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LARGE SCALE MAGNETIC FIELDS IN LENS GALAXIES

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ABSTRACT

Differential Faraday Rotation measurements between the images of same background source, of multiply-imaged gravitational lens systems can be effectively used to provide a valuable probe to establish the existence of large-scale ordered magnetic fields in lensing galaxies as well as galaxy clusters. Estimates of the magnetic field in lens galaxies, based on the radio polarization measurements do not appear to show any clear evidence for evolution with redhsift of the coherent large scale magnetic field between redshift of 0.9 and the present epoch. However, our method clearly establishes the presence of coherent large scale magnetic field in giant ellitpical galaxies.

Key words : gravitation lens – magnetic fields

I. INTRODUCTION

The origin of extragalactic magnetic fields is one of the most challenging problems in astronomy. Clearly, the detection and measurement of large-scale magnetic fields in cosmological objects would be important for our understanding of their role in theories of galaxy formation and evolution.The magnetic fields in nearby spiral galaxies have been studied by various methods (Beck, 2004). The kiloparsec scale magnetic field in the Milky Way shows a fairly complex structure like, for example, at least one field reversal superposed on a slowly decreasing field of ∼10 μG strength in the central part and less than 5μG in the outer regions (cf. Rand & Kulkarni, 1989). The ordered magnetic fields in several spiral galaxies have average field strength ∼ 10 μG with a coherence scale of several kpc. However, it is desirable to have completely independent tools to ascertain the global characteristcs of the pervading magnetic fields, specially in galaxies at a much earlier epoch. Equally, estimation of the strength of galactic magnetic felds over a range of redshifts will be highly valuable for understanding its origin and evolution.

The radiation emitted by distant sources, during its passage over cosmological distances, is likely to encounter a variety of objects en route such as galaxies, galaxy–clusters, Lyα clouds and metal line absorbers. The imprints left by these intervenors in the form of spectral absorption features and Faraday rotation of the polarized flux of the background source can, in principle, furnish valuable information about the chemical composition or magnetic fields associated with the intervening objects. The observed correlation of the Faraday rotation measure (RM) of high red-shift quasars with the optically detected absorption-line systems along the sightlines led Kronberg & Perry (1982) to estimate the magnetic field strength in high redshift systems. For studying magnetic fields in high redshift galaxies and galaxy clusters we should first identify extragalactic radio sources with polarized flux that are located behind these intervening deflectors and measure the Faraday rotation of radio waves coming from the background source. The Faraday rotation will naturally have contributions from (i) our Galaxy, (ii) intervening objects and absorption systems, and (iii) the source itself. Clearly, for inferring the average strength of high red shift magnetic fields, it is essential to subtract out the contributions to the Faraday rotation occurring at the source and in our own Galaxy. We need, of course, to have a reasonably independent estimate available of the electron column density in the intervening objects. Thus, as discussed by Blasi *et al.* (1999) the electron column density may be assumed to follow the corresponding density of neutral hydrogen in the intervenor which can be estimated from absorption line strengths. However, all these requirements may be very conveniently fulfilled for the case of radio-selected gravitationally lensed sources.

In gravitational lens systems we often encounter polarized radio sources (e.g. quasars, radio galaxies) that are being multiply imaged by an intervening 'normal' galaxy or a galaxy cluster. In such lensed systems the difference in the rotation measures between various images is not expected to be severely affected by the background source or by our Galaxy, except for possible contributions from absorption systems located en route and perhaps, contamination from small-scale inhomogeneities in our own Galaxy. In short, because there are more than one sightlines to the polarized radio source available for a multiply imaged system, it should be possible to filter out contributions from the source and our Galaxy by taking difference between rotation measures of various images. We propose to apply this

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technique for deducing the estimates of magnetic fields in galaxy and cluster lenses.

