Faraday Rotation by Metagalactic Magnetic Field

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Abstract

Evidence for the existence of metagalactic magnetic field is presented from Faraday rotations observed in distant extragalactic radio sources. Correlation of the rotation measure with magnitude of redshift is investigated for forty radio sources. Signs of the rotation measure near a region A in the sky ($l^{\rm II}\approx 100°$, $b^{\rm II}\approx -30°$) are positive for the radio sources with $z<0.1$, and they become negative for those with $z\geq 0.1$. This pattern is reversed near another region B ($l^{\rm II}\approx 290°$, $b^{\rm II}\approx 30°$). The reversal of the sense of rotation measure for distant radio sources indicates that there is a considerable contribution of metagalactic magnetic field to Faraday rotation. The metagalactic magnetic field seems to run in the direction B to A. The field strength is calculated as 10^{-9} gauss if we assume an intergalatic electron density of $n_e=10^{-5}$ electrons/cm^3. The rotation measures have a weaker correlation with the galactic latitude, which also supports the present conclusions for the sources with $z\geq 0.1$.

It is suggested that observation of Faraday rotation on radio sources at very large distance may lead to the determination of world model.

Rotation measures of Faraday rotation have been determined for many extragalactic radio sources by observing linear polarization over a range of wavelengths. GARDNER and DAVIES (1966) plotted the rotation measures in galactic coordinates and showed a large scale and quasi-cyclic distribution along galactic longitude. The positive rotation measures appear near the galactic plane in the regions $200°<l^{\rm II}<320°$ and $40°<l^{\rm II}<180°$, respectively. They asserted that contour lines of constant rotation measures give the direction and the structure of interstellar magnetic field in the solar neighborhood.

A similar plotting of rotation measures was made by BERGE and SEIELSTAD (1967). Some radio sources were added to and some unreliable ones were left out of the data of GARDNER and DAVIES. It was pointed out that contour lines such as those by GARDNER and DAVIES could no longer be delineated because of the more complicated distribution of rotation measures. For example, BERGE and SEIELSTAD added some new sources of positive rotation measures to the region, $45<l^{\rm II}<155°$, $|b^{\rm II}|\lesssim 15°$, where only the sources with the largest negative rotation measures had been found by GARDNER and DAVIES. BERGE and SEIELSTAD suggested that such a complicated distribution of rotation measures may be due to the irregular structure of the interstellar magnetic field in the solar neighborhood.

In the present note, we make distribution diagrams of rotation measures for distant and nearby radio sources separately. It is shown, as the result, that the metagalactic magnetic field contributes significantly to the Faraday rotation of distant radio sources.

Table 1 lists forty radio sources whose data on redshifts and rotation measures are available. Rotation measures in this table are due to BERGE and SEIELSTAD. The sources are divided into two groups according to the magnitudes of redshifts; group 1 for the sources of $z<0.1$ and group 2 for those of $z \geq 0.1$. For each group the values of the rotation measures are plotted in galactic

