PART IV

INTERSTELLAR POLARIZATION

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INTERSTELLAR POLARIZATION

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Abstract. A review of observational data on interstellar polarization is given. The degree of fluctuation in the direction of the galactic magnetic field is discussed. An empirical formula is given which fits all the observations of the wavelength dependence of interstellar polarization when they are normalized with the wavelength λ_{max} of maximum polarization. Well-defined regions on the sky with values of λ_{max} deviating from an average are found. Values of λ_{max} are correlated with the ratio of total to selective interstellar extinction. A unified wavelength dependence of interstellar extinction is obtained by normalizing the observations with the wavelength λ_{max} of maximum interstellar polarization.

In this review I shall try to indicate the principal *observational* facts concerning the interstellar polarization of starlight; these facts may serve as a basis for further discussion on the theoretical explanation of the observed polarization. The problems of interstellar polarization are closely related to those of circumstellar, intrinsic polarization of starlight, which were recently reviewed elsewhere (Serkowski, 1971; Zellner and Serkowski, 1972).

Fruitful discussion of the distribution of the orientations of polarization on the sky became possible after Mathewson and Ford (1970) extended to the southern sky the high galactic latitude polarimetric surveys of Behr (1959) and Appenzeller (1968). Figure 1, prepared by Mathewson and Ford, shows the distribution of the planes of vibration of the electric vector for the interstellar polarization of over 7000 stars*.

Mathewson (1968) explained the elliptical 'flow patterns' seen in Figure 1 by assuming that the magnetic lines of force, along which the dust grains are aligned by the Davis and Greenstein (1951) mechanism, form tightly wound righthanded helices with a pitch angle of about 7°. The helices lie on the surface of tubes having elliptical cross-section of axial ratio 3, with semimajor axes parallel to the galactic plane. The helices have been sheared through an angle of 40° on the galactic plane in an anticlockwise sense. The axis of the helices is directed towards galactic longitudes 90° and 270°, which is the direction of the local spiral arm as determined from H I measurements. Mathewson's helical model of the galactic magnetic field explains not only the optical polarization but also the spurs, ridges, and strongly polarized regions of the galactic radio emission (cf. Verschuur, 1970; Martin, 1971). The regions of strong radio emission are probably regions of magnetic field compression which take the form of elongated tubes, with the magnetic field lines parallel to their length. These tubes have the local directivity of the helical model derived from the optical polarization measurements.

* Polarization of another 1600 stars in the southern Milky Way has been measured by Klare *et al.* (1972).

Greenberg and Van de Hulst (eds.), Interstellar Dust and Related Topics, 145–152.

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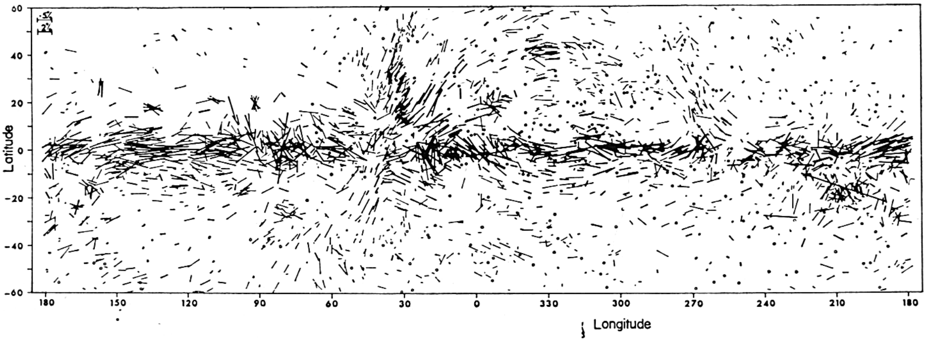

Fig. 1. The interstellar polarization of starlight plotted in galactic coordinates by Mathewson and Ford (1970). The length and position angle of each line indicate the degree of polarization, P, and the plane of vibration of the electric vector, respectively. Small circles are drawn about stars with $P < 0.08\%$. There are two scales for P which are shown in the top left-hand corner of the figure. The first scale operates for $P < 0.6\%$ and these vectors are drawn thin. The second scale operates for $P \geq 0.6\%$ and these vectors are drawn thick.

