Carl Bignell
Summer Student Lecture [illegible]
1973

POLARIZATION OF EXTRAGALACTIC RADIO SOURCES

The study of polarization is motivated by a desire to understand the physics and evolution of radio sources. It is through polarization observations that a good deal can be learned about the magnetic field structure and the distribution of ionized gas in the source. In addition the polarization of extragalactic radio sources can be used to study the interstellar medium in the Galaxy and the intergalactic medium. I shall briefly discuss the mathematical definition of polarization and how it is measured. Then some physics is outlined and finally the observations are discussed.

Polarization and the Stokes Parameters

The polarization of an electromagnetic wave is the description of the locus traced by the temporal variations of the electric field vector in the plane perpendicular to the direction of propogation. Visualize a plane wave propogating out of the page and suppose the locus traced by the time variations of the electric field vector of the wave is represented by the ellipse shown in Figure 1. Now the polarization of this wave is completely specified by three quantities: ellipticity, magnitude and orientation of the ellipse. These three quantities are sufficient to describe the polarization of a single

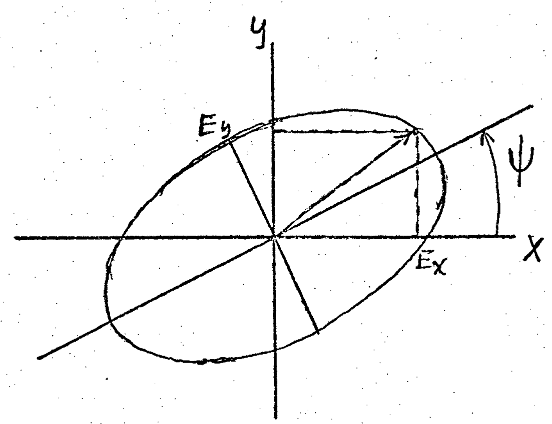


Figure 1

photon, however the radiation field which we measure with a radio telescope is the result of many photons emitted at the source and in most astrophysical conditions, these photons have widely different polarizations. The polarization of some these photons will partly cancel the polarization of some of the others, with the result that the signal measured with the telescope will be composed of two components: one (the polarized) component is described by the above three quantities and the other (the unpolarized) component is described by a magnitude only. Therefore, in general, the polarization of any signal is defined uniquely by four numbers which need not be the quantities given above.

Four quantities commonly employed are called the Stokes parameters. This system for describing the polarization is particularily useful because (a) the sum of the polarizations of incoherent signals is the arithmetic sum of the individual Stokes parameters (the parameters are additive) and (b) the output of a radiometer is directly related to simple combinations of the individual Stokes parameters of the signal. If the electric field of the signal at any instant in time is given by

$$E_x = E_1 \sin(wt)$$
$$E_y = E_2 \sin(wt+d) \qquad (1)$$

where d is the phase between the x and y components, $w=2\pi$xfrequency and t is time, then the Stokes parameters are defined to be

$$I = E_1^2 + E_2^2$$

$$Q = E_1^2 - E_2^2$$

$$U = 2E_1E_2\cos(d) \qquad (2)$$

$$V = 2E_1E_2\sin(d)$$

From equations (1) and (2) and Figure 1 note the following: proportional to

(a) The Stokes parameters are in units ~~of~~ power.

(b) If the signal is entirely linear polarized(d=0), the ellipse in Figure 1 degenerates into a straight line and V=0. The signal is completely specified by Q and U.

(c) If the signal is entirely circular polarized($d=\pi/2$, $E_1=E_2$), the ellipse becomes a circle and Q=U=0. The signal is completely specified by V.

(d) If the signal is entirely polarized elliptically then $I=\sqrt{Q^2+U^2+V^2}$, whereas $I>\sqrt{Q^2+U^2+V^2}$ for a partly polarized signal.

Unfortunately when discussing the polarization properties of a source, the Stokes parameters are a bit cumbersome to use. A more convenient way to specify the state of polarization is to quote the degree(P) of linear polarization, the angle(ψ) of the ellipse (usually referred to as the position angle of linear polarization) and the degree (P_c) of circular polarization. These quantities are related to the Stokes parameters by

$$P = \sqrt{Q^2+U^2}\,/I$$
$$\psi = \tan^{-1}(U/Q)/2 \qquad (3)$$
$$P_c = V/I$$

The position angle is defined to be the angle measured on the sky from North through East. Circular polarization is by definition left hand when V is positive (in Figure 1 the signal is left hand polarized when the electric vector, E, moves clockwise). In summary any signal consists of three parts: the unpolarized component(specified by $I-\sqrt{Q^2+U^2+V^2}$), the linear polarized component (specified by Q and U, or P and ψ) and the circular polarized component (specified by P_c or V). For a more detailed (and more lucid) discussion of the mathematical description of polarization see references (1), (2) and (3).

