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A SIMULTANEOUS INFRARED/OPTICAL POLARIMETER

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A polarimeter capable of making simultaneous observations in the optical and near infrared is described. The instrument achieves very small ($\lesssim$ 0.03%) instrumental polarization coupled with high efficiency over a very wide wavelength range. We present *UBVRIJHK* polarization measurements of a number of standard stars with large interstellar polarizations, and use them to compile composite interstellar polarization curves.

Key words: instrumentation—polarization—standards

I. Introduction

Measurements of the wavelength dependence of polarization are important in studying a variety of astronomical objects. Improvements in the sensitivity achieved with InSb detectors over the last few years has meant that such studies can be extended into the near infrared for most objects which are observable in the optical. A number of near-infrared polarimeters have been built. These instruments however, operate in the infrared region only, so that a complete determination of the optical and infrared wavelength dependence requires observations with two instruments. While inconvenient in all cases, this is a particular problem for wavelength dependence studies on objects which vary in polarization on short time scales. Examples are the AM Herculis binaries which show polarization variations on time scales of minutes, and the BL Lacertae objects which may vary on time scales of a few hours.

A second problem with most infrared polarimeters is that they use relatively crude polarimetery techniques and are generally incapable of achieving the standard of polarization accuracy which is regularly obtained at optical wavelengths. The polarimeter described here was designed to overcome these problems.

A detailed review of the various types of modulators which can be used for astronomical polarimeters has been given by Serkowski (1974). Essentially they can be divided into three types: (1) rotating polarizers, (2) variable retarders (Pockels cells or photoelastic modulators), and (3) rotating retarders.

The majority of infrared polarimeters have been of type (1). The problem with such polarimeters is that any inclined mirrors in the beam will introduce substantial instrumental polarization. This effect can be largely removed by the use of a Lyot depolarizer, or by employing a completely axial system (Cox, Hough, and McCall 1978). However, residual effects, notably a slight dependence of the instrumental polarization on the beam centering, introduce uncertainties into the polarimetry at about the 0.1% level, making such instruments unsuitable for high-accuracy polarization.

An infrared polarimeter employing photoelastic modulators has been described by Kemp et al. (1977). This gives a low instrumental polarization and is capable of high-accuracy polarimetry. However, this technique is unsuitable for simultaneous optical/infrared polarimetry. Although photoelastic modulators can be tuned to different wavelengths they cannot be used simultaneously at two widely separated wavelengths without a substantial loss in efficiency.

The polarimeter described here employs the third technique, rotating retarders. The principal advantage is that retarders can be achromatized by combining materials with different wavelength dependence of retardance (usually quartz and magnesium fluoride) giving high efficiency over a wide range of wavelengths. Although a common technique for optical polarimeters only Kobayashi et al. (1980) have used wave plates in the near infrared.

II. Description of the Instrument

Figure 1 shows the layout of the polarimeter in the configuration used for the observations described here. A Foster (Glan Thompson) prism divides the light into two beams at 90 degrees, with orthogonal polarizations. The straight through beam is fed to a cryostat containing an InSb detector operating at 63 K. The second beam is reimaged by a pair of lenses onto the aperture of a photomultiplier assembly. Both blue-sensitive and GaAs photomultipliers have been used with the system.

Above the Foster prism are two rotatable mounts for retarders. Although only a single half-wave plate is needed for linear polarization measurements, two rotating plates are needed to provide optimum efficiency for circular polarization or for simultaneous linear and circular polarization measurements. The retarders are continuously driven by high-angular-resolution stepping motors via geared drives. A filter slide above the retarders provides for the insertion of calibration polarizers into the beam.

