Publ. Astron. Soc. Japan **31**, 125-142 (1979)

Intergalactic Magnetic Fields and Faraday Rotation of Extragalactic Radio Sources

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(Received 1976 September 1; revised 1977 July 7 and 1978 March 1)

Abstract

This paper reexamines our earlier statistical analyses of rotation measures RM and redshifts z of extragalactic radio sources. Absolute magnitudes of RM of 97 sources at high galactic latitudes, $|b|>35°$, are shown to increase with z. Correlation coefficients r between RM and $z\cos\theta$ are calculated for various presumed directions of the intergalactic magnetic field, where θ denotes the angle between a source and the field direction. We have obtained a correlation coefficient of $r=0.60$ among 51 sources of $z\geq 0.5$ and $|b|>35°$. The z-dependence of RM is interpreted by a uniform intergalactic magnetic field of 2.7×10^{-9} G running in the direction of $l=100°$, $b=15°$ in space up to $z=2$.

Key words: Cosmology; Faraday rotation; Intergalactic space; Magnetic fields; Radio sources.

1. *Introduction*

Measurements of Faraday rotations of linearly polarized extragalactic radio sources have given information about the orientation and strength of galactic magnetic fields. A plot of absolute values of rotation measures |RM| against galactic latitudes b has shown that |RM| are distributed below a well-defined envelope $|\mathrm{RM}|\cong 32\cot|b|\ \mathrm{rad\ m^{-2}}$. This tendency in the |RM|-b diagram indicates that the Faraday rotation is due mainly to a magnetic field parallel to the galactic disk. A plot of RM on the (l, b) diagram has also confirmed that interstellar magnetic lines of force are parallel to the galactic plane; this is consistent with the distribution of polarization planes of starlights. The galactic field is approximately along the spiral arm; namely, it runs from $l=270°$, $b=0°$ to $l=90°$, $b=0°$ in the solar neighborhood [see a review paper by Whiteoak (1974)].

In addition to the galactic contribution, Sofue et al. (1968) pointed out that there is an intergalactic contribution. They found that sources with large redshifts ($z\gtrsim 0.5$) have larger scatter in the |RM|-b diagram than those with small z at high latitudes ($|b|>35°$). From a further statistical analysis, they have concluded that an intergalactic field of the order of 2×10^{-9} G exists, well ordered in space at least up to $z\sim 1$. Kawabata et al. (1969) and Fujimoto et al. (1971) (see also Verschuur 1970; Reinhardt and Thiel 1970; Reinhardt 1971) also suggested a similar result and obtained the following statistical relation:

$$\mathrm{RM}=-30z\cos\theta\ \mathrm{rad\ m^{-2}} \tag{1}$$

for sources at $|b|>35°$, where θ is the angle between radio sources and the best-fit direction of the intergalactic uniform field which points to $(l_0, b_0)=(115°, -15°)$. The correlation coefficient is $r=-0.6$. This relation holds at least up to $z=1.4$ and gives $n_e B \approx 2\times10^{-14}$ G cm^{-3}. If we assume $n_e=10^{-5}$ cm^{-3}, the field strength is 2×10^{-9} G.

In the present paper, we reexamine our earlier studies of intergalactic magnetic field using new data which have been obtained in the last decade. The statistical method used here is essentially the same as in the works by Kawabata et al. (1969) and Fujimoto et al. (1971).

2. *Rotation Measures and Redshifts of Extragalactic Radio Sources*

Table 1 lists 157 sources for which both RM and z are available. The RM data have been taken from Fujimoto et al. (1971), Vallée and Kronberg (1975), and Haves (1975). This table includes also sources whose RM are newly determined by the present authors, using polarization data from Gardner et al. (1975). The RMs were determined by the least-squares fits for plots of the position angle ϕ versus the square of wavelength λ^2 for each source, allowing for $180°\times j$ ambiguities ($j=0, \pm1, \pm2 \cdots$) in ϕ,

$$\phi=\mathrm{RM}\,\lambda^2+\phi_0\ , \tag{2}$$

where ϕ_0 is a constant. We discard the sources for which the standard deviation from this fit-line exceeds 10°. Sources whose |RM| exceeds 100 rad m^{-2} are excluded from our statistical analysis to avoid a spurious effect that would be included due to the limited number of data points (wavelengths).

3. *Intergalactic Magnetic Fields*

Figure 1a shows a plot of |RM| of extragalactic radio sources against cot $|b|$, where sources of $z\geq0.5$ and $z<0.5$ are shown with the open and filled circles, respectively. Most of the filled circles are distributed below the straight line represented by the equation $|\mathrm{RM}|=30\cot|b|$ rad m^{-2}, whereas the open circles are more scattered than the filled circles. In particular at $|b|\geq35°$ the difference between the distributions of the open and filled circles is significant. Figure 1b enlarges the left-bottom region of figure 1a separately for the sources with $z<0.5$ and $z\geq0.5$ to demonstrate this difference more clearly. This difference in the |RM|-distribution suggests strongly that RM depends not only on the galactic latitude but also on redshift.

In figure 2, we plot |RM| against z. Here we see again that |RM| scatters more widely at $z\geq0.5$ than at $z<0.5$, which is consistent with the comparison in figure 1b. (See also the discussion of a peculiar hump at $z\sim0.03$ in the |RM| distribution against z in section 5.) The mean |RM| for sources with $z<0.5$ and $|b|>35°$ (41 sources) is 13.9 rad m^{-2} and the root-mean-square deviation for it is 11.3 rad m^{-2}. On the other hand, the corresponding values for $z\geq0.5$ (51 sources) are 22.6 and 19.9 rad m^{-2}, respectively. From Student's t-distribution with ninety (41+51−2) degrees of freedom, we can conclude with more than 99.5% probability that the mean |RM| for $z<0.5$ is smaller than that for $z\geq0.5$.

If the intrinsic rotation measures RM_0 of the sources are independent of z

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Table 1. Faraday rotation measures (RM) of 157 radio sources with known redshifts z.

