Null detection of the excess rotation measure in the Virgo supercluster of galaxies (*)

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Summary. — The intracluster magnetic field of the Virgo supercluster of galaxies is investigated using an available data set of reliable Faraday rotation measures of extragalactic radio sources. Unlike the result reported by Valleé (*Astron. J.*, **99** (1990) 459), no excess RM were detected in the Virgo. Taking relevant physical values of the Virgo into account, this null detection, however, cannot rule out the possibility that the strength of Virgo's intracluster magnetic field be as strong as comparable to that of Coma (1 μG). More RM data are substantiated for better understanding of the nature of Virgo's magnetic field.

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1. – Introduction

The existence of intracluster magnetic fields has well been established directly from observations of diffuse radio emissions (radio halos) of several galaxy clusters over the last decade. These clusters include Perseus (A426; Gisler and Miley [1]) A754 (Waldhausen [2]; Andernach *et al.* [3]) Coma (Giovannini *et al.* [4]; Kim *et al.* [5]; Hanisch *et al.* [6], Jaffe *et al.* [7]; Willson [8]), Abell 1367 (Gavazzi and Trinchieri [9]; Hanisch [10]), Abell 2319 (Harris and Miley [11]), Abell 2255 (Jaffe and Rudnick [12]; Harris, Kapahi, and Ekers [13]), and Abell 2256 (Kim [14]; Röttgering *et al.* [15]; Bridle *et al.* [16]). The presence of a magnetic field in the intracluster medium would contribute to the Faraday rotation of polarized radio emissions from radio sources in or seen through a cluster. This polarization effect is sensitive to the integral of $n_e B_c$ along the line of sight through the cluster, where B_c and n_e are the strength of the intracluster magnetic field and the electron number density of the ICM, respectively.

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Therefore, one would expect an excess in the rotation measures (RMs) of the samples towards a certain cluster whose ICM is ionized and is known to be substantially magnetized.

Recently, the excess of RM due to the ICM has been discovered from the samples of Abell clusters (Kim, Tribble, and Kronberg [17]; KTK hereafter), from Coma cluster of galaxies [5], from A2319 (Valleé *et al.* [18]). One of the difficulties in this line of research is that there should be statistically enough number of RM samples. This is because B_c is likely to be tangled on a certain scale (l, say) so that the intracluster contribution to the RM is basically stochastic: it results in the broadening in the RM distribution of the samples. If B_c is stochastically disordered, the RM is expected to be reduced by a factor of $(l/L)^{1/2}$, where l is the largest-scale size of the field and L is the effective pathlength through the ICM. RM values of several cluster radio sources and the polarization emission structures of extended sources, notably those in Coma cluster, suggest that the intracluster magnetic field is likely to be tangled on scales of the order of an optical galaxy size [5].

The Virgo supercluster was first studied with RMs by Valleé [19] with his 123 quasars and galaxies. Virgo covers a huge area in the sky (about 10 degrees in radius) so that obtaining RM samples that are statistically enough is so most feasible. With these, he reported a possible detection of the cluster RM of -10 rad m^{-2} which corresponds to B_c near 1.5 μG. With all the latest data set of unambiguous RM of extragalactic radio sources, I present a statistical study for RM$_c$ for the Virgo supercluster, employing an analysis similar to KTK. Throughout this paper, $H_0 =$ 50 km s^{-1} Mpc^{-1} and $q = 0$ are used.

2. – The sample

The sample was limited to those extragalactic radio sources which have unambiguous RMs and those whose uncertainty in their GRMs was not too large. The sample was drawn from Simard-Normandin, Kronberg and Button [20]. The data from

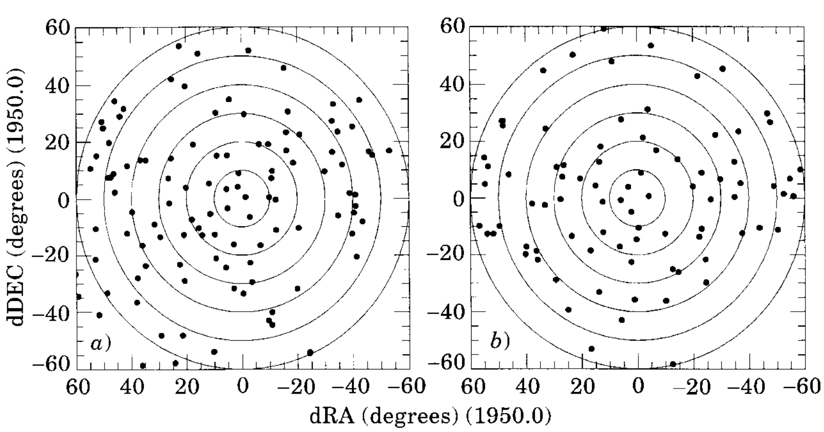

Fig. 1. – The distributions of the samples in space: QSOs (right panel) and galaxies (left panel). The samples were distributed more or less evenly over the sky. dRA and dDEC are the relative RA and DEC in degrees from the center of the Virgo supercluster. Sources whose |RRM| is greater than 100 rad m^{-2} are excluded (see text).

