RESEARCH ARTICLES

Gravitational lens systems to probe extragalactic magnetic fields

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The Faraday rotation measurements of multiply-imaged gravitational lens systems can be effectively used to probe the existence of large-scale ordered magnetic fields in lensing galaxies and galaxy clusters. The available sample of lens systems appears to suggest the presence of a coherent large-scale magnetic field in giant elliptical galaxies, somewhat similar to the spiral galaxies.

Keywords: Galaxies, gravitational lensing, magnetic fields, polarization.

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. It is hoped that observations of extragalactic objects and high redshift galaxies can, in principle, illuminate the basic issues relating to their origin and dynamical amplification.

Magnetic fields in external galaxies have been measured using radio observations of their synchrotron emission to have strengths of about microgauss. They have been detected to have a coherence over a scale of a few kiloparsecs (kpc). The large-scale ordered magnetic fields in several spiral galaxies were reported[1] to have an average field strength of ~10 μG with a coherence scale of several kpc. However, it is desirable to have completely independent tools to ascertain the global characteristics of the pervading magnetic fields in galaxies, both spiral and elliptical, at a much earlier epoch. Equally, estimation of the strength of galactic magnetic fields over a range of redshifts will be highly valuable for understanding their origin and evolution with the age of the universe.

Cosmological magnetic fields could be generated in the early universe by some mechanism such as the first order phase transition[2], coupling of electromagnetic field with curvature[3] or by a thermal battery operating in expanding ionization/shock fronts impinging on density inhomogeneities in the intergalactic medium[4,5]. But these seed field values ($\leq 10^{-19}$ G) need to be enhanced and maintained at the observed microgauss level by some kind of a dynamo

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process. We note parenthetically that the energy density of average galactic magnetic fields is of the same order as the energy density of cosmic rays of intergalactic thermal energy, and of cosmic microwave background radiation (of the order of 10^{-13} erg/cm^3).

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, magnetic fields 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 redshift quasars with the optically detected absorption-line systems along the sightlines prompted Kronberg and Perry[6] to estimate the magnetic field strength in high redshift objects. For studying magnetic fields in high redshift galaxies and galaxy clusters we should first identify extragalactic radio sources with polarized flux that are located within or 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 redshift magnetic fields, it is essential to subtract 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. The connection between damped Lyman systems and galaxies, and estimation of the hydrogen column density from the optical lines is extensively discussed in the literature[7,8]. As discussed by Blasi *et al.*[9] and Sargent *et al.*[10] the electron column density could be assumed to follow the corresponding density of neutral hydrogen in the intervenor, which can be estimated from absorption line strengths.

All these requirements may be 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 is more than one sightline 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 differences between rotation measures of various images. We propose to apply this technique for deducing the estimates of magnetic fields in galaxy and cluster lenses and particularly enquire about the nature and strength of magnetic fields in elliptical galaxies. It will be valuable if we can adopt this technique for inferring the large-scale magnetic fields in the intergalactic medium and even more illuminating if we can use the polarized cosmic microwave background as a source for probing the cosmic magnetic fields. We can only hope this may conceivably become feasible with rapidly advancing technology.

Inferred magnetic fields in selected gravitational lens systems

For the sake of illustration, we have sketched the phenomenon of gravitational lensing in Figure 1. A polarized source such as a quasar, S, is lensed by an intervening galaxy L producing multiple images $I1$ and $I2$. The phenomenon of gravitational lensing preserves surface brightness and also the polarization properties of the original lensed source. The fractional polarization as well as the direction of the electric field in the images should follow the value in the source. We have, therefore, shown the polarization vectors with same length and direction in the source as well as in all the images. However, the path of the light rays forming the two images sample different regions of the lens galaxy (shown through $C1$ and $C2$ in Figure 1) and hence will be affected differently by the interstellar medium of the lens. It was, therefore, recognized after the discovery[11] of the first gravitational lens system Q0957+561, that radio observations of such lens systems could furnish valuable information about the physical properties of the intervening lens and of the absorption systems along the lines of sight.