No. (1)	PKS (RA, Dec) (2)	Other name (3)	Identi-fication (4)	l (5)	b (6)	z (7)	RM(FKS) (rad m^{-2}) (8)	RM(SFK) (rad m^{-2}) (9)	RM(VK) (rad m^{-2}) (10)	RM(H) (rad m^{-2}) (11)	RM$_{ext}$ (rad m^{-2}) (12)	Remark (13)
1........	0003−00	3C2	Q	99°	−60°	1.037			−20±15	*−17 ±11*	−10.2	H
2........	0017+15	3C9	Q	112	−46	2.012	−25	*−24.7± 1.0*	−22± 2	−29 ±12	−13.6	SFK
3........	0034−01	3C15	G	115	−64	0.0733	−13	*−12.3± 1.9*	−12± 2	−12 ± 3	−6.2	SFK
4........	0035−02	3C17	G	115	−65	0.2201	1	*5.9± 5.4*	1± 7		11.7	SFK
5........	0038−020		Q	117	−64	1.176			286±11		291.9	VK
6........	0043−42		G	307	−75	0.0526		*1.2± 0.3*	2± 1	1 ± 2	−0.8	SFK
7........	0045−25	N253	G	97	−88	0.0011			92± 5	*94 ±12*	95.1	H
8........	0055−01	3C29	G	126	−64	0.0450	2	*1.1± 0.5*	2± 2	1.5± 1.3	6.9	SFK
9........	0056−00	PHL923	Q	127	−63	0.717	−1	*−3.1± 0.5*	−1± 2	−5.6± 0.7	3.0	SFK
10........	0106+01		Q	132	−61	2.107	−16	*−15.5± 0.3*			−9.2	SFK
11........	0106+13	3C33	G	129	−49	0.060	−11	*−15.0± 1.7*	−12± 1	−12.4± 1.0	−5.5	SFK
12........	0115+02	3C37	Q	136	−59	0.672			*23± 8*	18 ±26	29.5	VK
13........	0119−04		Q	142	−66	1.955			*0±14*		4.7	VK
14........	0122−00		Q	140	−61	1.070		*15.6± 6.3*			20.3	SFK
15........	0131−36	MSH 01−311	G	262	−77	0.0297	*5*	−18.0± 1.8	8± 2	7 ± 5	3.5	FKS
16........	0133+20	3C47	Q	137	−41	0.425	−17	*−13.9± 5.1*	−17± 4	−17 ± 5	−2.1	SFK
17........	0134+32	3C48	Q	134	−29	0.367	*−53*		−62± 2		−34.4	FKS
18........	0155−10		Q	169	−67	0.616			−275±16		−272.1	VK
19........	0152+43	3C54		135	−18	1.455				160 ± 7	190.6	H
20........	0159−11	3C57	Q	173	−67	0.669	4	*8.8± 5.1*		−294.1± 0.5	11.5	SFK
21........	0226−038	PHL1305	Q	172	−57	2.064			157±18		160.8	VK
22........	0232−04	PHL1377	Q	173	−56	1.436		*1.7± 5.9*			5.5	SFK
23........	0232−02		Q	171	−54	1.322		*12.1± 0.5*			16.4	SFK
24........	0237−03		Q	209	−65	2.223	18	*8.1± 3.8*	10± 1		7.7	SFK
25........	0300+16	3C76.1	G	163	−36	0.0326	−17	*−20.1± 1.1*	19± 1	−18.7± 0.6	−10.9	SFK

Table 1. (Continued)

No. (1)	PKS (RA, Dec) (2)	Other name (3)	Identi-fication (4)	l (5)	b (6)	z (7)	RM(FKS) (rad m^{-2}) (8)	RM(SFK) (rad m^{-2}) (9)	RM(VK) (rad m^{-2}) (10)	RM (H) (rad m^{-2}) (11)	RM$_{ext}$ (rad m^{-2}) (12)	Remark (13)
26	0305+03	3C78 N1218	G	175°	−44°	0.0289	12	*15.5± 1.7*	13± 2	14 ± 3	20.5	SFK
27	0307+16	3C79	G	164	−34	0.2561	−15	*−17.0± 1.7*	−17± 1	−19.7± 0.8	−7.6	SFK
28	0319−37	For A(A)		240	−57	0.0058	*−2.8*				−6.9	FKS
29	0322−37	For A(B)		240	−57	0.0058	*−3.5*				−7.6	FKS
30	0316+41	3C84 N1275	G	151	−13	0.0199	*55*				90.0	FKS
31	0325+02	3C88	G	181	−42	0.0302	21	*22.6± 1.0*	23± 2	21 ± 3	26.7	SFK
32	0336−01	CTA26	Q	188	−42	0.852	*23*	−450.1± 8.6			25.7	FKS
33	0350−07	3C94	Q	197	−42	0.962	23	*21.9± 0.5*	22± 1	18.0± 1.0	22.8	SFK
34	0356+10	3C98	G	180	−31	0.0306	82	*80.8± 1.8*	77± 1	78 ± 2	87.0	SFK
35	0403−13		Q	206	−43	0.571	4	*12.7± 3.3*	11± 3	12 ± 2	11.6	SFK
36	0410+11	3C109	G	182	−28	0.3056	−12	*−16.2± 1.3*	−16± 2	−16 ± 6	−10.0	SFK
37	0427−53		G	262	−42	0.0392		*28.8± 6.9*	−271± 8		18.6	SFK
38	0430+05	3C120	G	190	−27	0.0333	8	*4.1± 2.1*			7.5	SFK
39	0511+00	3C135	G	200	−21	0.127	47	*43.1± 0.8*	42± 6		42.2	SFK
40	0518−45	Pic A	G	252	−35	0.0342	47	*40.0± 7.3*	53± 2	51 ± 4	27.8	SFK
41	0518+16	3C138	Q	187	−11	0.760	0	*−2.0± 1.6*	0± 1	−1.8± 0.3	7.9	SFK
42	0521−36	MSH 05−36	G	241	−33	0.061	6	*4.8± 0.8*	9± 1	−8.4± 1.3	−6.2	SFK
43	0605+48	3C153		165	13	0.2771			*−61± 9*		−37.6	VK
44	0618−37	MSH 06−36	G	245	−22	0.0313	1	*−1.5± 2.9*	1± 1		−20.9	SFK
45	0620−52		G	261	−26	0.0511		454.8± 3.5	−232± 5		435.0	SFK
46	0634−20N		G	230	−12	0.056	41	*48.9± 2.6*			21.6	SFK
47	0634−20S		G	230	−12	0.056		*41.2± 4.2*			13.9	SFK
48	0651+54	3C171	G	162	22	0.2387	*59*		58± 4	58 ± 5	73.6	FKS
49	0710+11	3C175	Q	205	10	0.768	15	*15.8± 8.5*	9± 4		6.7	SFK
50	0725+14	3C181	Q	204	15	1.382				*54 ± 4*	48.2	H

Table 1. (Continued)

No. (1)	PKS (RA, Dec) (2)	Other name (3)	Identi-fication (4)	l (5)	b (6)	z (7)	RM(FKS) (rad m^{-2}) (8)	RM(SFK) (rad m^{-2}) (9)	RM(VK) (rad m^{-2}) (10)	RM(H) (rad m^{-2}) (11)	RM$_{ext}$ (rad m^{-2}) (12)	Remark (13)
51	........0736+01		Q	217°	11°	0.191	27	*24.1± 7.1*			4.0	SFK
52	........0738+80	3C184.1	G	133	29	1.022				*−19 ±10*	−2.0	H
53	........0802+10	3C191	Q	212	21	1.956			*97±12*	98 ±36	88.8	VK
54	........0802+24	3C192	G	198	26	0.0599	23	*24.5± 0.9*	20± 2	18 ± 3	23.4	SFK
55	........0806−10	3C195	G	231	12	0.1070	*−31*				−66.6	FSK
56	........0809+48	3C196	Q	171	33	0.871			−212± 3		−205.5	VK
57	........0812+02		Q	221	19	0.402			−333±12		−346.4	VK
58	........0835+58	3C205	Q	159	37	1.534				*−12 ± 2*	−3.8	H
59	........0838+13	3C207	Q	213	30	0.684	22	*30.9± 8.4*		25 ±10	24.9	SFK
60	........0843−33	N2663	G	255	5	0.0076	68	*70.3± 0.8*	70± 1	70 ±19	−24.4	SFK
61	........0850+14	3C208	Q	214	33	1.110			−153± 3	−155 ±12	−160.6	H
62	........0859−14		Q	242	21	1.327	8	*11.0± 1.0*	11± 3	−14 ±56	−10.4	SFK
63	........0915−11	3C218	G	243	25	0.0530			358± 5		340.4	VK
64	........0917+45	3C219	G	174	45	0.1745			*−10± 2*		−6.5	VK
65	........0945+07	3C227	G	229	42	0.0855	−7	*−8.3± 1.0*	−5± 1		−15.4	SFK
66	........0947+14	3C228	Q	220	46	0.200		*5.5± 2.4*	6± 2	5 ±10	0.5	SFK
67	........0951+69	3C231	G	141	47	0.0011			−225± 5		−215.2	VK
68	........0955+32	3C232	Q	194	52	0.533			−130±10		−130.4	VK
69	........1040+12	3C245	Q	233	56	1.029	31	*28.9± 1.8*	30± 1	29 ± 2	23.8	SFK
70	........1055+20		Q	222	63	1.110			*−34± 9*		−37.2	VK
71	........1100+77	3C249.1	Q	131	39	0.311				*−33 ± 2*	−21.4	H
72	........1111+40	3C254	Q	173	66	0.734	*−23*		−295± 3		−21.7	FSK
73	........1116−46		Q	287	14	0.710		*−11.3± 4.5*	5±10	5 ±25	−56.1	SFK
74	........1116+12	4C12.39	Q	242	64	2.118	−7	*−5.4± 1.1*			−10.0	SFK
75	........1123−35	MSH 11−33	G	284	24	0.0314	−107	*−30.5± 6.0*	−105± 4		−55.5	SFK