The retarder used for linear polarization measurements is a superachromatic half-wave plate made by

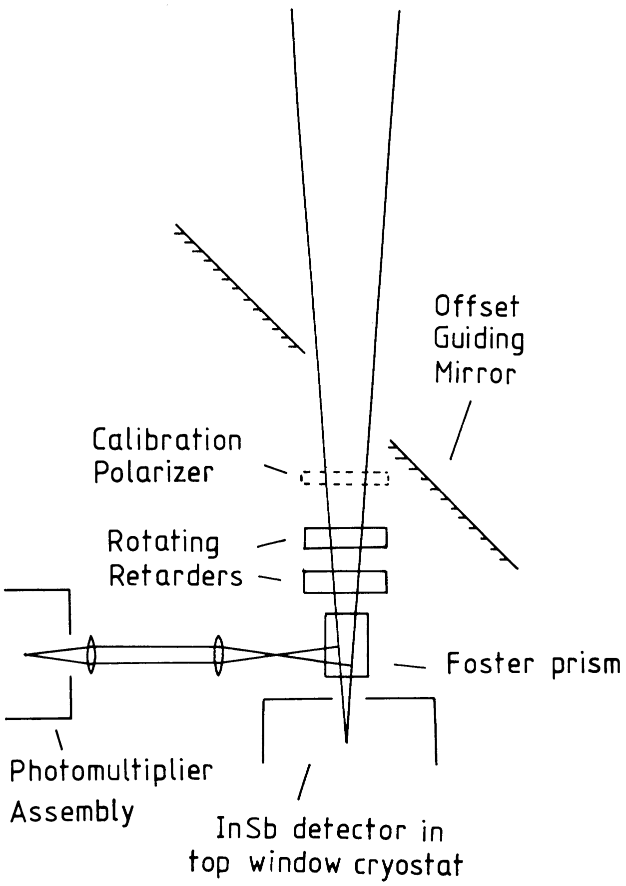

FIG. 1—The Hatfield dual-channel polarimeter. Only one of the two rotating retarders is required for linear polarization measurements.

Bernard Halle. It is designed to give a retardance within 1% of the nominal value between 0.3 μm and 1.1 μm. We have found that although the retardance deviates significantly from λ/2 at longer wavelengths it remains sufficiently close to allow effective polarization modulation in the *JHK* bands. We measure a modulation efficiency at K (2.2 μm) of 57%. This includes the effects of detector/preamp time constant (at a modulation frequency of ~ 10 Hz) as well as the departure of retardance from λ/2.

When using a retarder which deviates significantly from λ/2 several corrections to the data are necessary. First, the amplitude of the modulation is reduced. Second, the mean value of the signal no longer depends just on the intensity, but on the polarization also. Third, since the plate is of the Pancharatnam type, the angle of its fast axis, and hence the zero point of position angle is wavelength dependent. All these effects can be calibrated by means of observations through calibration polarizers and are easily corrected for. The necessary corrections are included in the real-time reduction software.

The signal from the infrared detector is amplified and fed to a voltage-to-frequency converter which generates a frequency in the range 0 to 200 kHz. These pulses are counted and the counters are read by the computer in synchronism with reference pulses generated by an encoder linked to the rotating retarder.

The optical photomultiplier can be operated in either dc or photon-counting modes. For dc operation the data acquisition is identical to that described for the infrared channel. In the photon-counting mode the photon pulses are counted directly. The dc operation is advantageous for observations of bright stars since it avoids the problem of coincidence losses which occur with photon counting at high count rates. Neutral density filters are also available to facilitate observations of very bright stars.

Background subtraction is performed by nodding the telescope between star and background positions under computer control, or by using a chopping secondary. Data acquisition and reduction is handled by a Z80 microcomputer system. All data are fully reduced in real time. At the end of each star-background pair, the cumulative results, together with errors calculated from the statistics of the data so far, are output. An observation can thus be continued until the required polarization accuracy is achieved.

III. Standard-Star Observations

All the observations were obtained with the instrument on the 1.5-m telescope of the Cabezon Observatory, Tenerife over the period 1981 July 30 to August 5. Details of the filters used are given in Table I. Note that two *I* bands were used, one corresponding to the Kron-Cousins band (referred to as I_K) observed with the GaAs tube, and one corresponding to the Johnson *I* band (0.90 μm) observed with the InSb detector.

