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A Large-Scale Metagalactic Magnetic Field and Faraday Rotation for Extragalactic Radio Sources

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Abstract

The Faraday rotation of emissions from 60 linearly polarized radio sources is investigated. It is concluded that the metagalactic magnetic field also contributes to the Faraday rotation. Distribution diagrams of the rotation measures against galactic latitudes show that scatters in the rotation measures are, at $|b^{II}|>35°$, significantly larger for the sources with large redshifts than for those with small redshifts. It is shown that the rotation measures correlate with $z\cdot\cos\theta$ with a correlation coefficient of 0.601 for radio sources at $|b^{II}|>35°$, where z denotes the redshift of the radio source and θ denotes an angle between the direction of the source and the direction ($l^{II}=115°$, $b^{II}=-5°$).

These observational characteristics can be explained, when the redshift is of cosmological origin and a large-scale metagalactic magnetic field, being approximately uniform at least up to a distance of $z=1.4$, is directed toward $l^{II}=115°$ and $b^{II}=-5°$. If the intergalactic electron density is $N_e=10^{-5}\,\mathrm{cm}^{-3}$, the strength of the large-scale metagalactic magnetic field is 2×10^{-9} gauss.

Combining the present results with other cosmological problems such as quasi-stellar objects, the diffuse component of the X-rays, and the background component of radio emission, we have been able to impose some constraints on quantities associated with the cosmology: the quasi-stellar objects must locate at a distance farther than 300 Mpc from us even in a local hypothesis, the strength of the metagalactic magnetic field must be smaller than 2×10^{-8} gauss, and the matter density in the intergalactic space must be larger than $1.7\times10^{-30}\,\mathrm{gr\,cm}^{-3}$.

1. *Introduction*

It has been found by GARDNER and WHITEOAK (1963) that, for most of the linearly polarized radio sources, the position angle of the linear polarization is related linearly with the square of the wavelength. This discovery reveals that the Faraday rotation of emission from the linearly polarized radio sources takes place mainly in the medium between the source and the observer, but not in the radio emitting region.

The constant of the proportionality, the rotation measure (R.M.), is related to the magneto-ionic parameters of the medium between the source and the observer as

$$\text{R.M.}=8.1\times10^{5}\int N_e B_{/\!/} dL \ \text{rad m}^{-2} ,$$

where N_e is the electron density in cm^{-3}, $B_{/\!/}$ is the longitudinal component of the magnetic field in gauss and dL is in parsecs. A positive value of the rotation measure denotes a magnetic field directed towards the observer.

Early investigations (GARDNER and WHITEOAK 1963, GARDNER 1963) have shown a strong dependence of rotation measures on galactic latitudes and have indicated that a substantial portion of the Faraday rotation takes place in the Galaxy. Further, MORRIS and BERGE (1964) have found a longitudinal dependence of the rotation measure, and later GARDNER and DAVIES (1966) have shown a large-scale order imposed on the distribution of rotation measures in galactic coordinates. From these investigations, these authors have attributed the Faraday rotation to the magnetic field within the local spiral arm of the Galaxy.

BERGE and SEIELSTAD (1967) have confirmed the large-scale order in the distribution of rotation measures, but they have mentioned that the variation of the rotation measure from place to place is very irregular and not nearly as smooth as GARDNER and DAVIES (1966) suggest.

Recently, SOFUE, FUJIMOTO, and KAWABATA (1968) have mentioned a difference in the distribution of rotation measures between radio sources with large redshifts and those with small redshifts, and they have suggested that Faraday rotation takes place in the metagalactic magnetic field as well.

2. *Sources of Data*

For each source, the intrinsic position angle of the linear polarization and the rotation measure can be determined from measurements at three or more wavelengths, by keeping in mind that the position angle of the polarization is ambiguous by multiples of 180°.

In the present paper, we use the estimates of rotation measures in the table given by BERGE and SEIELSTAD (1967). From the list by BERGE and SEIELSTAD, we select 61 radio sources whose data on redshifts are available. Table 1 gives the magnitudes of redshifts as well as the values of the rotation measures for these 61 radio sources. Sources of data on redshifts are listed in the last column.

Although, for some radio sources in Table 1, measurements of the redshifts have not been made, the cited values of the redshifts refer to the distances estimated from the optical magnitudes of the identified galaxies. In this estimate of the distances of identified galaxies, we take the absolute visual magnitude of −21.2 mag., the absolute photographic magnitude of −19.7 mag., and the Hubble constant as $100\,\text{km}\,\text{sec}^{-1}\,\text{Mpc}^{-1}$. Since such radio sources are all located at relatively small distances from the Galaxy, possible errors in the determination of redshifts produce only minor effects in the present investigations.

GARDNER and DAVIES (1966) have pointed out that at high galactic latitude

($|b^{II}|>60°$) the rotation measures for all but 3C 287 are very small. As is already pointed out by GARDNER and DAVIES (1966), and BERGE and SEIELSTAD (1967), the Faraday rotation of 3C 287 is so far from being typical that it must be produced in or near the source or in a very anomalous region in the Galaxy. Therefore, we exclude it from the present investigation and we use only the remaining 60 radio sources.

3. *Variation of Rotation Measures with Galactic Latitude*

The sixty radio sources listed in Table 1 are divided into three classes according to the magnitude of the redshift; class 1 for the sources with $z<0.05$, class 2 for those with $0.05 \leq z<0.2$, and class 3 for those with $z \geq 0.2$. For each class, absolute values of rotation measures are plotted against the galactic latitude (Figure 1).

