substantial fields in the gas associated with clusters of galaxies (see § 2).

If hot gas is a prominent source of RRM (as it can be in clusters), then, in the extreme case, strongly absorbing neutral gas may only be a "tracer" for the real Faraday rotating system, and the RRM could be telling us little about the magnetoionic properties of the gas which is detected in absorption. As another example, we could postulate a model in which RM arises primarily in the halos of galaxies (perhaps one might consider them to have significantly larger electron column densities than disks, to make up for their presumably smaller magnetic fields) and in which the magnetic field in the halo and hence the RM depend on viewing angle, in such a way that they are largest when one looks down through the disk and lower at glancing angles and large impact parameters where the line of sight does not pass through the disk (perhaps due to field reversals in the disk and halo fields perpendicular to the disk; cf. Hummel & Dahlem 1990). In this case, one could conceivably find a correlation of large RRM and strong H I absorption, in which the absorption in the disk could simply be a tracer of another "system"—the halo. Similarly, both KP and WPK were concerned that metal absorption-line systems might simply be tracers of inhomogeneous halos. Another speculative, but interesting, possibility is the following: *if* strong H I systems trace overdense regions of the universe (as would be likely in a biased galaxy formation picture), then an apparent correlation between excess RRM and strong H I systems may be the result of an extensive region of magnetized plasma which is hot and of low density.

Although these scenarios are largely speculative at this stage, they emphasize the value of detailed studies of single objects, in which there are prospects of disentangling the various sources of RRM (see § 2).

6. MAGNETIC FIELDS IN HIGH-REDSHIFT DISKS DETERMINED FROM RESIDUAL ROTATION MEASURE

Clearly, the determination of magnetic field strengths in the disks of galaxies at $z \approx 2$ is extremely important. However, the steps to carry out this determination from the RM data set are exacting, and this task is difficult, even without the handicap of a basic data set which consists of five objects, only two of which have $z \gtrsim 1.4$. In this section we shall discuss the uncertainties inherent in the attempt to extract *reliable* field strengths in high-redshift disk systems.

The determination of the *average* magnetic field strengths in high-redshift *disk* galaxies from *integrated* RRM data requires first that such disks be unambiguously identified. (We shall put aside the possibility, for now, that the strong H I absorbers may be H II galaxies rather than protodisks, and assume with WLO that they are indeed young disk galaxies.) The contribution of this subset of intervenors to quasar RRM must be quantified and separated from those of other intervening and intrinsic sources. One must then show that their measured RRM arises in the *disk* of the intervening galaxy and not in some other source associated with that galaxy. Finally one must use the disk's contribution to RRM to deduce a magnetic field strength.

There are several stumbling blocks here. First, the optical data may not sample precisely the same lines of sight (or have the same effective cross-beam weighting) as the radio data. (This will be especially important for large radio sources.) Also, as we have mentioned, the radio and optical data may sample different regions along the line of sight. Considerations such as these were first discussed by KP.

In an intervening contributor to RM, the gas which dominates the systems' contribution to RM and the gas which produces the observed absorption may well be physically distinct, but in some way related (such as the disk and halo components of a galaxy). Galaxy disks could be an important example, in which the H I gas is confined to a thinner layer than the ionized gas (which may be in a thicker disk and in the halo).

Furthermore, because RMs add in a signed sense, structure in the field both along and transverse to the line of sight can cause cancellations and variations in the *observed* RM. The observations required to determine an RM are usually made with telescopes whose beams are large compared with the anticipated size of variations in the RM across the source, which leads to the measurement of an *integrated* RM rather than a true RM. (This is the case for the low spatial resolution observations published by Simard-Normandin et al. (1981) and subsequently analyzed by KP, WPK, WP, and WLO, but is less so in recent high-resolution studies with the VLA.) The large beam has an averaging effect, and so the *integrated* RM lies between the extremes of the true RM and can be small even in the presence of large-amplitude variations in true RM.

