Polarization Measurements at La Silla

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During February this year measurements of interstellar polarization were carried out at La Silla. We used the Danish 1.5 m telescope equipped with a new type of multichannel double beam chopping polarimeter designed by one of us (V. P.). One of the purposes of our mission was to test the polarimeter and matching data acquisition system, and, in doing so, evaluate the performance of the equipment. The polarimeter was built in the shop of the Turku University Observatory under the supervision of T.K. Below, we shall describe the construction of the polarimeter and the aim of the programmes that were executed; we shall also report on some of the results obtained:

The polarimeter, which can easily be changed into a multichannel photometer, is a further development of an earlier design, described by V. Piirola (1973, 1975). The principle of the operation of the instrument is given in Fig. 1. The focal plane diaphragm has two apertures. The light of the observed star passes one of the apertures while the other allows an amount of background, equal to that which traverses the star aperture, to enter the instrument in the photometric mode (Fig. 1a). A rotating chopper alternately closes one of the apertures, leaving the other free, with a chopping frequency of 25 Hz. Thus the photocathode is illuminated alternately by the star and the sky apertures. The field lens forms on the photocathode an image of the telescope mirror, the exit pupil, through which the flux of both the star and the sky passes. Thus the radiation falls always on the same part of the cathode. The chopper also controls the light of two infrared emitting diodes which alternately illuminate two photodiodes. With the help of the signals of the photodiodes the registration electronics is synchronized so as to count pulses corresponding to the star and the background diaphragms separately by means of two counters.

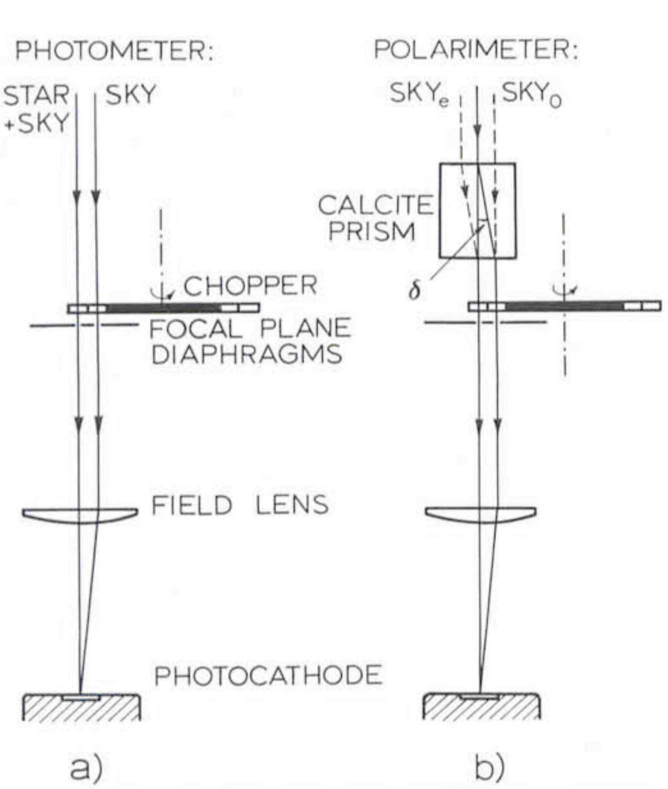

Fig. 1: *Principle of operation of the double beam chopping photometer-polarimeter.*

When the instrument is used for polarization observations, a plane parallel calcite plate is inserted in front of the focal plane, Fig. 1b. At the upper boundary the incoming light is divided into two mutually perpendicularly polarized components. The ordinary rays are refracted according to the normal refraction law but the extraordinary rays are deviated by an angle 6°14′. At the lower boundary the extraordinary rays are refracted back to their original direction. The result is a parallel displacement of the extraordinary rays. Hence, two perpendicularly polarized images of a star are formed in the focal plane of the telescope.