As already pointed out by GARDNER and DAVIES (1966), a large scatter in the rotation measures is evident at latitudes lower than 20°. This feature

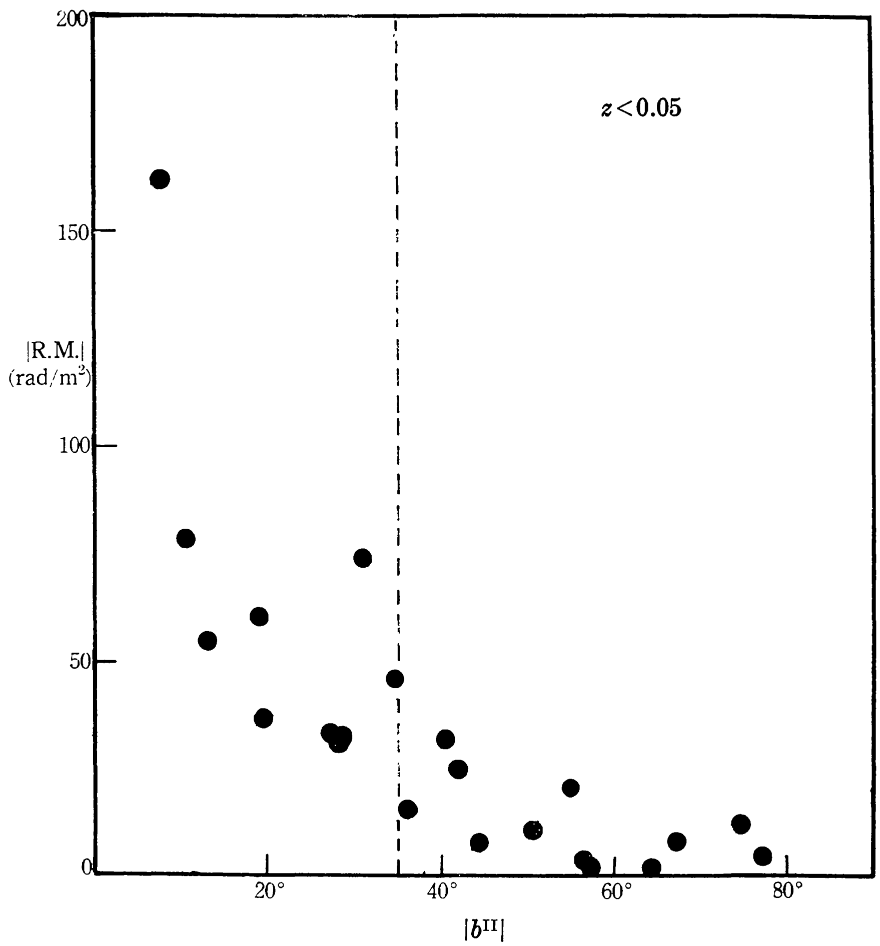

FIG. 1-a. Latitude dependence of the magnitudes of rotation measures for the radio sources with $z<0.05$. The abscissa and ordinate represent the absolute values of galactic latitude and rotation measures. A scatter of rotation measures (standard deviation) is 11.5 rad m^{-2} for radio sources of $|b^{II}| \geq 35°$.

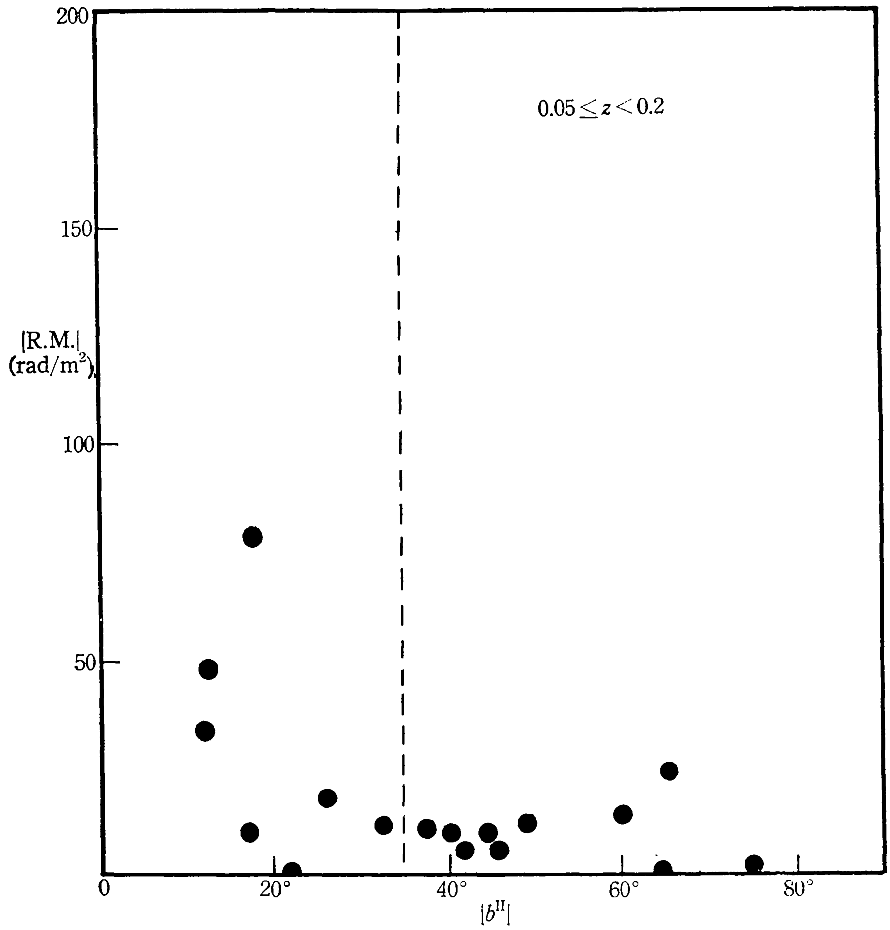

FIG. 1-b. Same as Figure 1-a, but for radio sources with $0.05 \leq z < 0.2$. A scatter of rotation measures in the same latitude range is 11.8 rad m^{-2}.

is commonly found for all classes and confirms that the bulk of rotation measure is of galactic origin for the radio sources at low latitudes.

