ROTATION MEASURES AND COSMOLOGY

Philipp P. Kronberg
Max-Planck-Institut für Radioastronomie, Bonn, F.R.G. and
Scarborough College, University of Toronto, Canada

1. FARADAY ROTATION IN AN INTERGALACTIC MEDIUM

1.1 General remarks

The very low upper limits on distributed intergalactic (i.g.) HI (Gunn and Peterson 1965, Wampler 1967), and H_2 (Field et al. 1966) have made it clear for some time now that if a smooth distributed i.g. gas exists in significant amounts ($\Omega_{ig} \gtrsim 10^{-3}$), it must be ionized. X-Ray emission from rich clusters of galaxies such as Coma, indeed show that an intracluster gas can be seen (cf. Field 1974). Also persuasive in this connection are the head-tail radio galaxies in clusters, whose prototype is NGC 1265 (Miley et al. 1972, Jaffe and Perola 1973).

The use of Faraday rotation data to test for i.g. gas has the advantage that it is insensitive to the temperature of a non-relativistic ionized gas (unlike the X-ray emission), and the disadvantage that we are measuring only the product $nB_{||}$ since a magnetic field is also required. The rotation measure due to an intergalactic magneto-ionic medium (RM_{ig}) can be written in its most general form as follows:

$$RM_{ig} = C \int_0^{z_s} \frac{n(z)\, B_{||}(z)}{(1+z)^2}\, dr(z) \qquad (1.1)$$

where z_s is the redshift of the source, $n(z)$ and $B_{||}(z)$ are the average values of electron density and line-of-sight component of magnetic field respectively, and C is a constant. If the local values of n and $\underset{\sim}{B}$ increase as

$$n(z) = n_0 (1+z)^3 \qquad (1.2)$$

$$|\underset{\sim}{B}(z)| = |\underset{\sim}{B}_0| (1+z)^2 , \qquad (1.3)$$

where n_0 and B_0 are the present-epoch values (B is assumed to decrease adiabatically as the universe expands), then the sharp increase of $nB_{||}$

D. L. Jauncey (ed.), Radio Astronomy and Cosmology, 367-377. All Rights Reserved.

overcomes the watering down effect of the Doppler shift ($\alpha(1+z)^{-2}$ — see eq. 1.1). Under these conditions our sensitivity to an intergalactic magneto-ionic medium improves with increasing redshift. It will be noted that our simple assumptions in 1.2 and 1.3 ignore accretion to galaxies or protogalaxies over the redshift range investigated — i.e. no local evolution up to the maximum look-back time. One might alternatively assume that the density of intergalactic gas clouds is determined by local gravity rather than the cosmological scale factor (cf. Rees and Reinhardt 1972), in which case the average values of n and $\underset{\sim}{B}$ are independent of z (again ignoring evolution).

Two basic kinds of intergalactic magnetic field may be envisaged — a uniform, aligned primordial field, and a turbulent, random i.g. field which changes on the scale of i.g. gas clouds or smaller. Since the effect of each case on the observed rotation measures is different, we shall discuss them separately below, and briefly review previous attempts using RM data to detect an intergalactic RM.

1.2 Effect of an aligned, primordial magnetic field associated with an early phase of the universe

The possibility of such a field has been discussed by Woltjer (1965) and Zel'dovich (1965). Given the presence of an intergalactic plasma we would see a prevailing component of rotation measure (RM_p) whose intensity would vary with direction and redshift in a Friedmann universe with zero cosmological constant as follows

$$RM_p(\theta,z) = \frac{e^3 B_{p_o} n_o \cos\theta}{H_o \cdot 2m_e^2 c^3 q_o^2} \left\{ (1+2q_o z)^{3/2} + (6q_o - 3)(1 - 2q_o z)^{1/2} + (2 - 6q_o) \right\} \tag{1.4}$$

(Brecher and Blumenthal 1970), where n_o, B_{p_o} are the local values of electron density and prevailing field, θ the angle between the line of sight and the primordial field direction, m_e, e the electron mass and charge and c the velocity of light. Plots of RM_p (Figure 1) show that the prevailing component of RM increases with redshift, given the assumptions of (1.2) and (1.3).