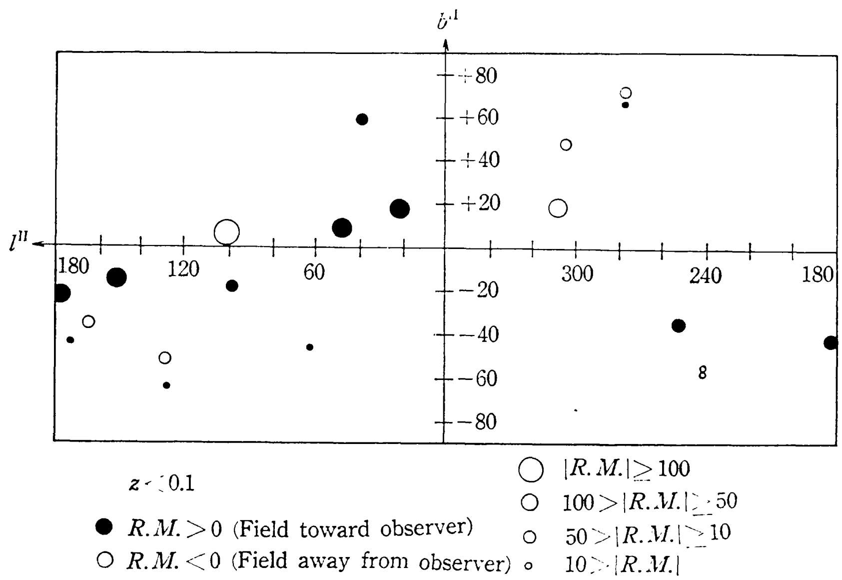

FIG. 1. Distribution of rotation measures in galactic coordinates for $z<0.1$. Filled and open circles correspond to the cases of positive (field toward observer) and negative (field away from observer) rotation measures, respectively. Their areas roughly indicate the absolute magnitudes of rotation measures.

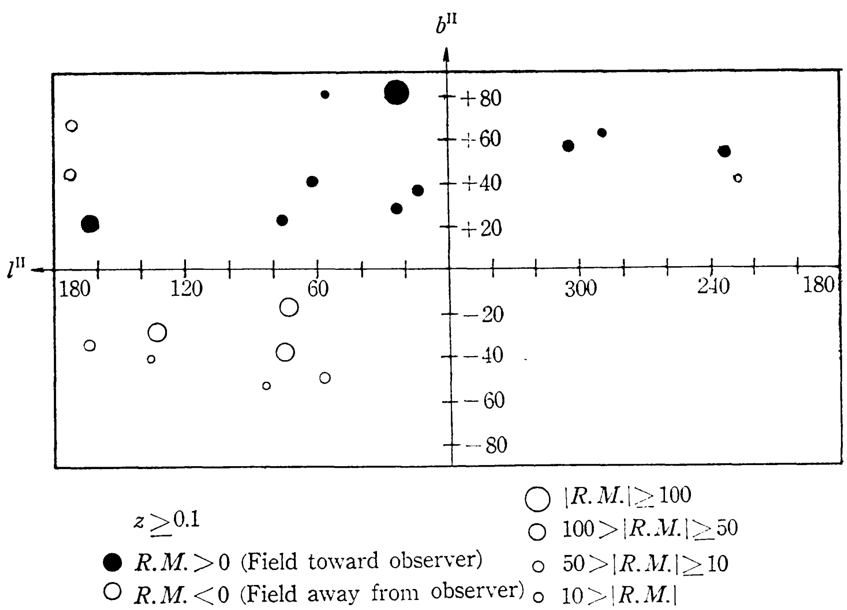

FIG. 2. Same as Figure 1 but for $z \geqq 0.1$.

coordinates (Figures 1 and 2). When Figures 1 and 2 are combined, BERGE and SEIELSTAD's distribution diagram reappears. In these diagrams, distributions of the rotation measures are rather smooth and the complicated distributions such as suggested by BERGE and SEIELSTAD tend to vanish. Comparing Figures 1 and 2, we find a remarkable difference in the distribution of rotation measures at $l^{II} \simeq 100°$, $b^{II} \simeq -30°$ (referred to as region A). Signs of the rotation measures near region A are positive for the sources of $z<0.1$ and they become negative for those of $z \geqq 0.1$. The same kind of difference, though not very clear, occurs in the opposite direction to region A, $l^{II}=280°$, $b^{II}=30°$ (referred to as region B). Signs of rotation measures are, contrary to those near region A, negative for the sources of $z<0.1$ and positive for the sources of $z \geqq 0.1$. Such a significant difference in rotation measures between groups 1 and 2 is indicative of the presence of Faraday rotation in the space between nearby and distant radio sources. From these results we may conclude that metagalatic magnetic field runs in the direction B to A.

For each group of the radio sources, the values of rotation measures are plotted as a function of galactic latitude (Figures 3 and 4). We find that the rotation measures of distant radio sources have a weaker correlation with the galactic latitude than those of nearby ones, which also supports our conclusions.