Another important feature of the latitude distribution is the greater spread in individual values of the rotation measures for radio sources with $z \geq 0.2$ compared with radio sources with $z < 0.2$ at intermediate and high latitude range. Standard deviations of the rotation measures in the latitude range $|b^{II}| > 35°$ are 11.5 rad m^{-2} and 11.8 rad m^{-2} for radio sources with $z < 0.05$, and for those with $0.05 \leq z < 0.2$, respectively. On the other hand, the standard deviation is 24.3 rad m^{-2} for radio sources with $z \geq 0.2$ in the same latitude range. Such a disagreement in the standard deviations of the rotation measures can be expected by chance only with a probability less than 1 percent.

Even if we use only radio sources with a small error in the rotation measure equal to or less than 5 rad m^{-2}, the standard deviations are 10.0 rad m^{-2} and 27.0 rad m^{-2} for radio sources with $z < 0.2$ and those with $z \geq 0.2$, respectively. These values of the standard deviations are essentially the same as those found above for respective classes of the radio sources. Therefore, the difference in the scatters of the rotation measures, at $|b^{II}| > 35°$, cannot be attributed to an error in determination of the rotation measures, but shows that a large portion of the Faraday rotation takes place in the intergalactic space for radio

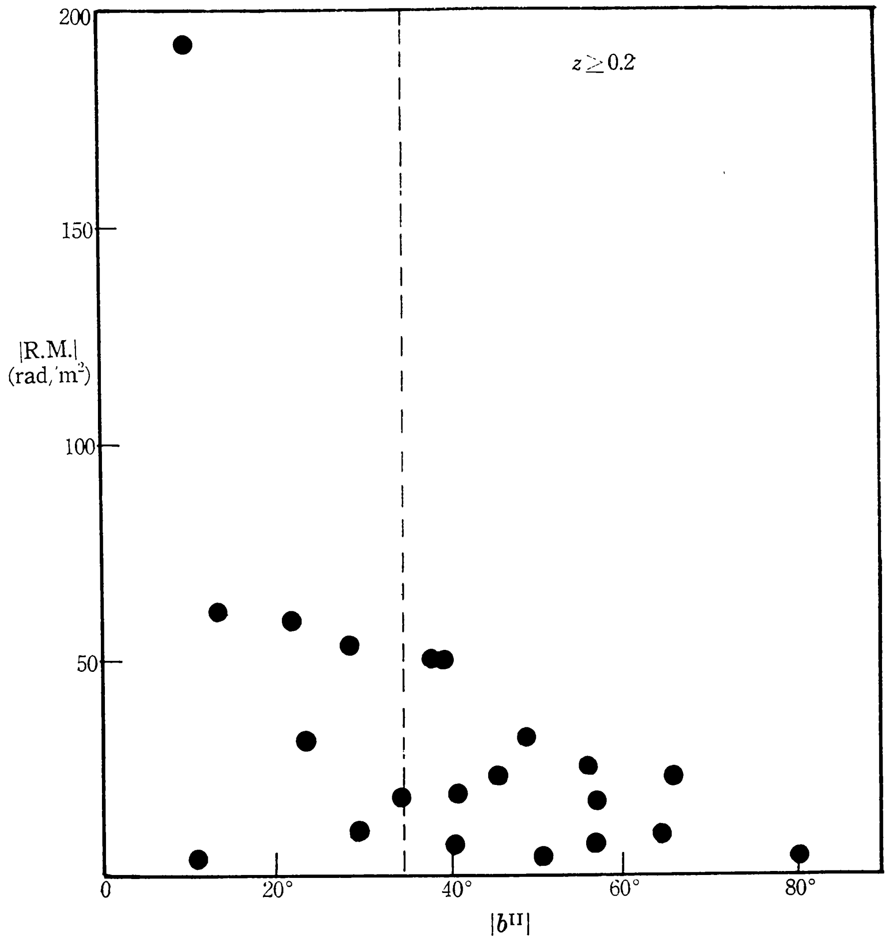

FIG. 1-c. Same as Figure 1-a, but for radio sources with $z \geq 0.2$. A scatter of rotation measures in the same latitude range is 24.3 rad m^{-2}.

sources with large redshifts, at intermediate and high galactic latitudes.

4. *Correlation between Rotation Measures and Redshifts*

Let us suppose that the redshift z of the radio source is proportional to the distance of the radio source and the Faraday rotation takes place in the metagalactic space containing a uniform magnetic field and a constant density of thermal electrons. If this is the case, the rotation measure should be proportional to $z \cdot \cos\theta$, where θ denotes the angle between the direction of the source and that of the uniform metagalactic magnetic field.

As is shown in Section 3, the dependence of the rotation measure on the redshift can be found only at intermediate and high galactic latitudes. Therefore, 35 radio sources at latitudes higher than 35° are selected out of the 60 radio sources listed in Table 1, and only these 35 radio sources are used for statistics in this section.

We carry out plottings of the rotation measures against $z \cdot \cos\theta$ and compute the correlation coefficients between them for various presumed directions of the metagalactic magnetic field (l_0^{II}, b_0^{II}) over the sky. The maximum correlation coefficient of 0.601 is obtained when we take the direction ($l_0^{II}=115°$, $b_0^{II}=-5°$).