Table 1. (Continued)

No. (1)	PKS (RA, Dec) (2)	Other name (3)	Identi-fication (4)	l (5)	b (6)	z (7)	RM(FKS) (rad m^{-2}) (8)	RM(SFK) (rad m^{-2}) (9)	RM(VK) (rad m^{-2}) (10)	RM(H) (rad m^{-2}) (11)	RM$_{ext}$ (rad m^{-2}) (12)	Remark (13)
76	1127−14		Q	275°	44°	1.187	*31*				19.1	FSK
77	1136−13	MSH 11−18	Q	277	45	0.554	−22	*−23.5± 1.6*	−26± 3		−34.9	SFK
78	1142+19	3C264	G	236	73	0.0206			15± 4	*−4 ± 8*	−6.9	H
79	1148−00	4C−00.47	Q	272	59	1.982	0	*−2.8± 2.3*	−1± 2	−1 ± 2	−10.0	SFK
80	1216+06	3C270 N4261	G	282	67	0.0070	67		12± 1	*9.0± 1.6*	3.7	H
81	1206+43	3C268.4	Q	148	71	1.400				*−1.2± 0.6*	0.9	H
82	1222+13	3C272.1 M84	G	278	74	0.0029	−5	*−8.8± 2.0*	−8± 1	−4 ± 3	−12.6	SFK
83	1222+21		Q	255	82	0.435			*−2±10*		−4.1	VK
84	1226+02	3C273	Q	290	64	0.158	1	*4.3± 1.7*		1.2± 0.3	−1.8	SFK
85	1228+12	3C274	G	284	75	0.0039		*57.6± 5.0*	816± 1		53.8	SFK
86	1241+16	3C275.1	Q	293	79	0.557	−18	*−13.9± 3.5*	−10± 3	−5 ±26	−16.8	SFK
87	1233−24		Q	298	38	0.355		*−31.1± 3.1*			−45.7	SFK
88	1252−12	3C278	G	304	50	0.0143	−12	*−14.2± 2.2*	−14± 1	−13.9± 1.0	−23.7	SFK
89	1253−05	3C279	Q	305	57	0.538	24	*13.7± 3.0*			6.2	SFK
90	1258+40	3C280.1	Q	115	77	1.659				*−21 ± 6*	−19.3	H
91	1317−00	4C00.50	Q	327	72	0.89			9± 3	*11.1± 0.6*	7.6	H
92	1318+11	4C11.45	Q	328	72	2.171		*−6.9± 0.7*	7± 2	−33 ±35	−10.3	SFK
93	1322−428	Cen A N5128	G	310	19	0.0019	*−60*	101.6± 5.4	−51± 1		−90.1	FSK
94	1327−21		Q	315	40	0.528			*−2±13*		−14.2	VK
95	1328+254	3C287	Q	22	81	1.055	−67	*−64.1± 6.2*	−61± 3	−100 ±10	−64.7	SFK
96	1328+30	3C286	Q	56	81	0.846	*4*		−1± 0		4.4	FSK
97	1330+02	3C287.1	G	326	63	0.2156	2	*0.0± 0.5*	0± 3	−2.2± 1.3	−5.1	SFK
98	1332−33	MSH 13−33		313	28	0.0114	*−32*				−51.3	FSK
99	1354+19	4C19.44	Q	9	73	0.720	7	*3.8± 1.7*	6± 2	4.7± 1.2	2.6	SFK
100	1355−41		Q	316	19	0.313		*−28.8± 0.3*	−28± 2	−29 ± 4	−57.1	SFK

Table 1. (Continued)

No. (1)	PKS (RA, Dec) (2)	Other name (3)	Identi-fication (4)	l (5)	b (6)	z (7)	RM(FKS) (rad m^{-2}) (8)	RM(SFK) (rad m^{-2}) (9)	RM(VK) (rad m^{-2}) (10)	RM (H) (rad m^{-2}) (11)	RM$_{ext}$ (rad m^{-2}) (12)	Remark (13)
101	1358−11		G	328°	48°	0.025		*1.4± 2.8*			−6.8	SFK
102	1409+52	3C295	G	97	61	0.4610			516±10		521.3	VK
103	1414+11	3C296 N5532	G	358	64	0.0237	−3	*−3.2± 1.0*	−3± 2	−3 ± 3.5	−5.7	SFK
104	1416+06	3C298	Q	352	61	1.439			*12± 5*		8.6	VK
105	1422+20	4C20.33	Q	19	67	0.871			*−31± 9*	−32 ±33	−31.6	VK
106	1453−10		Q	346	42	0.940		*58.9± 4.4*			51.9	SFK
107	1454−06		Q	350	45	1.249		*5.5± 1.1*	15±10	6 ±27	−0.3	SFK
108	1458+71	3C309.1	Q	110	42	0.905			*−81± 5*	67 ± 3	−69.6	VK
109	1502+26	3C310	G	38	60	0.0543	14		*5± 5*	3 ±13	6.5	VK
110	1508−05	4C05.64	Q	354	43	1.191		*−25.1± 2.2*	−24± 2	−25 ± 4	−30.5	SFK
111	1510−08	MSH 15−06	Q	352	40	0.361	−10	*−17.4± 3.1*			−23.7	SFK
112	1511+26	3C315	G	39	58	0.1068	*0*		−1± 2	−1 ± 2	1.8	FKS
113	1514+00	4C00.56	G	1	46	0.053		*−12.1± 0.8*	−12± 3	−12 ± 6	−15.7	SFK
114	1514−24		G	341	28	0.0300	−20	*−19.0± 1.8*		−19 ± 4	−31.9	SFK
115	1514+07	3C317	G	9	50	0.0351		*−39.1± 6.8*	257± 7		−41.1	SFK
116	1545+21	3C323.1	Q	34	49	0.264	20	*21.3± 1.4*	27± 8	24 ± 9	23.3	SFK
117	1559+02	3C327	G	12	38	0.1047	12	*8.8± 1.7*	10± 1	9 ± 2	6.9	SFK
118	1610−608		G	325	−7	0.0176	−72	−126 ± 4.0	−124± 5		−193.4	SFK
119	1615+32	3C332	G	52	45	0.152				*3 ± 3*	8.5	H
120	1618+17	3C334	Q	33	41	0.555		*44.0± 5.6*	22±12	44 ± 6	46.7	SFK
121	1622+23	3C336	Q	41	42	0.927	31	*25.8± 3.5*	29± 4	29 ±15	30.0	SFK
122	1637−77		G	314	−20	0.0423	50	*50.3± 0.2*	49± 4		24.3	SFK
123	1641+39	3C345	Q	64	41	0.595	*19*			18.3± 0.3	27.5	FKS
124	1648+05	3C348 Her A	G	23	29	0.1570	11	*11.2± 3.5*	12± 1	−5 ±20	12.5	SFK
125	1717−00	3C353	G	21	20	0.0307	36	*35.8± 4.3*	37± 1		37.3	SFK