In the case of spiral disks, the expected value of the integrated RRM is zero, independent of inclination, if the beam encompasses the entire disk. Only if a background radio source lies behind a spatially limited area of a foreground disk can the intervenor cause a net RRM in the background source. The maximum possible disk contribution should occur if a compact, core-dominated quasar lies directly behind a spiral arm in an edge-on disk. Normally the integrated RRM caused by a foreground disk system will be significantly less than the local amplitude of variation of intrinsic disk RM, diluted by $(1 + z)^{-2}$ (as is the case for PKS 1229+021). In nearby spiral galaxies, the amplitude of variation of RM is observed to be less than about 50 rad m^{-2} (reviewed in KPZ), although a few lines of sight through the *halo* of the Galaxy do have RMs as high as 200 rad m^{-2} (Simard-Normandin & Kronberg 1980). Therefore, even if disk galaxies at high redshift are similar to local spirals in their magnetoionic properties, a priori they would not be expected to account for the large RRMs observed in high-redshift quasars or to dominate the RRM distribution.

In §§ 3 and 4 we showed that there is, as yet, no evidence that high-redshift disks make a *unique* contribution to quasar RM. Nevertheless, for the purposes of this discussion, we shall put aside the conclusions of those sections in order to provide a definite example for our discussion.

6.1. *The RM of Disks Associated with Strong* H I *Absorption Systems*

Assuming that the contribution to RRM from strong H I systems can be determined, one must decide what fraction arises in the disk and what fraction arises *in matter associated* with the disk, such as halo gas and, on a larger scale, intragroup and intracluster gas. This is most likely to be established by a combination of statistical studies and high-resolution studies of individual objects in the local and distant universe, and at the moment is uncertain. However, it is reasonable to assume that the contribution from other sources is at least of similar strength to that from strong H I systems (see §§ 2 and 5). Contributions from such sources will lower the estimated disk magnetic fields by an uncertain factor of at least 2. Although this factor by itself is small, it is but the first of many uncertainties.

Having determined (or, in this example, assumed) the contribution to integrated RM from high-redshift disks, one must then derive the corresponding magnetic fields. One approach (which was taken by KPZ) is to use low-redshift galaxies to "calibrate" the transformation from RM to magnetic field strength B. In their case they used M81 as a template with which they compared their high-resolution observations of the RM variations across a $z \approx 0.4$ disk galaxy. Of course, this method relies on conditions in the template and in the unknown source being well matched.

In this example, the only one which has been studied in detail, KPZ found RMs at the intervening galaxy ($z = 0.395$) in PKS 1229−021 varying with an amplitude of 55 rad m^{-2} and a reversal scale of 0".66 ≈ 3.2 kpc, compared with an integrated, average RM of only 19 rad m^{-2} (at the intervenor). This demonstrates that resolution effects can lead one to seriously underestimate the large-scale ordered magnetic field strengths when one is working from integrated RRMs alone. The underestimate is by a factor of 3 in this example, although *considerably* larger factors are also conceivable. Even high-resolution observations could suffer from the effects of structure and cancellations *along* the line of sight. Going from RM to magnetic field strengths, even if the electron column density is known, requires the mapping of RM on a scale at least as small as that of changes in magnetic field direction and/or the adoption of models based on theory and field configuration determination in local galaxies.

In order to convert the *true* RM to a magnetic field, the electron column density must be extracted from the absorption-line spectrum (eq. [1]). To convert a column density in neutral hydrogen (or another species) to an electron column density, one needs to know the electron fraction $N_e/N_{\rm H\,I}$, the column density in a species such as H I, and the uniformity of the gas distribution along the line of sight. To guide one's choice of electron fraction, one can look to theoretical work on the global structure of the ISM in local and distant galaxies, and direct observation in local galaxies. Theoretical models have had very limited success in predicting the global structure of the ISM in our own Galaxy, and accordingly our view of the electron fraction is influenced most heavily by local observations. The analysis must be clear on this point before evaluating magnetic field amplification mechanisms. WLO assume that because the column density of neutral hydrogen in strong H I systems make them opaque to ionizing radiation, the electron fraction can be "conservatively" estimated to be less than 0.1. We think that estimates based on this assumption are likely to be incorrect, since the disk of our own Galaxy is similarly opaque, but there are other important processes within the disk which raise the average ionization fraction. Indeed, *observations* show that approximately half of the atomic hydrogen in our disk is ionized (Reynolds 1990). One may argue that there are differences between high-redshift galaxies and those we see around us today, but there are also fundamental similarities. Until we have a better understanding of the global structure and evolution of the ISM of our own Galaxy and others, we consider it prudent not to disregard the evidence of the local universe, namely, that $N_e/N_{\rm H\,I}$ may be at least as large as 0.5 in high-redshift disks. Therefore, we consider that N_e must currently be considered to be uncertain by *at least* an order of magnitude, leading to a corresponding uncertainty in $\langle B_\parallel \rangle$.