The calcite plate is dimensioned and oriented in such a way that when the ordinary image is centred in the star diaphragm the extraordinary image is automatically centred in the background diaphragm. Thus the polarized components are measured like star and sky in photometry and no changes in the equipment, except inserting the calcite plate and refocussing, are necessary. The Stokes parameters of the linearly polarized light are usually computed from measurements made in eight different position angles of the instrument. The construction has another important advantage: As we can see from Fig. 1b, both components of the sky background pass both diaphragms, and polarization of the sky is directly eliminated.

The direct elimination of the sky background polarization has been found especially valuable in the observations of faint stars and in moonlight. If a considerable amount of the background radiation is composed of scattered light, it can be highly polarized and very small relative changes in the sky background could cause large errors in the measured stellar polarization. Also the very small value of systematic errors obtained for brighter stars may be in part the result of the effective cancellation of the background polarization.

A new multichannel version of the polarimeter was put into operation in the Metsähovi Observatory of the University of Helsinki in early 1979. The colour bands (UBVRI) are separated by dichroic filters, which reflect a desired spectral interval and transmit the other wavelengths. By using four such selective beam-splitters the light is directed to five photomultipliers for strictly simultaneous recording. The resulting passbands are close to the standard UBVRI system, with equivalent wavelengths 0.36, 0.44, 0.53, 0.69, and 0.83 μm, respectively. The photomultiplier box is freon cooled to −20° C to reduce the dark current of the gallium arsenide photocathodes of the R and I photomultipliers.

The operation of the polarimeter is controlled by a microprocessor unit which is a modification of the KLT Data Adapter, programmed for the data acquisition and reduction with the chopping polarimeter. The unit is commercially available from KLT Elektroniikka Oy, Linnankatu 1, SF-00160 Helsinki 16, Finland. The present version is capable of counting pulses from five photomultipliers into 2 × 5 registers in the chopping mode. A complete polarimetric observation consists of eight integrations of starlight in different orientations of the polarimeter or the retarder, from which the normalized Stokes parameters, average intensities and error estimates from photon statistics are computed and printed.

In the automatic mode the processor generates pulses for the stepping motor rotating the retarder in front of the calcite plate. For linear polarization observations a half-wave retarder and for circular polarization a quarter-wave retarder is used. After the eight integrations the results are computed and listed. New observation is started automatically. The background values are stored and updated with desired intervals, usually about every 15 min. In the manual mode each integration is initiated by a start command. This mode is used in the most stringent applications where the whole polarimeter is rotated in steps of 45°.

The instrument is changed to a multichannel sky-chopping photometer by removing the calcite plate from the beam. Conventional (non-chopping) photometry is also possible, as it may be desirable in the case of bright stars and negligible sky intensity, or surface photometry with large diaphragms.

The multichannel polarimeter has been used in 1979–81 in the Metsähovi Observatory, and since 1981 in the Crimean Astrophysical Observatory, mainly for studies of interacting close binaries (see e.g. Piirola and Vilhu, 1982, Piirola et al., 1983, Efimov et al., 1984). The instrument for the present observations at La Silla is practically identical to the aforementioned polarimeter. Some modifications were made in the polarimeter head to enable a remote TV-control with the Danish 1.5 m telescope.

The following three programmes were carried out during the 17 nights allocated:

(i) measurements of polarization of stars with very small polarization, taken from J. Tinbergen's list (Tinbergen, 1979);

(ii) measurements of stars with large polarization, $P \geqq 1\%$, taken from D.S. Mathewson and V.L. Ford (1970), K. Serkowski (1974), and from J.S. Hsu and M. Breger (1982);

(iii) measurement of A and F type, Population II stars, of intermediate and high galactic latitudes for which good Strömgren four-colour and Hβ photometry exist (J. Knude, 1981).