Polarization Measurements

The actual measurement of polarization requires the use of a device which is selective in its response to a varying electric field. One such device is a simple dipole antenna. A current is induced in the dipole whenever the direction of the varying electric field associated with the signal is parallel to the direction of the dipole. The response of a dipole oriented perpendicular to the direction of the electric field of a 100 percent linear polarized signal is zero; there is a maximum response when the dipole is parallel to the direction of the electric field. Any relative orientation of the dipole and field between the two extremes induces some intermediate response whose magnitude depends on the relative orientation. When a radiometer with a dipole feed is used to measure a partially polarized signal by rotating the feed through 360 degrees, the output is proportional to a sine wave (see Figure 2).

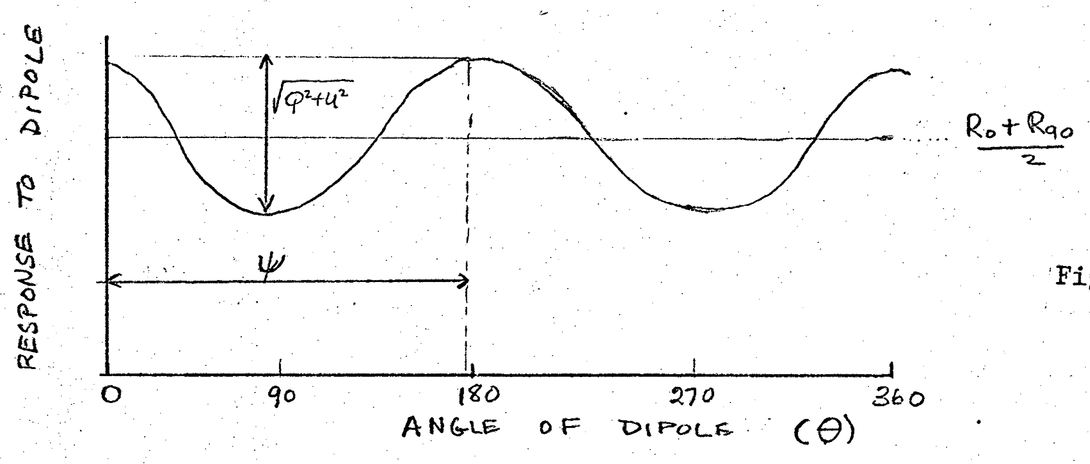


Figure 2

To give more physical meaning to the Stokes parameters we could define I,Q,U in terms of the power response (R_Θ) of the dipole at the position angle Θ; viz.

$$I = R_0 + R_{90}$$
$$Q = R_0 - R_{90} \qquad (4)$$
$$U = R_{45} - R_{135}$$

With very little algebra you can show that this definition reduces to the previous one which indicates that the new definition as given by equation (4) is not different from that of equation (2), but rather equation (4) represents the relationship between the response of a dipole and the Stokes parameters as defined by equation (2). The position angle of linear polarization is given by the angle of orintation of the dipole when the dipole's response is a maximum. Another selective device used to measure polarization is a helix feed. In this case the response of the helix to a partially polarized signal is directly proportional to the magnitude of the component of the electirc field which varies in the direction of the spiral of the helix. The definition given by equation (2) leads to V=LH-RH where LH and RH are the power responses to right and left hand spiral feeds.

The techniques used in measuring linear polarization range from rotating a dipole feed (or equivilent) on a single antenna to correlating the output of two oppositely circular polarized feeds of an interferometer. In general the measurement of polarization is difficult because of the low polarized signals (typically a few percent) and the large systematic errors (e.g. instumental polarization, ionospheric Faraday rotation) which can be difficult to calibrate accurately. The measurement of circular polarization can be achieved by similar techniques to the ones mentioned above (except rotating a simple dipole does not work) and it is even more difficult than linear polarization measurements because the signals are very weakly polarized (typically about 0.25 percent). Discussions of the techniques of measuring polarization and the errors involved can be found in references (4), (5) and (6).

Synchrotron Radiation

Since the details of synchrotron emission have already been discussed I will not pursue this topic at any great length. The motion of an electron in the presence of a magnetic field emitts radiation because the electron is being accelerated. A relativistic electron which is spiralling about a magnetic field line emitts most of the radiation in the direction it is moving because of the "light aberration" effect and the observer sees emission from this electron only when its motion (velocity vector) is in the direction of the observer. Emission is due to acceleration of the electron towards the magnetic field with the result that the electric field of the emitted radiation will be in the direction of acceleration (i.e. pointed towards, or more specifically perpendicular to the magnetic field). Therefore synchrotron emission will be linear polarized perpendicular to the direction of the magnetic field.