Mathewson's model suggests that most of the interstellar polarization is produced within about 250 pc of the axis of the local spiral arm, which passes about 100 pc from the Sun in the direction of the galactic anticenter. This is confirmed by Verschuur's (1970) discussion of the dependence of the degree of linear polarization on distance (Figure 2a). To reduce the 'noise' in polarization data and in distance determinations

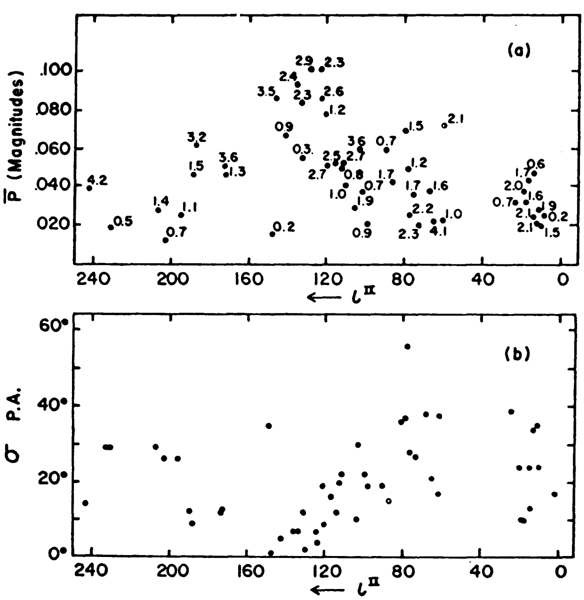

Fig. 2. Polarization properties of star clusters and associations according to Verschuur (1970). (a) Mean polarization as a function of galactic longitude. Numbers indicate the distance to the cluster or association in kpc. (b) The scatter in position angle of member stars as a function of longitude.

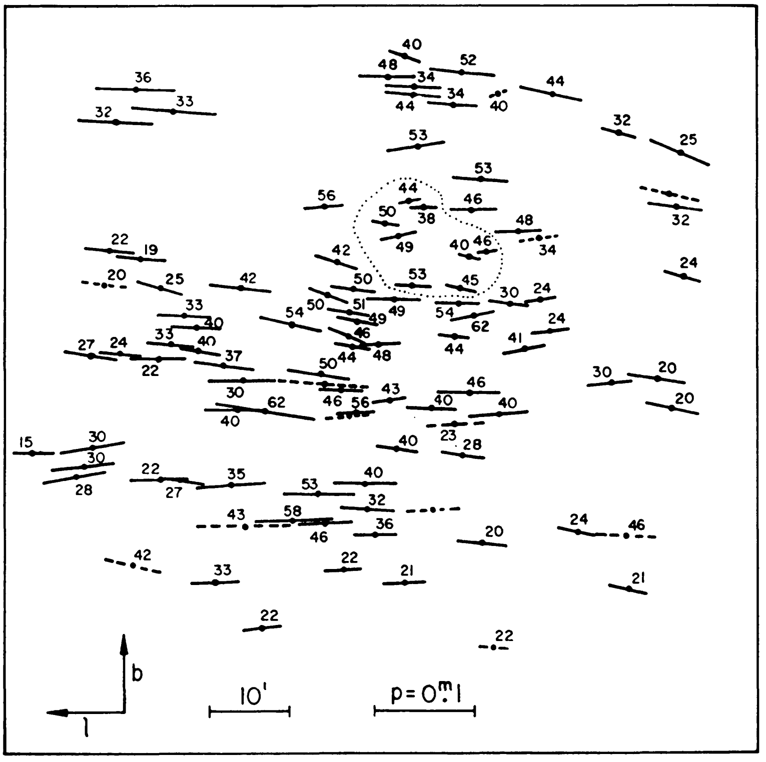

Fig. 3. Polarization of star cluster Stock 2, 320 pc distant, according to Krzemiński and Serkowski (1967). The length and position angle of each line indicate the amount of polarization in the yellow spectral region and the plane of vibration, respectively. The solid lines denote cluster members, dashed lines probable members. Numbers accompanying the lines give the reddening E_{B-V} expressed in hundredths of magnitude. The dotted line delineates the region of small polarization.

he considers only star clusters and associations instead of incividual stars*. Correlation between polarization and distance is very slight.