(i) The programme was designed for determining the instrumental polarization, that is the polarization due to telescope and polarimeter. The 35 stars that were measured in the U, B, V spectral regions during two nights are all nearby objects and their interstellar polarization should, therefore, be negligible. Thus the mean values of the observed Stokes parameter, $\overline{P}_x$, $\overline{P}_y$, represent the instrumental polarization by means of which the observed P_x, P_y must be corrected. When subtracting the instrumental polarization each colour was treated separately. In comparing our results with Tinbergen's (1982), denoted by 1/2(I + II) (see his Table 5) we have taken the average of our B and V parameter values. The small difference in effective wavelength, in the sense that ours is shorter, will hardly influence the results. Taking Tinbergen's values as reference, we get the following deviations in units of 10^{-5}:

$$\Delta P_x = -4.3 \pm 1.9$$
$$\Delta P_y = 3.9 \pm 1.5$$

In Table 1 we have listed the differences between Stokes parameter values for three other sources taken from Table 4 in Tinbergen's paper.

TABLE 1

	Schröder Tinbergen	Serkowski Tinbergen	Serkowski et al. Tinbergen	KPR Tinbergen
$\Delta\overline{P}_x$	-5.4 ± 1.5	-3.3 ± 2.9	-8.0 ± 4.3	-4.3 ± 1.9
$\Delta\overline{P}_y$	4.9 ± 1.9	1.2 ± 3.6	-0.7 ± 3.7	3.9 ± 1.5

Taking the weighted arithmetic mean of the first three sets of data, we get −5.2 and 3.3, respectively, in units of 10^{-5}, which differ by less than one unit from our ΔP_x, ΔP_y. It should be kept in mind that the Serkowski and Serkowski et al. data are from observations with a rotatable telescope. We conclude that systematic errors in our polarization values due to instrumental polarization are less than $2 \cdot 10^{-5}$.

(ii) Measuring stars with high polarization, $P \geqq 1\%$, would enable us to judge the quality of our material from several points of view. In this category we have observed 5 stars from the list of Hsu and Breger of polarization standard stars. 17 stars are common with those observed by Serkowski et al. for studying the wavelength dependence of interstellar polarization. Additional objects are from the Mathewson and Ford catalogue.

A comparison of our polarization values with those of Serkowski et al. leads to the following regression lines for the U, B, V pass bands:

$$P^U(\mathrm{KPR}) = \underset{\pm.017}{1.073}\, P^U(\mathrm{Serk}) - \underset{\pm.033}{0.097}$$
$$P^B(\mathrm{KPR}) = \underset{\pm.016}{1.015}\, P^B(\mathrm{Serk}) - \underset{\pm.036}{0.084}$$
$$P^V(\mathrm{KPR}) = \underset{\pm.014}{1.043}\, P^V(\mathrm{Serk}) - \underset{\pm.033}{0.077}$$

Not unexpectedly the largest deviations are found in the U channel. These relations should be regarded as preliminary and may be slightly changed by a more refined statistical