As a final point, independent information on the inclination of the field with respect to the line of sight is needed to correct the *parallel component* of the magnetic field, inferred from RM, to the *total* field strength. The average ratio of the parallel component to the total field is $\frac{1}{2}$, but RRMs for a large number of similar systems would be required before the inclination-corrected field could be estimated statistically. Such a correction will require an understanding of the selection effects bearing on the sample, and these are difficult to quantify. For example, we might only detect the RRM signature of almost edge-on disks, which would represent the peak of the distribution.

All of these uncertainties imply that the field strength estimates can be uncertain by *at least* an order of magnitude. It is safer to work in the terms of the contribution to RM and in $\langle B_\parallel \rangle$ than in direct field strengths.

6.2. *The Double Quasar 0957+561*

It is in this context that the analysis of the RRM of the double quasar 0957+561 is particularly instructive, and helps to illustrate the difficulty in assigning an observed RRM to any particular detected absorption-line system. The two sight lines to the quasar, A and B, have different observed RRMs but share two common absorption-like systems at $z_a = 1.3911$ and 1.1249; the RRMs of images A and B are -63 and -163 rad m^{-2} (Greenfield, Roberts, & Burke 1985). Because this object is of such interest in the study of gravitational lenses, considerable effort has been expended to image the lensing galaxy and to establish the optical ray paths to the quasar (Walsh, Carswell, & Weymann 1979; Greenfield, Burke, & Roberts 1980; Young et al. 1980; Stockton 1980). Although the lensing cD galaxy is in a rich cluster at $z_G = 0.36$ (Young et al. 1981) and is clearly an intervenor, it does not give rise to optical absorption in the spectrum of the quasar.

It is only because *two* sight lines to the quasar are available, with differing RRMs, that it is possible to *attempt* to separate the contributions of the galaxy (and/or its local cluster) and the detected absorption-line systems to the observed RRMs. Had only sight line B been available, and had its RRM of -163 rad m^{-2} been assigned entirely to the observed absorption-line system, then the RM at source would have been significantly overestimated. This object clearly demonstrates that more than one system may contribute to the observed RRM even at moderate redshifts of $z \sim 1.4$, and underlines the need to proceed with caution when analyzing objects at high redshift. WP noted that caution must be exercised in assigning the RRM to the absorber and galaxy (or cluster), and this must be reemphasized in light of the recent discoveries of significant RMs in intracluster gas. It is unclear whether the RRM of both sight lines arises in the intracluster gas of the $z_G = 0.36$ cluster. (See also the discussion of 0218+357 in § 2.) WP concluded that, *if the entire* 63 rad m^{-2} *common to both lines of sight is attributed to the* $z_a = 1.391$ *system*, then $N_{19}\langle B_\parallel \rangle \approx 133$ cm^{-2} μG. (The assignment of the RRM to the $z_a = 1.393$ system, rather than to that at $z_a = 1.1249$, was based on its higher inferred column density.) WP were unable to deduce an estimate for $\langle B_\parallel \rangle$, since the optical data only set a lower limit of $N_{\rm H\,I} \gtrsim 10^{19}$ cm^{-2}. However, using the value of $N_{\rm H\,I} = 2.5 \times 10^{20}$ cm^{-2} which has recently been reported (Turnshek 1992) and a value of $N_e/N_{\rm H\,I} = 0.5$, we find $\langle B_\parallel \rangle \approx 11$ μG (smaller than WLO's value of 54 μG because we assume $N_e/N_{\rm H\,I} = 0.5$). This large field implies either (*a*) that an error has been made in attributing the entire 63 rad m^{-2} to the $z = 1.391$ absorber (see Greenfield et al. 1985 and WP for a discussion of the contribution of the lensing cluster and galaxy); (*b*) that the electron column density has been underestimated; or (*c*) that substantially larger and more ordered magnetic fields exist in at least some high-redshift galaxies. WP further concluded that if the excess RRM on sight line B is assigned to the lensing galaxy, then the local $n_e\langle B_\parallel \rangle$ is less than or approximately 2.3×10^{-2} cm^{-3} μG, which is typical of values found for *halos* in the local universe. Detailed RM imaging of the extended radio source in 0957+561 could probably provide valuable information on the magnetic properties of the lensing/absorbing systems associated with this object.