Figure 2b indicates that the scatter in the polarization position angles is minimum around galactic longitude 140°, which may be explained with the helical model. Of particular interest is cluster Stock 2 at $l = 133°$ (Krzemiński and Serkowski, 1967) which is the only cluster not far from the Sun (320 pc) which shows a strong linear polarization, 2.3% on the average. This cluster is by far the most suitable for studying small scale fluctuations in the direction of magnetic field; the rms deviation of the position angle of the electric vector (Figure 3) from its mean value equals ± 8°. The fluctuations in the direction of interstellar magnetic field indicated by the polarimetry of Stock 2, as well as several other open clusters (Serkowski, 1968) and field stars (Schmidt, 1968), are quite large: the rms deviation of the direction of magnetic field lines from their mean direction is about ± 25°.

* For new polarimetric observations of star clusters see Grigoryan (1970) and Breger and Dyck (1972).

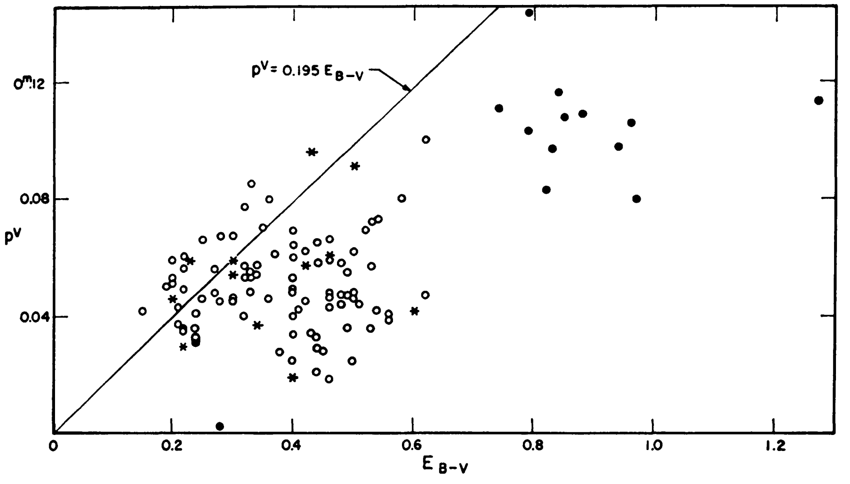

Fig. 4. Amounts of polarization in the yellow spectral region (in magnitudes) for the stars in the region of cluster Stock 2 plotted against the reddening E_{B-V} (Krzemiński and Serkowski, 1967). The cluster members are denoted by open circles, probable members by asterisks, non-members by filled circles. The straight line corresponds to $P/E_{B-V} = 9\%$ per magnitude.

The correlation between the degree of polarization and position angle of neighbouring stars in Stock 2 drops to $1/e$ for an angular distance of about 15′. If we assume that polarization is produced along all the path to the cluster, a microscale of 0.3 pc is obtained for fluctuations in the direction of the magnetic field. A similar value has been obtained by Davies (1968) from a study of depolarization of extragalactic radio sources. The distribution of reddening E_{B-V} in the cluster Stock 2 indicates a microscale of 1 pc for fluctuations in the spatial density of interstellar dust – about 3 times larger than for the magnetic field fluctuations.