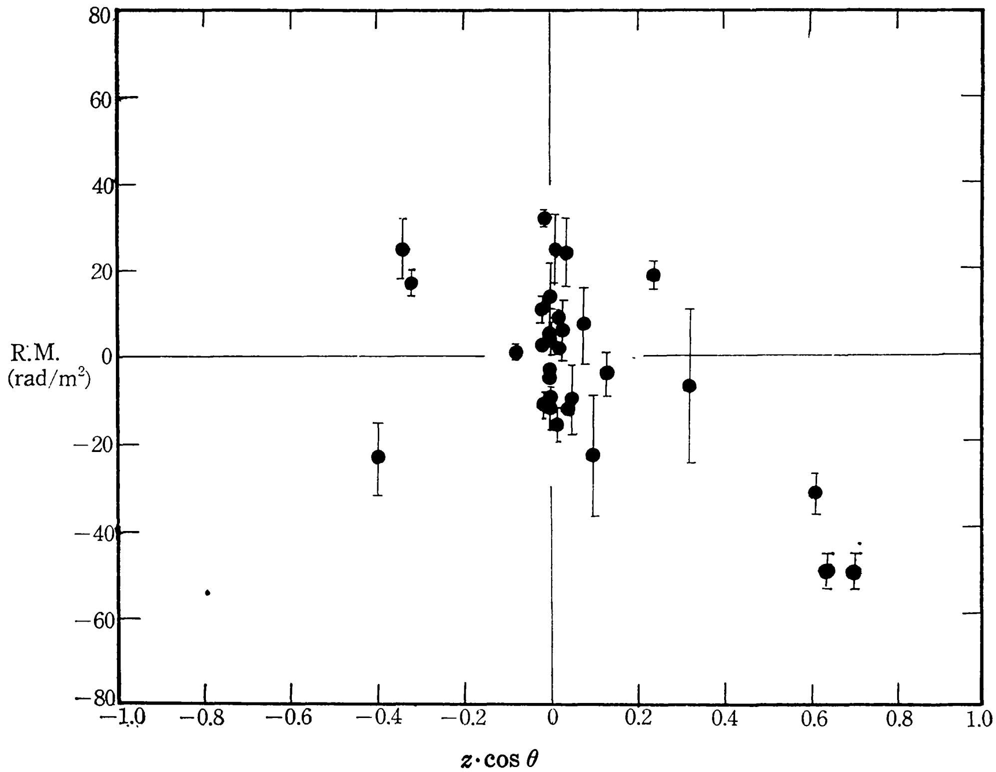

FIG. 2. Correlation between the rotation measures and $z \cdot \cos\theta$ for radio sources of $|b^{II}| \geq 35°$. The direction of the metagalactic magnetic field is assumed as $l_0^{II}=115°$ and $b_0^{II}=-5°$, in which the correlation coefficient attains its maximum value of 0.601.

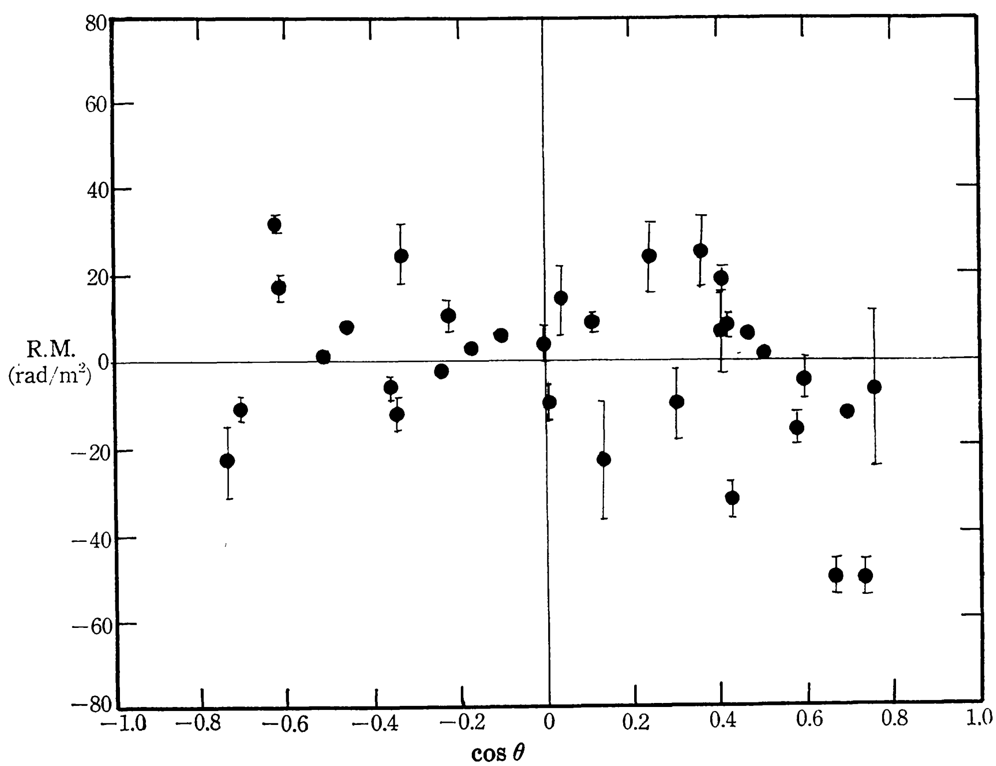

FIG. 3. Correlation between the rotation measures and $\cos\theta$ for radio sources of $|b^{II}| \geq 35°$. The value of the correlation coefficient is 0.25.

TABLE 1. Rotation Measures and Redshifts of Radio Sources.