The magneto-ionic plasma in the intervening lenses is expected to cause Faraday rotation of the radiation which will be different for each of the light paths from various images. The angle of rotation of the plane of polarization is given by:

$$\psi_F = \frac{e^3}{2\pi m_e^2 c^4} \int B_\parallel(l) n_e(l) \lambda^2 \mathrm{d}l, \tag{1}$$

where n_e is the electron number density, the wavelength of the radiation as seen by the absorber medium, $B_\parallel$ 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 as measured by the observer at redshift of zero is given by

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

For the Faraday rotation produced by a deflector at redshift z, the rotation measure of the intervening galaxy with the average line-of-sight magnetic field component,

$$\langle B_\parallel \rangle = \frac{\int n_e(z) B_\parallel(z) \mathrm{d}l(z)}{\int n_e(z) \mathrm{d}l(z)}, \tag{3}$$

and the electron column density, $N_e = \int n_e(z) \mathrm{d}l(z)$ may be expressed as

$$\mathrm{RM} \simeq 2.6 \times (N_e)_{19} \langle B_\parallel \rangle_{\mu G} / (1+z)^2 \, \mathrm{rad \ m}^{-2}. \tag{4}$$

Here $(N_e)_{19}$ is expressed in units of $10^{19} \, \mathrm{cm}^{-2}$ and $\langle B_\parallel \rangle_{\mu G}$ in units of microgauss. Though Faraday rotation may be caused by the source, the intervenor and the Milky Way, difference in the rotation angle between the multiple images is practically due to the lens which is contained in
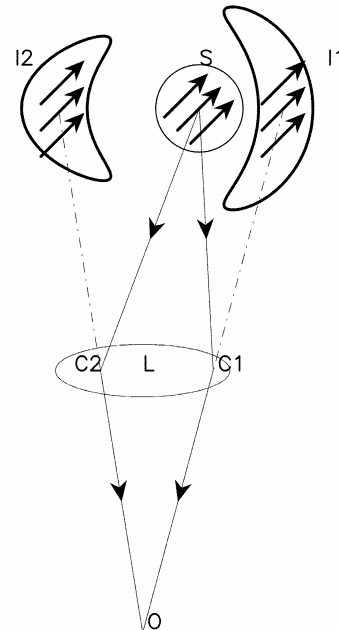
Figure 1. Schematic diagram of the phenomenon of gravitational lensing. Background source S is lensed by the intervening galaxy L and multiple images $I1$ and $I2$, having identical intrinsic properties are formed. Regions of the lens sampled by the light rays forming images $I1$ and $I2$, shown by $C1$ and $C2$, are separated by typically a few kiloparsecs.

eq. (4). Consequently, the magnitude of the difference in RMs between images turns out to be a valuable probe for estimating the average line-of-sight component of magnetic field in the lenses.

There have been a number of multi-frequency VLA polarization observations of gravitational lens systems through the 1980s and 1990s. The Faraday RMs and intrinsic polarization angles of the multiple images of some selected lenses (A. R. Patnaik, private commun., 1999)[12–19] are summarized in Table 1, along with the best fit estimation of the differential Faraday RMs between various images. Table 1 also denotes the difference between polarization angles at zero wavelength which, in principle, would have the value 0, were there no Faraday rotation in the source.

Effects of substructures

Most of the radio sources have substructures like core, knot and jet, and generally 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.*[20] for the 8.4 GHz VLBA images of the lens system B0218+357. The relative flux contribution between these components also happens to change gradually with frequency. There is an added uncertainty introduced in the estimation of Faraday rotation from the position angles of the polarization vector, if measurements at various frequencies are not made simultaneously.

The change in polarization vector with time, for example, as illustrated by Patnaik and Narasimha[19] can also be a factor. But, in principle, this uncertainty can be eliminated by obtaining the maps at similar spatial resolution and at close epochs, and correcting for the time delay between the images. Here we argue that (a) if we ignore the effects of non-simultaneous measurements of the position angle, (b) if further, we make the reasonable assumption that the Faraday rotation introduced by an intervening object does not vary considerably at milliarcsecond scale, and (c) provided the source variability and the time delay together do not seriously affect the differential Faraday RMs, then we can estimate the difference in the RMs between the lines of sight along the multiple images of a background source.