Sofue et al. (1968) and Kawabata et al. (1969) have interpreted earlier RM data as supporting the existence of a large-scale magnetic field, whereas Reinhardt (1972), Vallée (1975), and I (1976, unpublished) using successively larger RM data sets have concluded that there is no positive evidence for such a field. Any large scale asymmetry in the distribution of rotation measures on the sky due to a primordial field has to be disentangled from similar variations on a large angular scale due to Faraday rotation in the Galaxy. This separation is difficult to make. Ideally we could test for B_p by comparing the redshift dependence of the mean rotation measure for separate directions in the sky. Unfortunately, a three-dimensional subdivision of the limited RM sample (e.g. l, b, z) for highly redshifted QSO's

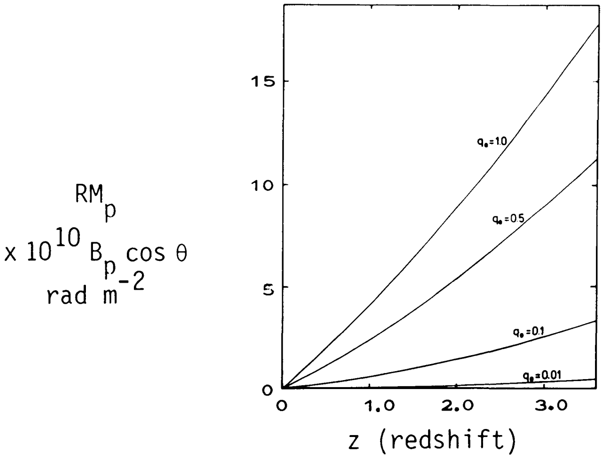

Figure 1. The variation of intergalactic rotation measure with redshift in the presence of a uniform i.g. gas and a primordial magnetic field aligned over $z \lesssim 3.5$ in a Friedmann universe.

drives us into the unhappy realm of small-number statistics. We shall need to have a larger and more homogeneous sample of RM data in order to conduct a sensitive test for any primordial magnetic field which is uniform over scales of up to $z \sim 3$.

1.3 Faraday rotation in a random, intergalactic magneto-ionic medium

In this case a polarized radio wave performs a random walk in Faraday depth as it traverses independent cells of $n_i\ B_{\parallel i}\ l_i$ (cf. Rees and Reinhardt 1972, Nelson 1973). This will cause a redshift dependence of the scatter, or variance of the distribution of rotation measures of extragalactic radio sources. Using a sample of sources in which $\sim$ 12 had $z > 1$, Mitton and Reinhardt (1972) found a systematic decrease with redshift in the RM scatter: Nelson (1973), whose data included 8 sources having $z > 1.1$, found the variance ($V(z)$) of RM to increase with redshift, and Vallée (1975) using the RM list of 251 sources of Vallée and Kronberg (1975) (of which 21 have $z > 1$) found no significant redshift-dependent effect. A more recent analysis by myself and M. Simard-Normandin (1976) will be described in §2. Before doing this, I shall briefly describe two simple intergalactic medium models in a Friedmann universe with zero pressure and zero cosmological constant ($\Lambda = 0$).

In the first case (model 1) we assume that the average values of $n(z)$ and $B_{\parallel}(z)$ scale according to (1.2) and (1.3) as before, and that the cell size, $l(z)$, also follows the cosmological scale factor $R(t)$, and that the number of cells to a distant QSO is large. Kronberg, Simard-Normandin and Reinhardt (1976) have shown that the variance $V(q_0,z)$ of RM can be expressed as

$$V(q_o,z) = 9.4 \times 10^{11}\ l_o\ \eta^2\ q_o^2\ H_o^3\ |B_{\|o}|^2 \left[\int_o^{z_s} (1+z)^{3/2} (1+2q_o z)^{-1/4} dz\right]^2 \mathrm{rad}^2\, \mathrm{m}^{-4}\ , \qquad (1.5)$$

where z_s is the source redshift, η the fraction of matter in the form of intergalactic ionized gas (assumed here to be 100% hydrogen and independent of epoch), H_o (km s^{-1} Mpc^{-1}) the Hubble constant, and l_o (Mpc), $|B_{\|o}|$ (gauss) the average zero-epoch values of cell size and magnetic field. The cells are assumed in this case to be contiguous, that is l_o represents both the average size and separation of the clouds.

