OBSERVATIONAL POLARIMETRY PROGRAMS FOR SMALL TELESCOPES

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ABSTRACT. A number of promising observational programs involving linear polarization measurements are discussed after consideration of the observational limits based on telescope size and instrumental accuracy. These projects include studies of interstellar extinction, circumstellar shells and extended envelopes, inhomogeneities on stellar surfaces such as nonradial pulsation, magnetic stars, and interactive binary systems.

1. INSTRUMENTAL AND OBSERVATIONAL LIMITS

The high observational accuracy of modern polarimeters has opened the door to many exciting, new astronomical applications. The choice of suitable polarimetric projects is limited by telescope size (through the number of available photons) and the accuracy of the equipment. Since a surprisingly large number of polarimetric papers in the literature contain doubtful results, considerable attention should be given to the size of the expected, as well as actual uncertainties of measurement. For a bright star measured with a modern polarimeter an accuracy in the range of ± 0.01% should be possible with repeated measurements and at least 2×10^8 photons. With our single-channel polarimeter (Breger 1979), for a 200-second integration the limit is set by scintillation noise, which results in ± 0.02% on a 2-meter telescope. In this talk we would like to mention a few promising linear-polarization projects and emphasize broadband measurements.

The type of polarimeter used may well be of secondary importance in determining the observational feasibility of the projects. The use of rapid modulation or multiple channels permits high accuracy to be achieved even under nonoptimum weather conditions. Observations of standard stars (Serkowski 1974, Hsu and Breger 1982) are strongly recommended. The unpolarized standard stars allow the determination of the size of, and possible small changes in instrumental polarization. On the other hand, the observations of polarized standards (or another suitable method of calibration) fix the zero-point of the position angle and provide

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TABLE I

LIMITING MAGNITUDES WITH A 1-METER TELESCOPE
(Single-beam, background not included)

Photon-Statistics Accuracy	Filter	10-minute integration	60-minute integration
0.01%	Open	$8^{m}.0$	$9^{m}.9$
	B	$6^{m}.6$	$8^{m}.5$
	V	$5^{m}.8$	$7^{m}.7$
0.1%	Open	$13^{m}.0$	$14^{m}.9$
	B	$11^{m}.6$	$13^{m}.5$
	V	$10^{m}.8$	$12^{m}.7$
0.5%	Open	$16^{m}.5$	...
	B	$15^{m}.1$	...
	V	$14^{m}.3$	$16^{m}.2$

a check on the size of the polarization value.

Table I lists typical magnitude limits (photon statistics) for different values of desired accuracy. In this table, the filter "Open" refers to filterless measurements with an efficient EMI 9658A photomultiplier tube. The actual observations require more time than listed because of background measurements and other observational activities such as recentering of the star in the aperture.

2. INTERSTELLAR POLARIZATION

The presence of interstellar dust leads to extinction as well as polarization of light passing through the interstellar medium. With modern polarimeters the resulting value of polarization is often more easily and accurately measured than the corresponding extinction or reddening value. An interstellar reddening of $E(B-V) = 0^{m}.01$ is difficult to determine accurately through conventional photometric or spectroscopic means. A reddening of $E(B-V) = 0^{m}.01$ is accompanied by a relatively easily measured polarization value near 0.06%. (The exact value depends on the direction of the interstellar magnetic field, among other factors). In order to use polarization as a probe for the interstellar medium, several properties of the interstellar medium need to be considered:

(i) Interstellar polarization follows a standard wavelength dependence of polarization, shown by Serkowski, Mathewson and Ford (1975,hereafter referred to as SMF) to be of the form

$$p(\lambda)/p(\max) = \exp\left[-1.15 \ln^2 (\lambda(\max)/\lambda)\right],$$

where $\lambda(\max)$ is the wavelength at which the polarization reaches its maximum value, p(max). Recent discussions (Wilking, Lebofsky and Rieke 1982) of a possible dependence of the constant, -1.15, on $\lambda(\max)$, and the presence of structure in the wavelength dependence (Wolstencroft and Smith 1984) indicate fascinating new areas of investigation. Nevertheless, applications of the general formula still appear meaningful and the wavelength dependence of polarization is a powerful tool to separate interstellar from other sources of polarization.