An ensemble of relativistic electrons will not be 100 percent polarized because not all electrons will have the same pitch angles. Le Roux (7) showed that the degree of polarization of a system of electrons with an isotropic velocity distribution and a power law energy distribution of the form $N(E)dE=KE^{-\gamma}dE$ is,

$$P(\gamma)=\frac{3\gamma+3}{3\gamma+7} \qquad (5)$$

when the magnetic field distribution is homogeneous and the source is optically thin. The degree of polarization expected from a system of electrons is 72 percent ($\gamma=2.5$). $P(\gamma)$ is not very sensitive to γ. The polarization spectrum (the variation of P and ψ with wavelength) is shown in Figure 3 where $\Phi=\lambda/\lambda_0$ and λ_0 is the wavelength at which the flux density reaches a maximum. Notice that the degree of polarization decreases and the position angle changes by 90 degrees as one passes from the optically thin part of the spectrum to the optically thick part. Otherwise these values remain the same value over decades of wavelengths.. The degree of polarization in the optically thick part of the spectrum is

$$P(\gamma)=\frac{3}{6\gamma+13} \qquad (6)$$

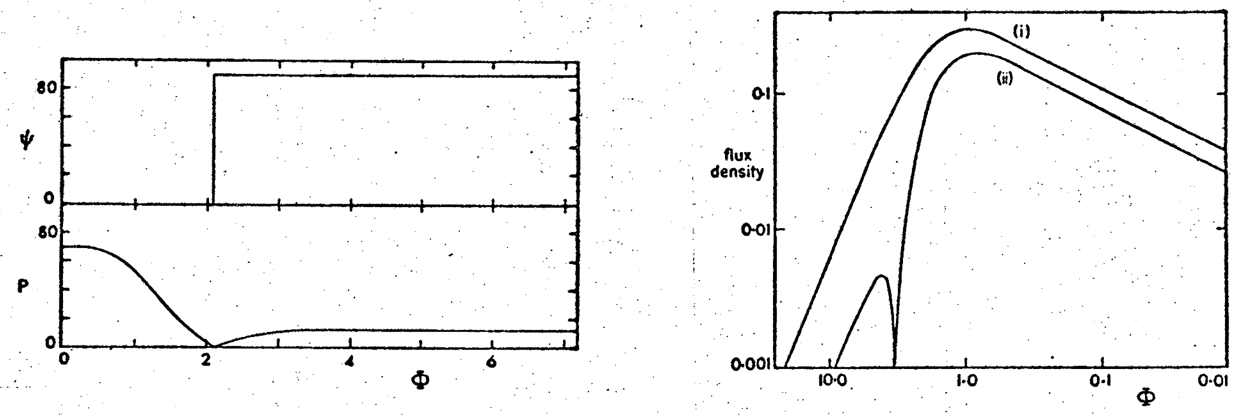


Figure 3. (i)Total flux density. (ii)Polarized flux density.

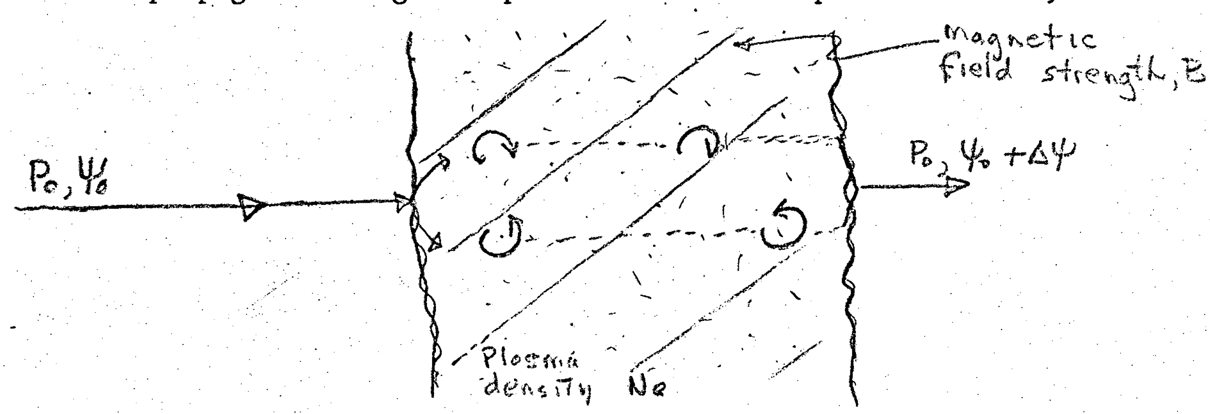
If the magnetic field is not entirely homogeneous the intrinsic degree of polarization will be even smaller. Burn (8) has shown that the intrinsic degree of polarization for a source with random fluctuations in the magnetic field is

$$P(\gamma)\frac{H_o^2}{H_o^2+H_r^2} \qquad (7)$$

where H_o and H_r are the strengths of the uniform and random components of the magnetic field respectively.

Faraday Rotation

The passage of a linear polarized signal through a magnetoactive plasma will change the polarization state of the signal. For most astrophysical conditions one can naively take the following viewpoint. Suppose the incoming signal is linear polarized with degree P_o in postion angle ψ_o (Figure 4). The signal will not propogate through the plasma in a linear polarized mode,



but rather in two oppositely circular polarized modes (referred to as the ordinary and extra-ordinary waves) because of the propogation properties of the plasma. Any linear polarized signal can be represented by two oppositely circular polarized waves of equal magnitude with a phase difference (see references (1) and (2)) which determines the position angle of linear polarization. In the plasma the two propogation modes have different refractive indices and hence velocities of propogations. different Since the velocities of the two modes are different, then the phase lag between the two modes constantly increases with passage through the plasna. When the signal emerges out of the plasma, the original phase difference between the two cirular modes has increased. The vector sum of these two modes will result in a linear polarized signal whose degree has remained the same but whose position angle has changed to

$$\psi_0 + \Delta\psi \quad (8)$$

where $\Delta\psi = RM\,\lambda^2$. The quantity

$$RM = 8.1\times10^5 \int N_e\, B_{\parallel}\, dl \quad \text{radians/meter}^2 \quad (9)$$

is referred to as the rotation measure (λ -wavelengths in meters). The angle through which the polarized signal is rotated depends directly on the plasma density (N_e -cm^{-3}), the longitudinal magnetic field strength ($B_{\parallel}$ -in gauss) and the path lingth through the plasma in parsecs.