In the second model, (2), the values of $n\ B_{\|}$ and r the cell radius are assumed independent of cosmological epoch; only the average separation scales as R(t). The variance in this case is given by

$$V(q_o,z) = 9.4 \times 10^{11}\ l_o\ |B_{\|o}|^2\ f_1^{2/3}\ \eta^2\ q_o^2\ H_o^3 \left[\int_o^{z_s} (1+z)^{-2} (1+2q_o z)^{-1/4} dz\right]^2 \mathrm{rad}^2\, \mathrm{m}^{-4} \qquad (1.6)$$

(Kronberg et al. 1976). For this model, the Faraday rotating cells must occupy only a fraction, f_1, of i.g. space, so that they do not overlap up to the maximum redshift, i.e. $f_1 < (1+z_s)^{-3}$.

Figure 2 shows plots of V(z) for different q_o values. In model 1 (equation 1.5) the variance (solid lines) increases rapidly with redshift, and hence also the prospects for detecting an intergalactic medium. A plot of the solution of V(z) for model 2 for $q_o = 0.5$ on the other hand shows that if this more aptly represents the true intergalactic medium the variance is relatively insensitive to redshift above $z \simeq 1$. It is also important to note that, for a given q_o, the variance increases as l_o in both models, and is a sensitive function of H_o, η and $|B_{\|}|$.

2. NEW EVIDENCE ON THE ORIGIN OF ROTATION MEASURE

2.1 The relative galactic and extragalactic contributions

It has been well established that the interstellar medium imposes a systematic variation of RM in (l,b) coordinates (Gardner and Davies 1966, Gardner, Morris and Whiteoak 1969, Mitton 1972, Vallée and Kronberg (1975). The extragalactic contribution has been commonly thought

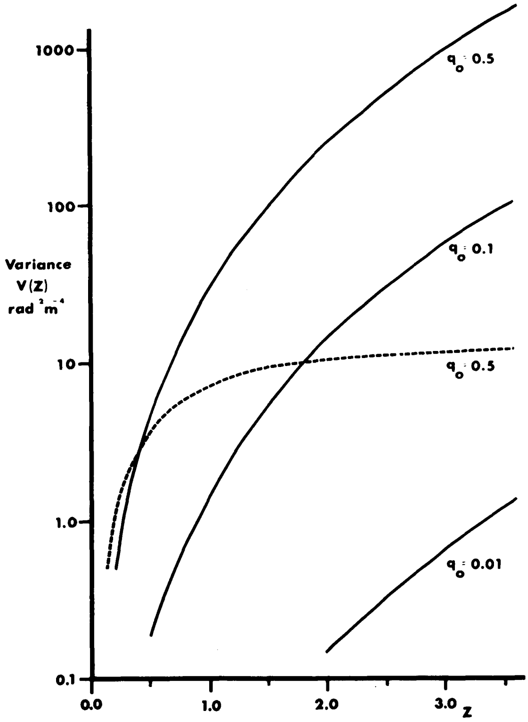

Figure 2. The calculated variation of V(z) for models 1 (solid lines) and 2 (dashed line) over the redshift range $0 < z < 3.6$. The following values were assumed: $B_0 = 1.8 \times 10^{-8}$ gauss, $\eta = 1$, $H_0 = 75$ km s^{-1} Mpc^{-1}, $l_0 = 1$ Mpc, and $f = 1/64$ for model 2. Model 1 is shown for q_0 $(= \Omega/2)$ values of 0.5, 0.1 and 0.01.

to be small; $\lesssim 10$ rad m^{-2}. From more recently published data I have assembled a list of 450 rotation measures, which is substantially larger than any sample previously available. I shall briefly summarize the results of an examination of the new data, which shed some new light on the nature of the extragalactic contribution to RM (Kronberg and Simard-Normandin 1976).