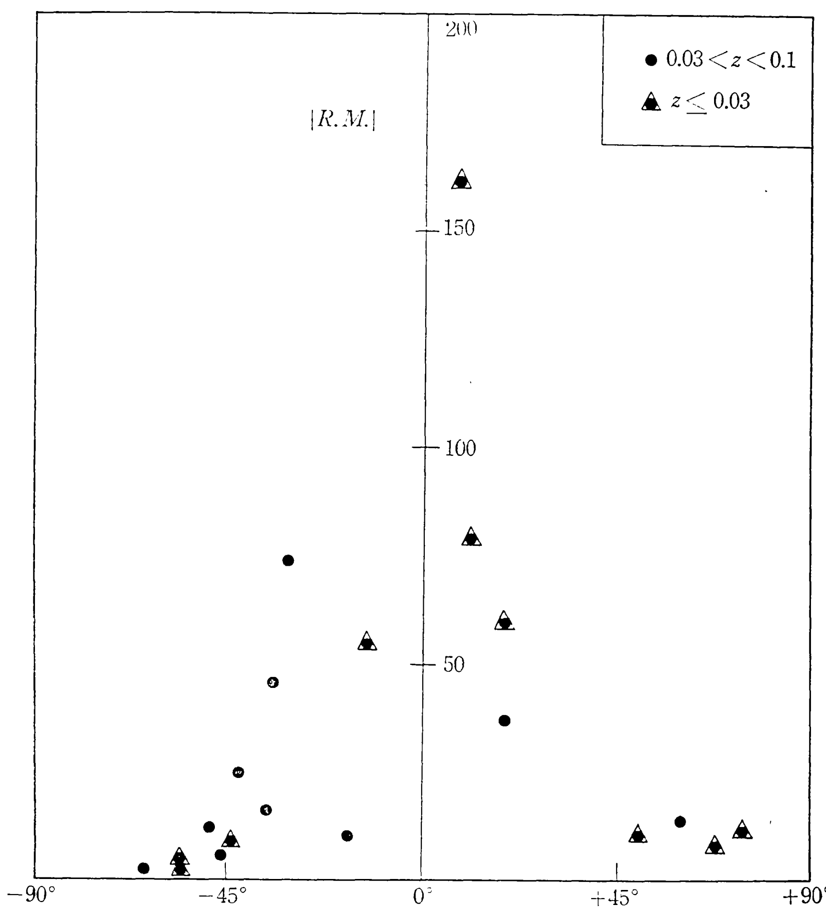

FIG. 3. Latitude dependence of absolute magnitudes of rotation measures for $z < 0.1$. Triangles denote the sources of $z \leq 0.03$.