Effects of Faraday rotation in the Milky Way

The Milky Way is amenable to detailed analysis of its magnetic field structure due to pulsar and other observations. There is evidence for the presence of magnetic field as well as its direction reversal from a small scale to the global scale of kiloparsec. However, there is a controversy about the magnetic field reversal due to difficulties in the analysis of Faraday RMs, specially when the line of sight crosses multiple spirals[21,22]. Nevertheless, it might be fair to accept that the Milky Way has (a) an ordered component of 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 RMs of a few tens of radians per square metre, if we pass

Table 1. Faraday rotation in selected lens systems

System	Lens redshfit	RM (rad m^{-2}) (literature)	Differential RM (rad m^{-2}) (best fit)*	Excess polarization angle (degree) ($\lambda = 0$)	χ^2**	No. of degrees of freedom	Time delay (days)	Reference
Spirals								
B0218+357	0.684	A-8920	AB: 913 ± 31	−10	0.3	2	10.5	12
		B-7920						
PKS1830–211	0.89	A-157	AB: 1480 ± 83	24	7	2	26	13
		B-456						
Ellipticals								
Q0957+561	0.36	A-61 ± 3	AB: 99 ± 2	−2	0.3	1		14
		B-160 ± 3					417	
B1422+231	0.31	A-4230 ± 60	AB: 125 ± 125	4.7	16.1	2	1.5	15, 16
		B-3440 ± 88	AC: 20 ± 70	3.4	5	2	7.6	19
		C-3340 ± 90	BC: 105 ± 77	−1.3	6.1	2	8.2	
1938+666	0.878	A-665 ± 14	AB: 960 ± 202	−26	27	1		17
		B-465 ± 14	BC1:85 ± 39	−10.5	19	1		
		C1-441 ± 3	C2C1: 56 ± 4	−1.1	2.6	3		
		C2 498 ± 3						
MG1131+0456	0.844	R1-910	R1R4: 1200 ± 10					18
		R2-72 ± 25						
		R3-18 ± 13						
		R4-290 ± 13						
		R5-308 ± 19						
		R6-56 ± 20						

*In some cases, the differential RM listed is at variance with the direct difference because of the ambiguity modulo π.
**See text for discussion on χ^2.

through a star-forming region. However, it could also produce substantial depolarization on subarcsecond scale and a change in the direction of polarization. More importantly, in such a case we are unlikely to observe the lensed images. 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 RM between the arcsecond scale images of gravitational lens systems would be marginal at less than about 10 rad m^{-2}, and may be safely ignored unless the image separation is tens of arcseconds. Nevertheless, this becomes important, for instance, when we attempt to estimate magnetic fields of galaxy-clusters using differential Faraday rotation between multiple images produced by the gravitational lensing action of the cluster. Consequently, it would be difficult to separate the 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.

Discussion

Polarization vector in lens systems as a cosmological probe

Nair et al.[23] had pointed out the suitability of the polarization vector as a cosmological probe. The thrust of the analysis was that modification of the position angle due to inhomogeneities such as individual stars or gas clouds in the lens would have no role to play, provided the scale over which the polarization direction changes is always larger than the scale over which the inhomogeneities can affect the background source. The problem will, of course, be serious if the scale length of the source polarization vector and the lens inhomogeneity conspire to become comparable. It is evident from the discussion in the previous section that the depolarization and Faraday rotation introduced in our own galaxy will be similar between the multiple images with separation of the order of arcseconds. Thus, if the depolarization is substantial when an image is intercepted by a cloud having partially ionized matter, the extinction in optical wavelengths would be noticeably high. The image B in PKS1830–211, for instance, could be one such case, and we should treat these rare configurations with proper care.

Estimation of differential rotation measure

The rotation measure and the excess position angle at zero wavelength are computed from the best-fit straight line between the measured polarization position angle and the square of the observed wavelength. The absolute RM will have an uncertainty in the position angle by a multiple of π. In the case of differential Faraday rotation, this problem is, by and large, absent and hence we expect that the differential RM is possibly a better indication of the magnetic field in the lens than the absolute RM. For typical Faraday rotation in the case of nearby galaxies, the expected rotation of the position angle can exceed π at frequencies lower than ~5 GHz. For the systems 0957 + 561, 1938 + 666 and 1830 + 211, this factor has been incorporated and as such there is no ambiguity of π. Errors in the observed position angles are available only for 0957 + 561, and Patnaik (private commun.) gives a value of 2° for the system 0218 + 357. For systems like 1938 + 666, the errors are given only for one frequency and there is no error information is available for other systems. Consequently, the χ^2 values shown in Table 1, with an assumed error of 2° should be taken with caution. However, the errors in the differential Faraday RM are not severely affected by this lack of information in the data. For instance, as King et al.[17] have demonstrated that for the absolute Faraday rotation for the system 1938 + 666, the fit and the uncertainty in the RM are fairly good if we accept the data at all the frequencies with equal weight. For differential Faraday rotation between the multiple images in gravitational lens systems, the excess position angle at zero wavelength should be ideally zero, which provides an independent check on the reliability of fits given in Table 1.