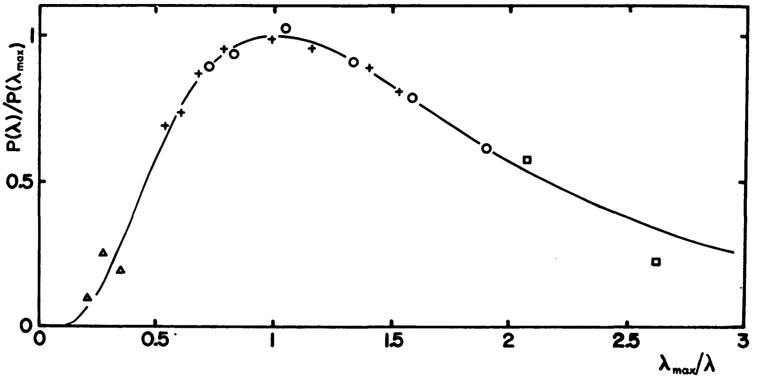

Fig. 5. Normalized wavelength dependence of interstellar polarization averaged for 6 stars in Perseus-Cepheus (crosses) for which $\lambda_{max} \cong 0.52\ \mu$ and for 5 stars in Scorpius (open circles) for which $\lambda_{max} \cong 0.70\ \mu$. Ultraviolet balloon observations for ζ Ophiuchi at $\lambda = 0.225\ \mu$ and $0.286\ \mu$ by Gehrels (1973; squares) and the infrared observations of HD 183143 at $\lambda = 1.6\ \mu$ and VI Cyg *12 at $\lambda = 1.6\ \mu$ and $\lambda = 2.2\ \mu$ by Dyck (1973; triangles) are also plotted. The solid line is calculated from Equation (1).

There is no correlation between polarization and reddening within the cluster Stock 2 (Figure 4). Such lack of correlation is expected if the ratio of space densities of interstellar dust (n_g) and gas (n_H) is constant. For incomplete Davis-Greenstein orientation, the theory of which has been revised recently by Cugnon (1971) and by Purcell and Spitzer (1971), the polarization per unit path length is proportional to n_g/n_H while the color excess is proportional to n_g. For the ratio of percentage polarization P to color excess E_{B-V} an upper limit of 9% per magnitude, derived by Schmidt-Kaler (1958) is usually assumed. Figure 4 suggests, however, an upper limit which may be as high as 12% per magnitude.

The shape of the wavelength dependence of interstellar polarization seems to be the same for all stars. This became evident only when I first normalized this wavelength dependence by plotting $P(\lambda)/P(\lambda_{max})$ against λ_{max}/λ, where λ_{max} is the wavelength of maximum polarization for a given star. The mean wavelength dependence of polarization for several stars with λ_{max} either close to 0.52 μ (Perseus-Cepheus) or close to 0.70 μ (Scorpius) is plotted in that way in Figure 5, using mainly the observations made at the University of Arizona (Coyne *et al.*, 1973). Ultraviolet balloon observations of ζ Ophiuchi ($\lambda_{max} = 0.60\ \mu$) by Gehrels (1973) and infrared observations of HD 183143 ($\lambda_{max} = 0.56\ \mu$) and of star No. 12 in the association VI Cyg ($\lambda_{max} = 0.45\ \mu$) by Dyck (1973) are also plotted. The observed wavelength dependence of interstellar polarization is well described by an empirical formula (cf. Serkowski, 1971, where it is incorrectly printed)

$$P(\lambda)/P(\lambda_{max}) = \exp\left[-1.15 \ln^2 (\lambda_{max}/\lambda)\right] \qquad (1)$$

used for calculating the curve shown in Figure 5. This curve is very close to theoretical curves calculated by Greenberg (1968, Figure 95) for an Oort-van de Hulst size distribution of cylindrical dielectric grains imperfectly oriented by the Davis-Greenstein mechanism. It was not possible to obtain a fit to the observed curve assuming other orientation mechanisms than that of Davis and Greenstein.

There is no observational evidence for any feature in the wavelength dependence of polarization at the λ 4430 absorption band (Wampler, 1966; A'Hearn, 1972). The observations indicate that if such a feature is present it must be limited to a spectral region not wider than 10 Å.

Whenever the orientation of aligned dust grains changes considerably along the light path from a star the presence of a circularly polarized component is expected (cf. Serkowski, 1962). The announcement of the discovery of such interstellar circular polarization was a highlight of this Symposium. The circular polarization was found to change its sign around the wavelength of maximum linear polarization (Kemp, 1973; Kemp and Wolstencroft, 1972). The largest amount of circular polarization, 0.04% for *o* Scorpii, is observed around the wavelength 0.5 μ.