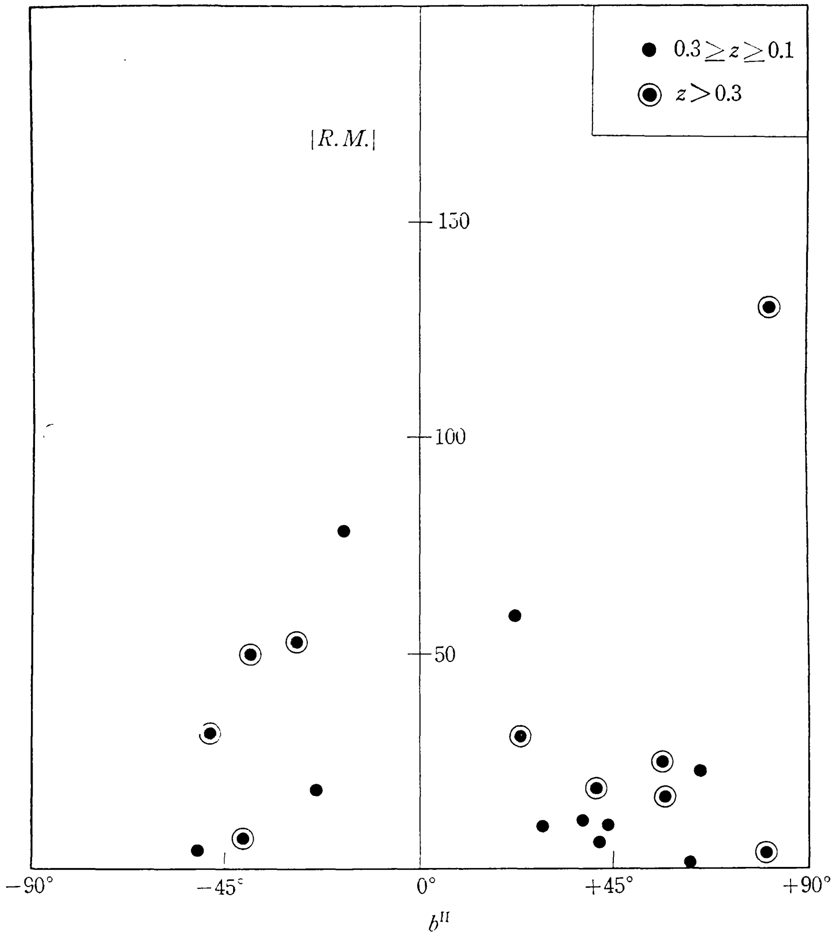

FIG. 4. Same as Figure 3 but for $z \geqq 0.1$. Double circles denote the sources of $z \geqq 0.3$.

A value of rotation measure in the direction of the metagalactic magnetic field can be estimated as $|\mathrm{R.M.}| \simeq 50$ for $z \simeq 0.5$ from Figure 2. If we assume the redshift to be cosmological, and if we take the Hubble constant to be 100 km $\sec^{-1}\mathrm{Mpc}^{-1}$ and the intergalactic electron density to be $10^{-5}\mathrm{cm}^{-3}$, the value of magnetic field strength is found to be of the order of 10^{-9} gauss.

Even with a local hypothesis of the quasi-stellar radio sources, large redshift may imply large distances, and therefore the reversal of the sense of rotation measure for radio sources with large redshifts could be explained. But in such a case, we have to assume a much larger value of metagalactic magnetic field stength.

Assuming that the redshift is cosmological and the metagalactic magnetic field is uniform, we derive a relation between magnitudes of redshifts and rotation measures. The rotation angle of the polarization plane in radians is given by

$$\phi = 7.3 \times 10^{10} \int_0^l \frac{n_e B_{//}}{\nu^2} dl \qquad \mathrm{rad}\ , \tag{1}$$

where n_e is the electron density in cm^{-3} in the intergalactic space, $B_{//}$ is the longitudinal component of the metagalactic magnetic field in gauss, ν is fre-

TABLE 1. Rotation Measures and Redshifts of Radio Sources.

Source	l^{II}	b^{II}	R. M.(r/m²)	z	Ref.* to z
3C 29(b)	126.4	−64.2	+ 2 ±1	0.0450	(1)
3C 33	129.4	−49.3	− 12 ±1	0.0600	(2)
3C 47	136.8	−40.7	− 7 ±17	0.425	(3)
3C 48	134.0	−28.7	− 53 ±12	0.367	(3)
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	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)
Pic A	251.6	−34.6	+ 46 ±1	0.0353**	(5)
3C 171	162.1	+22.2	+ 59 ±6	0.2387	(2)
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	(6)
3C 254	172.6	+65.9	− 23 ±14	0.734	(6)
3C 270	281.8	+67.4	+ 8.4 ±0.6	0.0037**	(5)
3C 272.1	278.2	+74.5	− 12 ±5	0.0037**	(5)
3C 273	290.0	+64.4	+ 1 ±2	0.158	(3)
3C 278	304.1	+50.3	− 11 ±3	0.0143	(7)
3C 279	305.1	+57.1	+ 17 ±3	0.536	(6)
Cen A	309.5	+19.4	− 60 ±2	0.0013	(8)
3C 286	56.5	+80.7	+ 4 ±4	0.846	(6)
3C 287	22.5	+81.0	+ 130 ±10	1.054	(6)
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	0.594	(6)
3C 348	23.0	+28.9	+ 10 ±4	0.1592	(9)
3C 353	21.2	+19.6	+ 37 ±4	0.0307	(2)
3C 380	77.2	+23.5	+ 31 ±8	0.691	(6)
3C 386	47.0	+10.6	+ 79 ±8	0.008	(2)
3C 430	99.7	+ 8.0	− 162 ±15	0.0167**	(5)
3C 433	74.5	−17.7	− 79 ±4	0.1025	(2)
3C 445	61.8	−46.7	+ 6 ±7	0.0568	(2)
3C 446	59.0	−48.8	− 32 ±5	1.404	(6)
CTA 102	77.4	−38.6	− 50 ±4	1.038	(6)
3C 425	98.1	−17.1	+ 10 ±6	0.0820	(2)
3C 459	83.0	−51.3	− 4 ±5	0.2205	(2)