The *K* filter response is altered by the long-wavelength cutoff of the calcite Foster prism, giving a slightly shorter wavelength and narrower bandwidth than normal.

Observations of nearby unpolarized stars were made to measure the instrumental polarization. The mean values from all such observations are given in Table II in the form of percentage Stokes parameters (*Q* and *U*). It will be seen that in no case does the instrumental polarization exceed 0.05%, while most of the measurements are not significantly different from zero. There is a marginally significant tendency for the optical data to show positive *U* values of ~ 0.03% while the infrared data show negative *U* values. The instrumental polarization is an order of magnitude improvement on most rotating polarizer systems (e.g., Dyck, Forbes, and Shawl 1971; Knacke, Capps, and Johns 1976, 1979) and is comparable with that achieved using photoelastic modulators (Kemp et al. 1977).

Table III lists measurements of standard stars with large interstellar polarizations. Most of these stars are

TABLE I

Filter Properties

Band	Central Wavelength (μm)	FWHM (μm)
U	0.36	0.05
B	0.43	0.10
V	0.55	0.10
R	0.72	0.20
I_K	0.80	0.14
I	0.90	0.18
J	1.21	0.28
H	1.65	0.28
K	2.14	0.34

TABLE II

Instrumental Polarization Measurements

Band	Q(%)	ϵ_Q	U(%)	ϵ_U
U	0.025	0.020	0.048	0.016
B	0.045	0.023	0.035	0.023
V	0.010	0.020	0.035	0.015
R	-0.006	0.015	0.024	0.013
I_K	-0.015	0.032	0.005	0.047
J	-0.003	0.010	-0.039	0.008
H	0.044	0.014	-0.006	0.023
K	0.007	0.015	-0.028	0.026

taken from the list given by Serkowski (1974). Most of the stars were observed on two or more nights and mean values are listed. The quoted errors have been obtained by combining the errors of the individual nights' observations, or from the night-to-night scatter of the measurements, whichever was larger.

In order to test the absolute accuracy of the polarimetry we have compared our data with previous results on the same stars. In the optical we used the data of Serkowski, Mathewson, and Ford (1975, hereafter SMF) which were obtained in *UBVR* bands similar to our own. A comparison of the results on the six stars in common is given in Table IV. It is clear that there is no significant systematic difference between the two sets of data. Furthermore the standard deviation of the differences (Hatfield — SMF) is comparable with the statistical errors of our observations. This indicates that the errors given by our reduction system are good estimates of the absolute accuracy of the polarimetry, at least down to levels of ~ 0.08%.

The infrared data have been compared with previous observations by Wilking et al. (1980) and by Dyck and Jones (1978). A comparison of the *J*-band data (where the polarizations are highest) is given in Table V. This comparison is complicated by the fact that there are significant differences for some stars between the results of Wilking et al. and those of Dyck and Jones. The biggest differences occur for HD 154445, HD 204827, and VI Cygni 12 for which Dyck and Jones observe substantially smaller polarizations. For all these stars our data agree

TABLE III

UBVRIJHK Polarization Measurements of Standard Stars with Large Interstellar Polarizations