The presence of an ionized gas within either the emitting region or "clouds" in front of the source produces a variation in the amount of Faraday rotation (FR) across the source. Because the polariztion now varies across the source the integrated polarization will be less than in the case when there is no Faraday rotation within or surrounding the source. The polarization spectrum of a spherical source with a dispersion in FR (FD) is shown in Figure 5.

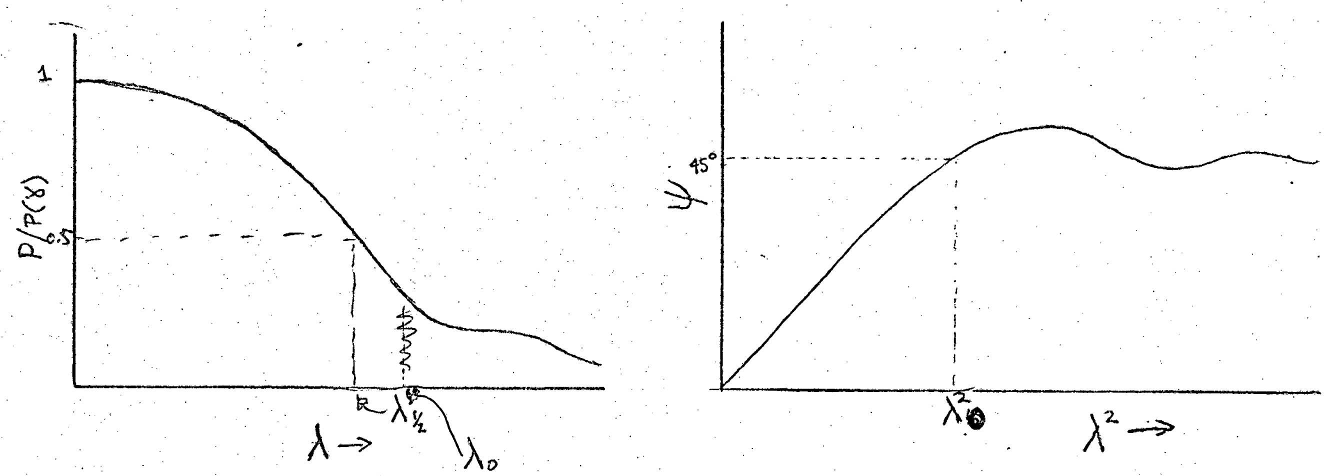


Figure 5

We have for this source

$$\langle RM \rangle \simeq 2/\lambda_{1/2}^2 \quad (10)$$

with an apparent rotation of $\lesssim 0.5$RM (equality holds only when the uniform component of the magnetic field determines the depolarization).