* (1) SANDAGE (1967), (2) SCHMIDT (1965), (3) SCHMIDT and MATHEWS (1964), (4) HUMASON, MAYALL and SANDAGE (1956), (5) AIZU, FUJIMOTO, HASEGAWA, KAWABATA and TAKETANI (1964), (6) SANDAGE (1966), (7) GREENSTEIN (1961), (8) SÉRSIC (1960), and (9) GREENSTEIN (1962).

** Distances of sources have been estimated.

quency of radio waves in Mc/s and l is the distance in parsec between the source and the observer. By taking the metric as

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

the rotation measure is written from equation (1) as

$$\begin{aligned}\mathrm{R.M.}&=K\int_0^l \frac{n_eB_{//}}{(\nu/\nu_0)^2}dl\\ &=Kn_{e0}B_{//0}R_0\int_0^r\left(\frac{R}{R_0}\right)^{-2}dr \qquad \mathrm{rad\ m^{-2}}\ ,\end{aligned}\tag{2}$$

where $K=8.1\times10^{-5}\,\mathrm{cm^3\ gauss^{-1}\ parsec^{-1}}$ is a constant and n_{e0}, $B_{//0}$, and R_0 are the electron density, longitudinal magnetic field strength and radius of the universe at the present cosmic time t_0 respectively. In deriving equation (2) we used the following relations,

$$\frac{n_e}{n_{e0}}=\left(\frac{R}{R_0}\right)^{-3}\ ,\ \frac{B_{//}}{B_{//0}}=\left(\frac{R}{R_0}\right)^{-2}\ ,\ \text{and}\ \frac{\nu}{\nu_0}=\left(\frac{R}{R_0}\right)^{-2}\ .$$

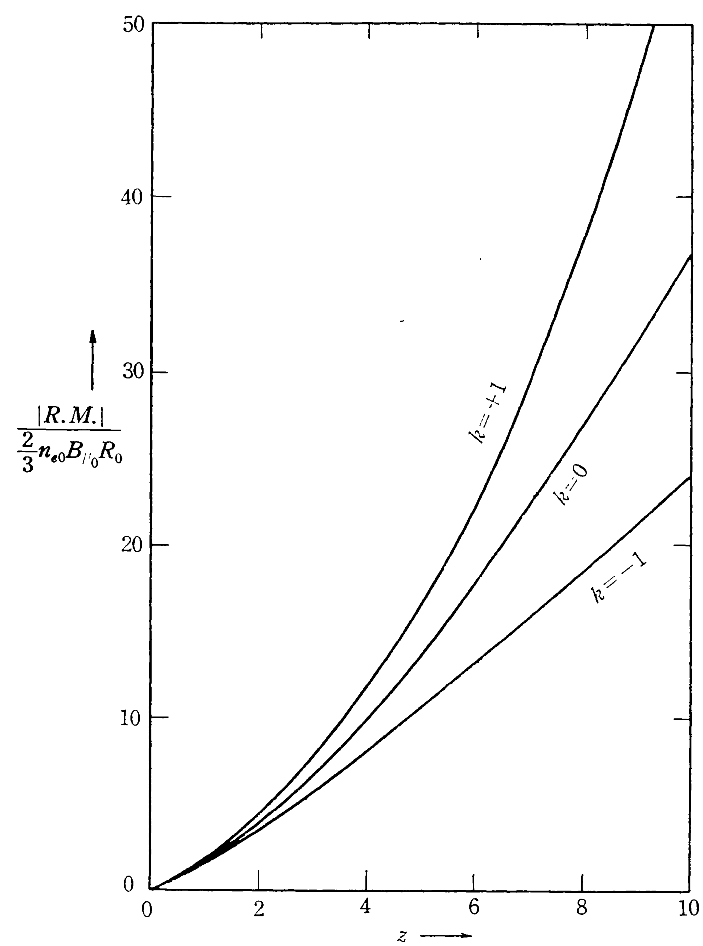

FIG. 5. Relations between rotation measure and redshift for open ($k=+1$), flat ($k=0$), and closed ($k=-1$) universes.