HD number	Band	P(%)	ϵ_p	θ	ϵ_θ
7927 φ Cas	U	3.12	0.08	92	1
	B	3.35	0.05	92	1
	V	3.35	0.06	91	1
	R	3.07	0.04	91	1
	I_K	2.79	0.03	91	1
	J	1.65	0.05	93	1
	H	0.81	0.03	91	1
	K	0.44	0.03	87	3
21291 2H Cam	U	2.78	0.05	114	1
	B	3.32	0.06	115	1
	V	3.29	0.05	115	1
	R	3.13	0.04	116	1
	I_K	2.82	0.04	116	1
	J	1.60	0.05	116	1
	H	0.84	0.03	118	1
	K	0.43	0.04	121	2
147084 o Sco	U	2.71	0.10	30	1
	B	3.42	0.06	32	1
	V	4.21	0.03	31	1
	R	4.47	0.06	32	1
	I_K	4.40	0.07	31	1
	J	2.73	0.05	32	1
	H	1.46	0.04	31	1
	K	0.80	0.04	31	1
147889	B	2.75	0.13	178	1
	V	3.56	0.09	177	1
	R	3.99	0.09	176	1
	I_K	4.08	0.07	173	1
	J	3.05	0.10	174	1
	H	1.98	0.06	176	1
	K	0.94	0.09	172	4
149757 Oph	U	1.10	0.05	124	1
	B	1.35	0.05	124	1
	V	1.44	0.04	126	1
	R	1.35	0.05	124	1
	I_K	1.18	0.03	124	1
	J	0.78	0.02	127	1
	H	0.41	0.02	132	3
	K	0.24	0.06	133	6
15445	U	2.93	0.09	87	1
	B	3.44	0.15	88	1
	V	3.75	0.09	89	1
	R	3.63	0.04	89	1
	I_K	3.18	0.04	91	1
	I	3.06	0.11	91	1
	J	1.70	0.04	91	1
	H	0.94	0.05	91	1
	K	0.65	0.05	86	5
183143	U	5.09	0.12	179	1
	B	5.75	0.05	180	2
	V	6.19	0.04	179	1
	R	5.70	0.04	178	1
	I_K	5.30	0.09	179	1
	I	5.11	0.08	179	1
	J	2.74	0.03	176	1
	H	1.48	0.03	175	1
	K	0.86	0.03	176	2
187929 η Aql	U	1.33	0.06	90	1
	B	1.60	0.08	91	1
	V	1.71	0.06	92	1
	R	1.62	0.05	91	1
	I_K	1.50	0.04	90	1
	I	1.52	0.05	91	1
	J	0.80	0.04	93	2
	H	0.44	0.03	95	2
	K	0.29	0.04	88	4
198748 55 Cyg	U	2.47	0.08	1	1
	B	2.60	0.12	2	1
	V	2.71	0.12	3	1
	R	2.67	0.04	2	1
	I_K	2.54	0.03	3	1
	I	1.97	0.09	2	1
	J	1.37	0.05	1	1
	H	0.88	0.03	1	1
	K	0.51	0.07	176	4

1982PASP...94..618B

TABLE III (Continued)

HD number	Band	P(%)	ϵ_p	Θ	ϵ_Θ
204827	B	5.68	0.09	59	1
	V	5.63	0.07	60	1
	R	4.86	0.05	60	1
	I_K	4.04	0.08	60	1
	J	2.16	0.05	63	1
	H	1.10	0.05	62	1
	K	0.54	0.12	55	6
V Cyg 12	V	9.08	0.25	119	1
	R	7.18	0.04	117	1
	I_K	7.13	0.06	117	1
	I	5.75	0.12	117	1
	J	3.70	0.08	116	1
	H	1.94	0.03	115	1
	K	1.13	0.04	118	1

TABLE IV

Comparison of Hatfield Polarimetry with that of Serkowski, Mathewson, and Ford (1975) (SMF)