Table 1. (Continued)

No. (1)	PKS (RA, Dec) (2)	Other name (3)	Identification (4)	l (5)	b (6)	z (7)	RM(FKS) (rad m^{-2}) (8)	RM(SFK) (rad m^{-2}) (9)	RM(VK) (rad m^{-2}) (10)	RM(H) (rad m^{-2}) (11)	RM_{ext} (rad m^{-2}) (12)	Remark (13)
126	1801+01		Q	28°	11°	1.522			−135±15		−124.6	VK
127	1828+48	3C380	Q	77	24	0.691	*31*				51.6	FKS
128	1836+17	3C386	G	47	10	0.0033	69	−215.7± 2.6	−213± 3	−211 ± 5	−186.9	SFK
129	1949+02	3C403	G	12	−12	0.0590	−39	*−41.8± 1.7*	−37± 1	−42 ± 5	−45.2	SFK
130	2040−26		G	18	−35	0.0406	−21	*−18.4± 1.3*	−18± 3	−19 ±20	−17.3	SFK
131	2058−28		G	18	−40	0.0394		*12.4± 2.8*	9± 2		13.4	SFK
132	2115−30	MSH 21−34	Q	16	−44	0.98	28	*27.4± 2.6*	29± 2	27 ± 4	27.9	SFK
133	2104−25		G	21	−40	0.0300		*2.7± 5.4*	3± 2		4.5	SFK
134	2117+60	3C430	G	100	8	0.0549			−166± 4		−89.3	VK
135	2121+24	3C433	G	74	−18	0.1025	−76	*−77.5± 1.1*	−73± 1	−69.7± 1.3	−47.7	SFK
136	2128−12			343	−45	0.501		*−1.4± 9.9*			−6.8	SFK
137	2135−14	MSH 21−115	Q	38	−43	0.200	19	*22.5± 1.2*	22± 1	22 ± 3	27.5	SFK
138	2152−69		G	321	−41	0.0266	34	*37.6± 2.4*	37± 2	37 ± 3	27.8	SFK
139	2209+08	4C08.64	Q	70	−38	0.486	−28	*−20.5± 3.1*	−19± 3	−13.1± 0.9	−8.4	SFK
140	2212+13	3C442 N7236	G	75	−34	0.0270	−38	*−30.9± 3.9*	−31± 3	−26 ±10	−16.4	SFK
141	2221−02	3C445	G	62	−47	0.0568	5	*13.2± 2.8*	12± 2	13 ± 3	21.3	SFK
142	2223−05	3C446	Q	59	−49	1.404	−21	*−28.2± 0.5*	−28± 2		−21.0	SFK
143	2230+11	CTA102	Q	77	−39	1.037	−47	*−50.0± 0.8*	−45± 1		−37.3	SFK
144	2243+39	3C452	G	98	−17	0.0820	−272		−272± 2	−272.1± 1.5	−236.0	FKS
145	2247+11	N7383	G	82	−41	0.0268	−19	*−20.2± 2.5*	−20± 3		−8.1	SFK
146	2249+18	3C454	Q	87	−36	1.757	−87	*−88.9± 3.0*	−86± 3	−85 ± 5	−73.7	SFK
147	2251+15	3C454.3	Q	86	−38	0.859	−52	*−52.8± 2.0*		−58 ± 0.4	−38.9	SFK
148	2252+12			84	−41	0.0334	13	*3.4± 9.7*			15.8	SFK
149	2300−18		G	92	−38	0.129		−133.0± 2.7			−118.7	SFK
150	2309+09	3C456	G	86	−46	0.2337	3	−84.3±11.7			−73.6	SFK

Table 1. (Continued)

No. (1)	PKS (RA, Dec) (2)	Other name (3)	Identi-fication (4)	l (5)	b (6)	z (7)	RM(FKS) (rad m^{-2}) (8)	RM(SFK) (rad m^{-2}) (9)	RM(VK) (rad m^{-2}) (10)	RM (H) (rad m^{-2}) (11)	RM_{ext} (rad m^{-2}) (12)	Remark (13)
151........	2313+03	3C459	G	83°	−51°	0.2205	*7*	305.7± 5.2	−4± 2		15.8	FKS
152........	2326−477		Q	337	−64	1.299		*24.2± 5.0*			21.5	SFK
153........	2335+26	3C465	G	103	−33	0.0301			−284± 4		−266.4	VK
154........	2345−16		Q	67	−71	0.600		*−19.3± 5.4*			−15.6	SFK
155........	2353−68			310	−48	1.716		*46.3± 4.2*			38.0	SFK
156........	2354+14		Q	103	−46	1.810		*−25.4±10.4*			−14.1	SFK
157........	2356−61		G	314	−55	0.0959	23	*17.6± 2.0*	18± 1	18± 2	11.5	SFK

Column 1: Running number of the sources.
Column 2: PKS number or approximate position of the sources in RA and Dec.
Column 3: Other designation.
Column 4: Optical identification: G: galaxy, Q: QSO (Véron and Véron 1974).
Columns 5 and 6: Galactic longitude and latitude of the source.
Column 7: Redshift z [data sources are Burbidge and O'Dell (1972) and Knight et al. (1976)].
Column 8: RM listed in Fujimoto et al. (1971).
Column 9: RM newly determined by the present authors. See the text.
Column 10: RM given in Vallée and Kronberg (1975).
Column 11: RM given in Haves (1975).
Column 12: RM corrected for the contribution from the galactic disk: $RM_{ext}=RM-RM_d$.
Column 13: Data source of RM used to calculate RM_{ext}.
FKS: Fujimoto et al. (1971), SFK: the present determination, VK: Vallée and Kronberg (1975), and H: Haves (1975).
Adopted values of RM are in italic (columns 8-11).