(ii) In clusters with constant values of foreground extinction from star to star, the amounts of polarization are usually also constant. Since cluster nonmembers are at different distances relative to cluster members, the nonmembers often show different amounts of extinction and polarization. For these clusters polarization can be used to separate members from nonmembers. This argument was successfully applied to NGC 7789 (Breger 1982), where it was shown that the blue-straggler candidates cooler than the main sequence do not belong to the cluster. In star clusters with variable reddening and polarization, the comparison of reddening and polarization values may permit a modeling of the different interstellar cloud patches. This is based on the fact that reddening is purely additive, while polarization is a vectorial quantity. The presence of a second cloud with a different magnetic-field direction, for example, increases the reddening value, causes a rotation of the position angles of polarization, and could lead to depolarization. The Pleiades cluster is a good example. Our model of a uniform foreground cloud and a patchy cloud moving through the western part of the cluster is also consistent with atomic-line data as well as radio and millimeter measurements.

(iii) The value of $\lambda(\max)$ is related to the ratio of total to selective extinction by $R = 5.5\lambda(\max)$, as pointed out by SMF. Polarization measurements are, therefore, important to locate unusual values of R in the interstellar medium.

For small telescopes a promising application seems to be the study of systematic regional versus local origins of abnormal values of R. The historical question whether or not values of R greater than the normal value of 3 (i.e. $\lambda(\max)$ greater than 0.55μm) show a systematic dependence on galactic longitude and latitude has not been settled (e.g. see SMF). Our speculation is that both local and large-scale systematic regional variations are involved. The Orion cluster is a good example for local effects near the stars, with variations in the value of R from 3 to 5.

On the other hand, the stars in the Scorpius-Ophiuchus region of the sky may be an example of unusually large R values covering a large region of the sky. For this region, Meyers et al. (1985) propose a weak shock in the interstellar medium in the Scorpius-Ophiuchus direction. The rotation of the position-angle of polarization up to a few degrees with wavelength, determined so far for a few stars, may be related to these processes in the interstellar medium.

To answer these questions, accurate determinations of λ(max) and position angles are required for many more relatively bright stars.

3. CIRCUMSTELLAR SHELLS AND EXTENDED ENVELOPES

Scattering in aspherical circumstellar envelopes surrounding stars leads to polarization which often exceeds 1%. Be, T Tauri and hot pre-main-sequence stars are good examples. Time variability and a noninterstellar wavelength dependence of polarization are important clues.

The variability of the polarization of the polarization in γ Cas led to the discovery of the intrinsic polarization in Be stars (Behr 1959). The polarization does not exceed 2%. Striking features of the wavelength dependence of polarization of Be stars are the rapid decrease in polarization shortward of the Balmer limit at 0.365 μm and the decrease of polarization in the Balmer emission lines. A good example of the wavelength dependence is shown in the paper by Poeckert, Bastien and Landstreet (1979), and a very thorough discussion can be found in the monograph on B stars (Underhill and Doazan 1982).

The extreme brightness of many Be stars encourages a time variability study with small telescopes. Due to the "discontinuous" wavelength dependence of polarization, the standard UBV filters would not be an optimum choice for such a study. The standard U filter, for example, does not avoid the Balmer jump, while the u filter of the uvby system would be more suitable for a cleaner ultraviolet measurement.

The polarization of T Tauri stars can be as high as 12% (Bastien 1983). A standard wavelength dependence of polarization does not seem to exist. The question of the existence of periodicities, or better, timescales, of these variations still needs to be settled. The hot pre-main-sequence stars also deserve considerably more photometric and polarimetric study. Many of these stars are brighter than 12th magnitude and can be observed with small telescopes.

4. INHOMOGENEITIES ON THE STELLAR SURFACE

Inhomogeneities, asymmetry and distortions of the stellar disk can, at those wavelengths where scattering dominates as an opacity source, lead to a small amount of linear polarization. The size of this polarization is near the present limit of detectability of 0.01%. Some origins of inhomogeneities could be nonradial pulsation, spots, or large convection cells. The small size of the resulting polarization makes it difficult to separate these intrinsic effects from interstellar polarization. However, the different wavelength dependence of polarization and the expected time variability are important clues.

