THE ASTROPHYSICAL JOURNAL, 350:367–371, 1990 February 10

HR 1362: A TEST CASE FOR STELLAR DYNAMO THEORIES

KLAUS G. STRASSMEIER,[1,4] DOUGLAS S. HALL,[1] WILLIAM S. BARKSDALE,[2]
ANTHONY T. JUSICK,[3] AND GREGORY W. HENRY[4]
Received 1989 June 20; accepted 1989 August 7

ABSTRACT

We have analyzed 11 yr of photometry of HR 1362 = EK Eri and find a well-established photometric period of 335 days. This confirms our earlier period determination of about 310 days from 3 yr of APT data and is consistent with our new $v \sin i$ determination of 2 ± 2 km s^{-1}. Recent Ca II H and K observations show moderately strong H and K emission lines at a flux level of log $\mathscr{F}'(K) \sim 6.5$ ergs cm^2 s^{-1}. If the photometric period is interpreted as the rotation period, this surface flux is more than one order of magnitude larger than what can be expected from empirical activity versus rotation relationships. The spectrum, and the $U-B$ and $B-V$ colors are consistent with a single G8 III-IV spectral classification, while the $V-R$ and $V-I$ values indicate a small color excess, typical of chromospherically active stars.

Subject headings: Ca II emission — photometry — stars: chromospheres — stars: individual (HR 1362) — stars: rotation

I. INTRODUCTION

Many recent studies have established a clear correlation between a variety of stellar atmosphere activity diagnostics and rotation among late-type stars in the sense: slower rotation less activity. The physical cause of these correlations is likely magnetic fields generated by some sort of dynamo mechanism in or close to the convection zone. The observed "activity" (in the chromosphere, in the transition region, and in the corona) is thought to be proportional to the emerging magnetic flux and thus directly dependent on the dynamo action. However, there exists no satisfactory model of the dynamo mechanism itself or of its dependence on stellar rotation (for a short review see Gray 1988). Knobloch, Rosner, and Weiss (1981), e.g., predict a transition from convective rolls to convective cells as the angular velocity is decreased. Durney and Robinson (1982) predict a simple dynamo theory that relates surface activity to angular rotation *and* depth-dependent differential rotation. However, since even solar data are still inadequate to determine a depth dependence of solar differential rotation (see. e.g., Duvall and Harvey 1984, and a summary in Schröter 1985), we are left with observable parameters such as stellar surface rotation periods and velocities to test such dynamo theories. The existence of an extremely slowly rotating star with appreciable surface activity does not fit into this picture, and we might have a case to test different dynamo theories.

Spectroscopic observations by Griffin (1972), Fekel, Moffett, and Henry (1986), and Balona (1987) show HR 1362 to have constant radial velocity, implying that it is a single star. The five radial velocities of Fekel *et al.* have an average value of 6.9 ± 0.4 km s^{-1}. This velocity is within 1 km s^{-1} of the average value (7.8 ± 0.3 km s^{-1}) listed by Griffin (1972) from four observations, while Balona (1987) reports 28 velocities with an average value of 5.1 km s^{-1} and a standard deviation of a single observation of 2.3 km s^{-1}.

Ca II H and K and Hα observations by Strassmeier *et al.* (1990) reveal moderately strong H and K emission lines at flux levels of log $\mathscr{F}'(K) \sim 6.5$ ergs cm^2 s^{-1} and log $\mathscr{F}'(H) \sim 6.4$ ergs cm^2 s^{-1}, respectively, and slightly filled-in Hα absorption. If plotted in a rotation versus H and K flux diagram, HR 1362 is overactive by more than an order of magnitude if compared with the empirical rotation versus activity trend of other cool giants (Strassmeier *et al.* 1990). Simon and Fekel (1987) report relatively small UV emission-line fluxes if compared to RS CVn type stars. Walter and Bowyer (1981) measured a soft X-ray flux of log $L_X/L_{bol} = -4.55$, which led Walter (1981) to predict a rotation period of 13 days.

In this paper we analyze photometric observations of HR 1362 (EK Eri, HD 27536) made between 1978 and 1989 and show that the star has a 335 day photometric period, probably caused by an uneven surface distribution of starspots, which we therefore interpret as the rotation period. Recent photometric investigations, based on only small fractions of the present data set, arrived at conflicting conclusions concerning the photometric period: Boyd *et al.* (1985)—154 days, Lloyd-Evans and Koen (1987)—160 days, Strassmeier and Hall (1988)—310 days, and most recently Derman, Demircan, and Özeren (1989)—330 days. None of these determinations, however, could convince an astronomer with a natural level of suspicion.

II. OBSERVATIONS AND ANALYSIS

Table 1 lists all available V-band photometry, their baseline in time, the number of data points, and the results from the Fourier analysis. The new photometry has been obtained in 1987, 1988, and 1989, with the 0.4 m Vanderbilt University Automatic Photoelectric Telescope (APT), with the 0.25 m Fairborn APT, with the 0.35 m telescope at Barksdale Observatory, and with the 0.2 m telescope at Stetson University. All observations have been made differentially with respect to HR 1332 (=HD 27179, $V = 5.94$ mag, $U-B = +0.94$ mag, $B-V = +1.08$ mag; Nicolet 1978) as the comparison star and HR 1383 (=HD 27861) as the check star. A Julian date plot of all photometry listed in Table 1 is shown in Figure 1. The different symbols in this figure correspond to the different observers. The result of a least-squares periodogram analysis, in which sine curves of various incremented periods are fitted

[1] Department of Physics and Astronomy, Vanderbilt University.
[2] Barksdale Observatory.
[3] Department of Physics, Stetson University.
[4] Center of Excellence in Information Systems, Tennessee State University.