HD number	Band	SMF	Hatfield		Hatfield-SMF	
		p	p	ϵ_p		σ
154445	B	3.42	3.44	0.15	0.02	
	V	3.66	3.75	0.09	0.09	
149757	U	1.10	1.10	0.05	0.00	
	B	1.32	1.35	0.05	0.03	
	V	1.44	1.44	0.04	0.00	
	R	1.40	1.35	0.05	-0.05	
183143	U	4.99	5.09	0.12	0.10	
	B	5.83	5.75	0.05	-0.08	
	V	6.17	6.19	0.04	0.02	
	R	5.83	5.70	0.04	-0.13	
147084	U	2.85	2.71	0.10	-0.14	
	B	3.54	3.42	0.06	-0.12	
	V	4.05	4.21	0.03	0.16	
	R	4.48	4.47	0.06	-0.01	
147889	B	2.86	2.75	0.13	-0.11	
	V	3.51	3.56	0.09	0.05	
	R	3.90	3.99	0.09	0.09	
187929	U	1.46	1.33	0.06	-0.13	
	B	1.72	1.60	0.08	-0.12	
	V	1.81	1.71	0.06	-0.10	
	R	1.69	1.62	0.05	-0.07	
Mean	U				-0.04	0.11
	B				-0.06	0.07
	V				0.04	0.09
	R				-0.03	0.08

TABLE V

Comparison of Hatfield $\underline{J}$-Band Polarimetry with that of Wilking et al. 1980 (W) and Dyck and Jones 1978 (DJ)

HD Number	Hatfield		W		DJ		Hatfield-W	Hatfield-DJ
	p	ϵ_p	p	ϵ_p	p	ϵ_p		
21291	1.60	0.05	1.7	0.1			-0.10	
147084	2.73	0.05			2.28	0.09		0.45
147889	3.05	0.10	3.2	0.1	2.80	0.22	-0.15	0.25
149757	0.78	0.02	0.73	0.03			0.05	
154445	1.70	0.04	2.28	0.07	1.77	0.06	-0.58	-0.07
183143	2.74	0.03	2.80	0.09	2.77	0.05	-0.06	-0.03
198748	1.37	0.05	1.42	0.05			-0.05	
204827	2.16	0.05	2.69	0.13	2.34	0.15	-0.53	-0.18
VI Cyg 12	3.70	0.08	4.10	0.13	3.31	0.17	-0.40	0.39
Mean							-0.23	0.14
Standard Deviation							0.24	0.26

better with those of Dyck and Jones than with those of Wilking et al. However, for all the other stars in common our results are in good agreement with those of Wilking et al.

One factor which may contribute to discrepancies in the *J*-band polarimetry is differences in the effective wavelength of the *J* filter, since interstellar polarization is varying substantially with wavelength over this region. Since the *J* band is relatively wide the effective wavelength will vary with star color also. However such effects do not seem to be capable of fully explaining the observed differences. The use of narrower-band filters might be useful in better determining the wavelength dependence of interstellar polarization over this wavelength region.

The polarimetry at H and K is generally in better agreement between the three sets of data, though the polarizations are of course smaller at these wavelengths.

The wavelength dependence of interstellar polarization can be well represented by an empirical formula of the form:

$$p/p_{\max} = \exp[-K \ln^2 (\lambda_{\max}/\lambda)] \quad .$$

Data in the optical region can be fitted by this relation with a constant value of $K = 1.15$ for all stars. However, Wilking et al. (1980) found that to fit data in the near infrared also, K must vary from star to star, with the value of K for most stars fitting the relation $K = 1.7\ \lambda_{\max}$.

In order to plot our data on composite curves we have divided the stars into groups with similar values of K. Figure 2(a) includes stars with K in the range 0.7 to 0.95 according to Wilking et al. (1980), while Figure 2(b) includes those stars with K greater than 1.

The values of $p_{\max}$ and $\lambda_{\max}$ were taken from SMF or from Wilking et al. (1980). The lines correspond to $K = 1.15$ on Figure 2(b) and $K = 1.00$ on Figure 2(a). Our data tend to be better fitted by slightly higher K values than those obtained by Wilking et al. for some stars because of the lower values of J polarization noted earlier. However, the trend of increasing K with $\lambda_{\max}$ is confirmed by our results.

