Astron. & Astrophys. 37, 275–279 (1974)

The Magnetic Field, Spectrum and Light Variations of the Ap Star HD 49976

C. A. Pilachowski, W. K. Bonsack and S. C. Wolff
Institute for Astronomy, University of Hawaii, Honolulu, Hawaii

Received September 3, 1974

Summary. The spectacular Sr II Ap variable HD 49976 is found to have a magnetic field which varies cyclically between the limits of ± 2.0 kilogauss with a period of $2\overset{d}{.}976$. Both Sr II and Ca II K line equivalent widths and *uvby* photometric observations vary as double waves with the same period, but the synchronous line and light maxima appear to lag the magnetic maximum by 0.15 in phase.
The oblique rigid rotator model is used to interpret these results. The axis of the magnetic field, represented as a dipole, lies almost in the plane of the rotational equator. Regions of enhanced strontium and calcium abundance near each magnetic pole produce the observed spectrum variation. Light variations are most probably caused by some mechanism associated with the strontium-calcium spots and not with the magnetic poles.

Key words: magnetic stars — peculiar A stars — spectrum variables — stars, individual

I. Introduction

HD 49976 (HR 2534) is an Sr-Cr Ap star with particularly strong Sr II variation. The star is noted in Babcock's (1958) catalogue of magnetic stars to have a variable, reversing magnetic field. Due to the broad, shallow lines in the spectrum, the measurement of magnetic field is difficult and only one value, a marginally negative field, is reported. Van den Heuvel (1971) obtained one Zeeman observation of HD 49976, which also indicated a marginally negative field. Maitzen (1973) reported that a period of near 3.0 days is consistent with photometric observations. We began to collect spectroscopic and photometric data of HD 49976 at the Mauna Kea Observatory in 1972 to look for periodic variations of the magnetic field, the spectrum, and the light.

II. Observations

Spectrographic observations were obtained at the coudé focus of the 224-cm telescope of the Mauna Kea Observatory. The Zeeman effect apparatus discussed by Wolff and Bonsack (1972) was used to separate the two senses of circularly polarized light for measurement of the longitudinal magnetic field. Nineteen spectrograms, widened to 0.4 mm in each sense of polarization, were taken at 6.8 Å mm^{-1} on baked Kodak IIa-0 plates. Most of the plates were suitable for spectrophotometry as well as wavelength measurement; an auxiliary spectrograph was used to obtain photometric calibration data.

The effective longitudinal magnetic field, H_e, was determined from the Zeeman component separation, and the radial velocity was obtained from the mean positions of the components, as described by Wolff and Bonsack. Fifty-one unblended and unsaturated lines, predominantly of iron and chromium, were selected for measurement. Lines of the rare earth elements except cerium are weak or absent and could not be included in the measuring list. Lines of iron, chromium, strontium, calcium, cerium and magnesium were examined for spectrum variation. However, only lines of Ca II and Sr II were found to vary, and the equivalent widths of these lines are given in Table 1.
The results of previous studies have suggested the importance of local line blocking as one source of light variations. The line blocking coefficient in the v filter band was computed from the digital microphotometer record of each spectrogram by weighting each data point with the v filter transmission from Crawford and Barnes (1970) and the continuum flux of an appropriate model atmosphere (Mihalas, 1966), and then integrating numerically.
Finally, tracings of HD 49976 were compared with artificially broadened spectra of γ Equulei, a particularly sharp-lined, late-type Ap star. Details of the technique are discussed in Bonsack *et al.* (1974). Despite the later type of γ Equ, the spectra are reasonably similar. A value of $v \sin i = 31 \pm 3$ km s^{-1} was obtained.
The results from the spectrographic data are summarized in Table 1, which includes the measured