Name of Source	l^{II}	b^{II}	R.M. (rad/m²)	z*	Ref. to z**
00-4*11*	306°.6	−75°.0	+ 2.6 ± 0.4	(0.11)	
3C 29 (b)	126.4	−64.2	+ 2 ± 1	0.045	(1)
3C 33	129.4	−49.3	−12 ± 1	0.0600	(2)
01-3*11*	261.9	−77.1	+ 5.4 ± 0.6	(0.027)	
3C 47	136.8	−40.7	− 7 ±17	0.425	(3)
3C 48	134.0	−28.7	−53 ±12	0.367	(3)
3C 62	181.4	−65.8	+24 ± 8	(0.14)	
3C 63	167.1	−56.9	+ 7 ± 9	(0.20)	
02-1*10*	201.3	−64.5	+ 9 ± 2	(0.2)	
3C 76.1	163.1	−36.0	−16 ± 4	0.0328	(1)
3C 78	174.8	−44.5	+ 8 ± 3	0.0289	(2)
3C 79	164.2	−34.5	−18 ± 3	0.2561	(2)
3C 84 (Per A)	150.6	−13.3	+55 ± 8	0.0199	(4)
For A(a)	240.1	−56.9	− 2.8 ± 0.8	0.0057	(4)
For A(b)	240.2	−56.4	− 3.5 ± 0.8	0.0057	(4)
3C 88	181.0	−42.0	+25 ± 8	0.0302	(2)
3C 98	179.8	−31.0	+74 ± 3	0.0306	(2)
3C 138	187.4	−11.3	− 4 ± 4	0.759	(5)
Pic A	251.6	−34.6	+46 ± 1	0.0353	(6)
05-3*6*	240.6	−32.7	+12 ± 2	0.055	(7)
3C 153	165.4	+13.4	−61 ±12	(0.2)	
06-3*7*	244.7	−21.9	0 ± 1	(0.07)	
06-2*10* (a)	229.9	−12.4	+48 ± 3	0.056	(7)
3C 171	162.1	+22.2	+59 ± 6	0.2387	(2)
3C 175	204.7	+10.0	+192 ± 7	0.768	(8)
3C 192	197.9	+26.4	+18 ± 2	0.0596	(9)
3C 219	174.4	+44.8	−10 ± 8	0.1745	(2)
3C 227	228.6	+42.3	− 6 ± 3	0.0855	(1)
3C 245	233.1	+56.3	+25 ± 7	1.029	(10)
3C 254	172.6	+65.9	−23 ±14	0.734	(10)
11-1*8*	277.5	+45.4	−23 ± 8	0.554	(11)
3C 270	281.8	+67.4	+ 8.4 ± 0.6	0.0070	(12)
3C 272.1	278.2	+74.5	−12 ± 5	0.0065	(12)
3C 273	290.0	+64.4	+ 1 ± 2	0.158	(3)
3C 278	304.1	+50.3	−11 ± 3	0.0143	(13)
3C 279	305.1	+57.1	+17 ± 3	0.536	(10)
Cen A	309.5	+19.4	−60 ± 2	0.0013	(14)
3C 286	56.5	+80.7	+ 4 ± 4	0.846	(10)
3C 287	22.5	+81.0	−60 ± 8	1.054	(10)
13-3*3* (a)	313.4	+28.1	−32 ± 1	(0.011)	
13-3*3* (b)	313.5	+28.0	−32 ± 1	(0.011)	
13-3*3* (c)	313.7	+27.7	−33.5 ± 1	(0.011)	
3C 310	38.5	+60.2	+14 ± 8	0.0543	(2)
3C 327	12.5	+37.8	+11 ± 3	0.1041	(2)
3C 345	63.3	+40.9	+19 ± 3	0.5940	(10)
3C 348 (Her A)	23.0	+28.9	+10 ± 4	0.1592	(15)
3C 353	21.2	+19.6	+37 ± 4	0.0307	(2)
3C 380	77.2	+23.5	+31 ± 8	0.691	(10)
3C 386	47.0	+10.0	+79 ± 8	0.008	(2)
3C 403	42.3	−12.3	−34 ± 3	(0.06)	
21-2*1*	21.4	−40.2	−10 ± 4	(0.07)	
3C 430	99.7	+ 8.0	−162 ±15	0.0167	(12)
3C 433	74.5	−17.7	−79 ± 4	0.1025	(2)
21-6*4*	321.3	−40.6	+32 ± 2	(0.023)	
3C 445	61.8	−46.7	+ 6 ± 7	0.0568	(2)

TABLE 1. (continued)

Name of Source	l^{II}	b^{II}	R.M. (rad/m²)	z*	Ref. to z**
3C 446	59°0	−48°8	−32 ± 5	1.404	(10)
CTA 102	77.4	−38.6	−50 ± 4	1.038	(10)
3C 452	98.1	−17.1	−272 ±10	0.0820	(2)
3C 454.3	86.1	−38.2	−50 ± 4	0.859	(8)
3C 459	83.0	−51.3	− 4 ± 5	0.2205	(2)
23-64	314.0	−55.1	+22 ± 2	(0.05)	

* Values in parentheses are estimated from visual or photographic magnitudes of identified galaxies. The magnitudes are due to BOLTON, CLARKE, and EKERS (1965), EKERS and BOLTON (1965), CLARKE, BOLTON, and SHIMMINS (1966), BOLTON and EKERS (1966 a, b, c, d, 1967), BOLTON, SHIMMINS, and MERKELIJN (1968), MERKELIJN, SHIMMINS, and BOLTON (1968), MERKELIJN (1968), HOWARD and MARAN (1965), and WYNDHAM (1966).

** References to z: (1) SANDAGE (1967), (2) SCHMIDT (1965), (3) SCHMIDT and MATTHEWS (1964), (4) HUMASON, MAYALL, and SANDAGE (1956), (5) LYNDS, HILL, HEERE, and STOCKTON (1966), (6) HOWARD and MARAN (1965), (7) SEARLE and BOLTON (1968), (8) SCHMIDT (1968), (9) SANDAGE (1966 b), (10) SANDAGE (1966 a), (11) BURBIDGE and BURBIDGE (1967), (12) MATTHEWS, MORGAN, and SCHMIDT (1964), (13) GREENSTEIN (1961), (14) SÉRSIC (1960), and (15) GREENSTEIN (1962).