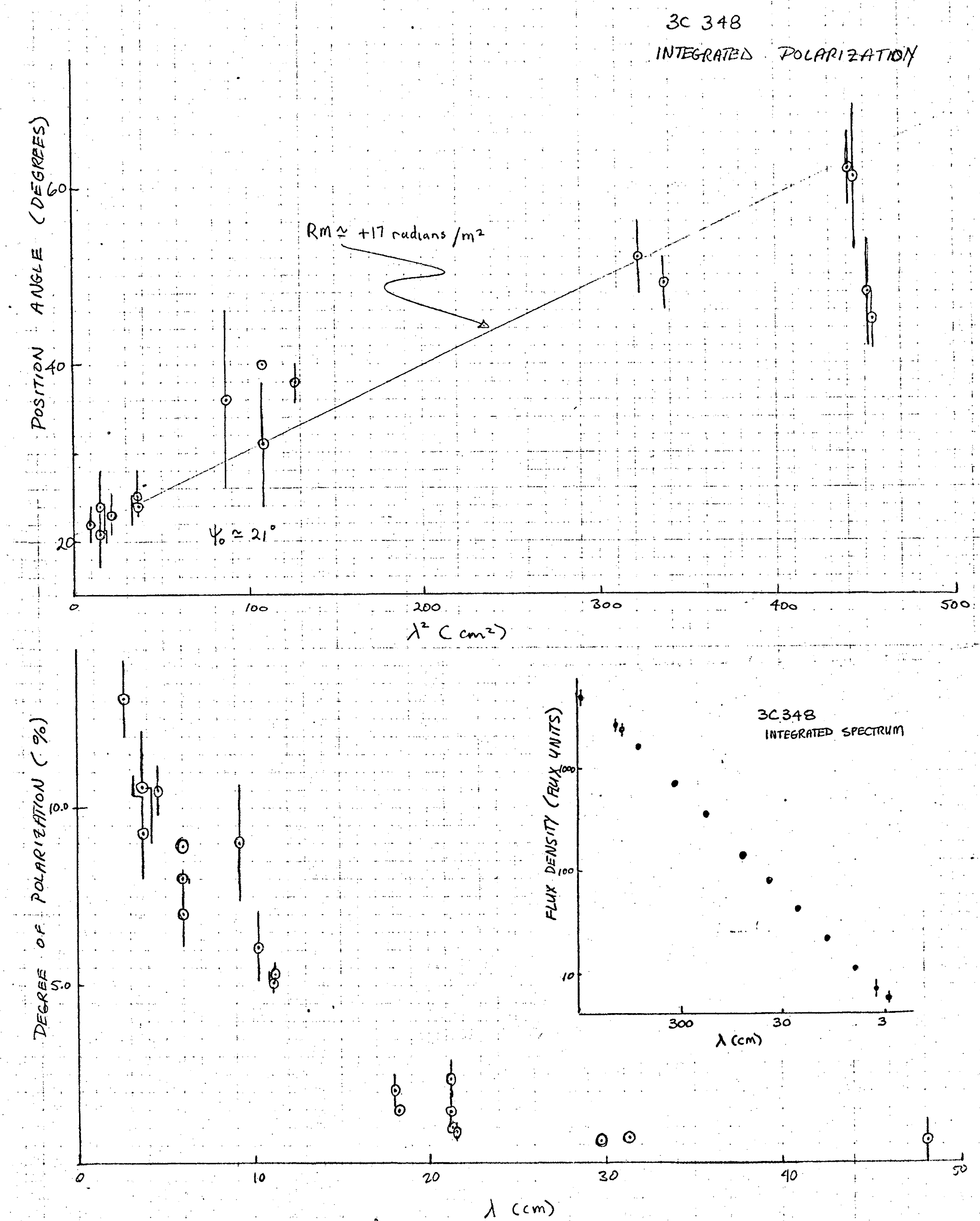

3C 348
INTEGRATED POLARIZATION
POSITION ANGLE (DEGREES)
RM ≃ +17 radians /m²
$\psi_0 \simeq 21°$
λ^2 (cm²)
DEGREE OF POLARIZATION (%)
λ (cm)
3C348
INTEGRATED SPECTRUM
FLUX DENSITY (FLUX UNITS)
λ (cm)

FIGURE 6

OBSERVATIONS

The integrated polarization and flux density spectra of a "typical" source, the radio galaxy 3C 348, are shown in Figure 6. Most sources show a variation of ψ and P with wavelength. Note that the variations do not agree with the simple sychrotron model where P and ψ are expected to be constant over large wavelength ranges. In an attempt to summarize the current "understanding" of the observations I will discuss the position angle information separately from the degree information simply as a matter of convenience only.

Position Angle Information:
Notice that the variation of ψ with the square of the wavelength appears ~~to be linear. Could this be due to Faraday rotation? At present it is not~~ possible to prove or disprove that FR is respnsible. However observations of many sources show that the variation of ψ with λ^2 is linear over wavelength ranges for which the degree of polarization shows large changes. These observations favour the FR interpretation. Besides, this explanation is more natural than others (e.g. optical depth effects and spatial variations in the direction of the magnetic field) in that it requires a less "contrived" model. Let us examine four possible explanations for the observed variations of ψ with λ^2: Faraday rotation within (a) the Galaxy, (b) the intergalactic medium (IGM), (c) the source and finally (d) contributions from regions within the source which have different intrinsic polarizations (e.g. the vector sum of two components with different P and ψ).

(a) The strongest evidence favouring Faraday rotation within the Galaxy is the correlation of $|RM|$ of extragalactic radio sources with galactic latitude (b^{II}) in the sense that $|RM|$ increases as $|b^{II}|$ decreases. Furthermore the signs of RM are correlated with galactic longitude (l^{II}) and latitude. These are the correlations that are expected if Faraday rotation arises within the Galaxy. Typical values of $|RM|$ for sources near the plane are 100 rad./m^2 or more, whereas above the plane values of 20 rad./m^2 or less are usual. Although it is well established that FR occurs within the Galaxy, the exact amount which it contributes to any particular source is not known. See references (10), (11) and (12) for greater detail.

(b) There is a weak correlation of the signs of RM of extragalactic radio sources with redshift, z, and galactic coordinates. (ref. (13)). There is also a weak correlation of $|RM|$ with z (ref. (14)). Although these observations are what is expected for FR by the IGM, the unknown Galactic Faraday rotation biases the correlations. The direction of the intergalactic magnetic field as deduced form the signs of RM of extragalactic radio sources is similar to that deduced for the direction of the Galactic magnetic field, suggesting an ambiguous interpretation of the data. Attempts to remove the Galactic contribution have failed to show any significant correlations (see ref. (15) for a discussion of this attempt and the uncertainties of the present correlations). At present it can only be concluded that FR by the IGM may be possible and that any such effect is much smaller than the Galactic contribution.