Table 1. Spectroscopic results

HJD (2440000+)	Phase	H_e (kilogauss)	v_r (km s^{-1})	Equivalent width (mÅ) Ca II 3934	Sr II 4215	Line blocking v band
1399.81	.95	−0.99	23.7	480	328	0.18
1400.77	.28	+0.55	18.4	1960	844:	0.19
1585.06	.20	+0.73	18.1	1560	758	0.20
1586.06	.54	−0.81	19.4	1300:	420	0.17:
1694.86	.10	+1.56	13.6	1165	514	0.17:
1696.80	.75	−1.76	20.7	1260	464	0.19
1697.00	.82	−1.94	22.2	490	456	0.17
1697.85	.10	+1.67	12.8	960	565	0.16
1698.01	.16	+2.22	15.4	1280	596:	0.16
1751.76	.22	+1.38	17.1	1665	758	0.18
1753.77	.89	−1.41	25.3	380	340	0.17
2094.78	.48	+2.08	23.8	1097	528	...
2094.92	.53	−0.67:	21.7	...	...	...
2095.86	.84	−0.90	23.2	530	375:	...
2096.80	.16	+1.83	14.2	1421:	642:	...
2097.87	.52	−0.21	20.1	1065:	448	...
2098.86	.85	−0.71	− 3.0	502	388	...
2099.89	.20	+1.46	16.9:	1908:	792	...
2138.81	.27	+1.25	18.8	2048:	789	...
Mean p.e.		±0.34	± 0.6	± 115	± 32	±0.003

Table 2. Photometric comparison stars

Star	V	$b-y$	m_1	c_1
HR 2505	5.641	−0.018	0.132	1.026
HR 2570	6.381	0.098	0.189	1.057

Table 3. Photometric observations of HD 49976

HJD (2440000+)	Phase	V	$b-y$	m_1	c_1
1613.13	.64	6.284	−0.002	+0.201	+0.966
1615.10	.30	6.265	−0.014	+0.224	+0.956
1644.02	.01	6.299	−0.002	+0.198	+0.994
1644.98	.34	6.270	−0.016	+0.226	+0.956
1730.79	.17	6.281	−0.010	+0.216	+0.968
1731.87	.53	6.285	−0.008	+0.210	+0.968
1732.79	.84	6.285	−0.010	+0.210	+0.981
1733.78	.18	6.283	−0.014	+0.220	+0.966
1759.78	.91	6.295	−0.006	+0.204	+0.988
1766.74	.25	6.274	−0.015	+0.228	+0.956
1767.74	.59	6.281	−0.008	+0.214	+0.965
1769.78	.27	6.269	−0.014	+0.223	+0.962
1773.77	.61	6.278	−0.004	+0.209	+0.962
1776.75	.61	6.283	−0.009	+0.210	+0.970
2093.78	.14	6.293	−0.004	+0.204	+0.976
2094.80	.49	6.287	−0.003	+0.205	+0.964
2095.81	.83	6.289	−0.013	+0.210	+0.981
2096.83	.17	6.289	−0.005	+0.205	+0.972
2097.84	.51	6.284	−0.005	+0.209	+0.965
2098.75	.81	6.290	−0.009	+0.208	+0.975
2099.85	.18	6.283	−0.009	+0.210	+0.976
2100.78	.50	6.288	−0.004	+0.208	+0.963

effective longitudinal field, the radial velocity, the equivalent widths, and the line blocking coefficient. The bottom row gives a mean probable error for each column, computed from the individual internal probable errors. Measurements with internal probable errors exceeding the mean by more than 50% are marked with a colon. The r.m.s. difference between the results for the two senses of polarization on each plate is used as the internal probable error of the equivalent width measurements and the line blocking coefficient.

Four color (*uvby*) measurements of the light variability of HD 49976 were made with the 61-cm telescope of the Mauna Kea Observatory. The apparatus and techniques used have been described by Wolff and Morrison (1973). The magnitudes and color indices derived for the two comparison stars are given in Table 2; a linear transformation equation relating y and V (Crawford and Barnes, 1970) was used to derive the V magnitude.

The results of the photometry of HD 49976 are given in Table 3 and are plotted in Fig. 3 as variations in the individual bands to give better insight into the nature of the variation. The typical probable error of a single observation is 0.003 mag (Wolff and Wolff, 1971; Wolff and Morrison, 1973).

III. The Variations

The magnetic field measurements were analysed using a technique based on the method of Lafler and Kinman (1965). One measurement reported by van den Heuvel (1971) was incorporated into the analysis, permitting us to determine the period to four significant figures. Only one of the trial periods, $2^{\mathrm{d}}976$, yielded orderly variations in both the spectroscopic data and the independent photometric observations. We derive the ephemeris:

JD (positive crossover) = 2441298.76 + 2.976 E

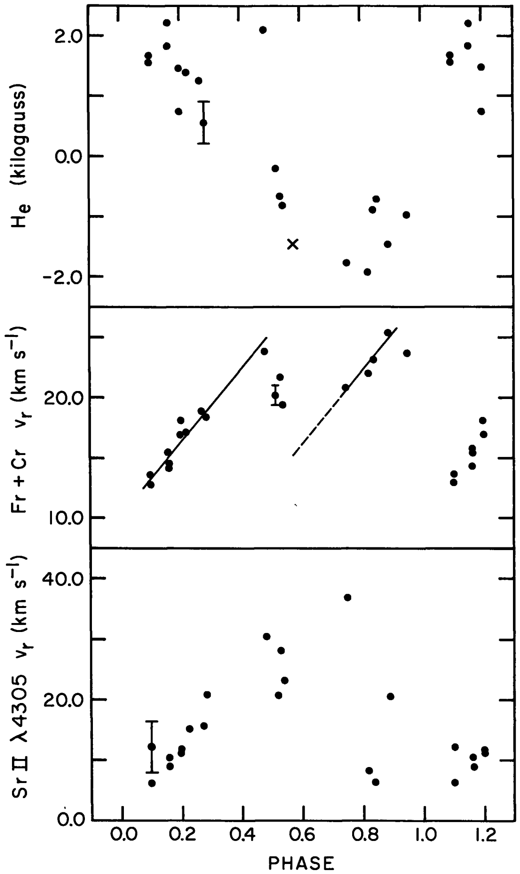

Fig. 1. Magnetic field and radial velocity variations in HD 49976. In the top panel, one measurement by van den Heuvel is represented by a cross. In the center panel, one discrepant measurement at phase 0.85 has been omitted. A hand drawn curve represents the sense of the radial velocity variations. All observations are plotted according to the ephemeris in § III. Note that the lower two panels have different radial velocity scales. Typical probable errors are indicated

where phase 0.0 occurs when $H_e = 0$, $dH_e/dt > 0$. The period is uncertain by $\pm 0\overset{d}{.}001$ and the epoch by $\pm 0\overset{d}{.}06$ (0.02 in phase). This period agrees with the near $3\overset{d}{.}0$ period suggested by Maitzen (1973).

The magnetic data are plotted in Fig. 1. The field varies from plus to minus 2.0 kilogauss in a nearly symmetric manner. The shape and amplitude of the magnetic variation are similar to other Ap stars of longer period; e.g., 49 Cam (Bonsack *et al.*, 1974) and HD 126515 (Preston, 1970). One point at +2.1 kG and phase 0.48 remains discrepant. This point may be due to either an unusually shaped magnetic maximum, a short term but large fluctuation in the stellar magnetic field, or to uncommonly large measurement errors. Remeasurement of the spectrogram does not confirm this last suggestion, and previous experience indicated that plate errors as large as 1 kG are unlikely. Equivalent width and radial velocity measurements of this spectrogram are entirely consistent; only the magnetic field appears peculiar. Further data at this phase are needed to resolve the discrepancy.

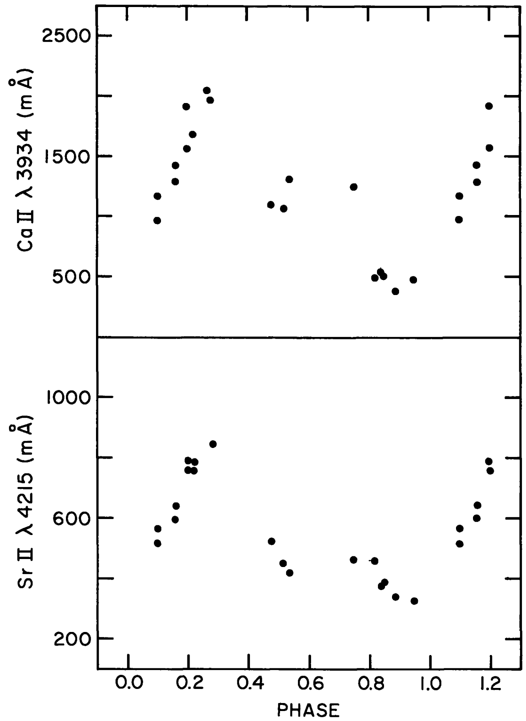

Fig. 2a and b. Equivalent width variations in HD 49976 plotted according to the ephemeris in § III. a) Ca II λ 3934; b) Sr II λ 4215

The variations of Sr II λ 4215 and Ca II λ 3934 are plotted in Fig. 2. The variation of Ca II K is similar to that discussed by Sadakane (1974) for the A2p star 73 Dra: the central depth remains nearly constant while broad shallow wings appear and disappear through the cycle. The equivalent width of the line changes by a factor of 5 from 0.4 Å to 2.0 Å, depending on the presence or absence of the wings. Both the central depth and the equivalent width of Sr II λ 4215 vary regularly with phase. The equivalent width ranges from 0.3 to 0.8 Å. Both lines appear to vary as double waves, with a well defined maximum at phase 0.3 and a possible maximum at phase 0.7. In both cases the first maximum has the larger amplitude; furthermore, primary maximum for these variations occurs 0.15 later in phase than the apparent magnetic maximum.