II. FARADAY ROTATION IN LENSED SYSTEMS

(a) Faraday Rotation

The phenomenon of gravitational lensing preserves surface brightness and also the polarization properties of the original lensed source. It was, therefore, recognized after the discovery of the first gravitational lens system $Q0957+561$ by Walsh *et al.* (1979) that radio observations of such lens systems could furnish valuable information about the physical properties of the intervening lens and of absorption system along the lines of sight. The magneto-ionic plasma in the intervening lenses is expected to cause Faraday rotation of the radiation which will, of course, vary for each of the light paths from various images. The rotation measure may be expressed as

$$RM = \frac{e^3}{2\pi m_e^2 c^4} \int B_{\parallel}(l) n_e(l) \left[\frac{\lambda(l)}{\lambda(obs)}\right]^2 dl$$

where n_e = electron number density, $B_{\parallel}$ is the line of sight component of the magnetic field and the integral is over the path length through the intervening absorbers. The rotation measure of an intervening object located at redshift z with the average line of sight magnetic field component,

$$< B_{\parallel} > = \frac{\int n_e(z) B_{\parallel}(z) dl(z)}{\int n_e(z) dl(z)}$$

and the electron column density, $N_e = \int n_e(z) dl(z)$ may be expressed as

$$RM \simeq 2.6 \times (N_e)_{19} < B_{\parallel} >_{\mu G} (1+z)^2 rad\, m^{-2}$$

where $(N_e)_{19}$ is expressed in units of $10^{19} cm^{-2}$ and $< B_{\parallel} >_{\mu G}$ in units of microgauss.

(b) Contributions from the Milky Way

The Milky Way is amenable to detailed analysis of its magnetic field structure due to pulsar observations. There is evidence for magnetic field as well as its direction reversal from very small scale to the global scale of kiloparsecs. Equally, there is controversy on the magnetic field reversal due to difficulties in the analysis of Faraday rotation measurements specially when the line of right passes through multiple spirals, similar to what we discussed earlier (cf. Sofu *et al.* , 1986, Rand & Kulkarni, 1989). Nevertheless, it might be fair to accept that the Milky Way has (a)an ordered magnetic field of 2 to 10 μG on the scale of spiral arms, with the field strength generally increasing as we go inwards to the central regions of the Galaxy and (b) at scales of star forming regions or stellar environment ($\sim 10^{15}$ cm), there is evidence for milliGauss magnetic field. Consequently, we could expect differential Rotation Measure of a few tens if we pass through a star forming region; however, it could also produce substantial depolarization at subarcsecond scale. The expected contribution will depend crucially on the extent of ionization in the molecular cloud. On the other hand, near the galactic plane we might expect Faraday Rotation due to the global magnetic field almost aligned along the spiral arms; but the differential Faraday rotation between the arcsecond scale images of gravitational lens systems would be marginal at less than about 10 rad m^{-2}, and could be safely ignored unless the image separation is tens of arcsecond. Nevertheless, this becomes important, for instance, when we try to estimate magnetic fields of galaxy–clusters using differential Faraday rotation between multiple images produced by the gravity of the cluster. Consequently, it would be difficult to separate effects due to our Galaxy and an intervening galaxy-cluster located almost along the Galactic plane, unless the cluster magnetic field is at least of the order of 100 nG.

(c) Source Substructures

Another major difficulty encountered when we use quasars as the background sources is variation in the fraction as well as direction of intrinsic polarization across the substructures of the emitter. Most of these radio sources have substructures like core, knot and jet. The source polarization vector among these components is not aligned. A good illustration of the change in polarization angle across the substructures can be found in Biggs et al (1999) for the 8.4 GHz VLBA images of the lens system $B0218+357$ The relative flux contribution between these components too changes gradually with frequencies. There is an added uncertainty introduced in the estimation of Faraday rotation from the position angles of the polarization vector if the measurements at various frequencies are not taken simultaneously. The change in polarization vector with time and its use in time delay measurements is illustrated by Patnaik & Narasimha (2001). But, in principle, this uncertainty can be eliminated by getting the maps at similar spatial resolution and at close epochs. Here we show that (a) if we do ignore the effects of non-simultaneous measurements of the position angle by an intervening object does not vary considerably at millarcsecond scale, then we can estimate the difference between the Rotation Measure between the lines of sight along the multiple images of a background source. Assume that the source consists of two milliarcsecond-scale separated compact objects with source polarization position angle of 0 and