6.3. *The Other Strong* H I *Systems in WLO's Sample*

The assertion that the class of strong H I absorbers make a distinct contribution to the observed quasar RRM underlies WLO's conclusion that the galactic dynamo is not capable of producing the magnetic field strengths they derive at $z \approx 2$. However, only one of the strong H I systems in their sample has an absorption redshift near 2—the system at $z_a = 1.775$ in 1331+170. Thus their conclusions depend on their assumption that both the observed RRM distribution andthe RM properties of the intervenors are redshift-independent. Neither of these assumptions is statistically valid. Nevertheless, the individual systems are worthy of attention.

The source 3C 196 ($z_e = 0.871$) has the largest RRM in the sample of strong H I systems, with an RRM of -145 rad m^{-2}.

The strong H I system seen in absorption in its spectrum has a redshift of $z_a = 0.437$. Therefore, if the RRM arises at z_a, the integrated RM *at source* is -299 rad m^{-2}. This is a *lower limit* on the small spatial scale local RM in the system. Since this exceeds the maximum observed amplitude of variation of RM in known disk galaxies (which is ~ 50 rad m^{-2}; see KPZ), we feel that, until the RM distribution in 3C 196 is mapped at high resolution, it is unsafe to assign the RRM to a disk system at z_a rather than, say, to the intercluster medium or to a cooling flow. If the RM does arise in a disk system, we expect that the disk will be found to be edge-on.

The other two low-redshift H I systems are in 3C 286 and PKS 1229−021, both of which we have discussed above. As KPZ showed, magnetic fields at $z \sim 0.4$ which are comparable to those typical in nearby spiral galaxies do not set limits on seed fields incompatible with the standard galactic dynamo. Therefore, we do not consider that these three objects can be used to argue against the viability of standard dynamo theory.

The one high-redshift H I system in the WLO sample, at $z_a = 1.775$ in front of 1331+170, has a redshift close to that of the quasar at a relative velocity of only 1750 km s^{-1}. Furthermore, the absorption-line spectrum is very rich; two additional systems are present at $z_a \sim 1.7$, and several possible lower redshift systems have been reported (see KP). It is thus difficult to assign the RRM to any system unambiguously, and if the quasar is in or behind a rich cluster, the RRM could be due to the cluster. *If* the RRM is assigned to the $z_a = 1.775$ absorber, then $\langle B_{\parallel} \rangle \sim (13 \pm 4) N_{20}^{-1}$ (KP), where $N_{20} \equiv 10^{-20}\ N_e$. For disk formation at $z_{\rm form} \gtrsim 5$ the time elapsed between $z_{\rm form}$ and z_a is $t_{\rm elapse} \gtrsim 2 \times 10^9$ yr. Assuming that the dynamo amplification time scale is of order of the rotation time and that the magnetic field exponentiates as $B/B_{\rm seed} \sim \exp\,(t_{\rm elapse}/t_{\rm rot})$, the required seed fields need to be of the order of 10^{-9} to 10^{-11} G. Although these fields are at the upper end of the range of estimated cosmological seed fields (Ruzmaikin, Sokoloff, & Shukurov 1988b, hereafter RSS), they agree with the estimates of seed fields produced by outflows from supernovae and hot young stars (RSS). Therefore, this single system—if indeed the entire RRM arises in the strong H I system—would challenge the theory of the generation of galactic magnetic fields by the standard dynamo if the available seed field were significantly less than tenths of a nanogauss. Given the uncertainty in the assignment of the source of the observed RRM, we consider estimates of required seed fields based on this one observation to be highly unreliable. Again, high-resolution mapping is clearly required in order to discuss this object in detail.

6.4. Mg II *and* C IV *Systems*

A further point concerns the magnetic fields in Mg II and C IV systems. WLO conclude from their statistical analysis that the contribution of these systems is small compared with that of the strong H I systems. Furthermore, since Mg II systems probably arise in the halos of normal, field spiral galaxies and may have higher electron column densities than sight lines through strong H I systems, they state that this indicates that the magnetic fields in halos are weaker than those in the disk. They wisely refrain from drawing conclusions about magnetic fields in C IV systems, since the origin of these systems is still uncertain. Given the distinct redshift distributions of observed Mg II and C IV systems (Mg II systems are observed only at low redshifts, whereas the C IV systems form the bulk of the large RRM sample at high redshift), it is not possible at the present time to divide the RRM sample into statistically significant subsets which are large enough to test for intrinsic differences. This may be possible when new RRM data become available.