Radial velocity variations in the spectrum of HD 49976 are shown in Fig. 1. Lines of iron and chromium, though of constant equivalent width, vary with an amplitude of ± 6 km s^{-1} about the mean radial velocity of 19 km s^{-1}. Sr II λ 4305 varies through a larger amplitude of ± 12 km s^{-1} from the mean. The total range of each is an order of magnitude larger than the probable error of a single measurement. These velocity ranges are consistent with an origin in "spots" on the surface of a star rotating with $v \sin i = 31$ km s^{-1}. Mean radial velocity crossing of the iron and chromium lines occurs at phase 0.3, coincident with line strength maximum at that phase, and the curves show two distinct branches, corresponding to the two "spots". The curves in Fig. 1, center panel, represent the

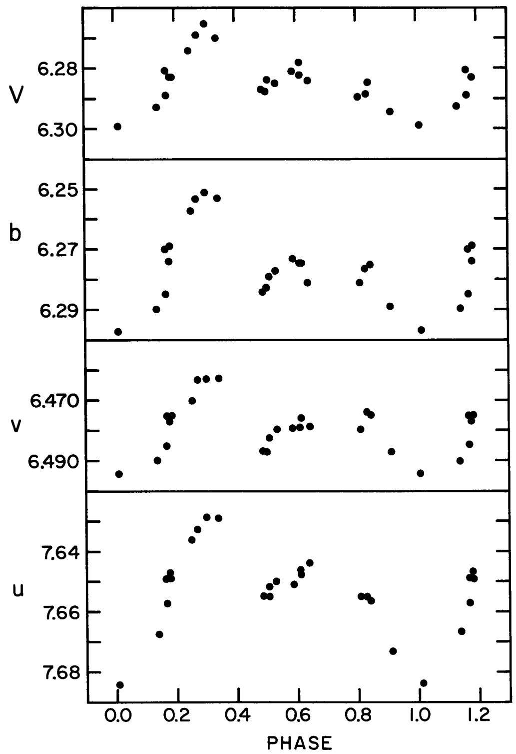

Fig. 3. Four color photometric variations of HD 49976 plotted according to the ephemeris in § III. The probable error of a single point, excluding zero-point effects, is ± 0.003 mag

expected variations due to the two spots. The points near phase 0.5 presumably result from the blending of lines formed in the two regions.

Light variations in the *uvby* system in HD 49976 are plotted in Fig. 3. At each wavelength the variation is a double wave, with light maximum coincident with Ca II and Sr II line strength maxima. The amplitude in each filter is near 0.05 mag, more than ten times the uncertainty in the measurements. Primary maximum at phase 0.3 agrees with primary line strength maximum. The secondary maximum is poorly defined by both the photometric and the spectroscopic data, but its probable occurrence in both sets of data supports its reality. Photometric observations kindly sent to us prior to publication by Maitzen confirm the double wave nature of the light curves and the phases of light maxima.

Coincident line strength, light, and magnetic field extrema are frequent in the study of Ap stars (Preston, 1968b; Preston and Stepien, 1968; Wolff and Wolff, 1971). The simultaneous occurrence of line strength and light maxima in HD 49976 is one verification of the 2.976^d period. The rise to maximum at phase 0.3 in both sets of data is well defined and does not occur at earlier phase. Similarly, the magnetic maximum at the slightly earlier phase 0.15 and the subsequent decline seem well substantiated; magnetic maximum is not likely to be as late in the cycle as phase 0.30. We conclude that line strength and light maxima probably lag the magnetic pole by 0.15 in phase. Non-coincidence of maxima, though unusual, is not unprecedented; light variations in the star 17 Com A (Preston *et al.*, 1969) lag the magnetic field by 0.25 period, and the spectrum variations of HR 7575 (Babcock, 1954) lead the magnetic field by 0.10 cycle.