4.1 Nonradial Pulsation

Among hot stars, in which electron scattering is an important opacity source, the distortions of the visible disk could lead to polarization variability with small amplitudes. The size and phasing of the linear polarization as well as the position angles are dependent on the particular pulsation mode(s). This was suggested as a test for mode-typing by Odell (1979) as well as Stamford and Watson (1980). It was also shown in these papers that the amplitudes of polarization variability should be larger in the ultraviolet and blue regions than in the visible. The most promising objects for study appear to be hot pulsators with low orders of nonradial pulsation, ℓ and m, as well as objects in which one pulsation mode is dominant. A (possibly large) number of pulsation cycles could be averaged for better signal-to-noise ratios. Prior knowledge of the photometric frequencies and epochs would be useful, but not an absolute requirement.

The β Cephei variables appear well-suited for such polarimetric studies since many members of the class fulfil the conditions listed above and are also bright enough for a high count rate. In a pioneering paper, Odell (1981) measured the star BW Vulpeculae during four nights. He found a statistically significant (4 sigma) change of polarization during the 0^{d}.201 cycles and a peak-to-peak amplitude of 0.008%. The phase of maximum polarization occurred near maximum light.

Such a small polarization amplitude below the accuracy of a single observation must naturally be treated with some caution. According to a private communication by Odell, Kemp has repeated the measurements of BW Vulpeculae and finds a similar amplitude, although uncertainties due to possible large phase disagreements are suspected.

A polarimetric project to remeasure BW Vulpeculae over a larger number of cycles would be important. Other bright β Cephei stars with a strong nonradial mode (such as β CMa and ν Eri) also appear promising.

4.2 Convection Cells in the Photosphere

It has been known for a long time (e.g. Dyck 1968) that cool giants and supergiants show polarization, which is intrinsic and variable with time. A plausible physical explanation is the scattering from a photosphere with brightness variations across the photospheric surface. According to Schwarzschild (1975), large convection cells appear and disappear on the surface over a few months. The resulting linear polarization would be less than 1%.

A well-studied example is the M supergiant α Ori (Hayes 1981, Schwarz and Clarke 1984). In another recent study (White, Shawl and Coyne 1984), 15 out of 39 red giants in the globular clusters M3 and M13 were found to show intrinsic polarization with sizes generally less than 2%. This shows that relatively high intrinsic polarization may well be a common property of cool giants and supergiants. More polarimetric surveys with attention given to the subtraction of the interstellar component, if any, are needed.

5. MAGNETIC STARS

The study of linear polarization variability in magnetic CP2 stars has a long and contradictory observational history. The presence of intrinsic linear polarization and its variability (caused by the rotation of the star) has been predicted many times. Demkina and Obridko (1973), for example, have pointed out that the transverse component of the magnetic field causes linear polarization over a wide spectral range. In a field strong enough for the Zeeman components to be completely resolved,

$$p \sim W_{\pi}(\eta_0) - 2\, W_{\sigma}(\eta_0/2),$$

where p is the degree of linear polarization in the line; W_{π} and W_{σ} are the equivalent widths of the π and σ components, respectively; and η_0 is the ratio of the line-center opacity relative to the continuum opacity. For weak lines the polarization cancels out. For partially saturated lines the polarization reaches a maximum value. Rough calculations show that the net broad-band linear polarization in the typical CP2 star should be less than 1%. A careful choice of wavelength regions (through examination of the lines in the regions) could maximize the measurable amounts of polarization. As is the case for other intrinsic sources of polarization, time variability and a nonstandard wavelength dependence of polarization would allow us to distinguish between interstellar and intrinsic polarization.

The early reports of polarization variability were regarded by Serkowski and Chojnacki (1969) to be "not incontestable". Serkowski and Chojnacki measured a number of CP2 stars and found no evidence for a linear polarization variability at the 0.1% level. In particular, the variability reported earlier for HD 71866 (0.1 to 0.3%, Thiessen 1961) was not confirmed.