We feel that there are problems in treating Mg II systems which are independent of general shortcomings in statistical analyses such as WLO's. These problems are intimately tied to the nature and physical conditions in the absorbing gas; one concern is the ionization condition of the gas and whether it is representative of the entire system. The ionization conditions which have been derived for Mg II systems are based on the assumption of photoionization of a slab of material by an external, intergalactic UV field (Bergeron & Stasińska 1986; Steidel 1990). This model is plausible but has yet to be proved; when applied to our own halo, it has not found universal acceptance (Bregman & Harrington 1986). Mg II is not universally found in ionized gas at all temperatures, and it is possible, even likely, that the halos of galaxies contain significant amounts of hot gas within which warm Mg II condensations are embedded. In such a situation, the Mg II systems might tell us little about the properties of the bulk of the gas. Our limited understanding of physical properties of these systems makes estimates of the electron column density problematic at best, and this translates directly into an uncertainty in a magnetic field derived from an RM. Furthermore, there are likely to be radical differences in structure between magnetic fields in the halo and the disk (Hummel & Dahlem 1990). Direct comparison between RMs adopted for each Mg II and H I system is probably misleading.

7. THE STATUS OF THE GALACTIC DYNAMO

Present-day galactic magnetic fields of several microgauss are thought to have been generated by either or both of two mechanisms. Perhaps the most popular is the standard α-Ω dynamo, by which a small seed field is amplified by the combined actions of differential rotation and turbulence on a large scale in galactic disks (Steenbeck, Krause, & Rädler 1966; Parker 1971). Alternatively, a primordial fossil field could be amplified in the process of the collapse of protogalaxies (Piddington 1972; Kulsrud 1990) or by dynamo action in oblique shocks as a protogalaxy collapses (Pudritz & Silk 1989). In addition to primordial seed fields, it has also been suggested that the small-scale (100 pc) magnetic fields generated by supernovae could be amplified by a dynamo action to the strengths observed today (RSS).

Observations of the field configuration in nearby spirals (Krause 1990; Beck 1991) so far do not uniquely favor one theory over the other. This is partly because the observations reveal examples of both axisymmetric ($m = 0$) and bisymmetric ($m = 1$) configurations, both of which could be amplified by a dynamo action (RSS; Krause et al. 1990), and also because other aspects of the field configuration (e.g., above and below the galaxy disks) may exist which have not been revealed by this type of observation.

One can hope that a discriminant between theories of magnetic field amplification and structure might be provided by the study of galaxies at large redshift. However, as shown in the preceding parts of this paper, we are still at an early stage in our ability to provide such observational discriminants. To date, the strongest constraint on the seed fields required by the standard dynamo theory of large-scale field generation has been provided by KPZ in their observations of the quasar PKS 1229−021. They show that the variations in the RRM along the radio jet of the quasar are best fitted by a bisymmetric field in the galaxy responsible for the $z = 0.395$ absorption system seen in 21 cm absorption and in optical absorption lines (Briggs et al. 1985). They calculate the constraints placed by this interpretation on the dynamo theory, within the uncertainties of the dynamo time scale of young galaxies and the epoch of galaxy formation, and they conclude that the seed fields required for the dynamo are at least 2×10^{-18} G for $\Omega_0 = 1$ and 4×10^{-23} G for $\Omega_0 = 0$. These initial field strengths are not dissimilar to the ones which have appeared in the literature over the last 20 years, and do not provide a serious problem for the dynamo theory. We also note that the time scale for dynamo action down to $z \approx 0.4$ depends significantly on cosmology, so that varying Ω_0 from 0 to 1 changes the required seed field by nearly five orders of magnitude.

These constraints are weaker than those in WLO, primarily because WLO assumed that fields of order 1 μG are common in disk systems at larger redshifts. The primary consequence of this is the reduction in the amount of time available for the dynamo to amplify a preexisting seed field. Unfortunately, as we have shown, the statistics are inadequate to conclude field strengths in individual high-redshift systems, and thus an observational constraint on the dynamo mechanism *on this basis* is premature.