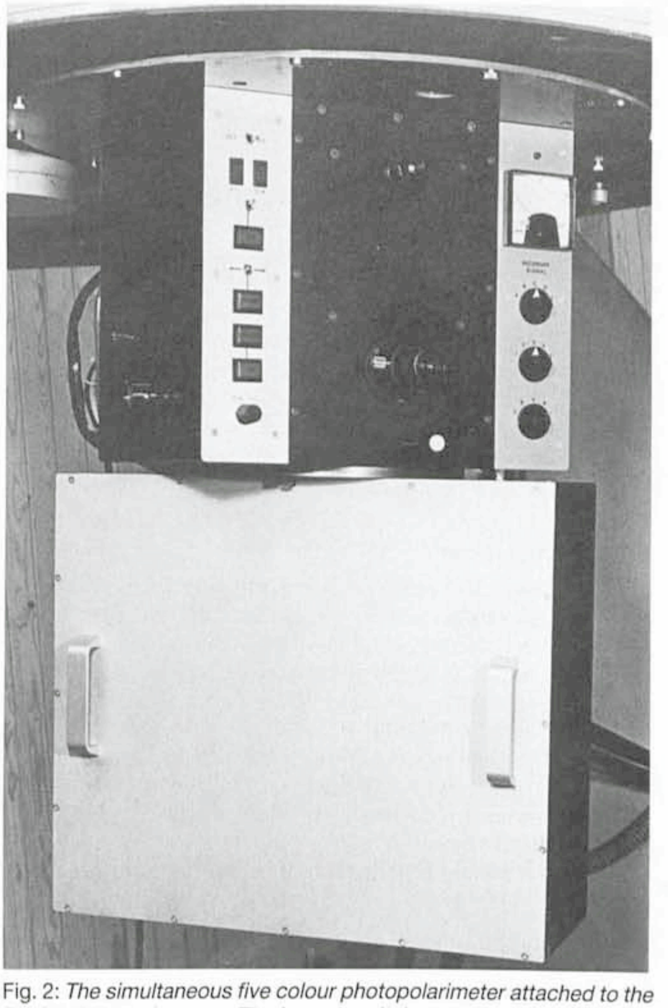

Fig. 2: *The simultaneous five colour photopolarimeter attached to the Danish 1.5 m telescope. The lower box is freon cooled to −20° C and contains five photomultipliers to which light is directed through dichroic filters.*

treatment. We have done the same excercise comparing our polarization values with those of Mathewson and Ford, measured in the B region. Three stars for which polarizations differ markedly have been omitted. We have made two least square solutions, one where the star HD 160529, P = 7.12 has been omitted

$$P(KPR) = 1.010\ P(MF) - 0.032, \text{ HD 160529 omitted}$$
$$\pm .0.14 \qquad \pm 0.030$$

$$P(KPR) = 1.010\ P(MF) - 0.031, \text{ HD 160529 included}$$
$$\pm .010 \qquad \pm 0.024$$

They give identical results. Repeating the solution, assuming errors in both coordinates, we get the values 1.016 and −0.042, respectively.

The same material has been used for examining how well our data fit Serkowski's empirical formula relating the ratio $P(\lambda)/P(\lambda_{max})$ to the corresponding ratio λ_{max}/λ (Serkowski et al., 1975)

$$P(\lambda)/P(\lambda_{max}) = \exp(-K \ln^2 \lambda/\lambda_{max}), K = 1.15 \qquad (1)$$

Recent polarization observations in the near infrared by B.A. Wilking et al. (1980, 1982) have led to a revised form of this relation reflecting a linear variation of K with λ_{max}. However, for the optical region in which our observations have been made, the two expressions will give almost identical results.

Even though the material is limited, 37 stars observed in the U, B, V, R spectral regions, most of them during more than 10 nights and none less than two nights, we think that the observations fit the curve calculated from Eq. (1) quite well (Fig. 3). Summing up the results obtained from a preliminary analysis of the large polarization data, we conclude that they show very minor scatter, the systematic errors being at the 10^{-4} level.

(iii) With regard to the third group of stars our plan was to reobserve those A and F Population II objects of intermediate and high galactic latitude for which well determined colour excesses and distances were available (J. Knude, 1981) and for which polarizations had been measured in an earlier run, March 1980. Altogether about 200 stars had been observed in the B spectral region, distributed over 8 areas. The instrument used on that occasion was a prototype of the present double beam chopping polarimeter (Piirola 1973 and 1975).

The purpose of the programme was to study the correlation between polarization and colour excess in an endeavour to determine an upper limit for the ratio between these two quantities and hence a lower limit for the colour excess. Various attempts based on photometric observations have been made in recent years to determine the interstellar reddening in the polar caps (c.f. Appenzeller, 1975). With the exception of Knude's photometric work, using Strömgren four-colour and Hβ photometry in much denser net than before, the results have come out negative or inconclusive. On the other hand accurate polarimetry has demonstrated that light from stars in the galactic polar caps is polarized, and that, therefore, interstellar dust must be present also at high galactic latitudes. It would then be of considerable interest to fix an upper limit for the ratio between polarization and colour excess. In the paper by Serkowski et al. the following upper limit has been derived:

$$P_{max}/E(B-V) \leqq 0.195, \qquad (2)$$

where P_{max} is the maximum interstellar polarization.

This relation, which puts a lower limit on the colour excess, seems to hold for most galactic stars, also for objects in regions where the interstellar reddening law deviates noticeably from its standard form.