Faraday rotation due to spiral galaxies

In our sample we have two lens systems, B0218+357 and PKS1830–211, where the lens is confirmed to be a spiral galaxy. There is a large rotation measure ~ 8000 rad m^{-2} that is common to both the images A and B in the lens system B0218+357. The large intrinsic RM could be from absorbing clouds en route. On the other hand, the relative fluxes of the two VLBI components change with frequency. We cannot, therefore, rule out the possibility that part of the change in the Faraday rotation as function of frequency may be caused by the presence of milliarcsecond substructures. This is amply borne out by the detailed 8.4 GHz VLBA images of Biggs et al.[24]. The polarization images of the core of both images exhibit a difference of the order of 10° in the polarization direction between the hot spots separated by a milliarcsecond. Consequently, In the absence of detailed VLBA polarization maps, we may not be in a position to estimate the RM at the source. However, the difference in RM between images B and A is found to be 980 ± 10 rad m^{-2}, when the Faraday rotation angle for four frequencies between 8.4 and 43 GHz in Patnaik et al.[12] is used. This could conceivably be a contribution of the lens galaxy. The result should be trustworthy considering the error estimate, since for an uncertainty in the position angle of polarization vector of ~ 2°, χ^2 is 0.65 for two degrees of freedom. With the neutral hydrogen column density of ~ 2×10^{21} cm^{-2} and using the electron column density N_e ~ 10^{21} cm^{-2}, we get from eq. (3), the mean field magnetic component, along the sightline, in the lensing galaxy of order 1 μG. The magnetic field could be even higher, provided the relative RM is not significantly overestimated.

Differential Faraday rotation in elliptical galaxies

Both the lens systems, Q0957+561 and B1422+231, have a giant elliptical galaxy as the dominant lens. While the former is part of a galaxy-cluster, the latter might be associated with a group of galaxies. An analysis of the Faraday RMs in these and similar systems could provide evidence for possible existence of coherent large-scale magnetic fields in elliptical galaxies.

Two important problems need to be addressed: (a) effects of time delay between the multiple images, which could become important for large time delays and (b) Faraday rotation introduced at the source. Possibly the first lens system, Q0957+561, with a time delay of ~420 days, is a good example for the examination of these issues. Earlier measurements by Greenfield *et al.*[14] for the system Q0957+561 reported RMs of images A and B to be respectively -61 ± 3 and -160 ± 3 rad m^{-2}. This gives the difference in RM between images A and B of ~100 rad m^{-2}, which is at variance with the corresponding difference of ~30 rad m^{-2} measured by Patnaik *et al.*[16]. Indeed, Nair *et al.*[23] had pointed out the importance of polarization measurements for time-delay estimations. Following the work of Biggs *et al.*[24], the well-established time variability of the polarization vector was used by Patnaik and Narasimha[19] to numerically derive the time delay between the images in the system 0218+357, thereby demonstrating the possible effects of time delay on the differential Faraday rotation. The discrepancy in measurements between Greenfield *et al.*[14] and Patnaik *et al.*[16] might be indicative of time variability of the polarization vector in the system Q0957+561 over a timescale of a decade. This is a major problem while comparing polarization position angles at two or more different epochs.

There is also a need to discuss the contribution of the intervening medium to Faraday rotation. Greenfield *et al.*[14] attributed the difference between the RMs along the sightlines to the two images, of ~100 rad m^{-2}, entirely to the lensing cD galaxy with intracluster medium making a negligible contribution. This seems to be a reasonable deduction, as also implied by our best-fit excess position angle (PA) of 2°. Perry *et al.*[25] argue that because of the availability of separate RMs along two sightlines to images A and B, it should be possible to identify the contribution from the absorption line systems detected en route at redshifts $z_{abs} = 1.39$ and $z_{abs} = 1.12$. They speculate that the RM of -63 rad m^{-2} that is common to both images A and B should be assigned to the absorption system located at $z_{abs} = 1.39$ because of its large inferred electron column density. This implies $(N_e)_{19}\langle B_\parallel \rangle_{\mu G} \simeq 130$ cm^{-2} μG. With the reported $N_e \approx 1.25 \times 10^{20}$ cm^{-2}, the mean line-of-sight magnetic field in the lensing galaxy is inferred to be $\langle B_\parallel \rangle \approx \geq 10$ μG. On the other hand, the common RM might merely be an artifact of the sub-structure in the source. A systematic analysis of the RM along the multiple images of an extended feature like a jet, similar to what Kronberg *et al.*[26] did for a single image, will help resolve this important issue.