2.2 A revised interpretation of the RM data

When we compare the RM distributions of the 450 sample at high and low $(|b| \gtrless 30^o)$ galactic latitudes (Fig. 3), we see that the fraction of very large RM's (> 200 rad m^{-2}) is to first order independent of galactic latitude (compare Figs. 3(a) and (b)), whereas the very small RM's (< 25 rad m^{-2}) occur almost exclusively at the high latitudes. Comparison of the distributions in Fig. 3(a) and (b) (see especially the insets) shows that the effect of the galaxy is to "smear out" the sharp peak near $|RM| = 0$, but only to ~ 120 rad m^{-2} at most. It is very likely that the galactic RM commonly exceeds this limit at

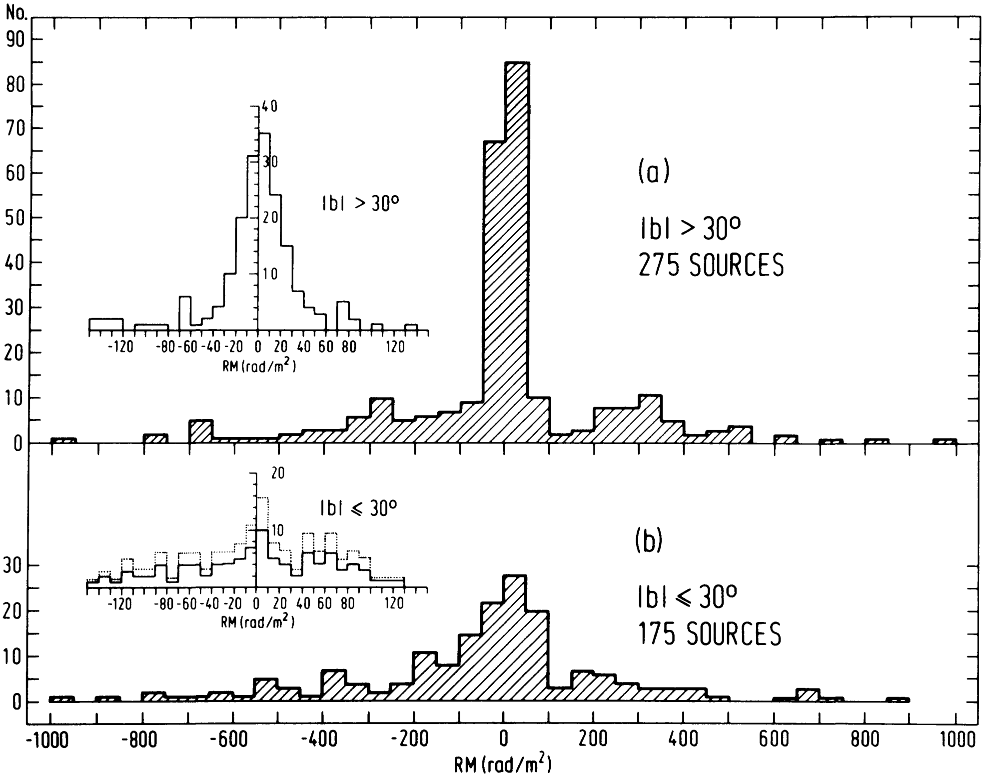

Figure 3. Histograms showing the distribution of the rotation measures for (a) $|b| > 30^\circ$ and (b) $|b| < 30^\circ$. The insets show the central peaks with intervals of 10 rad m^{-2}. The dotted profile in (b) shows the same distribution scaled by 275/175 for comparison with that in (a). (Reproduced from Kronberg, P.P. and Simard-Normandin, M., Nature 263, 653, 1976.)

very low latitudes ($|b| \lesssim 5^\circ$), however our sample contains too few sources at $|b| < 5^\circ$ to reliably test the galactic contribution in this region. Figure 3 is instructive, and leads us to some new and interesting conclusions. The first is that at $|b| \gtrsim 5^\circ$, the very large RM's ($\gtrsim 200$ rad m^{-2}) must be produced outside of the galaxy, since the fraction of sources with $|RM| > 200$ is independent of path length through the galactic disc. It follows that the galactic contribution to RM is usually less than ~ 120 radians in the range $5^\circ < |b| < 30^\circ$, and very much smaller at the higher latitudes. The distribution for $|b| > 30^\circ$ (Fig. 3(a)) therefore closely approximates the distribution of extragalactic RM's. This brings me to the third conclusion, namely that there appear to be two quite distinct RM populations; those with very low extragalactic RM which I shall call class I which form the narrow peak in Fig. 3(a), and a class II with RM $\gtrsim 120$ rad m^{-2} which is largely extragalactic in origin.