Our polarization measurements from the 1984 run are complete for only 4 areas; the number of stars observed is 85,

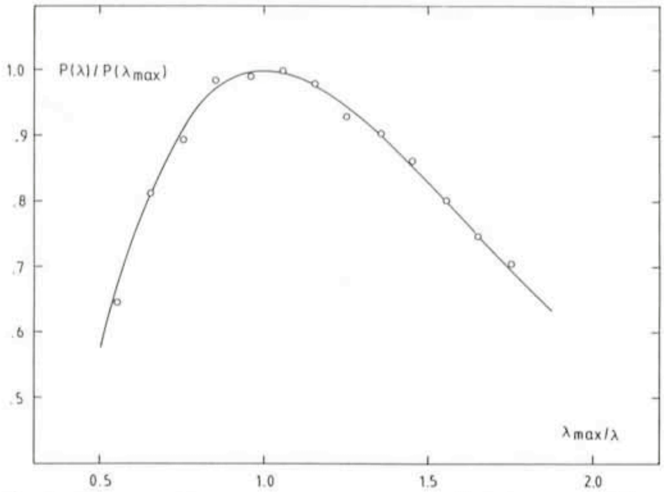

Fig. 3: *The normalized wavelength dependence of interstellar linear polarization derived from observations with the double beam chopping polarimeter at La Silla. The open circles represent mean values of $P(\lambda)/P(\lambda_{max})$ calculated for equidistant arguments of λ_{max}/λ. The solid line represents equation (1). The figure is based on 165 polarization measurements in the UBVRI pass bands.*

of which 70 have reliable colour excesses. During the 1980 run the polarization in the B pass band was recorded for 172 stars for which colour excess and distance were available (Knude, 1981). We have, therefore, resolved to make use of this material. In Table 2 we have given mean values of polarization and colour excess for the 8 areas.

TABLE 2

$\overline{l}$	$\overline{b}$	$\overline{p}$ %	$\overline{E}$(B–V)	$\overline{p/r}\,10^6$	N
23°	82°	0.050	0.019	7 ± 1	23
282	66	.095	.021	14 ± 2	36
38	60	.122	.009	18 ± 2	22
352	60	.363	.029	52 ± 8	16
9	50	.213	.018	23 ± 2	18
232	46	.076	.019	13 ± 2	26
12	38	.492	.053	64 ± 9	13
23	29	.676	.076	96 ± 14	18

Adopting a linear relation between $\overline{P}$ and $\overline{E}$(b–y) we get

$$\overline{P}_m = 0.163\,\overline{E}(B-V) - 0.001, \qquad (3)$$

P_m polarization in magnitudes, where we have used the relation 1.42 E(B–V) = E(b–y) and further assumed that $\overline{P}$ and $\overline{E}$ are both liable to errors. The slope of the regression line, 0.163, is lower than the value 0.195 quoted from Serkowski et al., which refers to the maximum interstellar polarization and the colour excess E(B–V). It lies also below the often cited value 0.18 (see e.g. Mathewson and Ford). As an order of magnitude estimate of the interstellar reddening at the north galactic pole we take from Table 2 $\overline{P}$ = 0.050 %; by means of Eq. (3) we get E(B–V) ≧ 0.007 which is lower than the value 0.012, derived from P_{NGP} = 0.0020 given by Appenzeller (1975).

In Table 2 we have also listed mean values of P/r for each of the 8 areas (r is the distance in parsec). There is marked scatter from $7 \cdot 10^{-6}$, which coincides with the value given by Markkanen (1979, 1975) to a value 14 times larger at the galactic latitude ~30°. It should be kept in mind, when comparing these data with those given by Tinbergen (Table 7), that, in our case, the stars for which polarization has been measured have distances ranging from 50 to 650 parsecs with the majority larger than 150 parsecs.