For the star HD 215441, Kemp and Wolstencroft (1973) detected large changes, up to 2%, in the linear polarization of the Hß center and wings. Continuum values were relatively constant. For the star 53 Cam, the detected small variations (less than 0.1%) in both Hß and the broad-band continuum could be correlated with the star's magnetic phases.

Polarimetric studies of both the Hß profile and the broad-band continuum in magnetic CP2 stars appear very promising. A number of bright candidates are available.

In the previous sections we could list only some astrophysical areas for which linear polarimetry with small telescopes appears promising. The high accuracy of modern polarimeters permits us to examine bright stars to study new problems. It is regrettable that the highly polarized polars (AM Her stars) had to be omitted from our list of proposed programs for small telescopes because of the combination of their relative faintness and rapid polarization variability. (We note that AM Her itself, with an intermediate V magnitude of $12^{m}.9$ could be studied with a one-meter telescope.)

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DISCUSSION

Burki: Is the polarization technique more sensitive than the study of line profile variations for the determination of non-radial modes?

Breger: No, but the study of line profile variations requires large telescopes and high dispersion spectrographs. In order to understand non-radial pulsations we need to use as many techniques as possible : line profiles, photometry for variability and relationships between light and colour variations, radial velocity and polarisation measurements.

Finkenzeller: I fear that the main problem when doing polarimetry of pre-main sequence objects is not that of getting the vector, but its astrophysical interpretation. Almost all objects are surrounded by reflection nebulosity which introduces strong aperture-size effects. Thus, one would wish to have both high data quality *and* high spatial resolution. Together, with typical magnitudes of T Tauri stars fainter than 11, one is likely to rely on intermediate and large size telescopes.

Breger: I believe that important work can still be done with small telescopes. An example might be the star W90 in NGC 2264. It appears to lie below the main sequence and moves parallel to the main sequence. Its polarization is about 2%. Are the polarization and abnormal position in the HR diagram caused by intracluster dust or shells?

Rucinski: I think that eclipsing binaries and close binaries in general should not be forgotten. The polarization methods can be used to obtain additional information on the geometry and, indeed, can be used to discover pole-on close binaries which should show a constant but rotating vector of polarization.

Warner: The statistics of limiting magnitudes for linear polarization is similar to that for circular polarization. As we now know, many AM Her stars which have circular polarizations in excess of 10 percent, accuracies of only ~ 1 percent are adequate for the study of time variability. With broad-band polarimetry, magnitude 15½ can be reached with time resolution of ~ minutes even with telescopes of 1 metre aperture or less. Because of the great variability of the AM Her stars, on timescales ranging from minutes to years, a much greater body of data needs to be accumulated for analysis and this can only be done with the large amounts of time available on small telescopes.

Breger: Before the discovery of the high polarization of polars (AM Her stars), the amount of known circular polarization was too small to be measured with small telescopes. The interesting circular polarization of AM Her stars can be observed with small telescopes.

Warner: The problem is that we don't have standards with 50% circular polarization and we therefore have to extrapolate from objects with a few tenths of a percent polarization.

Schober: Very few polarimeters are working at visiting observatory sites. ESO has tried for 15 years to set up a polarimeter. It requires an experienced resident observer. Also the alignment of optical elements is critical for instrumental calibration and with frequent instrument changes on telescopes this can be difficult.

Breger: Firstly, my suggestion is to take your own polarimeter, which you can probably trust, to the other observatories. The instrumental correction (which is usually small) can be checked by observing unpolarised standards (see Serkowski 1975, and Hsu and Breger 1982) and at least one or two of these should be observed each night.

Schober: It is very expensive to have one's own instrument!

A'Hearn: Yet another area in which useful polarimetry can be done from small telescopes is the polarimetry of cometary dust. Thus far, polarimetry of comets has not been very fruitful both because the interpretation has been done usually with Mie theory rather than with laboratory measurements of irregular particles and because, with a few exceptions such as the recent work by Myers and Nordsieck at Wisconsin, the data have not been obtained systematically. These measurements can be made with a very small telescope for bright comets such as Halley and only relatively low precision is needed, say 1%.

Breger: Since we are mentioning the many promising applications of polarimetry that had to be omitted from the talk, I will mention an omission myself. The polarimetric study of asteroids to determine their rotation and surface variation appears to be very important.