The separation into class I and class II RM's is both good and bad for the purpose of analysing their origin. For the galaxy it is good, in that by simply omitting all RM's > 150 rad m^{-2} the galactic contribution can be seen more clearly than hitherto. For our present purpose, the existence of class II (high extragalactic RM) tends to raise the level at which we can expect to see an intergalactic contribution.

Kronberg and Simard-Normandin (1976) have investigated the variance of RM with redshift for 108 of the 450 which are QSO's of known redshift up to $z \simeq 2.5$. The variances (after removing the galactic contribution) are $3 - 6 \times 10^4$ rad^2 m^{-4}, and we detected no convincing redshift dependence of V(z). We repeated the investigation for a control sample of 90 radio galaxies over their (much smaller) range of z. The variances again showed no clear z-dependent variation, furthermore collectively they are indistinguishable from those of the more distant QSO's. Although the samples are different, this result suggests that the large RM's are not a sensitive function of intergalactic path length and must be generated around or in the sources themselves. This result is not entirely surprising (it was also surmised by Reinhardt (1972)), in that the very rapid depolarization rates in some sources suggest *a priori* an associated large RM at the source. However an attempt to correlate depolarization rate and RM shows a poor correlation. If we could succeed in isolating class I sources by some independent measured parameter (e.g. surface brightness or source size), it is clear that this class of source would make a much more sensitive probe of intergalactic Faraday rotation than the present total sample of QSO's.

2.3 Application of the RM data to i.g. medium models

When we compare the formal variances of various sub-groups of our sample of 108 QSO RM's we can place an approximate upper limit of 1×10^4 rad^2 m^{-4} on any systematic increase of V(z) over the range $0 < z < 2.5$. This, for $q_0 = 0.5$ and $z = 2.5$, gives an upper limit for model 1 of $\eta\, n_0 |B_{||_0}|\, l_0^{\frac{1}{2}} \lesssim 2.4 \times 10^{-13}$ gauss cm^{-3} $Mpc^{\frac{1}{2}}$ which is only a factor of 4 above the value of 6.3×10^{-14} gauss cm^{-3} $Mpc^{\frac{1}{2}}$ which corresponds to the curve for $q_0 = 0.5$ (model 1) in Figure 2. The present data can rule out a model 1 - type i.g.m. in which $q_0 = 1$, $l_0 = 10$ Mpc and $|B_{||_0}| = 5 \times 10^{-8}$ gauss, and $\eta = 0.8$. On the other hand if model 2 is more nearly correct, the RM data are much too insensitive (by 2 or more orders of magnitude in the variance) to detect an i.g. medium.

Ignoring the formal variances discussed above we can also test for the presence of a sub-group of high-z QSO's with very small RM's — by analogy with Class I in Figure 3(a). Figure 4 shows the distributions of residual RM (RRM) for the QSO's after subtracting the galactic contribution, and that there may be such a sub-group visible at high z. The numbers in this sample are too small to give reliable results, but if more data were to reveal the presence of the class I component (Fig. 3a) over $0 < z < 2.5$ our sensitivity to i.g. rotation

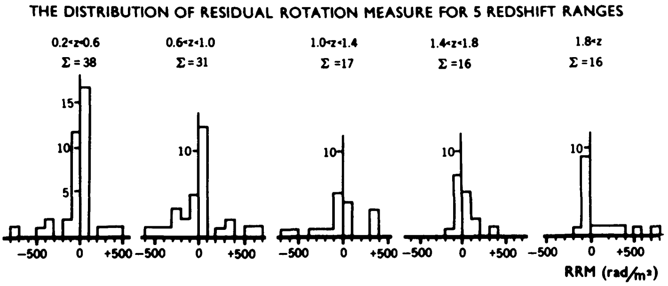

Figure 4. Histograms showing the distribution of the residual rotation measures (RRM) for 5 equal redshift intervals beginning at z = 0.2. (Kronberg, P.P. and Simard-Normandin, M., Nature 263, 653, 1976.)

measure would improve by at least an order of magnitude and provide a much more stringent upper limit on the quantity $(q_0 \eta |B_{\|_0}| l_0^{1/2} H_0^{3/2})$.