Nevertheless, we would emphasize that establishing the necessity for either field amplification mechanisms in addition to the standard slow galactic dynamo, or seed fields as large as ~ 1 nG, requires only that the rotation measure distribution and strengths in disks at $z \approx 2$ be found to be similar to those observed in the local universe; it is *not* necessary to establish that strong H I systems dominate the RRM distribution. Indeed, this may not be easy, given the known existence of many nondisk contributors to large RRMs. It would suffice to demonstrate a magnetic field measurement for one or two well-studied and verified H I disk systems at high z.

Having said this, one cannot but be intrigued by the possibility that high fields might be common in high-redshift disk galaxies, as well as in other high-redshift systems (KP; WPK; WP; Wolfe 1988), even though it currently remains a speculation. An indication of the implications of this possibility can be gained from a consideration of the integrated RMs *at source* in the intervening strong H I systems under WLO's hypothesis. These would range up to 360 rad m^{-2}, which is considerably in excess of the KPZ observation of an integrated RRM corresponding to ~ 20 rad m^{-2} at the intervenor in front of PKS 1229−021, and to observations of local galaxies which suggest comparably small integrated RMs.

A future confirmation of such a general result would indeed place the *standard* dynamo theory (or, more precisely, the small primordial seed field theory) in a position of severe difficulty. However, if such large fields were found to be *unique* to galaxy disks, then some very effective magnetic field amplification mechanism must exist which likewise is uniquely associated with disks, and hence presumably with disk formation.

Although the mean field dynamo theory is both an elegant and a credible field amplification process, there may be other competing processes occurring at one or more stages of a galaxy disk's evolution. Among other effects under study, compressible gasdynamic effects may cause a more rapid growth of flux than predicted by current calculations (Kahn 1993). Alternatively, Pudritz (1990) has proposed that the dynamo mechanisms may generate strong fields in the dark matter *halos* of young galaxies, and thus be capable of generating microgauss fields by $z \sim 3$. The supernovae and young star outflow seed fields (RSS) may be as high as 10^{-9} G, strong enough also to generate microgauss fields within a few billion years. Direct evidence of this process during the starburst phase has recently been demonstrated for M82 by Reuter et al. (1992). In addition, a more highly ionized early universe, such as that envisioned in the decaying dark matter theory of Sciama (e.g., Sciama 1990) is perhaps capable of generating fields both larger and earlier than hitherto envisaged.

The most certain magnetic field strengths determined to date for diffuse matter in the local and distant universe seem to fall in the range of 1–5 μG. Most experiments have not been sensitive to weak fields, so one is left asking whether this is the result of selection criteria or of a more fundamental process which drives fields to this value throughout the universe. Clearly, if this is the case, saturation effects must then operate. The continuing discovery of such fields challenges our understanding of their generation, sustenance, and influence, and it may be that we shall have to revise our opinions of the importance of magnetic fields in large-scale processes and in cosmology.

8. SUMMARY

We have discussed the complications inherent in the search for the source of RRM in quasars, including those due to the nature of RM, its measurement, and the inhomogeneity of the data. Studies involving absorption-line data have an additional set of problems associated with limited redshift coverage of this data. We have drawn much of this discussion from KP, WKP, and WP.

The difficulties inherent in using statistics of integrated RMs to give accurate magnetic field *strength* estimates, due largely to the sparsity of data, show the importance of detailed studies of individual objects. In particular, the electron densities within the same volume as the relevant magnetic field are uncertain, usually by factors of at least an order of magnitude. In order to allow more direct determinations of field strengths, these electron densities must be established through companion absorption-line data. Such detailed studies of (fewer) systems can also help to answer questions which canot be answered by statistical means, namely, the extent to which the absorbing gas is, or is not, a direct tracer of the gas which coexists with the magnetic field we wish to measure.

In this paper we have investigated the claim by WLO that strong H I absorption-line systems are the originators of a significant proportion of the RRM of quasars and have shown that, at the moment, the statistics of the *integrated* RM data do not support this hypothesis. Given the small number of objects in our current test sample, we cannot determine whether or not strong H I systems make a dominant contribution to excess integrated RRM; more data are needed to evaluate this hypothesis rigorously.

The lack of evidence that strong H I systems are an important cause of excess integrated RRM, and hence that such systems may possess large magnetic fields at high redshift, removes the basis for WLO's conclusion that the α-Ω galactic dynamo cannot be responsible for the formation of the regular large-scale magnetic fields of spiral galaxies. The standard dynamo theory (operating on weak cosmological seed fields) appears difficult to reconcile with large galaxy disk fields at high redshift, but at the moment there is no *firm* evidence for or against large fields in such systems beyond a redshift of 0.4 (KPZ). This in itself does not appear to provide a conclusive constraint. For the moment, the strongest constraints remain those of KPZ for PKS 1229−021. These will not cause too much discomfort for those who believe that dynamo action is the prime mechanism for the amplification of magnetic fields.