IV. Potential for Development

The results presented here demonstrate the low-instrumental-polarization and high-polarization accuracy (by infrared standards) achievable with the polarimeter. Another important factor is its sensitivity. The transmission and efficiency of the system in the infrared are relatively high, and the infrared efficiency could be improved further by the use of a retarder which remained closer to $\lambda/2$ in the infrared. Thus the sensitivity is limited only by the available detectors. Using a 'state of the art' InSb system on a 4-m telescope we anticipate being able to measure polarization of a sigma of 1% in 30 minutes integration time magnitudes of at least $J = 14.5$ or $K = 13.5$. The faintest objects yet observed (on a 1.5-m telescope) were of $K \sim 10.5$.

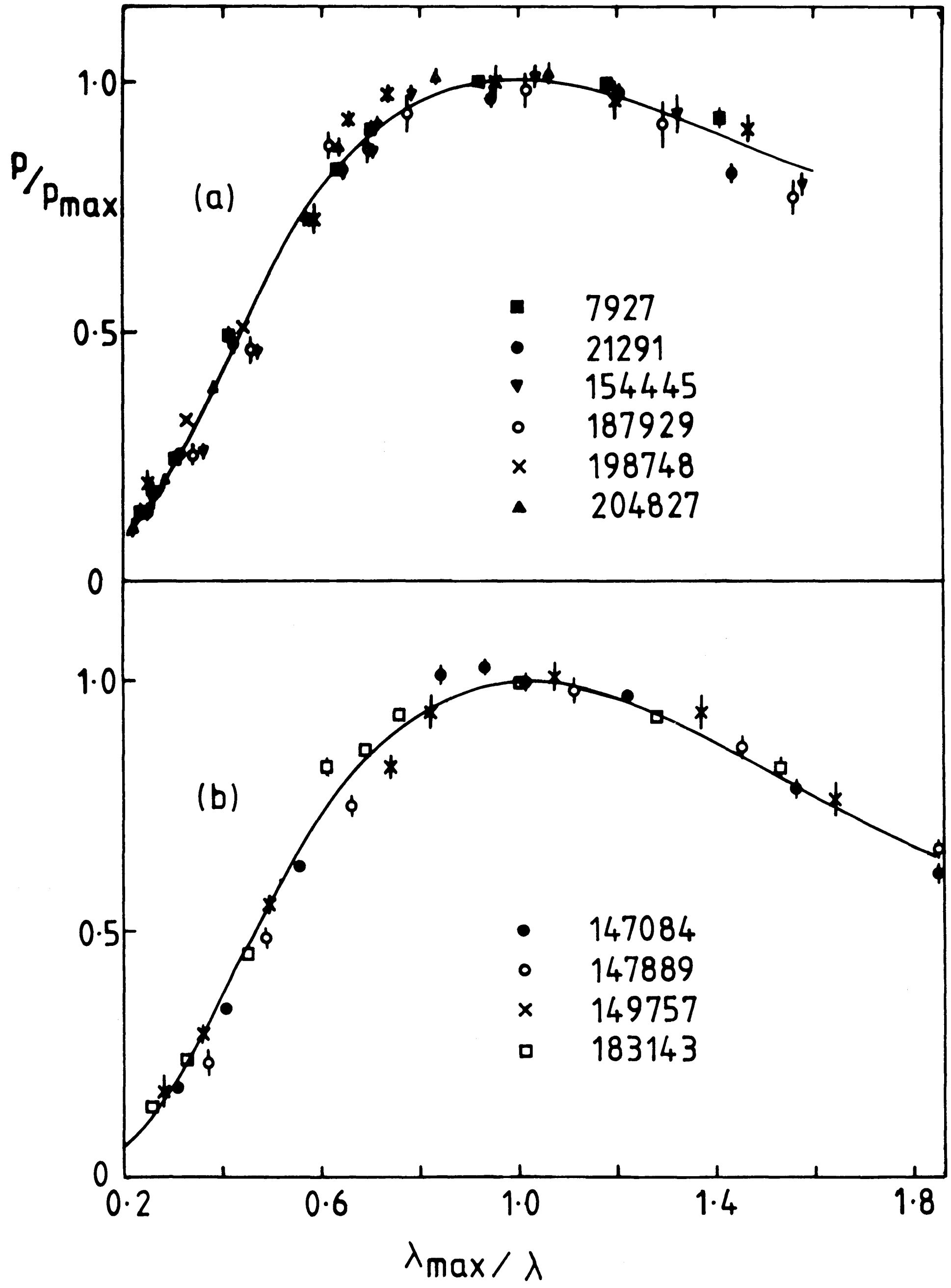

FIG. 2—Normalized interstellar polarization curves: (a) For stars with small K values (according to Wilking et al. 1980). The line corresponds to $K = 1.0$; (b) For stars with larger K values. The line corresponds to $K = 1.15$.

Another advantage of the polarimeter is its versatility. Many different modes of operation are possible as follows.

A. Using a system of two retarders it is possible to measure circular polarization, or to simultaneously measure circular and linear polarization with close to optimum efficiency. Such modulation systems are described by Serkowski (1974).

B. The beam splitter dividing the two channels is a polarizing prism rather than a dichroic mirror. Thus either channel can be used for infrared or optical measurement. The system can therefore be used with either top-window or side-window cryostats, and it could also be used with two infrared or two optical channels rather than one optical and one infrared as described here.

C. Unlike the case of a rotating polarizer polarimeter, mirrors placed after the modulation system will not introduce any further instrumental polarization. Thus dichroic beam splitters could be used in either beam to further increase the number of simultaneous channels.

D. The system could be used for infrared spectropolarimetry in conjunction with a cryostat containing a

CVF or a cooled grating spectrometer. This is not possible with polarimeters which use Lyot depolarizers as these work by scrambling up polarization as a function of wavelength.

E. Although the system as described is limited to wavelengths shorter than 2.5 μm by the calcite Foster prism, the rotating retarder system could be used at wavelengths of 3 μm to 5 μm, in a single-channel mode using a MgF_2 retarder and a fixed wire-grid polarizer. The polarizer could be placed inside the cryostat to reduce background at these wavelengths.