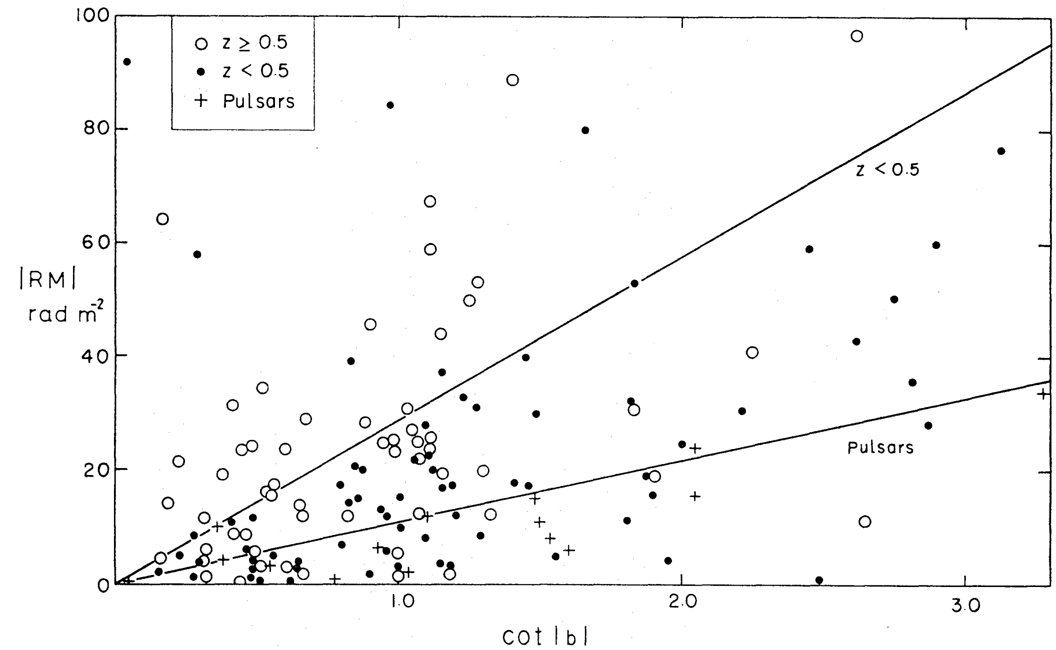

Fig. 1a. Absolute magnitudes of RM of extragalactic radio sources plotted against cot$|b|$. |RM| of the sources with large redshifts ($z \geq 0.5$) are indicated with the open circles, and those of nearby sources ($z<0.5$) with filled circles. The crosses indicate |RM| of pulsars (see also figure 8). Two inclined lines show upper envelopes of the RM distributions for pulsars and nearby extragalactic sources with $z<0.5$. Note that |RM| with $z>0.5$ (open circles) are more scattered than the others.

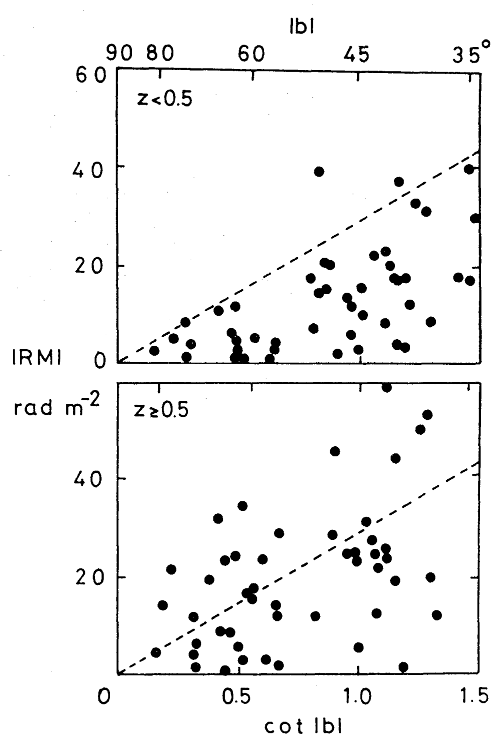

Fig. 1b. Enlarged plots of the |RM|-cot $|b|$ relation from the left-bottom corner of figure 1a, separately for extragalactic sources with $z<0.5$ and ≥ 0.5. This figure demonstrates the z-dependence of the distribution.

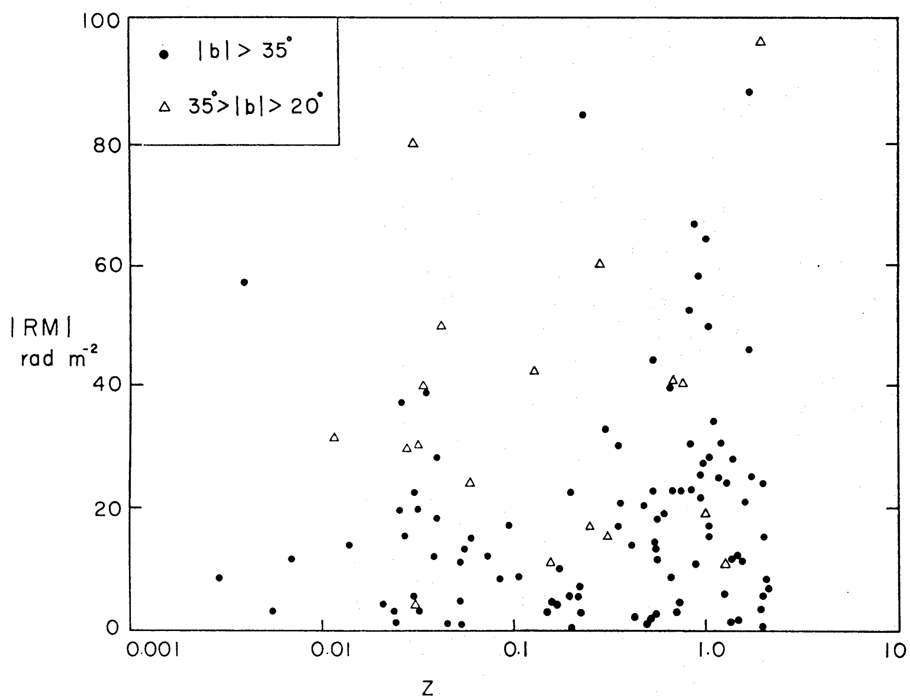

Fig. 2. Absolute magnitudes of the observed RM of extragalactic radio sources plotted against their redshifts z.

and no Faraday rotation takes place in the intergalactic space, the observed RM should decrease with z as $RM=RM_0(1+z)^{-2}$ (Sofue et al. 1968). The z-dependence of RM in figure 2 is clearly in the opposite sense to this relation.

Two possible interpretations can be made of the origin of the z-dependence of RM: (A) It is due to an evolutionary effect within the sources, namely, the rotation measure intrinsic to a source was larger when it was younger and more compact. (B) Polarized radio waves propagate in the intergalactic space with magnetic field and plasma. Kawabata et al. (1969) and Fujimoto et al. (1971) have stressed that the latter interpretation is more reasonable by pointing out a directional correlation between RM and $z\cos\theta$ among the sources, where θ is the angle between a source and the direction of the magnetic field which has been assumed to be uniform.

In the present paper, we examine the second possibility, following our earlier analyses. We determine first a correlation between RM and $\cos\theta$ (*not* $z\cos\theta$) of the form,

$$RM=A\cos\theta+C \tag{3}$$

for sources at high galactic latitudes ($|b|>35°$) in various redshift intervals, z–$(z+\Delta z)$. Table 2 gives A, C, (l_0, b_0), and correlation coefficients r in the intervals $z=0$–0.5, 0.5–1.0, 1.0–1.5 and $z\geq1.5$. Here (l_0, b_0) are the assumed field direction in the galactic coordinates which gives the maximum correlation in each z-range. Figure 3a shows the variation of A against z.