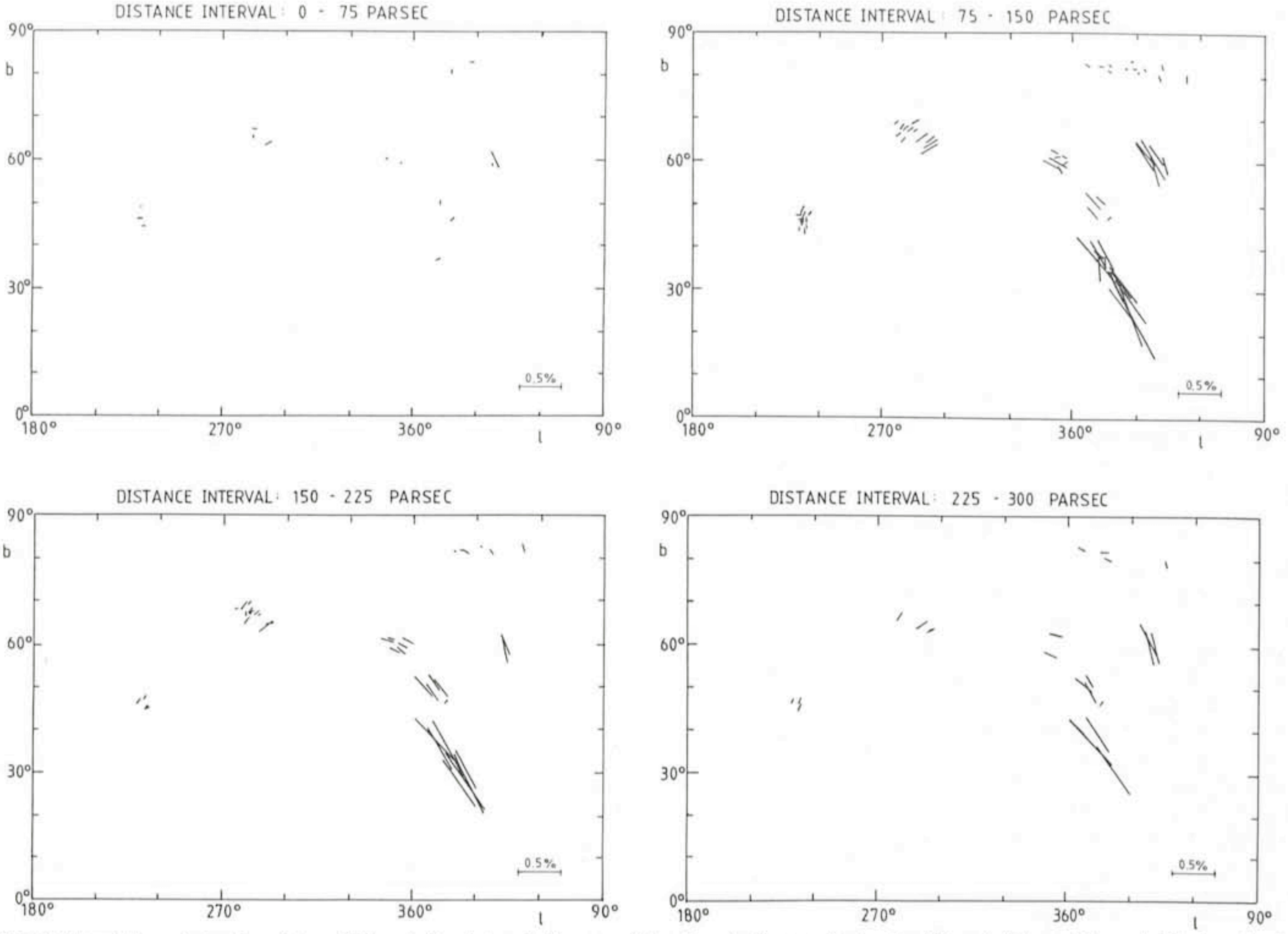

Fig. 4: *Interstellar polarization of A and F Population II stars in 8 areas, plotted in galactic coordinates for different distance intervals. The length of the bars indicates the amount of polarization, their orientation the electric field vectors.*