(c) Gardner and Davies (10) obtained a crude estimate to the amount of FR associated with the source, by calculating the scatter in the $|RM|$ of extragalactic radio sources (EGRS) at high $|b^{II}|$. They foud $\langle |RM| \rangle \lesssim 5$ rad/m^2, a rather small value. The evidence for FR associated with the source itself is indirect and is summarized as follows:

i. Five sources well away from the Galactic plane have $|RM| > 100$ rad/m^2 and in four of these sources the radio emission is confined to the optical object (ref. (16)).

ii. The rotation measures, RM, of radio galaxies show no correlation with any particular direction in the sky (ref. (17)).

iii. For some sources the rotation measures defined at short wavelengths are found to be significantly different from the RM defined at long and short wavelengths combined. One expects this generally, only if the rotation is associated with the source.

iv. The sign of the circular polarization at short wavelengths agrees with ~~the signs of the rotation measures at short wavelengths~~, which is consistent with the synchrotron hypothesis for the generation of the circular polarization and with the assumption of Faraday rotation. A negative RM and a negative P_c both imply that the magnetic field is directed away from the observer.

v. High resolution polarization observations show significant variations in RM across the source. In particular, the $|RM|$ in Cygnus A is found to increase across the surface of each of the two components and reach a maximum at the outer edges of both components (ref. (18)). This is difficult to reconcile in terms of any model but one in which the FR is associated with the source. It may be argued that Cygnus A is an unusual source (which it is) and that its properties are not typical of other sources. However, there is at least one other source, 3C 348 (ref. (19)), in which $|RM|$ appears to increase towards the outer parts of the source.

(d) Contributions from more than one component of different polarizations is certainly possible. High resolution polarization observations show that many sources have components with different polarization properties. These observations also show that there is a correlation between the rate of depolarization and $|RM|$ across some sources. Therefore, even if the integrated polarization of the source is due to the addition of different polarizations of more than one component, the polarization properties of the individual components is no doubt partly the result of Faraday rotation associated with the source.

Correlations of RM with other source parameters have been searched for in the past. For example one might expect there to be a tendency for the direction of the magnetic field in radio sources to be correlated with another preferred axis, say the line joining multiple components. The average intrinsic position angle (ψ_0) of the average linear polarized signal emitted by the source is found by extrapolating the variation of ψ with λ^2 to zero wavelength (FR does not affect the ψ at zero wavelength). The average direction of the magnetic field in the source is perpendicular to ψ_0. Observations show that there is an insignificant trend for more sources to have their magnetic fields perpendicular to the axis joining the multiple components (ref. (16)). However, such a comparison can be biased because if the intrinsic polarization of the two components are different the value of ψ_0 determined from the integrated properties may not be directly related to the magnetic field direction. There are no significant correlations of RM with other source parameters.

Degree of Polarization Information:

Most sources show a decrease of P with an increase of λ, however some exhibit the opposite trend, while others show a maximum value of P at some wavelength and finally a very few sources show almost a constant value of P with wavelength. With the exception of the latter, the observations do not agree with the simple sychrotron model. Again the possibilities of explaining these include a variation of Faraday rotation within the (a)Galaxy, (b) IGM, (c) source or (d) the vector sum of two or more components with different polarizations. Unfortunately, the explanation for the observed depolarization has been a more difficult problem to tackle in the past because the expected correlations have either been very weak or non-existent.

(a) If the FR within the Galaxy varies across the surface of the source being observed, then one expects the radiation from the source to be depolarized. Although repo rts in the past have stated that there is (i)a correlation of the rate of depolarization (defined by the ratio of the degrees of polarization at two different wavelengths) with b^{II} and (ii) there is a tendency for larger sources to be more depolarized than smaller ones (both in favour of Galactic depolarizaiton), the most recent surveys (ref. (20), (21) and (22)) have shown no significant correlation of depolarization rate with $|b^{II}|$ or source angular size. In fact the least depolarization is associated with sources of the largest size.

(b)At present there is no evidence for depolarization by the IGM. The correlation between depolarization and source angular size is the best evidence against this effect.

(c) The evidence for depolarization by the source itself is indirect and results from correlations with source properties.

i. There is a tendency of sources with flat spectra to have a larger degree of polarization at 49 cm (ref. (20)).

ii. There is a decrease in $1/\lambda^2_{1/2}$ with an increase in the size of Quasars and Galaxies (ref. (23)). There is a similar relation for the rate of depolarization versus linear size. Recall that $1/\lambda^2_{1/2} \sim \frac{1}{2}\langle RM \rangle$ (page 6). Intuitively, the smaller the compnent, the greater N_e^2 and the larger B (adiabatic expansion $\Rightarrow$ B decreases) which implies that $1/\lambda^2_{1/2}$ should decrease as size increases, exactly what is observed. In addition sources of high luminosity tend to show greater depolarization.

iii. There is a correlation of $\lambda_{1/2}$ in the rest frame of the source with the redshift of the source in that there are no high redshifted sources with a small amount of depolarization (depolarization by the IGM might explain this observation).