Table 3 and figure 3b give also the results of similar trials to find a correlation between RM and $z\cos\theta$ in the form

$$RM=A'z\cos\theta+C' \tag{4}$$

Table 2. RM–$\cos\theta$ correlations for radio sources at $|b|>35°$ ($RM=A\cos\theta+C$ is assumed).

	z			
	0.0–0.5	0.5–1.0	1.0–1.5	>1.5
Number of sources	49	24	15	12
A (rad m^{-2})	−21.3	−32.2	−67.5	−67.6
C (rad m^{-2})	1.7	3.1	− 5.9	−12.4
l_0, b_0	105°, 20°	135°, 20°	35°, 15°	75°, 10°
Correlation coefficient	− 0.33	− 0.40	− 0.72	− 0.84

Table 3. RM–$z\cos\theta$ correlations for radio sources at $|b|>35°$ ($RM=A'z\cos\theta+C'$ is assumed).

	z			
	0.0–0.5	0.5–1.0	1.0–1.5	>1.5
Number of sources	49	24	15	12
A'(rad m^{-2})	−83.7	−58.2	−53.31	−33.8
C'(rad m^{-2})	0.3	1.9	− 5.9	−12.4
l_0, b_0	95°, 20°	125°, 15°	90°, 15°	85°, 15°
Correlation coefficient	−0.22	− 0.53	− 0.67	− 0.82

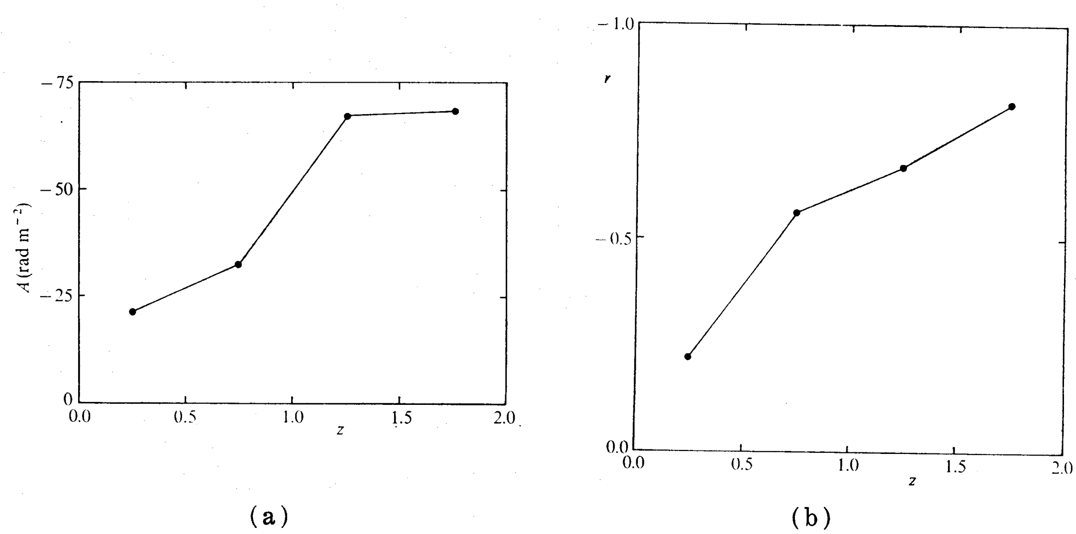

Fig. 3. (a) Plots of the coefficient A against $z<0.5$, $0.5\leq z<1.0$, $1.0\leq z<1.5$, $z\geq 1.5$. $RM=A\cos\theta+C$. (b) The correlation coefficient of $RM=A'z\cos\theta+C'$ for sources of the same z-intervals.

for the same data and the same redshift intervals. We find a good correlation between RM and $z\cos\theta$ for $z\geq 0.5$.

It is to be noted that the value of A in equation (3) increases steeply with

z beyond $z \simeq 0.5$. If there is no intergalactic contribution to the Faraday rotation and RM is determined only by the fields in our Galaxy, the value of A must remain unchanged against z. The above results in tables 2 and 3 and in figure 3a can be reasonably interpreted, if we assume the existence of magnetic fields in the intergalactic space with ionized gas. Furthermore, the good correlations with $\cos\theta$ and $z\cos\theta$ at larger z are understood well by a uniform field extending up to $z \sim 2$, but not by random fields. This result is consistent with our earlier conclusion that a large-scale ordered magnetic field exists in the intergalactic space. We note that the good correlation of RM–$z\cos\theta$ cannot be attributed to the evolutionary effect of the sources [interpretation (A)].

We have also calculated the correlation coefficient of RM–$z\cos\theta$ relations among all sources with $z \geq 0.5$ and $z \geq 1.0$ at $|b| > 35°$. The results are shown in figures 4 and 5, which give the maximum values of $r=0.60$ and 0.73, respectively, for $z \geq 0.5$ and ≥ 1.0. See also figure 3b for r of the sources with $z=0.0$–0.5, 0.5–1.0, 1.0–1.5, and ≥ 1.5. The probability that these correlation coefficients are realized among 51 sources ($z \geq 0.5$) and 27 sources ($z \geq 1.0$) is 0.05, which is small enough to make these correlations significant. In figure 6 we show the distribution of r on the (l_0, b_0) plane calculated for the sources with $z \geq 0.5$.

The linear relationship in figures 4 and 5 is approximately expressed by the equation,

$$\mathrm{RM} \cong -30(\pm 10) z \cos\theta \,. \qquad (5)$$

From the coefficient, we can estimate $n_e B = 8 \times 10^{-15}$ G cm^{-3}, where n_e and B are the electron density and field strength in the intergalactic space. If we take the intergalactic gas density to be equal to the critical density of the expanding universe, we have $\rho_c = 3H^2/8\pi G = 3 \times 10^{-6}$ proton cm^{-3} for the Hubble constant of 50 km s^{-1} Mpc^{-1}. This leads to the strength of the intergalactic field of $B = 2.7 \times 10^{-9}$ G. The uniform field runs from $(l, b) = (280°, -15°)$ toward $(l_0, b_0) = (100°, +15°)$ up to $z \approx 2$.

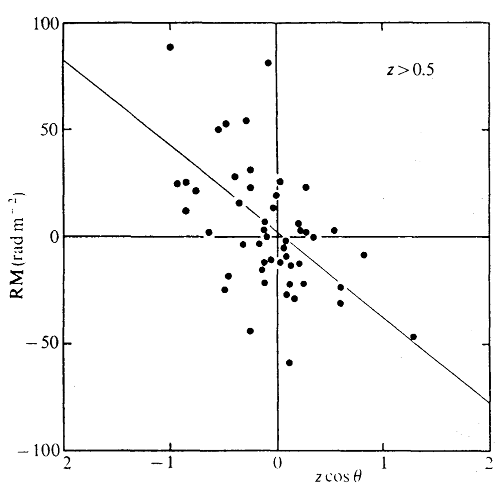

Fig. 4. RM plotted against $z\cos\theta$ for the sources with $z \geq 0.5$ and $|b| > 35°$. The best correlation with the coefficient $r = -0.60$ is obtained when we choose $l_0 = 100°$, $b_0 = 15°$.

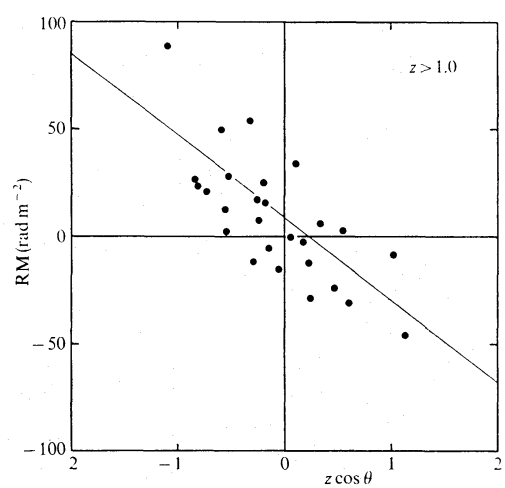

Fig. 5. Same as figure 4, but for the sources with $z \geq 1.0$. The best correlation with the coefficient $r = -0.73$ is obtained when $l_0 = 85°$, $b_0 = 15°$.