Possibly the source structure in the lens system B1422+231 has similarities with B0218+357 at VLB scales. Not surprisingly, straightforward estimation of the absolute Faraday rotation along individual images results in a large value of RM for both these systems. The source in B1422+231 has smaller fraction of polarization and hence the change in polarization direction within the milli-arcsecond scale structures is expected to affect the RM estimates. Interestingly, the differential RM is coincidentally similar to the value arrived at for 0957+561, where the rotation is probably caused by a similar giant elliptical galaxy at comparable redshift. The different ratio of fluxes between the images in radio and optical wavebands is possibly an indication of extinction.

The nature of the lensing object in the systems MG1131+0456 and 1938+666 has remained enigmatic for a long time, although the redshifts have now become available[27,28]. The main lens in both the systems appears to be a passively evolving giant elliptical, but probably there are two clusters or rich groups of galaxies in the field of MG1131+0456. Still, we believe that RM estimates for these systems are important due to the presence of extended structures in the background source. We expect Einstein rings and giant arcs to provide valuable probes of the large-scale magnetic field in the intervening objects because, in principle, we can trace the gradual variation of position angle of the field vector along the quasi-linear image structure. With better long-term observations of these systems, we should be able to determine the length scale, signature and strength of the magnetic field in the lenses.

For the system MG1131+0456, the reported[18] Faraday RMs are primarily for bright regions of the Einstein ring. It is conceivable that these features are perhaps not identifiable with images of the same source-region and hence we cannot speculate on the intrinsic magnetic field of any absorbers near the source. However, based on detailed analysis (cf. figure 6, Chen and Hewitt[18]), we speculate that the difference in RM between spots R1 and R4, of ~1200 rad m^{-2}, is an indication of the presence of a magnetic field in the lens galaxy. This value is practically similar to what is estimated for B0218+357. As pointed out earlier, Faraday RMs for the system MG1131+0456 will be valuable even if the image identification may not be robust.

For the four-image system 1938+666, the images C1 and C2 are highly magnified and have a sub-arcsecond separation; so they are unlikely to be affected by many of the other systematics discussed earlier. They have a small differential RM of 56 rad m^{-2}, for the two images separated by approximately 5 kpc at the lens and the excess position angle extrapolated to zero wavelength is negligible. But they have a common RM of almost 500 rad m^{-2}, which is also seen in the other two images.

Thus, based on the differential Faraday rotation between the multiple images in 0957+561, 1938+666, MG1131+0456 and B1422+231, there appears to be suggestive evidence that giant elliptical galaxies may also

have ordered magnetic field with strength comparable to that of spiral galaxies. The fit for differential Faraday rotation is overall reasonable, but with lower fraction of polarization, it is certainly not as good as in the case of B0218+357. In spite of the range of Faraday RM common to the images, it is remarkable that for the four systems having small image separation, the differential Faraday rotation (introduced by the main lensing galaxy alone) is of order 1000 rad m^{-2} for systems with vastly different properties. This possibly suggests that by the redshift of 1, most of the magnetic fields we see in galaxies (of the order of a few microgauss), which were presumably generated in the pre-galactic epochs, might have become saturated. It is tempting to surmise that perhaps already by redshift ~1, magnetic fields of strength of the order of microgauss are generated over length scales of ~10 kpc in the universe. However, we should emphasize again that we have put together data on polarized images taken by various groups at different times for different purposes, and hence the results may not be as robust as we might hope. Kronberg (private commun., 2004) emphasized the need for coordinated VLBA/VLBI observations of extended multiply-imaged systems to overcome many of the defects we have mentioned, and for making an attempt to get a reliable magnetic field profile at least in a few lens systems.

It should, of course, be conceded that the present method based on differential Faraday RM maps is not without limitations. The primary reason for the inadequacy of the data is that observations were not intended for the measurement of the lens magnetic fields. However, considering the importance of probing the large-scale cosmic magnetic fields at high redshift, we have used the available data for deducing the existence of ordered magnetic field in external galaxies. Clearly, a determination of the large-scale magnetic structures in the universe at all scales is a fundamental problem in astronomy. To address this question, it is imperative to undertake coordinated multifrequency, multi-epoch VLBI/VLBA observations. A selection of non-varying sources (e.g. knots) will help alleviate some of the problems associated with time delays between the images.