(d) Finally the depolarization observed in some sources (in particular those which exhibit a peak polarization at some wavelength) are the result of two or more components which have different polarization properties. A well known example is 3C 405 (others are 3C 353, 3C 403). High resolution observations still show that the individual components are depolarized. A correlation between RM and the rate of depolarization (discussed later) implies that a variation in FR within the source may be responsible.

In summary the present observations suggest that the variations of polarization with wavelelngth of most radio sources is the result of Faraday [illegible] associated with the source.

rotation and/or Faraday dispersion produced by an ionized gas associated with the source. Even though we know the Galaxy imposes a significant amount of Faraday rotation upon the signal, particularly for sources at low $|b^{II}|$, it is quite uncertain whether the IGM affects the integrated polarization of extragalactic radio sources.

There is no source, with the possible exception of 3C 279 (discussed later), which shows the difference in position angle or degree between the optically thin and thick parts of the spectrum predicted by the ideal synchrotron model. This is not at all surprising since not only are observations at long wavelengths lacking to test the model but high resolution observations show that most sources have at least two components and a detailed comparison of the integrated polarization with the model is difficult.

Distribution of Linear Polarization

The major extensive surveys at present are limited to observations at 6, 11 and 21 cm (ref. (19), (24), (25), (26) and (27)) of about one dozen sources. The degree of polarization is found to vary greatly across the source from regions of low degree to regions of very high degree (up to 70%). The largest degree of polarization does not always occur near the peak of the total brightness distribution. The position angle in some sources is constant over large areas while in other sources ψ may vary greatly. Although the magnetic field appears to be distributed uniformly over large areas, in no source does the magnetic field have the same direction over the entire source.

Distribution studies have revealed the following:

(a) There is a tendency for the magnetic field in the central part of the source, between the major components, to be aligned perpendicular to the source major axis (Centaurus A is an exception). This is incompatible with the model in which plasmoids are ejected from the galactic nucleus and drag the field lines out with the ejecta. There does appear to be one source which is compatible with the model and that is 3C 273 (ref. 28)).

(b) The magnetic field lines in the outer components tend to be either parallel or perpendicular to the major axis joining the compomemts. If the field distribution results from compression of the interstellar magnetic field, then a high P and a magnetic field perpendicular to the outer edges of the source are expected. In those sources where the magnetic field in the outer components is in the correct direction, the expected high degree of polarization is not observed.

(c) Rotation measures vary greatly across the surface of the source ($\Delta|RM| \sim$ few$\times 10$ rad/m^2) and where the variation in RM is large so is the variation in the rate of depolarization. In several sources there is a correlation in the variations of these parameters, in the sense that as $|RM|\uparrow$ the rate of depolarization increases which strongly suggests that differential Faraday rotation is responsible for the observed depolarization.

There is still no clear picture of a preferred magnetic field distribution in a radio galaxy and as a result, there is no conclusive and unambiguous picture of the formation and evolution of radio sources.

Variability of Linear Poalarization*

The first convincing evidence of radio emission variability in EGRS came in 1965 (ref. (29)) and by 1967 several of the variable sources were shown to possess variable polarization. To date the only extensive surveys for polarization variability have been conducted at wavelengths between 2.8 and 4.5 cm (ref. (30) and (31)). The variations in degree and position angle have been found to be large (factors of 2 or more) for some sources with time scales ranging from a few hours to years. There tends to be a correlation between the dlux density and polarization variations, although a few sources show variations in polarization during periods when their flux density is constant. The results may be summarized as follows:

(a) The variable components appear to be polarized by as much as 10 percent.

(b) Most of the observed variations are consistent with those predicted by an adiabatically expanding source which emitts synchrotron radiation (ref. (32)) and varies because of a decrease in optical depth due to expansion. A detailed comparison is not possible because of the influence of other significantly polarized components. The 90 degree change in position angle expected during the outburst was seen in 3C 279 and possibly in DA 55 (ref. (33)).

(c) The complex nature of the flux density variations in some sources and the variation of polarization during periods when the flux density was constant for other sources suggests that there is either more than one variable component or there is semi-continuous supply of relativistic electrons.

(d) The small change in position angle accompanied by a variable polarized flux density before, during and after an outfurst in some sources suggests that the successive bursts or regions of activity occur in one part of the source and not in physically separate regions.

(e) Simultaneous polarization observations at 2 and 3 different wavelengths suggests that a variation in Faraday rotation may at least in part be responsible for the variations in polarizations (ref.(34)).

(f) Large changes in $|RM|$ and flux density imply complex variable structure.

Observations point to changes in optical depth and Faraday rotation as causes for the variations in polarization. More extensive multiple frequency observations in the future may determine if one of these effects dominates.

* References (42) & (43) describe the temporal variations of polarization of the synchrotron model

Circular Polarization

Circular polarization has been detected in approximately a dozen sources (observations range in wavelength from 6 to 73 cm). Typical values are about 0.25 percent. Synchrotron theory predicts that the degree of circular polarization in an optically thin source is (ref. (35))

$$P_c = 1.74(2.8B\sin(\theta)\lambda/c)^{0.5}\cot(\theta) \qquad (11)$$

where θ is the angle between the direction of the magnetic field and the observer. The degree of polarization increases as the wavelength increases. For an optically thick source P_c begins to decrease with increasing λ just after λ_{max}(wavelength at which flux density is a maximum) and finally changes sign near $\lambda \simeq \lambda_{max}/2$. The $|P_c|$ can reach values comparable to or slightly greater than the $|P_c|$ in the optically thin part of the spectrum.(ref. (36) and (37)).