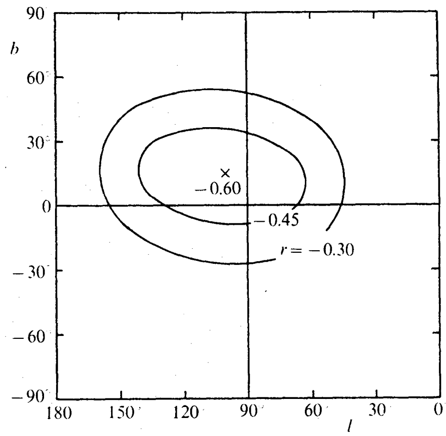

Fig. 6. Distribution of correlation coefficients r on the (l_0, b_0) plane obtained for the RM-$z\cos\theta$ plot of the sources with $z \geq 0.5$ and $|b|>35°$. When (l_0, b_0) is in the ellipse of $r=-0.3$, the non-zero correlation coefficient of the RM-z $\cos\theta$ relation for 51 sources is guaranteed with the 95% probability.

We note that the correlation coefficient is reduced to less than 0.3 for the sources with $z<0.5$. This tendency could be understood as a result of the superposition of random fields whose typical scale is about 0.2 measured in z and with the strength comparable to the uniform component. Irregular components of the intergalactic Faraday rotation measure have been discussed in details by Fujimoto et al. (1971). Similar works on intergalactic irregular magnetic fields have been developed by Nelson (1973) and Kronberg and Simard-Normandin (1976).

4. *Correction for the Galactic Faraday Rotation*

In the above consideration, we used only the sources at high galactic latitudes $|b|>35°$ in order to reduce the contribution from the galactic disk. Here we try to correct for the galactic contribution using the RM data of pulsars with the hope of improving our statistics. Figure 7 gives a plot of |RM| of 38 pulsars from Manchester (1974) against galactic latitude. Most of the pulsars are distributed below the line,

$$|\mathrm{RM}|=11 \cot |b| \ \mathrm{rad\ m^{-2}}\ . \quad (6)$$

This distribution is understood by the interstellar magnetic fields which are parallel to the galactic plane. Furthermore, the local field direction in the disk may be determined by using the line-of-sight components of the mean magnetic field B_r between the Sun and pulsars which have been given for each pulsar by Manchester (1974). From a correlation analysis, we obtained the following field configuration:

$$B_r=-2\times10^{-6}\cos\theta \ \mathrm{G}\ , \quad (7)$$

with a maximum correlation coefficient of 0.74 for an assumed local field direction $(l_d, b_d)=(107°, -4°)$. Namely, the uniform component of the local galactic field runs toward (l_d, b_d) with a strength of 2×10^{-6} G. (In the above analysis, we have omitted PSR 2822−09 which has an exceptionally large RM.) From positions

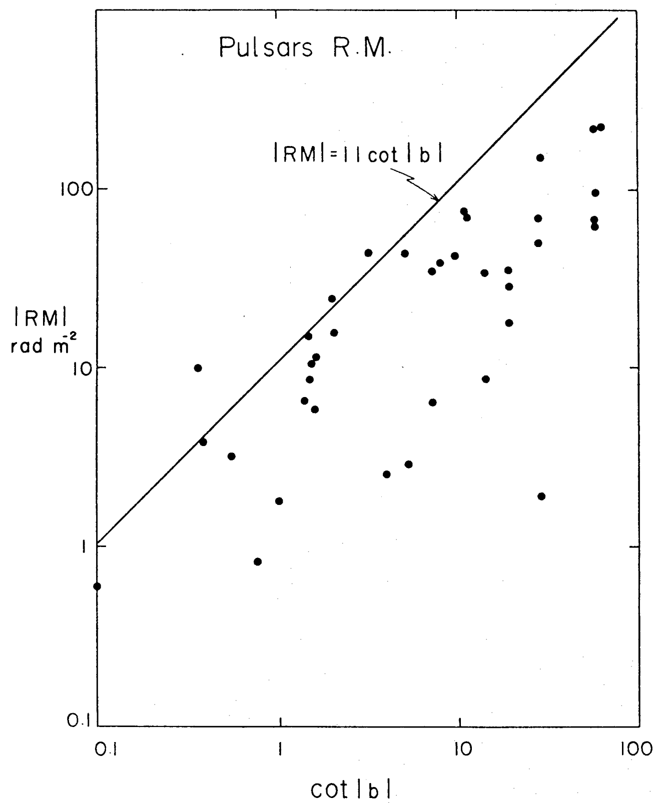

Fig. 7. Absolute magnitudes of RM of pulsars plotted against cot$|b|$. The upper envelope of the plots is fitted approximately by the line $|\mathrm{RM}|=11$ cot$|b|$ rad m^{-2}. (The same data are indicated with + symbols in figure 1.)

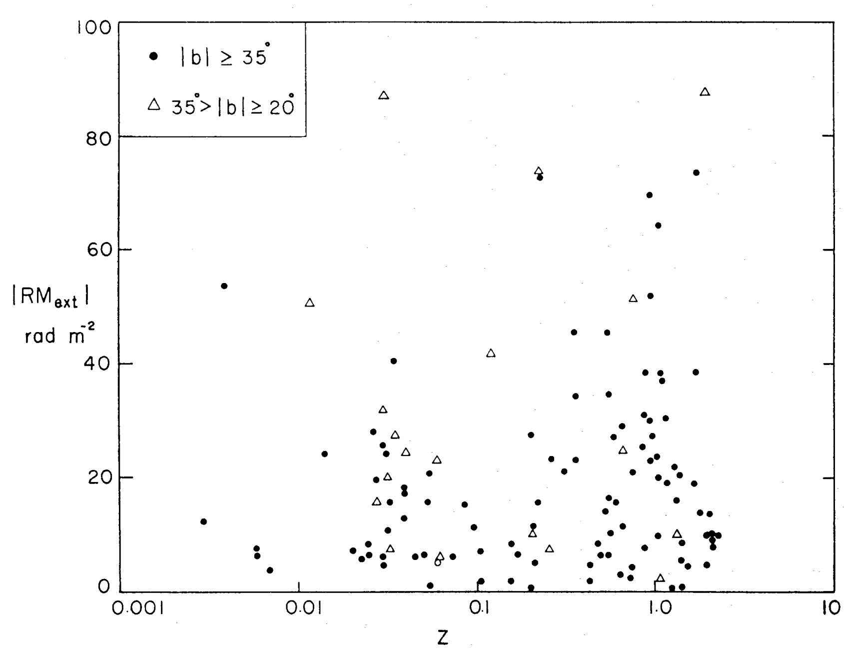

Fig. 8. Same as figure 1, but for rotation measures corrected for the galactic disk contribution: $\mathrm{RM_{ext}}=\mathrm{RM}-\mathrm{RM_d}$, where $\mathrm{RM_d}=-11\cos\theta/\sin|b|$ rad m^{-2}, with $l_d=107°$, $b_d=-4°$. No significant difference from figure 1 is found.

of the 38 pulsars (Manchester 1974), we consider that the field distribution (7) holds in the space within 400 pc from the galactic plane and 3 kpc from the sun.