Case for ordered magnetic fields in clusters?

Galaxy-clusters are the largest gravitationally bound systems and probably, the rich galaxy-clusters are virialized after the formation of spiral galaxies. The existence of microgauss global fields on kiloparsec scale, that are almost aligned along the spiral structure has been observationally well established[1]. It is evident from the foregoing discussions that probably the global magnetic field we see in the nearby spirals is not different from that found in galaxies at redshift of 0.5 to 1. We have attempted to demonstrate that there is evidence suggesting the existence of magnetic fields of microgauss strength, coherent over tens of kiloparsec scale even in giant elliptical galaxies. Naturally, as the next step it is worthwhile searching for global-scale cluster magnetic fields.

Many independent observations[29,30] over the past decade have provided evidence for cluster magnetic field of the order of microgauss. The synchrotron emission from radio halos associated with several galaxy clusters has now been detected. In particular, the radio halos of the Coma and several other clusters have been extensively studied recently. These halos have typically sizes ~megaparsec and are concentrated close to the centre of X-ray emission[31]. Indeed, observations of the diffuse radio source in Abell 85 showing enhanced X-ray emission were effectively used by Bagchi *et al.*[32] to deduce a magnetic field of ~1 μG. Estimates of magnetic fields in cluster halos, based on minimum energy arguments range from a fraction of a microgauss to one microgauss[33]. Thus, from radio observations of the Coma cluster[34], a lower bound on the magnetic field of a tenth of a microgauss in the halo region has been placed[35]. A similar bound has also been obtained from the gamma-ray flux above 100 MeV observed by EGRET[36]. Remarkably, the magnetic field strength derived by Kim *et al.*[37] using the minimal energy arguments, also yields similar estimates for the field.

It should be recognized that the results for intracluster global fields within the galaxy-clusters are not so robust, although there is reliable information on the magnetic fields in member radio galaxies in the clusters[38]. An impressive study of a sample of sixteen Abell clusters was undertaken by Clarke *et al.*[39] to probe intracluster magnetic fields using radio and X-ray data. From a statistical analysis of cluster sources situated in the hot cluster gas and of the controlled background sources located behind the cluster medium, they found evidence for intracluster magnetic fields in the Abell clusters of order ~ 5 μG $(l_B/10 \text{ kpc})^{-1/2}$, l_B being the coherence scale-length of the magnetic field. This led them to conclude that the high Faraday rotation in embedded radio sources in galaxy-clusters indeed originates from the foreground ICM[30,40,41]. However, Rudnick and Blundell[42] argue the case in favour of local magnetic fields in the source. Greenfield *et al.*[14] had earlier pointed out the use of a radio lobe associated with the lensed image 0957+561A to rule out a significant contribution to the RM from the ICM of the lens cluster for this system.

It is clear that Faraday rotation studies of both radio galaxies in clusters as well as background radio sources aligned with the cluster can provide valuable probes for cluster magnetic fields. Thus, in the core of the cooling flow cluster 3C295, a magnetic field of order 12 μG has been estimated[43] with a coherence scale-length of about 5–10 kpc, based on the patchiness of RM, somewhat similar to the value[7] given for 3C129. The multi-frequency observations of the radio galaxies embedded in the X-ray cluster 3C129 reveal significant difference in the Faraday RMs towards radio galaxies 3C129.1 located at the cluster centre and 3C129 at its periphery, implying cluster magnetic field strength of ~6 μG out to a distance of ~ 450 kpc. A remarkable trend of the RMs was observed in Hydra A, which is positive to the north of the nucleus

and negative to the south[8] indicating a field strength ~7 µG with a coherence scale of ~100 kpc. The Faraday RMs of multiply-imaged extended background sources will be valuable to probe this kind of structure. The differences in RMs between various images should filter out contributions from the background source and from our galaxy with the residual RM providing a value of $N_e \langle B_{11} \rangle$ for a suitably averaged line-of-sight magnetic field component. An independent estimate of the electron column density from the thermal X-ray emission or from the measurements of Sunyaev–Zel'dovich effect would provide an estimate of the magnetic field strength in the cluster. Also the change in the field strength along the images of an extended structure will further pinpoint the coherence length of this field[44].