The observations at present support the synchrotron theory in that $|P_c|$ increases as the wavelength increases (ref. (38)). But a detailed analysis shows that the $\lambda^{1/2}$ dependence does not hold (ref. (38) and (39)). Furthermore, observations of PKS2134+004, on the long wavelength side of λ_{max} show no change in the sign of P_c as expected from theory. Unfortunately, the interpretation is prejudiced by the assumption that the source consists of a single and simple component, whereas in all likelyhood this is probably not the case. Magnetic field strengths calculated from equation (11) are found to be higher by an order of magnitude or more. However, Seaquist (41) finds that the circular polarizations of all but one source at 10 cm are not inconsistent with the synchrotron hypothesis when estimating magnetic field strengths from the sychrotron self-absorption assumption and taking into account the multiple component structure of these sources. Another observation that favours the synchrotron interpretation is the correlation between the signs of the P_c and the signs of RM mentioned reviously.

The circular polarization of at least three sources, PKS1127-14, BL Lac and CTA 102 vary in time (ref. (40) and (41)). The variations occur over a magnitude range as large as 1.0 percent (there are also changes in sign) in time scales ranging from hours (ref. (38)) to as long as 1.5 years. The interesting feature about the observations is that the circular polarization variations at 10 cm appear to be correlated with the flux density variations at 2.8 cm ! So far no interpretation is given to these variations apart from the possible synchrotron origin of the circular polarization.

than calculated by synchrotron self-absoption assumption

References

(1) Krauss, Radio Astronomy, McGraw Hill, 1966
(2) Born and Wolf, Principles of Optics, Pergamon Press, 1959
(3) Chandrasekhar, Radiative Transfer, Dover, 1960
(4) Gardner and Davies, Aust. J. Phys., 19, 441, 1966
(5) Conway and Kronberg, MNRAS, 142, 11, 1969
(6) Morris, Radhakrishnan and Seielstad, Ap. J., 139, 551, 1964
(7) Le Roux, Ann. d'Astroph., 24, 71, 1961
(8) Burn, MNRAS, 133, 67, 1966
(9) Gardner and Whiteoak, Annual Rev. of Astron. and Astrophys., 4, 245, 1966
(10) Gardner and Davies, Aust. J. Phys., 19, 129, 1966
(11) Berge and Seielstad, Ap. J., 148, 367, 1967
(12) Gardner, Morris and Whiteoak, Aust. J. Phys., 22, 813, 1969
(13) Reinhardt and Thiel, Ap. Letters, 7, 101, 1970
(14) Arp, Nature, 232, 463, 1971
(15) Reinhardt, Astron. & Astrophys., 19, 104, 1972
(16) Mitton, MNRAS, 155 373, 1972
(17) Mitton and Reindhardt, Astron. & Astrophys., 20, 337, 1972
(18) Mitton, Ap. Letters, 13, 19, 1973
(19) Seielstad and Weiler, AJ, 76, 211, 1971
(20) Conway, Gilbert, Kronberg and Strom, MNRAS, 157, 443, 1972
(21) Strom, preprint, 1973
(22) Gardner and Whiteoak, Aust. J. Phys., 22, 107, 1969
(23) Strom, Nature, 239, 19, 1972
(24) Gardner and Whiteoak, Aust. J. Phys., 24, 899, 1971
(25) Davies and Gardner, Aust. J. Phys., 23, 59, 1970
(26) Morris and Whiteoak, Aust. J. Phys., 21, 475, 1968
(27) Cooper, Price and Cole, Aust. J. Phys., 18 589, 1965
(28) Conway and Stannard, Nature, 239, 22. 1972
(29) Dent, Science, 148, 1458, 1965
(30) Aller, Ap. J., 161, 1, 1970
(31) Bignell and Seaquist, AJ, in press, 1973
(32) Laan, H. van der, Nature, 211, 1131, 1966
(33) Aller and OLsen, AJ, 76, 671, 1971
(34) Bignell, AJ, in press, 1973
(35) Legg and Westfold, Ap. J., 154, 499, 1968
(36) Pacholczyk and Swihart, Ap. J., 171, 405, 1971
(37) Melrose, Proc. Astron. Soc. Of Aust., 2, 140, 1972
(38) Roberts, ibes, Murray and Cooke, Nature Phys. Sci., 236, 3, 1972
(39) Conway, Gilbert, Raimond and Weiler, MNRAS, 152, 1P, 1971
(40) Seaquist, Nature Phys. Sci., 231, 93, 1971
(41) ________, Astron. and Astrophys., 22, 299, 1973
(42) Takarada, P.A.S.J., 22, 551, 1970
(43) Allen, Ap. J., 161, 19, 1970