The plottings of R.M. and $z\cdot\cos\theta$ for this direction is shown in Figure 2, where one finds graphically a remarkable correlation. A correlation coefficient larger than 0.601 in 35 data can be expected by chance only with a probability of 10^{-3}, so that we feel the correlation in Figure 2 is significant. When we take another direction ($l_0^{II}=100°$, $b_0^{II}=-30°$), we obtain a similar but a little more scattered distribution diagram of R.M. and $z\cdot\cos\theta$, whose correlation coefficient is 0.567. Note that this direction was determined as that of the metagalactic magnetic field previously by SOFUE, FUJIMOTO, and KAWABATA (1968).

In Figure 3, the rotation measures are plotted against $\cos\theta$. A large correlation can be expected also in this figure if the Faraday rotation takes place in the Galaxy and the local magnetic field is directed towards (l_0^{II}, b_0^{II}). Only slight correlation can be found in this figure and the correlation coefficient is 0.25. A correlation coefficient higher than this value in 35 data can be expected by chance with a probability of 0.15. Therefore, the correlation in Figure 2 cannot be attributed solely to the local magnetic field in the Galaxy. Thus, it must be concluded that the rotation measure for the radio source with a large redshift depends on the magnitude of the redshift as well as the direction of the source, in so far as we consider that the correlation in Figure 2 is significant.

5. *Magnetic Field and Matters in Metagalactic Space*

In the cosmological hypothesis on quasi-stellar radio sources, the correlation between rotation measures and $z\cdot\cos\theta$ implies a contribution of the uniform component of the metagalactic magnetic field to the Faraday rotation of emissions from linearly-polarized radio sources. From the correlation diagram in Figure 3, we obtain the relation

$$N_eB=2\times10^{-14}\ \text{gauss cm}^{-3}\ , \tag{1}$$

for the strength B of the large-scale metagalactic magnetic field and the density of thermal electrons N_e in the metagalactic space, by taking the Hubble constant to be 100 km sec^{-1} Mpc^{-1}. If we take the value of electron density in the metagalactic space as large as 10^{-5} cm^{-3}, the strength of the large-scale metagalactic magnetic field becomes 2×10^{-9} gauss.

Since measurements of the Faraday rotation yield only the product of the electron density and the strength of the magnetic field in the medium between the source and the observer, another clue is required for unique determination of the field strength and the electron density. It has been discussed by FELTEN and MORRISON (1966) that the observed diffuse component of X-rays is of the cosmic origin as the inverse Compton radiations from the relativistic electrons in the cosmic blackbody radiation at 2.7°K. If this is the case, the same relativistic electrons gyrate around the metagalactic magnetic field discussed so far, emitting synchrotron radiation. Therefore, we can obtain other information on the metagalactic magnetic field by combining the observed X-ray background radiation and the radio background radiation in nonthermal component.

Let the radius of the universe at cosmic age t be denoted by R, then the density of the relativistic electrons in a region of the metagalactic space, having an energy E, may be taken to have a power-law form given by

$$n(\gamma)d\gamma=K(t_0/t)^{\beta}(R_0/R)^3\gamma^{-\alpha}d\gamma\ ,$$

where

$$\gamma=E/(mc^2)\ .$$

Here the suffix "0" denotes the quantities referred to the values at the present cosmic age t_0. Other symbols have their usual meanings. In the above expression, $(t_0/t)^{\beta}$ represents the evolutionary effect of sources of relativistic electrons with still unspecified parameter β, and $(R_0/R)^3$ represents a dilution effect of relativistic electrons due to expansion of the universe.

Such electrons kick low energy photons of the cosmic blackbody radiation up to the X-ray region. The resultant volume emissivity of X-rays is given by

$$\left(\frac{dP}{d\nu d\tau}\right)_c=\frac{2}{3}\sigma_T c\left(\frac{h}{3.6k}\right)^{\frac{3-\alpha}{2}}\rho T^{\frac{\alpha-3}{2}}\nu^{\frac{1-\alpha}{2}}K\left(\frac{t_0}{t}\right)^{\beta}\left(\frac{R_0}{R}\right)^3, \qquad (2)$$

with

$$\rho=\frac{4\sigma}{c}T^4\ ,$$

where σ and σ_T represent the Stefan-Boltzmann constant and the Thomson cross-section, respectively. In the expanding universe, the temperature T of the cosmic blackbody radiation can be expressed by

$$T=T_0(R_0/R)\ ,$$

using the present temperature of the cosmic blackbody radiation, T_0=2.7°K.

The volume emissivity of synchrotron radiation due to the same relativistic electrons with the metagalactic magnetic field B is given by

$$\left(\frac{dP}{d\nu d\tau}\right)_s=0.1\frac{c}{\pi}K\sigma_T\left(\frac{4\pi mc}{3e}\right)^{\frac{3-\alpha}{2}}\nu^{\frac{1-\alpha}{2}}B^{\frac{1+\alpha}{2}}\left(\frac{t_0}{t}\right)^{\beta}\left(\frac{R_0}{R}\right)^3. \qquad (3)$$

Here, strength of the metagalactic magnetic field is assumed to vary as $B_0(R_0/R)^2$

in the expanding universe.