The polarization measured in 1980 for all A and F Population II stars for which reliable distances were available have been plotted in galactic coordinates (Fig. 4). The length of the line is a measure of the polarization, the orientation is relative to the north galactic pole. For stars closer than 75 parsec, there is no sign of parallel orientation of the E vectors; the interstellar polarization of stars in this group is markedly smaller than for the other distance groups, hence the position angle shows a considerable scatter. The low interstellar polarization suggests a low dust content in this part of space. There are too few stars in this sample to decide whether there is an increase in polarization and hence in dust content at lower galactic latitudes. There is clearly a discontinuity between the interstellar polarization of stars in the first distance group and those at distances larger than 75 parsec; but one cannot tell from the present material *where* the discontinuity sets in. For stars at distances larger than 75 parsec the orientation of the E vector is approximately the same in each area and distance group. There are no clear signs that interstellar polarization increases with distance. There is a clear indication of increasing interstellar polarization when moving towards the galactic plane, but this could, in part, be explained by local effects.

The observations of the interstellar polarization in the southern sky will be continued in November 1984. Further planned work includes e.g. simultaneous multicolour polarimetry and photometry of magnetic compact binaries (AM Her-type). These objects have a white dwarf component whose field ($B > 10^7$ Gauss) controls the accretion flow onto the magnetic poles. Optical cyclotron radiation is emitted from the fast electrons moving in the magnetic field. This results in high circular polarization (10–30%) of the observed light, varying with the phase of the orbital period, as the angle between the line of sight and the magnetic field changes. Simultaneous observations in different colours are essential due to the short periods ($P < 3$ h) and the rapid flarelike activity.

There is considerable interest also in star forming regions and young stellar objects. Polarimetry is an effective tool in monitoring circumstellar dust envelopes and particle size distribution. Work is also being done on later stages of stellar evolution, e.g. rapidly rotating giant stars (FK Comae-type) which probably are the result of the coalescence of the components of a close binary star system.

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References

Appenzeller, I.: 1957, *Astron. Astrophys.* **38,** 313.
Efimov, Y.S., Piirola, V., and Shakhovskoy, N.M.: 1984, *Astron. Astrophys.* (in print).
Hsu, J.C. and Breger, M.: 1982, *Astrophys. J.* **262,** 732.
Knude, J.: 1981, *Astron. Astrophys. Suppl.* **44,** 225.
Markkanen, T.: 1979, *Astron. Astrophys.* **47,** 201.
Mathewson, D.S., Ford, V.L.: 1970, *Mem. Roy. Astron. Soc.* **74,** 139.

Piirola, V.: 1973, *Astron. Astrophys.* **27**, 383.
Piirola, V.: 1975, Ann. Acad. Scient. Fenn. Series A, VI. Phys. 418.
Piirola, V. and Vilhu, O.: 1982, *Astron. Astrophys.* **110**, 351.
Piirola, V., Vilhu, O. and Tuominen, I.: 1983, in Cataclysmic Variables and Related Objects, M. Livio and G. Shaviv (eds.), Proc. IAU Coll. No. 72, **101**, p. 207.
Piirola, V.: 1983, ibid., p. 211.
Serkowski, K.: 1974, in Methods for Experimental Physics, Vol. 12, Astrophysics, Part A, Eds. M.L. Meeks and N.P. Carelton, p. 361, Academic Press, New York.
Serkowski, K., Mathewson, D.S., Ford, V.L.: 1975, *Astrophys. J.* **196**, 262.
Tinbergen, J.: 1979, *Astron. Astrophys. Suppl.* **35**, 325.
Tinbergen, J.: 1982, *Astron. Astrophys.* **105**, 53.
Wilking, B.A., Lebovsky, M.J., Martin, P.G., Rieke, G.H. and Kemp, J.C.: 1980, *Astrophys. J.* **235**, 905.
Wilking, B.A., Lebovsky, M.J. and Rieke, G.H.: 1982, *Astron. J.* **87**, 695.