Magnetic field measurements at high redshifts are still at an early stage, with the experiments insensitive to small magnetic field strengths and the samples heterogeneous. Nevertheless, we can summarize the current status of our investigation of extragalactic magnetic fields as follows:

1. It is increasingly clear that widespread magnetic fields exist in galaxy disks, halos, clusters, and groups to redshifts of order 0.5, and possibly in the precursors of these systems to significantly higher redshifts.
2. In those galaxy disks, galaxy clusters, and the few quasar absorption systems with good field estimates (e.g., 3C 191 and PKS 1229−021), the field *strength* estimates nearly all fall in the range 1–5 μG. We find it remarkable that there is such a small range of field strengths over such a variety of systems and redshifts.
3. In particular, there is thus far an absence of observational evidence for cosmological evolution of magnetic field strengths, although such evolution has been expected, associated with the nonlinear amplification mechanisms prescribed by most theories of magnetic field amplification.

We thank an anonymous referee for a useful report suggesting clarifications in the presentation of this paper, and J. S. Gallagher and R. J. R. Williams for valuable comments on the manuscript. J. J. P. thanks the University of Toronto and the University of Wisconsin–Madison for their hospitality, and the Leverhulme Foundation (UK) for financial support. A. M. W. acknowledges support from a NASA grant WF/PC-II to J. S. Gallagher. This research was supported in part by the Natural Sciences and Engineering Research Council (NSERC) of Canada.