From equations (2) and (3), and by making use of the Robertson-Walker metric,

$$ds^2=dt^2-\frac{R^2(t)}{c^2}\frac{1}{\left(1+\frac{\kappa}{4}r^2\right)^2}\{dr^2+r^2(d\theta^2+\sin^2\theta d\varphi^2)\},$$

one obtains the fluxes of the background radiation at the earth in the X-ray and radio-wave regions, ν_X and ν_R, as

$$j_X(\nu_X)=J_X\nu_X^{\frac{1-\alpha}{2}}\int_{t_e}^{t_0}\left(\frac{t_0}{t}\right)^\beta\left(\frac{R_0}{R}\right)^3 dt\ .$$

and

$$j_R(\nu_R)=J_R\nu_R^{\frac{1-\alpha}{2}}\int_{t_e}^{t_0}\left(\frac{t_0}{t}\right)^\beta\left(\frac{R_0}{R}\right)^{\frac{3+\alpha}{2}} dt\ .$$

Here, the constants J_X and J_R are given by

$$J_X=\frac{2}{3}\frac{c}{4\pi}K\sigma_T\sigma\left(\frac{h}{3.6kT_e}\right)^{\frac{3-\alpha}{2}}\rho_0\ ,$$

and

$$J_R=0.1\frac{c}{4\pi}K\sigma_T\left(\frac{4\pi mc}{3e}\right)^{\frac{3-\alpha}{2}}B_0^{\frac{1+\alpha}{2}}\ ,$$

and t_e is the cosmic age at which the expanding universe starts to be transparent against X-rays and non-thermal radio waves emitted by the relativistic electrons.

Taking the ratio of j_R and j_X, we obtain

$$\frac{j_X}{j_R}=\frac{J_X}{J_R}\eta(m,\beta)\left(\frac{\nu_X}{\nu_R}\right)^{\frac{1-\alpha}{2}}, \tag{4}$$

where

$$\eta(a,\beta)=\int_{t_e}^{t_0}(t_e/t)^\beta(R_0/R)^3dt\Big/\int_{t_e}^{t_0}(t_0/t)^\beta(R_0/R)^{\frac{3+\alpha}{2}}dt\ . \tag{5}$$

Since we have a good approximate relation, $R(t)\propto t^{2/3}$, for various models of the expanding universe, equation (5) is written as

$$\eta(\alpha,\beta)=\frac{\alpha+3\beta}{3(\beta+1)}\frac{(t_0/t_e)^{1+\beta}-1}{(t_0/t_e)^{(3+\alpha)/2}-1}\ .$$

Observations of the X-ray spectrum in the diffuse component give $(1-\alpha)/2=-0.8$ or $\alpha=2.6$ (BLEEKER, BURGER, DEERENBERG, SCHEEPMAKER, SWANENBURG, TANAKA, HAYAKAWA, MAKINO, and OGAWA, 1968). The numerical values of t_0/t_e and β are to be determined by the opacity of the universe and the evolution of relativistic electron sources which are still in controversy. However, as is shown numerically in Table 2. $\eta(2.6,\beta)$ is insensitive to these values. Therefore, it is not necessary to be so concerned about the evolutionary effect of relativistic electron sources and the exact value of t_e/t_0.

TABLE 2. Numerical Values of $\eta(2.6, \beta)$ for Various Combinations of β and t_0/t_e.

t_0/t_e \ β	0	2
10	1.2	1.3
30	1.4	1.5

Thus, the ratio (4) becomes

$$\frac{j_X}{j_R}=(9.3\sim11.6)\times10^{-13}B_0^{-1.8}\left(\frac{\nu_X}{\nu_R}\right)^{-0.8} . \tag{6}$$

The X-ray intensities j_X in diffuse component have been observed by rockets to be 2.4×10^{-26} erg cm^{-2} sec^{-1} str^{-1} Hz^{-1}, for example, at $h\nu_X$=6 kev (BLEEKER et al. 1968). The brightness temperature of the background radio emissions at 178 MHz is 80°K in the direction of minimum temperature (TURTLE and BALDWIN 1962). Therefore, we can put an upper limit of the radio intensities at 178 MHz as 2×10^{-19} erg cm^{-2} sec^{-1} str^{-1} Hz^{-1} for the metagalactic synchrotron background radiations, corresponding to a brightness temperature of 20°K.

Then we can obtain an upper limit of the metagalactic magnetic field as small as 2×10^{-8} gauss from equation (6). This value of the upper limit of the strength of the metagalactic magnetic field gives a lower limit of the density of thermal electrons in the metagalactic space as large as 10^{-6} cm^{-3}, by using equation (1). The lower limit of the density of the thermal electrons in the metagalactic space implies that the mass density in the meta- galaetic space is higher than 1.7×10^{-30} gr cm^{-3}, being about 6 times as large as OORT's (1958) value of the density of visible matter, 3×10^{-31} gr cm^{-3}, in the universe.

6. *Discussion and Conclusions*

SOFUE, FUJIMOTO, and KAWABATA (1968) have mentioned a difference on distributions of the rotation measures in galactic coordinates between radio sources with large redshifts and those with small redshifts. The difference is most conspicuous in a region located near $l^{\rm II}=100°$, $b^{\rm II}=-30°$. The rotation measures in this region have small positive values for the radio sources having redshifts less than 0.1 and they become large positive values for the radio sources having redshifts larger than 0.1. The difference on the distributions of the rotation measures occurs, although not so clear, also in a region near $l^{\rm II}=280°$, $b^{\rm II}=30°$, which is located in a direction opposite to the above-mentioned region. The disagreement indicates that the rotation measure of a radio source depends not only on the direction of the source but also on the redshift of the source. As a model that can explain this feature on the distribution of the rotation measure, SOFUE, FUJIMOTO, and KAWABATA (1968) have suggested a metagalactic magnetic field directed towards $l_0^{\rm II}=100°$, $b_0^{\rm II}=-30°$.

As is shown in Section 3, scatters (standard deviations) in rotation measures are small for the radio sources with redshifts less than 0.2 and large for radio sources with redshifts larger than 0.2 at intermediate and high galactic latitudes. The difference in scatters of the rotation measures confirms the early conclusion that the rotation measure depends not only on the direction of the source but also on the redshift of the source.