Ideally, we should attempt to search for radio arcs in well-studied Abell clusters and measure the Faraday rotation along the arcs in order to deduce intracluster magnetic field strength and its coherence length. Assuming there is no active radio source in the lensing cluster contributing to the RM, we should enquire if we can deduce an intracluster magnetic field of strength ~0.1 µG coherent over a scale-length exceeding 100 kpc. Such an exploration will be facilitated if we should be able to locate magnetized sources such as polarized radio jets, starburst galaxies and the associated synchrotron jets and even supernovae in distant galaxies which are suitably aligned behind the foreground lensing clusters. A multiply imaged polarized gamma ray burst source together with its afterglow in radio located behind a foreground cluster lens would also serve a useful purpose of indicating the strength of the intervening cluster magnetic field.

It will be valuable to have radio maps in polarization at a few closely separated frequencies to estimate the RMs. A candidate lens system like B1359 + 154, which is a six-image configuration of a high redshift source ($z_{source} = 3.235$) having a flux of 66 mJy at 5 GHz frequency (with unknown lens redshift) could have the advantage of tracing the large-scale magnetic field of the intervening lens. Due to the six-image nature of the system, the problem associated with time delay between the images might be alleviated. It will be useful to examine unconfirmed lens candidates, especially radio-weak systems with substantial image separations. These could serve as ideal cluster mass dark lenses for probing the intracluster magnetic fields. Amongst the six dozen or so lensed quasars discovered to date, most have few arcsecond image separations which can be produced by galaxy-mass lenses. However, theoretical CDM models of structure formation predict large quasar image separations of several arcsecs, capable of being generated by dark matter aggregates. Indeed, Inada et al.[45] have recently reported the discovery of a quadruply lensed quasar with a maximum image separation of 14.62 arcsec, an evident case of gravitational lensing by a dark matter-dominated intervening object. There should be several such large-separation image configurations with hitherto undetected dark cluster mass objects acting as lenses.

A favourable set of observations for Faraday rotation of lensed background sources as well as embedded radio sources within the cluster, for a range of cluster redshifts, could provide valuable information on the possible origin of magnetic fields in galaxy clusters:

1. Seed magnetic field produced during the protocluster formation[4]: This will be a global field spread over Mpc scale which is likely to be rather weak, unless clusters grew by mergers.
2. Field produced by embedded radio sources: The jet propagating into the intracluster medium will introduce an oriented field, the strength of which will decrease away from the radio source.
3. Local fields due to anisotropic electron velocity distribution[46]: Chandra observations of rich galaxy clusters show evidence for sharp discontinuity in the density of X-ray emitting regions as well as temperature over length scales of a few hundred kpc in systems like Abell 2142, where the electron anisotropic velocity could drive a Biermann current.

A systematic observational study of these three effects will be valuable in understanding the substructures in galaxy clusters.

Conclusion

The multiply-imaged gravitational lens systems can be effectively used to establish the presence of global ordered magnetic fields in lensing galaxies and to estimate their average field strength. It turns out that the difference in position angles between various images is generally a reliable indicator of the existence of magnetic fields in intervening lenses. An advantage of multiple path RM measurements is that they are potentially capable of sensing the direction as well as coherence length scale of the magnetic field. We have further argued that the contributions due to inhomogeneities in our galaxy need not be a major hurdle in estimating these ordered magnetic fields, unless the depolarization effects between images turns out to be substantial. The compact flat-spectrum sources will have substructures in polarization, which will naturally be subject to differential magnification across the image, if the source is in the vicinity of a caustic. Evidently, a non-varying polarized radio source would be ideal for differential Faraday RMs and equally to monitor the lensed images for polarization changes in order to correct for the time delay. The main conclusions of our study are the following:

1. There appears to be suggestive evidence for the presence of coherent, large-scale magnetic field in the lens systems that we have examined, in particular, in giant elliptical lens galaxies.
2. Substantial amount of RM common to all the images is observed in almost all cases, which probably originates in the medium in the neighbourhood of the source or may even be a result of not resolving the source substructures.

3. In spite of a range of absolute RMs for the various systems and along different images, the differential RM appears to be in the range of several hundred radius per square metre for the elliptical galaxy lenses and ~1000 per square metre for the spirals.

4. The available sample of lens systems does not seem to indicate any obvious evolution with redshift of the observed RM.

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