The wavelength of maximum linear polarization is expected to be proportional to the mean value of the parameter $(m-1)a$, where m is the refractive index of dust grains and a their radius. Since interstellar extinction considered as a function of $(m-1)a/\lambda$ should have the same shape all over the sky, a unified wavelength dependence of interstellar extinction can be obtained by normalizing it with the wavelength λ_{max} of maximum interstellar polarization. Large differences in the shape of conventional extinction curves for Scorpius, as compared to the Perseus-Cepheus regions (Figure 6a) vanish when $[A(\lambda)-A(\lambda_{max})]/[A(\frac{3}{4}\lambda_{max})-A(\frac{4}{3}\lambda_{max})]$ is plotted against λ_{max}/λ (Figure 6b). Figure 6 is based on the same stars which were used in Figure 5. Of course, the normalization of the wavelength dependence of interstellar extinction with λ_{max} makes sense only for those spectral regions where the refractive index is

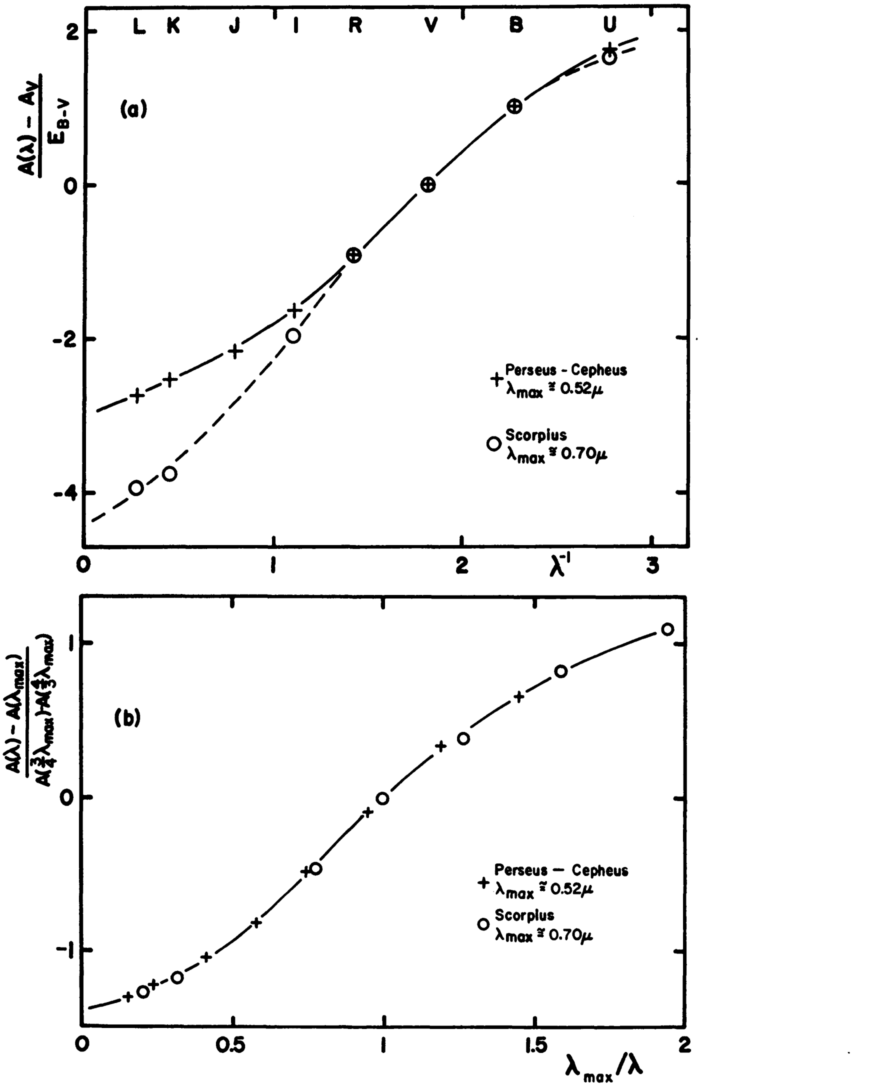

Fig. 6. Wavelength dependence of interstellar extinction for the same stars in Perseus-Cepheus (crosses) and in Scorpius (open circles) for which polarization is plotted in Figure 5. (a) Conventional extinction curve. (b) Wavelength dependence of extinction normalized with λ_{max}, the wavelength of maximum polarization. Infrared photometry in Scorpius by Carrasco *et al.* (1973) is used.