Chromospheric Modelling in Late-Type Dwarfs: 1. Quiescent Objects

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1. The Purpose of Chromospheric Modelling

Observational facts about chromospheres are now well established. The existence of a layer at a higher temperature than the underlying photosphere in a star like the Sun gives rise to "superthermal" emission features of relatively low excitation which are strong and easily recorded. Nevertheless, there are many unanswered basic questions about chromospheres which still merit the attention of observers and theorists alike. In a recent article in the *Messenger* (No. 35) Pallavicini described some of the observations which go into producing a picture of a typical chromosphere. He dwelled in particular on two types of observations which can be made with the CES (Coudé Echelle Spectrograph) which operates with either the 3.6 m or the CAT at La Silla. These were the use of high spectral resolution to try to derive the rotational velocities of slowly rotating objects via Gray's asymmetry method, and close examination of the cores of the Ca II H and K emission lines. He also picked out X-ray luminosity, measured by the Einstein satellite, as a parameter strongly correlated with rotation, and hence with the existence and strength of chromospheres.

In this article we will be dealing more directly with some of the problems which arise when trying to use observational material to clarify the mechanisms which heat the chromosphere of a late-type star, in order to obtain a clear physical picture of what a chromosphere is like, how it is related to the underlying photosphere, and to the overlying corona. It is usually said that the chromospheres of late-type stars are heated by mechanical deposition of energy from the convective zone of the upper photosphere, or alternatively by magneto-acoustic energy. To what extent can we distinguish in practice between these two mechanisms, and is either of them the same as that which heats coronae? How directly can we translate information given to us in the form of high resolution line profiles of, say, the H and K resonance lines of Ca II, or their Mg II h and k analogues into a semi-empirical model which incorporates energy sources and their distribution with depth. We will illustrate our points with observations taken with the CES and also with the IUE satellite long wavelength spectrograph.

2. Reliable Data and Reliable Interpretation

The cool star observer has an apparently major asset compared with those who are trying to interpret the spectra of other stars, which is his ability to make comparisons with the Sun. This can, however, be misleading, and as an example we can cite our experience with IUE spectra in the h and k resonance lines of Mg II. Thanks to some careful and beautiful balloon-borne solar spectroscopy by Lemaire and Skumanich (*Astronomy and Astrophysics,* **22,** 61), it was clear as early as 1973 that a chromospheric emission line would have a significantly different appearance and strength depending on whether it came from the quiet chromosphere or from a plage "active" region; its strength varies from one chromospheric regime to another, from plages, to supergranular cells, to cell boundaries. To some degree also the shape changes, so that the central self-absorption appears differentially shifted with respect to the chromospheric emission core. Clearly, even from this small sample of information we can see that it will not be easy to interpret the spectra of other stars, which are of course the integrated products of all the regions of their chromospheres. In a star which may have stronger velocity fields than the Sun, it will be hard to take out the line structure imposed by the combination of velocity fields, leaving only the dependence of density, electron density and temperature with height, which must typify the model. In fact the Mg II spectra of G dwarfs taken with IUE, of which four examples are shown in Fig. 1, appear to give striking evidence for the widespread existence of such velocity fields. The central self-absorption is displaced by several km s^{-1} with respect to the emission core, sometimes to the red, sometimes to the blue. Most papers dealing with Mg II until 1983 (with the notable exception of one by Bohm-Vitense) dealt with such line profiles as showing evidence for chromospheric motions, although few attempts were seriously made to provide physical explanations. The values for the red-shifts or blue-shifts were from a few km s^{-1} to ten or even twenty. It is inconceivable that whole chromospheres could be moving outwards or inwards at those kinds of speeds, but one problem was that accurate absolute velocity data with IUE were hard to derive (typical precision was of order ± 10 km s^{-1}), so it was never wholly clear whether the emission or the self-absorption at the centre was shifted with respect to the photospheric radial velocity. Circumstellar shells, either in expansion, or even in collapse, could be ruled out as the mass-losses or mass accretions implied were orders of magnitude too large. Finally, after several years of effort in improving the wavelength and photometric fidelity of the spectra, it could be ascertained that the whole story was a "red herring" (or a blue herring as the case may be) in that most