Finally I should remark that in our model 1 we did not assume clumping of the i.g. gas. If the i.g. gas clumps conserving mass and magnetic flux, the variance increases as f_2^{-2} where f_2 is the volume filling factor. In other words, one can make plausible versions of models 1 and 2 in which the same mass of i.g. HII clouds can produce a larger Faraday rotation.

3. CONCLUDING REMARKS

We have shown that most of the source-to-source scatter in the RM of extragalactic sources is produced at or in the sources themselves, and that the contribution by the galaxy or intergalactic Faraday rotating clouds is usually small by comparison. This makes it difficult to look for variations of V(z) unless class I type can be independently isolated, in which case they would constitute a sensitive probe for an intergalactic medium. RM data on QSO's may in the near future provide an important test for intergalactic matter and on the deceleration parameter.

I wish to thank the Alexander von Humboldt-Foundation (Federal Republic of Germany) and the National Research Council of Canada for support of this work.

REFERENCES

Brecher, K.I. and Blumenthal, G.R. 1970, Astrophys. Letters 6, 169
Field, G.B. 1974, IAU Symp. No. 63 "Intergalactic Gas", p. 13
Field, G.B., Solomon, P.M. and Wampler, E.J. 1966, Astrophys. J. 145, 351
Gardner, F.F. and Davies, R.D. 1966, Australian J. Phys. 19, 129
Gardner, F.F., Morris, D. and Whiteoak, J.B. 1969, Australian J. Phys. 22, 813
Gunn, J.E. and Peterson, B.A. 1965, Astrophys. J. 142, 1633
Jaffe, W.J. and Perola, G.C. 1973, Astron. Astrophys. 26, 423
Kawabata, K., Fujimoto, M., Sofue, Y. and Fukui, M. 1969, Publ. Astron. Soc. Japan 21, 293
Kronberg, P.P. and Simard-Normandin, M. 1976, Nature 263, 653
Kronberg, P.P., Simard-Normandin, M. and Reinhardt, M. in preparation
Miley, G.K., Perola, G.C., van der Kruit, P.C. and van der Laan, H. 1972, Nature 237, 269
Mitton, S. 1972, Monthly Notices Roy. Astron. Soc. 155, 373
Mitton, S. and Reinhardt, M. 1972, Astron. Astrophys. 20, 377
Nelson, A.H. 1973, Publ. Astron. Soc. Japan 25, 489
Rees, M.J. and Reinhardt, M. 1972, Astron. Astrophys. 19, 189
Reinhardt, M. 1972, Astron. Astrophys. 19, 104
Sofue, Y., Fujimoto, M. and Kawabata, K. 1968, Publ. Astron. Soc. Japan 20, 388
Vallée, J.P. 1975, Nature 254, 23
Vallée, J.P. and Kronberg, P.P. 1975, Astron. Astrophys. 43, 233
Wampler, E.J. 1967, Astrophys. J. 147, 1
Woltjer, L. 1965, "The Structure and Evolution of Galaxies" (Interscience, New York)
Zel'dovich, Ya.B. 1965, Soviet Phys. JETP 21, 656

DISCUSSION

Conway: The z-dependent variance of rotation measure in your "narrow peak" is equivalent to $[3 \text{ rad m}^{-2}]^2$. In other words, sources at z = 2.5 suffer rotation measure equal to one tenth of that imposed by the Milky Way. This seems to argue rather strongly against absorption in quasars being due to intervening galaxies, unless these are unusual, or else exactly face-on.

Goldstein: How many frequencies go into a typical Faraday rotation measurement?

Kronberg: The average is about 5.5 different frequencies, but it is never less than 4.