Combining equations (6) and (7), we can evaluate the galactic-disk contribution to the observed Faraday rotation:

$$RM_d = -11\cos\theta/\sin|b| \text{ rad m}^{-2} . \quad (8)$$

Now we subtract the disk component (8) from the RM data in table 1, and make similar statistical analyses about the $|RM_{ext}|$-z, $|RM_{ext}|$-$\cot|b|$, RM_{ext}-$\cos\theta$, and RM_{ext}-$z\cos\theta$ relations, where $RM_{ext}=RM-RM_d$. (Corrected RM_{ext} are given in column 12 of table 1.) An example of the results is given in figure 8 for the $|RM_{ext}|$-z relation. However, there is no essential difference between figures 2 and 8. Similar results are also obtained from other correlation analyses. This may be due to the fact that the galactic disk contribution at $|b|>35°$ is relatively small compared with the intergalactic contribution for sources with $z\geq0.5$.

Finally we note that there is a significant difference of $\sim$20 rad m^{-2} in $|RM|$ between the upper envelope in figure 1 (extragalactic sources of $z<0.5$) and the envelope in figure 7 (pulsars), which suggests the presence of magnetic fields and ionized gas in the space (halo) beyond the galactic disk whose thickness is 800 pc.

5. *Conclusions and Discussion*

We have found the statistical dependences of RM on z and $z\cos\theta$, which suggest the existence of a uniform magnetic field in the intergalactic space up to $z\sim2$. The intergalactic contribution to the Faraday rotation measure is derived from figures 4 and 5, leading to the following relation:

$$RM = -30(\pm10)\, z\cos\theta \text{ rad m}^{-2} , \quad (9)$$

where θ is the angle with the field direction $(l_0, b_0)=(100°, 15°)$. If the gas density in the intergalactic space is the critical density of the expanding universe, we have $n_e=3\times10^{-6}$ cm^{-3} for the Hubble constant of $H=50$ km s^{-1} Mpc^{-1}, which yields the intergalactic field strength to be 2.7×10^{-9} G. This is in agreement with our previous estimation.

In the course of this study, we found some interesting facts concerning the relation between RM and z.

i) A peak of $|RM|$ at $z=0.03$: Figures 1 and 8 show that the RM distribution of extragalactic sources has a peculiar hump at $z\cong0.03$, superposed on a general trend to increase with z. The width of the hump is about $\Delta z=0.04$, and no other such peak is found beyond $z\cong0.05$. Figures 9a and 9b plot $|RM|$ versus z separately for radio galaxies and QSOs. We note that near sources ($z\lesssim0.05$) are mostly radio galaxies, while those with $z\gtrsim0.1$ are dominated by QSOs. If the large $|RM|$ for distant QSOs can be attributed entirely to the intergalactic Faraday rotation, the apparent peak of $|RM|$ around $z=0.03$ suggests that the radio galaxies have intrinsic rotation measures larger than QSOs. This has been noted also by Mitton and Reinhardt (1972), although they did not take into account the intergalactic contributions.

ii) Magnetic fields in the galactic halo: The $|RM|$-$\cot|b|$ plot in figure 1 shows that absolute values of RM for sources with $z<0.5$ are distributed roughly below a line given by the equation $|RM|=30\cot|b|$ rad m^{-2}. Such a b-dependence

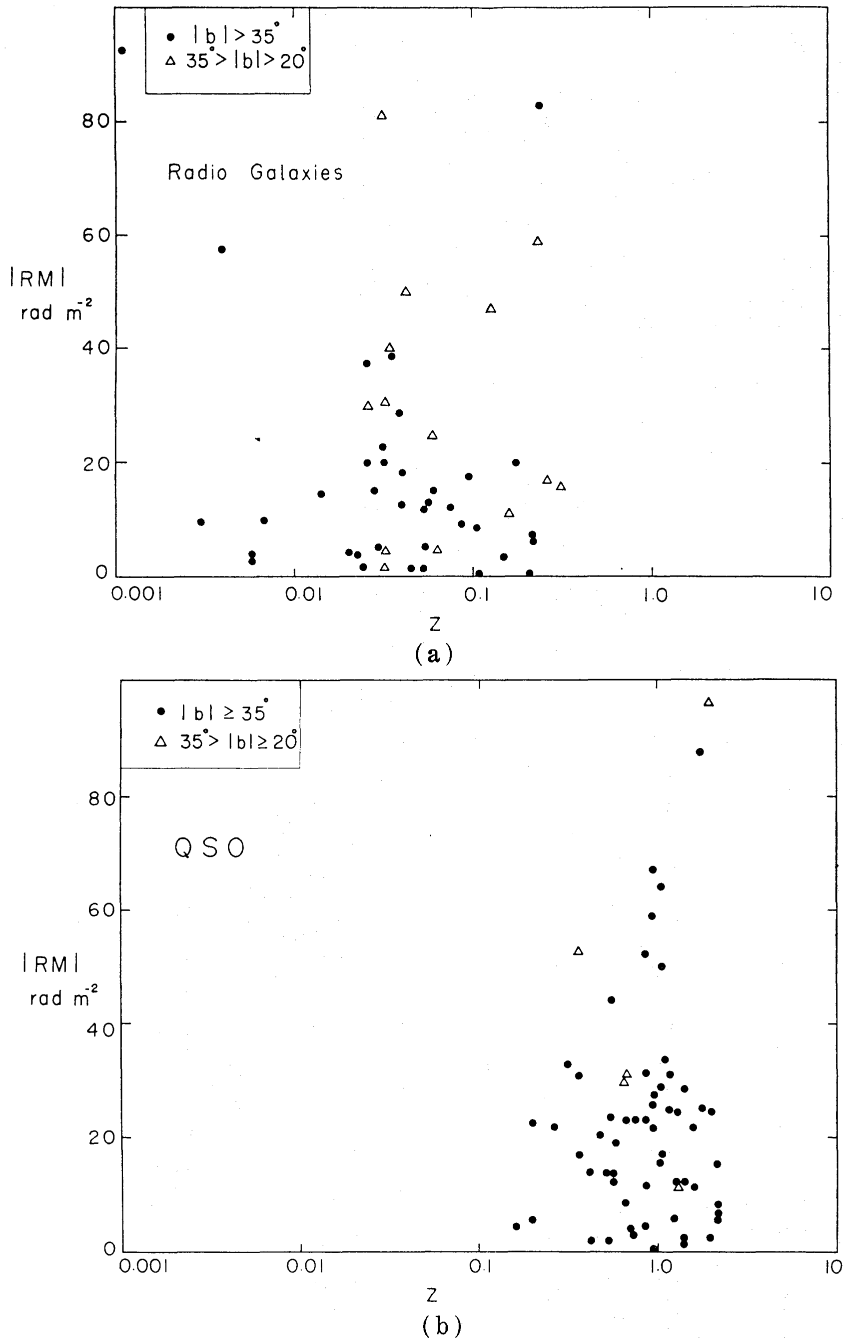

Fig. 9. Absolute magnitudes of observed rotation measures plotted against z, separately, for (a) radio galaxies and (b) for QSOs.

of RM may be due to our Galaxy. On the other hand, |RM| of pulsars are distributed below $11 \cot |b|$ rad m^{-2} as shown in figure 7 (compare with figure 1), which can be explained by an ordered magnetic field in the local galactic disk as given by equation (7). The remaining galactic contribution to the extragalactic sources, $\sim 20 \cot |b|$ rad m^{-2}, may, therefore, be due to the galactic halo beyond $\sim$400 pc from the galactic plane. If we tentatively assume a thickness of the layer responsible for the halo component as 5 kpc and the electron density there as 10^{-3} cm^{-3}, then the line-of-sight strength of the halo fields is estimated to be about a few micro-gausses.

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