The correlation diagram in Figure 2 is another evidence on the redshift dependence of the rotation measure. As is already mentioned, the correlation between the rotation measure and $z\cdot\cos\theta$ implies, in the cosmological hypothesis on quasi-stellar radio sources, a contribution of the uniform component of the metagalactic magnetic field to the Faraday rotation of emissions from linearly-polarized radio sources. The largest value of the redshift for the sources used in the present investigation is 1.403, and then the large-scale metagalactic magnetic field is approximately uniform at least up to a distance of this order of z. Although observational data are meager for a precise determination of the direction of the large-scale metagalactic magnetic field at the present time, a possible direction of this component is determined as $l_0^{\text{II}}=115°$, $b_0^{\text{II}}=-5°$, after searching for a maximum correlation between R.M. and $z\cdot\cos\theta$.

When we subtract the contribution of the metagalactic magnetic field from the observed rotation measures in Table 1, we can build a distribution map of the net rotation measures in the Galaxy (Figure 4). Comparing Figure 4 with the distributions of the rotation measures of GARDNER and DAVIES (1966), BERGE and SEIELSTAD (1967), and GARDNER, WHITEOAK, and MORRIS (1967), we find that the anomalous region of the negative rotation measures near $l^{\text{II}}=75°$, $b^{\text{II}}=-40°$ vanishes in Figure 4. However, no drastic changes are found between them,

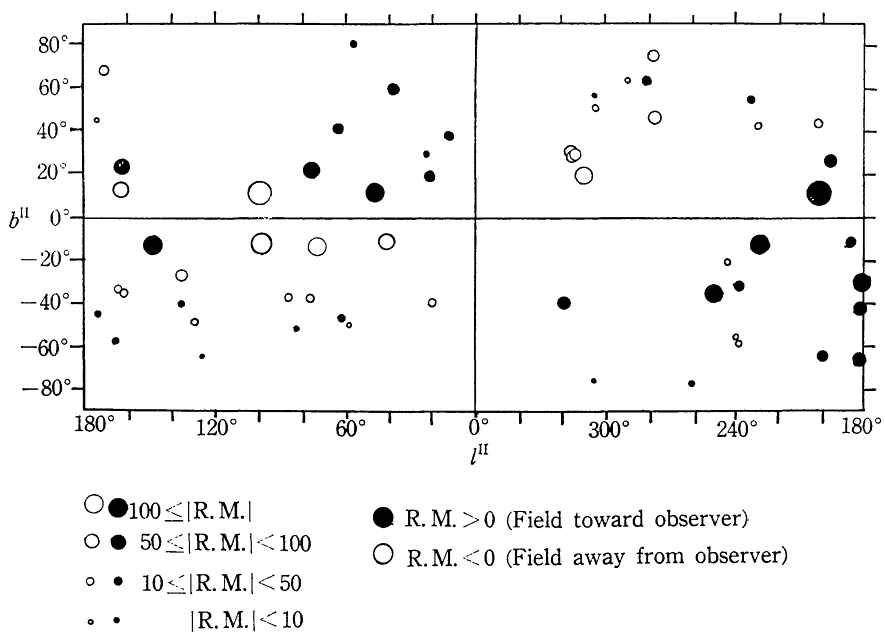

FIG. 4. Distribution of the net rotation measures in galactic coordinates. Contribution from the metagalactic magnetic field is subtracted from the observed rotation measures listed in Table 1. Filled and open circles correspond to the cases of positive (field toward the observer) and negative (field away from the observer) rotation measures, respectively. Their area roughly indicate the absolute magnitudes of the rotation measures.

and the original features of a large-scale order imposed on the distributions of rotation measure in galactic coordinates are still valid.

So far we have assumed that the redshift is of cosmological origin. It seems necessary now to discuss the local hypotheses on quasi-stellar objects from our present results. Even in local hypotheses on quasi-stellar objects, large redshift may imply large distance in some theory (see, e.g., KAHN and PALMER 1967), and then the correlation diagram in Figure 2 could be explained. For instance, quasi-stellar objects could be regarded as being ejected out of the Galaxy or some nearby galaxies with extremely high velocity comparable to the light-velocity. If a sufficient time is elapsed after the ejection, all objects could be observed to have redshifts by the Doppler effect. The objects with the larger redshifts are, therefore, the farther from us.

Some radio sources in Figure 2 are optically identified with galaxies and their redshifts are believed to be of the cosmological origin. The maximum value of the redshift for such radio sources may be taken as $z=0.1$, corresponding to a distance of 300 Mpc. As is shown in Table 1 and in Figure 2, the rotation measures for these radio sources are small compared with quasi-stellar radio sources with large redshifts, e.g., $z=1$, and the redshifts of the identified galaxies and the quasi-stellar radio sources seem of the same origin. Therefore, the quasi-stellar radio source must be located at a distance larger than 300 Mpc ($z\sim0.1$). Since the lower limit of the distance for quasi-stellar radio sources is the same order of magnitude as the cosmological distance, the correlation between the rotation measure and $z\cdot\cos\theta$ is in favor of the cosmological hypothesis of the quasi-stellar objects.

The correlation between rotation measures and $z\cdot\cos\theta$ gives a serious difficulty against other local hypotheses such as the hypothesis of the gravitational redshift, because a large redshift does not imply a large distance in such a theory.

The large scale metagalactic magnetic field is directed nearly parallel to the plane of the supergalaxy.* The large-scale metagalactic magnetic field, however, extends up to a distance of $z=1.4$, far beyond the scale of the supergalaxy of 30 Mpc. Then the large scale metagalactic magnetic field cannot be considered to have an origin in the supergalaxy.

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* Sakashita and Kaneko have pointed out in private communication that our previously-determined direction of the large scale metagalactic magnetic field ($l_0^{II}=100°$, $b_0^{II}=-30°$) is in the plane of the supergalaxy.

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