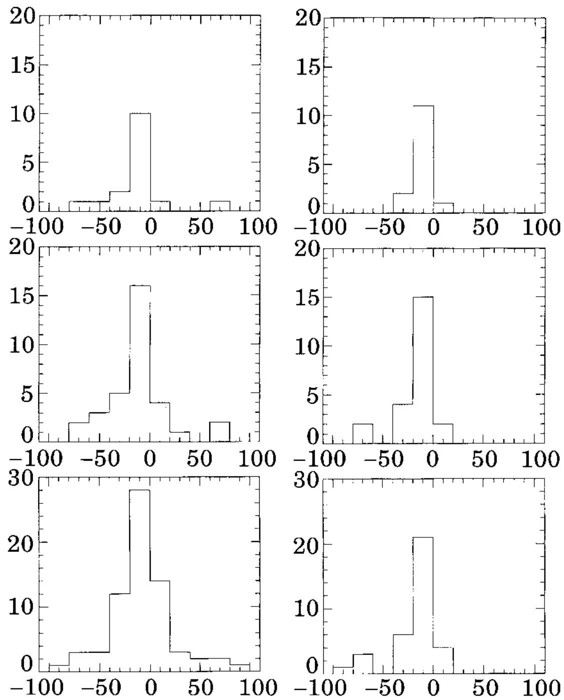

Fig. 2. – The histograms of RRMs: galaxies (first row), QSOs (second row), all (bottom row) are compared between the samples within 40°–60° radii (control samples; left panels) with the samples within 20° radius from the cluster (right panels). The RRMs are in units of rad m^{-2}.

Broten, Macleod and Valleé [21], which Valleé [19] used, were not incorporated into the database, to make the comparison clear. Like the selection criteria mentioned in [19], RM samples were limited to those which lied within 60° from the Virgo cluster center (RA = $12^h\ 28^m$, DEC = $+12°\ 40'$) and those which $|\mathrm{RRM}| < 100$ rad m^{-2}. (For RRM see below.) The Abell radius (Abell [22]) is $R_A = 1.7/z$ arcmin $= 3\,h_{50}^{-1}$ Mpc and using $z = 0.004$ for the Virgo [19], this gives $R_A = 7.08°$.

The total rotation measure that is observed can be decomposed into the following three parts:

$$\mathrm{RM} = \mathrm{IRM} + \mathrm{RM_g} + \mathrm{RM_c}. \tag{1}$$

IRM is the intrinsic RM of a source, $\mathrm{RM_g}$ is the Galactic contribution and $\mathrm{RM_c}$ is the intracluster contribution to RM. We define the residual RM as

$$\mathrm{RRM} = \mathrm{RM} - \mathrm{RM_g}. \tag{2}$$

Since IRM is unknown and GRM cannot be removed completely, only a statistical type of analysis is possible to estimate $\mathrm{RM_c}$. Thus the samples were further limited to those with good estimates of $\mathrm{RM_g}$. Note that there is a peculiar zone in the Galaxy in which $\mathrm{RM_g}$ cannot be sure: $200° < l < 260°$, $-30° < b < 30°$. Those sources (12 sources) falling in this region were excluded from the samples.

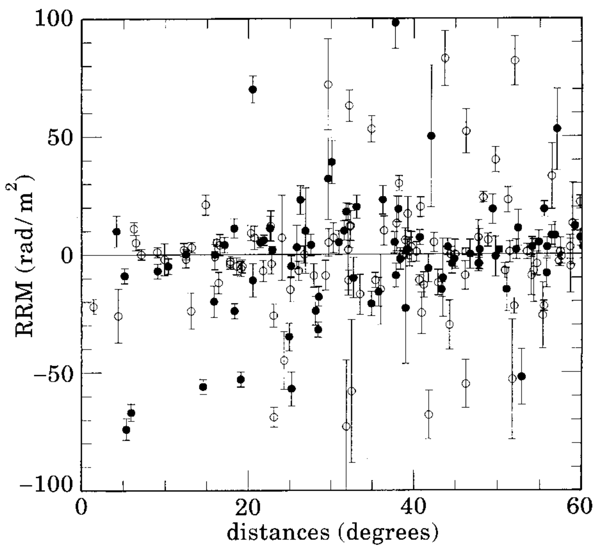

Fig. 3. – The RRM distributions of the samples: 85 QSOs (open circles) and 116 galaxies (filled circles). The distances are in units of degrees from the center of the Virgo supercluster. Sources whose $|\mathrm{RRM}|$ is greater than 100 rad m^{-2} are excluded (see text). No trend is apparent in the distribution.