REFERENCES

Beck, R. 1991, in The Interpretation of Modern Synthesis Observations of Spiral Galaxies, ed. N. Duric & P. C. Crane (San Francisco: ASP), 43
Bergeron, J., & Stasińska, G. 1986, A&A, 169, 1
Bosma, A. 1981, AJ, 86, 1825
Bregman, J. N., & Harrington, J. P. 1986, ApJ, 309, 833
Briggs, F. H., Turnshek, D. A., Schaeffer, J., & Wolfe, A. M. 1985, ApJ, 293, 387
Dreher, J. H., Carilli, C. L., & Perley, R. A. 1987, ApJ, 316, 611
Greenfield, P. E., Burke, B. F., & Roberts, D. H. 1980, Nature, 286, 865
Greenfield, P. E., Roberts, D. H., & Burke, B. F. 1985, ApJ, 293, 370
Hummel, E., & Dahlem, M. 1990, in IAU Symp. 140, Galactic and Intergalactic Magnetic Fields, ed. R. Beck, P. P. Kronberg, & R. Wielebinski (Dordrecht: Kluwer), 219
Hunstead, R. W., Pettini, M., & Fletcher, A. B. 1990, ApJ, 356, 23
Kahn, F. 1993, in preparation
Kato, T., Tabara, H., Inoue, M., & Aizu, K. 1987, Nature, 329, 223
Kim, K.-T., Kronberg, P. P., Dewdney, P. E., & Landecker, T. L. 1990, ApJ, 355, 29
Kim, K.-T., Kronberg, P. P., Giovannini, G., & Venturi, T. 1989, Nature, 341, 720
Kim, K.-T., Tribble, P. C., & Kronberg, P. P. 1991, ApJ, 379, 80
Krause, F., Meinel, R., Elstner, D., & Rüdiger, G. 1990, in IAU Symp. 140, Galactic and Intergalactic Magnetic Fields, ed. R. Beck, P. P. Kronberg, & R. Wielebinski (Dordrecht: Kluwer), 97
Krause, M. 1990, in IAU Symp. 140, Galactic and Intergalactic Magnetic Fields, ed. R. Beck, P. P. Kronberg, & R. Wielebinski (Dordrecht: Kluwer), 187
Kronberg, P. P., & Perry, J. J. 1982, ApJ, 263, 518 (KP)
Kronberg, P. P., Perry, J. J., & Zukowski, E. L. H. 1990, ApJ, 355, L31
———. 1992, ApJ, 387, 525 (KPZ)
Kronberg, P. P., Reinhardt, M., & Simard-Normandin, M. 1977, A&A, 61, 771
Kronberg, P. P., & Simard-Normandin, M. 1976, Nature, 263, 653
Kulsrud, R. M. 1990, in IAU Symp. 140, Galactic and Intergalactic Magnetic Fields, ed. R. Beck, P. P. Kronberg, & R. Wielebinski (Dordrecht: Kluwer), 527
Lanzetta, K. M., Wolfe, A. M., Turnshek, D. A., Lu, L., McMahon, R. G., & Hazard, C. 1991, ApJ, 77, 1
O'Dea, C. P. 1989, A&A, 210, 35
O'Dea, C. P., Baum, S. A., & Morris, G. B. 1990, A&A, 82, 261
O'Dea, C. P., Baum, S. A., Stanghellini, C., Dey, A., van Breugel, W., Deustua, S., & Smith, E. P. 1992, AJ, 104, 1320
Parker, E. N. 1971, ApJ, 163, 252
Patnaik, A. R., Browne, I. W. A., King, L. J., Muxlow, T. W. B., Walsh, D., & Wilkinson, P. N. 1992, preprint
Perry, J. J., & Dyson, J. E. 1990, ApJ, 361, 362
Pettini, M., Boksenberg, A., & Hunstead, R. W. 1990, ApJ, 348, 48
Pettini, M., & Hunstead, R. W. 1990, Australian J. Phys., 43, 227
Piddington, J. H. 1972, Cosmic Electrodyn., 3, 129
Pudritz, R. E. 1990, in IAU Symp. 140, Galactic and Intergalactic Magnetic Fields, ed. R. Beck, P. P. Kronberg, & R. Wielebinski (Dordrecht: Kluwer), 519
Pudritz, R. E., & Silk, J. 1989, ApJ, 342, 650
Ratra, B. 1992, ApJ, 391, L1
Reuter, H. P., Klein, U., Lesch, H., Wielebinski, R., & Kronberg, P. P. 1992, A&A, 256, 10
Reynolds, R. J. 1990, in IAU Symp. 144, The Interstellar Disk-Halo Connection in Galaxies, ed. H. Bloemen (Dordrecht: Kluwer), 67
Ruzmaikin, A. A., Sokoloff, D. D., & Shukurov, A. M. 1988b, Nature, 336, 341 (RSS)
Sciama, D. W. 1990, Comm. Astrophys., 15, 71
Simard-Normandin, M., & Kronberg, P. P. 1980, ApJ, 242, 74
Simard-Normandin, M., Kronberg, P. P., & Button, S. 1981, ApJ, 45, 97
Steenbeck, W., Krause, F., & Rädler, K.-H. 1966, Z. Nat., 21a, 369
Steidel, C. C. 1990, ApJ, 74, 37
Stockton, A. 1980, ApJ, 242, L141
Tajima, T., Cable, S., Shibata, K., & Kulsrud, R. M. 1992, ApJ, 390, 309
Taylor, G. H., Perley, R. A., Inoue, M., Kato, T., Tabara, H., & Aizu, K. 1990, ApJ, 360, 41
Turner, M. S., & Widrow, L. M. 1988, Phys. Rev. D, 37, 2743
Turnshek, D. A. 1992, private communication
Vallée, J. P., MacLeod, J. M., & Broten, N. W. 1987, Astrophys. Lett., 25, 181
von Mises, R. 1964, Mathematical Theory of Probability and Statistics (New York: Academic)
Walsh, D., Carswell, R. F., & Weymann, R. J. 1979, Nature, 279, 381
Watson, A. M., & Perry, J. J. 1991, MNRAS, 248, 58 (WP)
Welter, G. L., Perry, J. J., & Kronberg, P. P. 1984, ApJ, 279, 19 (WPK)
Wolfe, A. M. 1988, in QSO Absorption Lines: Probing the Universe, ed. J. C. Blades, D. A. Turnshek, & C. A. Norman (Cambridge: Cambridge Univ. Press), 297
Wolfe, A. M., Lanzetta, K. M., & Oren, A. L. 1991, ApJ, 388, 17 (WLO)
Wolfe, A. M., Turnshek, D. A., Smith, H. E., & Cohen, R. D. 1986, ApJ, 61, 249
Yee, H. K. C., & Green, R. F. 1987, ApJ, 319, 28
Young, P., Gunn, J. E., Kristian, J., Oke, J. B., & Westfall, J. A. 1980, ApJ, 241, 507
———. 1981, ApJ, 244, 736