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GUEST INVESTIGATORS AT PALOMAR OBSERVATORY

Palomar Observatory will make a few observing facilities available in 1983 to qualified Guest Investigators from other institutions. Telescopes available are the 5-m, 1.5-m, 1.2-m Schmidt, 0.46-m Schmidt; the 1.5-m telescope is operated jointly by California Institute of Technology and the Carnegie Institution of Washington. The general availability of time on the 1.2-m Schmidt telescope is severely limited by a sky survey now in progress.

Only proposals which show exceptional instrumental or scientific use of the telescope can be allocated 5-m time. Proposals which provide new or innovative instrumentation for the 5-m telescope or which employ new techniques for utilizing that telescope will be given special consideration.

Proposals must be received by the Palomar Observatory not later than *October 1, 1982*. Interested researchers must obtain the *current* application forms and instructions by contacting

Palomar Observatory 105-24
California Institute of Technology
Pasadena, California 91125
(213) 356-4033.

Publications of the Astronomical Society of the Pacific
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EDITOR'S NOTICE

Effective January 1983 (Volume 95, No. 563) the *Publications* of the Astronomical Society of the Pacific will be published monthly, that is, twelve issues per year. We anticipate that this change will result in a faster publication time for authors.

Authors desiring their submitted papers to receive special attention (for example, publication within 90 days) because of important results, can do so by a special request to the Editors. Although the *Publications* has traditionally published papers that are relatively short, we wish to make known that we will consider manuscripts of any length. We hope that these changes will be favorably accepted by the astronomical community and that the high quality of the *Publications* will be maintained with these modifications.

Well-prepared manuscripts, in accord with the Instructions to Authors found on the inside back cover of each issue, will greatly enhance the possibility of authors' manuscripts being published in the shortest possible time.

The Editors would like to take this opportunity to express their gratitude to the innumerable referees who have aided both the authors and editorial staff in improving the quality of the papers appearing in the *Publications*.