θ. The magnification due to the macrolens does not vary appreciably between these two components. Following Nair (1994), discussed in the next section, we do not have to consider the microlens effects on the polarization vector. If the relative flux averaged weight be $[1-\beta(\lambda)]$, the source position angle of the polarization will be $p_s(\lambda) = \beta * \theta$, which naturally, varies with λ. Let R_1 and R_2 be the Rotation Measure introduced by the lens along the two sightlines of the images of this source. The observed position angle of the polarization vector along the directions will be

$$p_i(\lambda) = p_s(\lambda) + R_i\lambda^2$$

If we estimate the Rotation Measure, R_i for the images individually, we get an erroneous result due to the factor $\beta(\lambda)$ in the source position angle. For example, consider a system like $B0218+357$ with milliarcsecond scale core and knot. Let the knot contribute 10% of the radio flux at 15 GHz and 30^o of the flux at 8.4 GHz, with a difference in the position angle of 40^o . This introduces an artificial Faraday rotation, seen at all the images, mimicing a contribution at the source. For this hypothetical example, the estimate of the artificial Rotation Measure would be ~ 160 rad m^{-2}. But if we use the difference in the position angles between the images, the uncertainty due to the $\beta(\lambda)$ factor is removed.

(d) Time Variability and Microlensing

Time variability in the source plarization and time delay between the images is a major problem in estimating differential Faraday Rotation. Nair (1994) had discussed the suitability of Polarization vector as a cosmological probe. The thrust of the analysis was that modification of the position angle due to lens inhomogeneties may not be a serious problem unless the scale length of the source polarization vector and the lens inhomogeneity conspire to be the same. But invariably, such inhomogeneties also introduce depolarization as well as noticeable amount of optical extinction. It might happen that the image B in $PKS1830-211$ could be one such case.

It is difficult to estimate the uncertainty introduced due to time delay between the images. The Faraday rotation measurements by Greenfield *et al.* (1985) for the system $Q0957+561$ differ from those reported by Patnaik *et al.* (1993), which could be due to time–delay effects, since the system has a moderately large time delay of ∼423 days. But for most of the lens systems with time delay of days to weeks, the effect of time delay does not appear to be a major hindrance.

III. INFERRED MAGNETIC FIELDS IN SELECTED GRAVITATIONAL LENS SYSTEMS

We have analysed six systems where the main lens is a galaxy for which the redshift is known. The results are shown in Table 1. The absolute Faraday Rotation is taken from the literature while the differential Faraday Rotation has been computed. We also tried to study $MG2016+112$, a high redshift system with multiple images, lensed by a galaxy–cluster at a redshift of 1. But the source does not show polarized flux that can be used for this analysis.

The main features evident from our analyses are

1. There is strong evidence for coherent, large scale magnetic field in all the lens systems we have examined.
2. Substantial amount of Rotation Measure common to all the images is observed in almost all the cases. Probably this originates from the medium in the neighbourhood of the source or it could even be a result of not resolving the source substructures.
3. In spite of a range of absolute Rotation Measure for the various systems and along different images, the differential Rotation Measure appears to be ~ 100 rad/m^2 for the confirmed elliptical galaxy lenses and ~ 1000 rad/m^2 for the other systems.
4. The available sample of lens systems do not seem to suggest any obvious evolution with redshift of the observed Rotation Measure.

It is evident, from the foregoing discussions, that probably the global magnetic fields we see in the nearby spirals are not very different from that found in galaxies at redshift of 0.3 to 1. As we tried to demonstrate, there is evidence for magnetic fields of almost microgauss strength, coherent over tens of kiloparsec scale even in giant elliptical galaxies. But it would be very useful to carry out Faraday Rotation measurements along the multiple images of radio jets and trace the magnetic field structure in the lens galaxies similar to the detailed work of Kronberg *et al.* (1992). Specially in a four-image system, such an exercise will be a valuable tool to study the symmetry structure of the coherent kpc scale magnetic field.