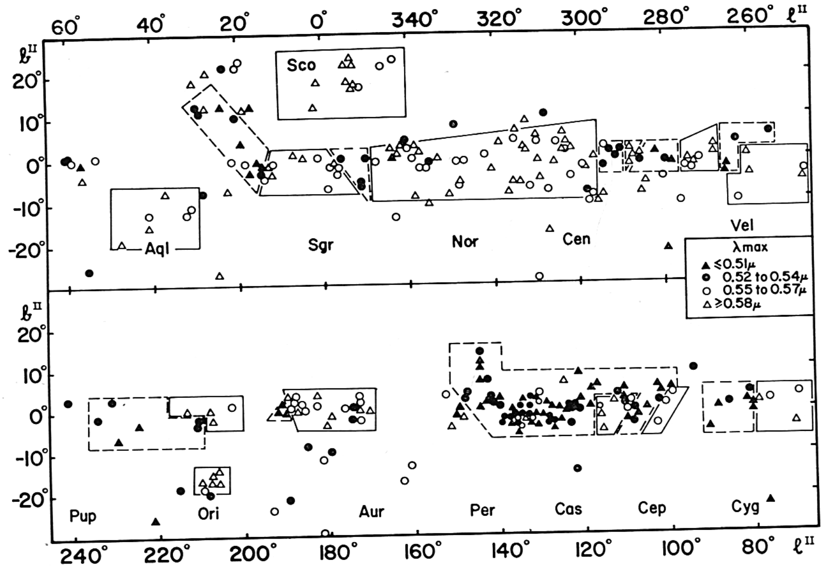

Fig. 7. Wavelength of maximum interstellar polarization, λ_{max}, plotted in galactic coordinates by Serkowski *et al.* (1973). Filled symbols denote the stars with λ_{max} smaller than the median value, open symbols those with λ_{max} larger than the median value. The regions in which the stars of any of these groups predominate are surrounded by dashed or solix lines, respectively.

constant. Therefore it cannot be applied in the far ultraviolet where the wavelength dependence of extinction is dominated by a strong absorption feature around 0.22 μ (Bless and Savage, 1972).

The number of stars with known wavelength of maximum interstellar polarization (λ_{max}) has been nearly doubled by a survey with a multi-channel polarimeter at Siding Spring Observatory recently completed by Serkowski, Mathewson, and Ford (1973); values of λ_{max} are presently known for about 350 stars. The distribution of λ_{max} on the sky is shown in Figure 7. Filled symbols represent the stars with λ_{max} less than the median value of 0.545 μ, open symbols those with $\lambda_{max} > 0.545\ \mu$. An obvious conclusion from inspecting this Figure is that there are some well defined regions on the sky within which λ_{max} is smaller than the median value and regions with λ_{max} larger than the median value. These two types of regions are surrounded in Figure 7 by dotted and solid lines, respectively. The largest and best defined region of low λ_{max} lies along the galactic equator at longitudes 115° to 150°, one of high λ_{max} at longitudes 295° to 350°. The largest values of λ_{max} are observed for these relatively nearby stars in Upper Scorpius and in Orion which are characterized by a large ratio R of total to selective interstellar extinction. In general, the nearby stars have considerably larger λ_{max} than the stars more distant than 0.4 kpc.

The linear size of regions with similar wavelength dependence of interstellar polarization, i.e. with similar average size of dust grains, is about 150 pc, which is approximately the size of large 'clouds' of interstellar medium derived by Scheffler (1967). In view of the correlation between λ_{max} and the ratio R of total to selective extinction

(Serkowski, 1968) Figure 7 may give an idea about the distribution of the ratio R over the sky. Studies of interstellar polarization may thus find a practical application for improving the astronomical distance scale.

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