$\mathrm{RM_g}$s were estimated by taking as the average those sources within 15° of the source after outliers had been removed. This is done iteratively: first a 2σ cut-off was used, and then the RM distribution checked by hand. In all, a total of 201 RM sources were selected (116 galaxies and 85 QSOs). In most cases, errors in RM are small; the error in the residual rotation measures is dominated by the uncertainty in GRM.

There is a total of 16 high RM sources excluded from the sample ($|\mathrm{RRM}| >$ 100 rad m^{-2}). All of these, except one, are unrelated with the Virgo and inclusion of large RM sources would skew the variance values and make conventional statistical estimators unstable. Therefore, this justifies the exclusion of the large RMs.

The distributions of the samples in space, RRM and RM histograms, and in RRM-distances are shown in fig. 1, 2, and 3, respectively.

3. – Statistical tests and results

3·1. *Nonparametric tests.* – Using the same ring method employed in [19], the samples were divided into 6 groups depending on their locations. The ring width was chosen to be 10°. It is the optimum choice in that it is not only close to R_A but also the number of sources contained within it is not too scanty. The mean values and the standard deviations of the RRMs were calculated for 6 subsamples and these are all listed in table I.

As opposed to the expectation that the intracluster contribution to RM would cause the RM distribution near the cluster center to be broader than the rest of the sample, the "broadening" is by no means noticeable. The result is the same even with the RMs themselves (without $\mathrm{RM_g}$ corrected; cf. table I).

TABLE I. – *Statistical parameters.*

Sample (1)	N (2)	μ (3)	σ (4)	N (5)	μ (6)	σ (7)	N (8)	μ (9)	σ (10)
0–10	12	− 9.6	28.9	7	− 0.5	14.6	5	− 29.3	38.3
		− 6.6	29.4		− 3.2	14.2		− 13.4	41.9
10–20	23	− 4.1	18.3	14	0.3	10.2	9	− 10.3	25.2
		− 6.5	18.5		0.5	10.0		− 12.2	25.8
20–30	33	− 3.1	28.8	16	− 8.5	29.8	17	− 0.5	28.8
		− 4.8	27.2		− 3.6	26.6		− 5.4	28.8
30–40	36	6.0	29.9	20	5.3	30.9	16	7.1	29.3
		4.7	32.7		7.8	34.6		2.4	32.3
40–50	34	1.4	27.7	21	2.9	33.2	13	− 2.0	17.1
		1.3	29.6		3.1	33.8		− 1.8	22.1
50–60	35	1.3	24.4	20	− 3.2	27.2	15	5.5	21.5
		6.6	29.5		− 0.3	31.9		16.3	26.9
0–20	35	− 5.6	22.4	21	0.1	11.5	14	− 14.4	30.2
		− 6.5	22.4		− 1.0	11.4		− 12.4	31.0
20–40	69	− 0.9	29.5	36	0.0	30.0	33	1.7	29.2
		− 0.0	30.3		2.9	31.1		− 1.7	30.4
40-60	69	1.3	25.8	41	0.4	29.9	28	2.7	18.9
		4.0	29.5		0.5	32.4		8.0	25.4

Note: Column (1): inner and outer radii of the annular in degrees. Columns (2), (3), (4): number of RRM sources, mean and standard deviation of the sample (in rad/m^2). This sample contains all RRMs: galaxies and quasars. Columns (5), (6), (7): samples contain galaxies only. Columns (8), (9), (10): samples are quasars only. Values in the second raws are the ones without RM_g correction. The second part of the table contains the same statistics but with different size of annular: that is 20° in width.

From a visual inspection alone on the RRM distributions shown in fig. 2, it is clear that both distributions are not much different. The question is: "Are the two distributions different? If so, how are they different quantitatively?"

Two non-parametric tests, Kolmogorov and Smirnov test (KS-test in short) and Ansari-Bradley [23] rank sum test (W-test in short) were applied. I have somewhat surprising results: as opposed to what is expected, these tests indicate that the samples within 10–20 degree annular are narrower in distribution than others.