By taking $R/R_0=(t/t_0)^{2/3}$ equation (2) is rewritten as

$$\mathrm{R.M.}=\frac{2}{3}Kn_{e0}B_{//0}R_0\times\begin{cases}\displaystyle\int_1^{\eta_e}\frac{d\eta}{\eta^2\cosh^2(1-\eta^{1/3})} & \text{for}\quad k=-1\,,\\[2ex] \displaystyle\int_1^{\eta_e}\frac{d\eta}{\eta^2} & \text{for}\quad k=0\quad,\\[2ex] \displaystyle\int_1^{\eta_e}\frac{d\eta}{\eta^2\cos^2(1-\eta^{1/3})} & \text{for}\quad k=+1\,,\end{cases}$$

where $\eta_e=t_e/t_0$ and t_e is the cosmic time when the radio waves were emitted. Combining equation (3) and the relation $\eta_e/\eta_0=(1+z)^{-3/2}$, we obtain relations between the magnitudes of rotation measures and those of the redshifts. The results are given in Figure 5.

The number of observed sources is insufficient at present to determine a model of the universe. If rotation measures and redshifts are observed on very distant radio sources, it will be possible to examine our conclusions. Moreover, if the radio sources distribute along one of the lines in Figure 5, we will be able to determine not only the strength of the metagalactic magnetic field, but also the Friedman model of the universe.

References

AIZU, K., FUJIMOTO, Y., HASEGAWA, H., KAWABATA, K. and TAKETANI, M. 1964, *Suppl. Progress Theor. Phys.*, No. 31, 31.

BERGE, G. L. and SEIELSTAD, G. A. 1967, *Astrophys. J.*, **148**, 367.

GARDNER, F. F. and DAVIES, R. D. 1966, *Austr J. Phys.*, **19**, 129.

GREENSTEIN, J. L. 1961, *Astrophys. J.*, **133**, 335.

GREENSTEIN, J. L. 1962, *Astrophys. J.*, **135**, 679.

HUMASON, M. L., MAYALL, N. U. and SANDAGE, A. R. 1956, *Astr. J.*, **61**, 97.

SANDAGE, A. 1966, *Astrophys. J.*, **146**, 13.

SANDAGE, A. 1967, *Astrophys. J.* **150**, L145.

SCHMIDT, M. and MATHEWS, T. A. 1964, *Astrophys. J.*, **139**, 781.

SCHMIDT, M. 1965, *Astrophys. J.*, **141**, 1.

SÉRSIC, J. L. 1960, *Z. Astrophys.*, **51**, 64.

Errata

In the paper "On the Cause of the Unexplained Secular Change in the Obliquity of the Ecliptic" by SEKIGUCHI, (*Publ. Astr. Soc. Japan*, **19**, 596, 1967), on page 596, the sentence on 14th-15th lines from the bottom should read as "AOKI (1967) tried to revise the Oort constant *B*," in place of "AOKI (1967) investigated the possibility that it may be reconciled by revising the Oort constant *B*,". On page 602, the expression $-C_0\omega d\theta/dt$ in the 6th line from the bottom should read as $-(C-C_0)\omega d\theta/dt$. Therefore the expression (15) must be rewritten as

$$\lambda=\frac{C_0^2 n^2 \sin\theta_0 \cos\theta_0}{-(C-C_0)\dfrac{d\theta}{dt}} .$$

The expression (16) on page 608 should be replaced as

$$\lambda=0.07\times 10^{37}\,\mathrm{g\cdot cm^2\cdot sec^{-1}} ,$$

instead of

$$\lambda=0.49\times 10^{37}\,\mathrm{g\cdot cm^2\cdot sec^{-1}} ,$$

and the values of β, α and $\Delta\theta$ should be

$$\beta=3.'5 ,$$
$$\alpha=1.'5 ,$$
$$\Delta\theta=0''.044 .$$