The question of Faraday Rotation introduced at the source has been debated extensively. While Carilli & Taylor (2002) and Clarke *et al.* (2001) show evidence that the high Faraday Rotation in embedded radio sources in galaxy–clusters indeed originates from the foreground ICM, Rudnick & Blundell(2003) argue the case for source–local magnetic fields. Discussions on detailed observations of cluster magnetic fields are covered in this meeting by Clarke (2004), Johnston-Hollit & Ekers (2004) and Kronberg(2004). Gravitational lensing can provide an independent probe to this problem. The rotation measure common to the images along two opposite directions of the lens galaxy and the extrapolated postion angle difference at zero wavelength are some indicators of the in-source Faraday Rotation. Possibly $1938+666$ (King *et al.* 1998) is a case of Faraday rotation introduced at the source. The images C1 and C2 are highly magnified and are at sub–arcsecond separation and so they are unlikely to

Table 1. Absolute and differential Faraday Rotation in lens systems

System	Lens Redshift	RM (rad m^{-2}) (literature)	Diff. RM (rad m^{-2}) (best fit)	Excess P.A. (degree)	Ref
Ellipticals					
$Q0957+561$	0.36	A-61 B -191	AB: 99±2	-2	Patnaik *et al.* (1993)
$B1422+231$	0.31	A -4230 B -3440 C -3340	AB: 125±125 AC: 20±70 BC: 105±77	4.7 3.4 -1.3	Patnaik &Narasimha (2001)
Spirals					
$B0218+357$	0.684	A-8920 B-7920	AB: 913±31	-10	Patnaik *et al.* (1993)
$PKS1830-211$	0.89	A -157 B 456	AB: 1480±83	24	Nair (1994)
Unclassified					
$1938+666$	0.878	A 665± 14 B 465± 14 C1 441± 3 C2 498± 3	AB: 960±202 BC1:85±39 C2C1: 56±4	-26 -10.5 -1.1	King *et al.* (1998)
$MG1131+0456$		R1 910 R2 -72 R3 18 R4 -290 R5 -308 R6 56	R1R4: 1200		Chen & Hewitt (1993)

be affected by many of the other systematics discussed earlier. But they have a common Rotation Measure of almost 500 rad/m^2 which is also seen in the other two images, though the differential rotation measure is only 56 rad/m^2. In the case of $B0218 + 357$ too, the Rotation Measure common to the images, at the two opposite direction of the lens spiral galaxy, is huge while the difference is only $\sim$ 1000 rad/m^2. In the case of $PKS1830 - 211$, the problem with absolute Rotation Measure has been discussed by Nair (1994), but the differential rotation appears to provide a result with acceptable error bars.

IV. SUMMARY AND CONCLUSIONS

We tried to demonstrate that differential Faraday rotation can avoid many pitfalls of direct method. We have derived estimates for the Faraday Rotation in some of the lens systems and also discussed some of the limitations of the method. We showed that the contributions from Milky Way cannot affect the result significantly but the Faraday rotation in the vicinity of the source could be important in some cases. We also tried to show that multi–epoch observations would be desirable to estimate the effects of time–delay between the images. Having taken care of some of the problems, we appear to get a general picture on the coherent magnetic field at kpc scales in the lens galaxies between reshift of 0.3 and 0.9.

The qualitative and quantitative features of magnetic fields in local spiral galaxies are observationally well studied and the existence of μG global field at kpc scale which is almost aligned along the spiral structure has been observationally established. Our analysis indicates that the high redshift spiral galaxies have similar coherent magnetic field at kpc scale. In the absence of independent determination of electron column density, we cannot give a quantitative estiamte of the field strength; but comparing the column density of various molecules observed in the lens galaxies with the corresponding values for the Milky Way, we are tempted to suggest that field of the order of 10μG is present even in moderate redshift lens galaxies like $B0218 + 357$ or $PKS1830 - 211$. Our analysis also indicates the presence of large scale magnetic fields in giant elliptical galaxies, though with a smaller magnitude. We argue a case for applying the method at least to some of the rich galaxy–clusters where multiple images of radio sources have been observed.

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