To be more specific, the W-test is a two-tailed distribution-free rank test which is designed to detect a difference of scale parameters (*e.g.*, variance) when the two underlying populations have a common median. In the present case, this test requires that the parent populations of samples under the consideration have zero median and that the unknown distribution function governing the sample near the cluster (the set 1, say) in the absence of any intracluster effect is the same as that of the rest. The

TABLE II. – *Statistical tests.*

Set 1 (1)	Set 2 (2)	$N1$ (3)	$N2$ (4)	W^* (5)	$p(W^*)$ (6)	KS (7)	Note (8)
20–30	10–20	33	23	− 2.6056	99.5	94.5	10°
30–40	10–20	36	23	− 1.9339	97	99.1	10°
20–40	0–20	69	35	− 2.4746	99.3	99.3	20°

Note: Columns (1), (2): two sets in comparison (see text). Columns (3), (4): the numbers of samples in the sets. Columns (6), (7): W-test rejected the null hypothesis (H_0) that the two samples in comparison were drawn from the same population with confidence levels listed in column (7) and the W values listed in column (6). The results of Kolmogorov and Smirnov are listed in column (8).

result is a test statistics W^*, which in the large-sample approximation (Hollander and Wolfe [24]) is valid here. When the samples located within 10°–20° (set 2) are compared particularly with the samples in 20°–30° (set 3), $W^* = -2.60$, indicating a broadening (negative sign) of the set 3 with a 99.5% level of confidence. In table II, the results of these statistical tests are summarized for several cases.

3˙2. *The results.* – The results of the tests can be summarized as below.

1) The Virgo samples do not show any hint for an RRM broadening. Hence the Virgo shows no excess RM detectable in the sample. This, however, does not necessarily mean that no magnetic fields exist in the Virgo Supercluster of galaxies.

2) One may note that there exists the “narrowing” in the RRM distribution of the Virgo sample at a high level of confidence, especially those within 10–20 degree radii (see tables I, II). This particular sample also shows the same trend with their RM, meaning that the GRM correction was not the source of error for that.

3) Interestingly enough, the RRM distribution of the galaxies in the regions within 20 degree radius from the center is notably narrow (see table I). As opposed to what was suggested in [19], the RRM distribution of the QSOs of the sample appears to be normal.

4. – Discussion

4˙1. *Is there an* RM *void in the supercluster*? – One idea that can explain the “narrow” RRM distribution invokes an “RM void” in the supercluster. To be consistent with the result 3) above, this RM void should yield no RM contributions to the galaxies seen in the sky within about 20 degree radius from the cluster center. On the other hand, those galaxies seen elsewhere should experience some contributions to their RMs arising from the intercluster medium outside the Virgo supercluster. The point is that the RM contribution of the intercluster medium should somehow exceed that of the supercluster itself. This may be an interesting possibility worth studying with more RM sources.

4˙2. *The magnetic-field strength.* – Since the Virgo has a somewhat low central electron density and has a small core radius ($n_0 \approx 5\cdot 10^{-4}\,\mathrm{cm}^{-3}$, $r_\mathrm{c} \approx 0.2$ Mpc, $\beta = 2/3$;

Forman and Jones [25]), it can produce no RM contribution in two ways: with a uniform B_c at a normal strength (1 μG or so), with a tangled weak B_c. Using the two relevant formulations in KTK, these situations can be summarized for the given sample in the following two equations. Define the observed standard deviation to be the quadratic sum of σ_i (the intrinsic) and σ_c (the cluster contribution), that is $\sigma^2 = \sigma_i^2 + \sigma_c^2$. In case B_c is tangled,

$$\sigma_c \leqslant 1\ B_0 \sqrt{r_0/10\ \text{kpc}} \left(\frac{n_0}{5 \cdot 10^{-4}\,\text{cm}^{-3}} \right) \left(\frac{r_c}{0.2\ \text{Mpc}} \right)^{1/2} \text{rad m}^{-2}. \tag{3}$$

If B_c is uniform, say 1.5 μG at 30° as suggested by Valleé [19], one can have

$$\sigma_c \leqslant 4 B_0 \sqrt{r_0/10\ \text{kpc}} \left(\frac{n_0}{5 \cdot 10^{-4}\,\text{cm}^{-3}} \right) \left(\frac{r_c}{0.2\ \text{Mpc}} \right)^{1/2} \text{rad m}^{-2}. \tag{4}$$

Here B_0 is the magnetic-field strength at the cluster center in units of microgauss (μG).

The primary reason for which the Virgo cannot contribute measurable RMs to the RM probes is the low electron density. This situation cannot be improved even if B_c is of the order of 1 μG. Therefore, the possibility that Virgo's B_c be as strong as comparable to the Coma cannot be ruled out by the null detection of the cluster RM.

The strength and the structure of the magnetic field of the Virgo can be studied directly in two ways: investigation for galactic wakes (Jaffe [26]) and RM distributions in some extended regions of polarized radio sources in and seen through the cluster. Together with this, observations for more RM sources in the field of the Virgo supercluster undoubtedly help understand the nature of the intracluster magnetic field of the Virgo supercluster of galaxies.

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