IV. A Model

The results of this study may be partially interpreted with the rigid rotator model. The period of 2.976^d indicates (Preston, 1972) an equatorial rotational velocity of 46 km s^{-1}. The width of spectral lines in HD 49976 corresponds to a projected equatorial rotational velocity ($v \sin i$) of 31 km s^{-1}. We compute the angle between the line of sight and the rotation axis to be $42° \pm 7°$. The nearly symmetrical magnetic variation both in amplitude and in phase, places the axis of the magnetic field, represented as a dipole, almost in the plane of the rotational equator. At magnetic extremum, the angle between the line of sight and the magnetic axis is slightly less than 48°.

Ca II K and Sr II variations may be interpreted as regions of enhanced abundance of those elements in the stellar atmosphere. One such region, with prominent Ca and Sr, lags the positive magnetic pole by 30° to 40°, while a second region, less overabundant in these elements occurs preceding the negative magnetic pole. Visual comparison of HD 49976 spectra with standard stars indicates that calcium is generally deficient. Following the model of Sadakane (1974), we suggest that the profile of Ca II K is formed from two components: a sharp, deep core produced over most of the stellar surface, which is deficient in calcium, and broad, shallow wings resulting from saturated lines produced at two small, calcium-enriched spots. No radial velocity variations are seen because it is the Ca II line core which is measured. The Sr II regions, though centered on the Ca II spots, are less concentrated. Extensive Sr II wings are not seen.

The mechanism responsible for the light variations appears to be associated with these regions. However, since the two light maxima are of similar amplitude while the equivalent width maxima are of quite different strength, we cannot assume that either calcium or strontium is responsible. No other elements vary noticeably in the spectrum of HD 49976; our measurements indicate that local line blocking is not the cause. A redistribution of flux into the visible due to very strong absorption in the region 2000–3000 Å is not inconsistent with the observations; however, we are uncertain as to the cause of the blanketing. Neither strontium or calcium appears to have sufficient lines in the ultraviolet near the star's flux maximum to cause the necessary backwarming. Lines of the rare earth elements are weak or missing in the visible spectrum, as are lines of silicon. The detailed mechanisms of Wolff and Wolff (1971) and of Peterson (1970) cannot be applied. The phase shift between magnetic and light maxima also excludes the magnetic mechanisms of Trasco (1972) and of Rakosch *et al.* (1974). We must attribute the light variations to some mechanism unseen in the visible spectrum.

If line blanketing in the UV region produces the observed light variations, then phase 0.95 at Sr II minimum most nearly corresponds to the unblanketing flux. The mean $b-y$ color at this phase is -0.004. From the $(b-y)$ vs temperature calibration of Olson (1974), HD 49986 may be assigned a temperature of 10000 K. However, the spectrum when compared with the spectra of A type standard stars, most closely resembles that of an A 3 star, corresponding to a temperature of 8840 K (Morton and Adams, 1968). This shift in spectral class is apparently caused by ultraviolet blanketing as discussed by Leckrone (1973). The blanketing is substantial at all phases.

The radial velocity variations of the iron group elements may perhaps be explained as rather diffuse regions of slightly enhanced iron and chromium abundance. As the star rotates, the total iron group absorption would be nearly constant, but the line centers would shift as the spots pass across the disk. The phase of mean radial velocity crossing occurs at Ca-Sr maximum, indicating that the iron-chromium spots are associated with the calcium-strontium spots.

The phase lag of the abundance anomalies is difficult to explain. Current theories concerning peculiar A stars (Strittmatter and Norris, 1971; Michaud, 1970; Havnes and Conti, 1971; Havnes, 1974) associate the formation of abundance anomalies with the magnetic field, forming a "spot" at one or both magnetic poles (Strittmatter and Norris have the spots forming along the magnetic equator). In no case does the region of spot formation lag behind the magnetic pole by 30° to 40°. Since the anomaly includes such species as Fe II, Cr II, Sr II and Ca II, the spot is unlikely to "drift" across field lines to its present position. Recent work by S. Wolff (unpublished) indicates that the depth of line formation may influence the phase of magnetic variations. Since the magnetic variations are based on much weaker lines than the Ca II and Sr II resonance lines, we compared the equivalent widths of Sr II λ 4215 and λ 4305, which should be formed at different depths. No phase shift was found between these two sets of measurements. Thus, the cause of this discrepancy remains obscure.