THE POLARIZATION OF 3C123 AND 3C427.1

R.G. Strom

P.P. Kromberg and I have made high resolution studies of the luminous radio galaxies 3C123 and 3C427.1 with the NRAO interferometer at 8085 MHz and the Westerbork telescope at 4995 MHz. Both objects, which appear to be very distant (for 3C123, z=0.637), have an integrated degree of polarization which drops very rapidly with increasing wavelength. The 8085 MHz map of 3C123 shows a weak radio bridge extending from the more compact component to the edge of the optical galaxy. At both frequencies we find no emission from the galaxy itself stronger than 0.1 Jy, which combined with the 15 GHz flux density of 0.1 Jy reported by G. Pooley suggests $\alpha \geqslant 0$, much flatter than any other emission within the source.

At 4995 MHz, our good sensitivity to extended emission reveals structure well south of, and connected with, the high brightness component. This gives an overall size of nearly 1' arc, or a linear extent of 320 kpc (90=0.1, H_o=75 kms^{-1} Mpc^{-1}). Comparing the polarization structure in the two maps when convolved to the same resolution, we find the projected magnetic field is directed along the axis of the extended component. Changes in rotation measure exceeding 400 rad m^{-2} along the component can be explained by the projection of a unidirectional magnetic field running from one end of the component to the other. In 3C427.1 we also observe rotation measure changes exceeding 200 rad m^{-2}. Radio emission from the optical galaxy associated with 3C427.1 does not exceed 1% of that from the outer components.

McEllin: C.J. Jenkins and I have been working on the classification of a complete sample of sources in terms of the proportion of flux density coming from 'hot spots'. We find a strong tendency for high luminosity sources to have very prominent hot spots and weak or non-existent bridges, and, as Strom suggests, this is also the case for the unidentified sources. The population of unidentified objects is in fact very similar to the population of identified sources with powers at 178 MHz greater than 5×10^{26} W $\mathrm{Hz}^{-1}\mathrm{sr}^{-1}$, and quite different from the population of objects with powers less than this. We conclude that most of the unidentified objects must be at redshifts larger than about 0.5.

INTERGALACTIC FARADAY ROTATION

Yoshiaki Sofue

Statistical analyses are made of Faraday rotation measures RM and redshifts z of extragalactic radio sources. Correction for local contribution from the galactic disk has been made by using the polarization data of pulsars. Absolute magnitude of RM of extragalactic sources increases with redshift. A correlation coefficient r between the corrected RM and $z \cdot \cos\theta$ is calculated for various assumed directions (l_o, b_o) of a uniform intergalactic magnetic field, where θ denotes an angle between the source direction and the field direction. The correlation coefficient attains its maximum of r=0.65 for 30 sources with $z > 1.0$, when the field is assumed to run toward $(l_o, b_o) \cong (64^o, 12^o)$. Whereas the maximum correlation coefficient for sources with $z < 1.0$ is only 0.12. These facts indicate the existence of Faraday effect due to a large scale and ordered magnetic field, uniform at least up to $z \cong 2$. The uniform field is of strength of $\sim 10^{-9}$ gauss, if the intergalactic electron density is $10^{-5}\mathrm{cm}^{-3}$.

If we take into account the effect of the space curvature and its evolution in a Friedmann universe, we may be able to get a better fit to the observed RM than by using the straight line fitting. In fact, we have discussed magnetic field configurations which may occur in a Friedmann universe when there is no electric current, and have further derived theoretical expressions for the Faraday rotation measure of distant objects in the Friedmann universes (open, flat and closed), assuming that the field lines are geodesics. These expressions are then used to determine the deceleration parameter q_o by use of the χ^2 - fitting method for the observed RM of distant QSOs $(z > 1.0)$. The best χ^2 fit was obtained for $q_o \gtrsim 1$, suggesting a closed universe, although the conclusion may be rather tentative because the amount of data seems not yet sufficient.

[References: SOFUE, Y., FUJIMOTO, M. and KAWABATA, K. 1976, submitted to Publ. Astron. Soc. Japan; and GAFFET, B. and SOFUE, Y. 1976, submitted to Publ. Astron. Soc. Japan]