The short period of HD 49976 may indicate its relative youthfulness, if present theories of Ap star evolution are correct. Stellar rotation should slow on the time scale of a star's main sequence lifetime. The evolution of surface abundance anomalies is less clear. The accretion hypothesis of Havnes and Conti (1971) predicts that the anomalies should increase as the star ages, but the diffusion hypothesis of Michaud (1970) and Strittmatter and Norris (1971) does not clearly predict changes in the degree of spectral peculiarity or variability with time. Neither theory explains both the spectacular variation of Sr II and Ca II and the near absence of the rare earth elements in HD 49976.

The simple rigid rotator model only partially explains our observations of HD 49976. The 2.976^d period of rotation produces systematic variations in the magnetic field, the Ca II and Sr II line strengths and the light. The geometry of the star, with the magnetic field in the plane of the rotational equator, is commonly found in studies of Ap stars (Preston, 1967a). The source of the light variations, the phase shift between magnetic and line and light maxima, and the radial velocity variations of the iron group elements remain as puzzles. We point out, finally, that the period of HD 49976 is the shortest yet found for an Ap star in which the magnetic field can be reliably measured; it may be that at short periods the limitations of the rigid rotator model will become apparent.

Acknowledgements. We thank Dr. H. M. Maitzen for sending us his observations of HD 49976 in advance of publication and we acknowledge with pleasure the able assistance of Frank Cheigh, Peter Hendricks, Harrison Ward, and Herbert Wurster, who obtained more than half the photometric observations for us. This research was supported by National Science Foundation Grant GP-29741.

References

Babcock, H. W. 1954, *Astrophys. J.* **120**, 66
Babcock, H. W. 1958, *Astrophys. J. Suppl.* **3**, 141
Bonsack, W. K., Pilachowski, C. A., Wolff, S. C. 1974, *Astrophys. J.* **187**, 265
Crawford, D. L., Barnes, J. V. 1970, *Astron. J.* **75**, 978
Havnes, O. 1974, *Astron. & Astrophys.* **32**, 161
Havnes, O., Conti, P. S. 1971, *Astron. & Astrophys.* **14**, 1
Heuvel, E. P. J. van den 1971, *Astron. & Astrophys.* **11**, 461
Lafler, J., Kinman, T, D. 1965, *Astrophys. J. Suppl.* **11**, 216
Leckrone, D. S. 1973, *Astrophys. J.* **185**, 577
Maitzen, H. M. 1973, *Mitt. Astron. Ges.* No. 32, p. 252
Michaud, G. 1970, *Astrophys. J.* **160**, 641
Mihalas, D. 1966, *Astrophys. J. Suppl.* **13**, 1
Morton, D. C., Adams, T. F. 1968, *Astrophys. J.* **151**, 611
Olson, E. C. 1974, *Publ. Astron. Soc. Pacific* **86**, 80
Peterson, D. M. 1970, *Astrophys. J.* **161**, 685
Preston, G. W. 1967a, *Astrophys. J.* **150**, 547
Preston, G. W. 1967b, *Astrophys. J.* **150**, 871
Preston, G. W. 1970, *Astrophys. J.* **160**, 1059
Preston, G. W. 1972, *Astrophys. J.* **175**, 465
Preston, G. W., Stepien, K. 1968, *Astrophys. J.* **151**, 583
Preston, G. W., Stepien, K., Wolff, S. C. 1969, *Astrophys. J.* **156**, 653
Rakosch, K. D., Sexl, R., Weiss, W. W. 1974, *Astron. & Astrophys.* **31**, 441
Sadakane, K. 1974, *Publ. Astron. Soc. Japan* **26**, 93
Strittmatter, P. A., Norris, J. 1971, *Astron. & Astrophys.* **15**, 239
Trasco, J. D. 1972, *Astrophys. J.* **171**, 569
Wolff, S. C., Bonsack, W. K. 1972, *Astrophys. J.* **176**, 425
Wolff, S. C., Morrison, N. D. 1973, *Publ. Astron. Soc. Pacific* **85**, 141
Wolff, S. C., Wolff, R. J. 1971, *Astron. J.* **76**, 422

C. A. Pilachowski
W. K. Bonsack
S. C. Wolff
Institute for Astronomy
2860 Woodlawn Drive
Honolulu, Hawaii 96822
USA