TABLE 1

V PHOTOMETRY OF HR 1362

OBSERVATORY	REFERENCE	2,440,000+ first	last	n	AMPLITUDE FROM FOURIER FIT P = 167.5 days	335 days
SAAO	1	3856	4974	51	0.083±0.011	0.162±0.020
Ankara University	2	4867	5300	54	0.122±0.009	0.158±0.019
various	3	5650	6045	51	0.095±0.010	0.141±0.015
0.25 m APT	4	5700	7159	260	0.064±0.005	0.100±0.005
0.40 m APT	5	7112	7605	175	0.015±0.004	0.021±0.004
Barksdale	5	7179	7613	70	0.011±0.005	0.027±0.011
Stetson University	5	7584	7620	14	0.080±0.050	...

REFERENCES.—(1) Lloyd-Evans and Koen 1987; (2) Derman, Demircan, and Özeren 1985; (3) Boyd *et al.* 1985; (4) Strassmeier and Hall 1988; (5) this paper.

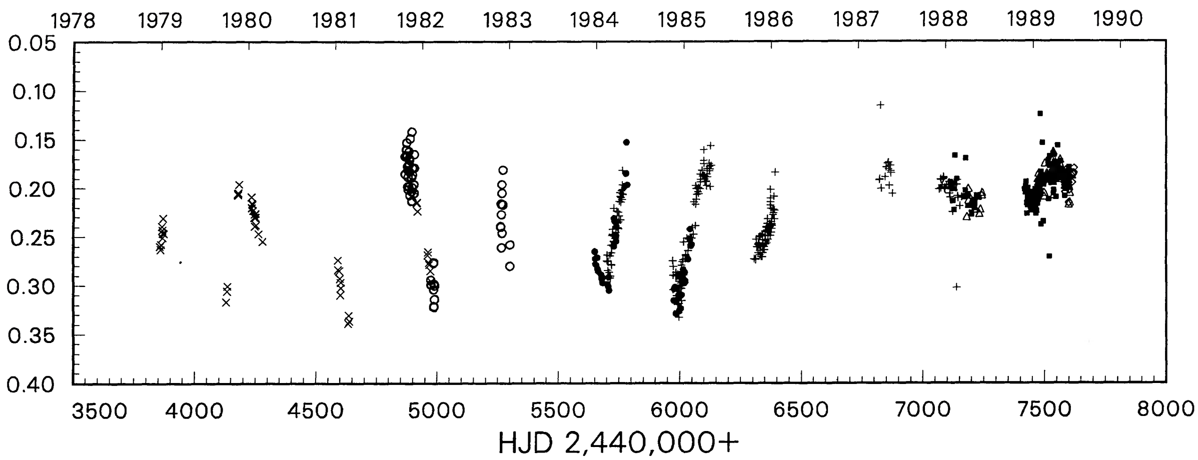

FIG. 1.—ΔV vs. Julian date, where Δ is in the sense HR 1362 minus HR 1332. The different symbols belong to the different observers: SAAO (cross); Ankara University (*open circle*); various (*filled circle*); 0.25 m APT (*plus sign*); 0.40 m APT (*filled square*); Barksdale (*open triangle*); Stetson University (*open diamond*). See Table 1.

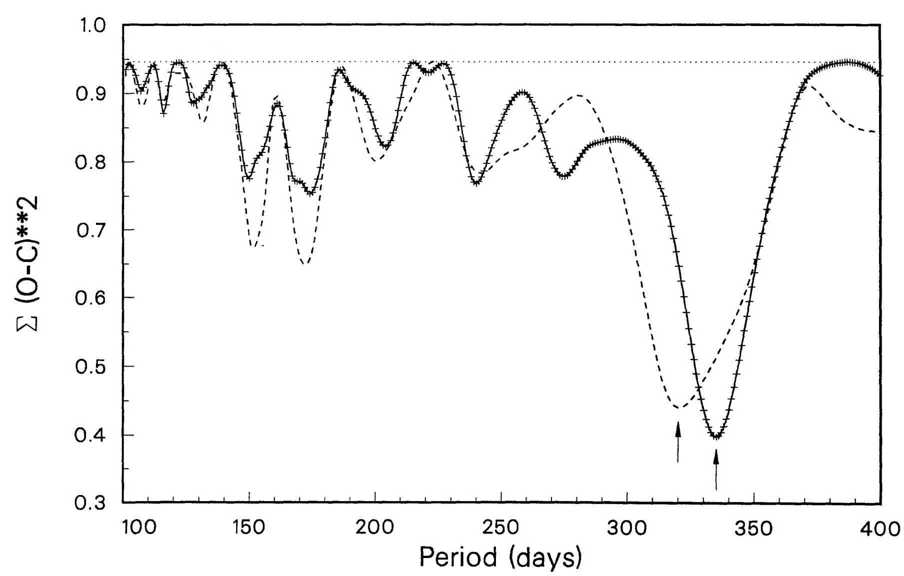

FIG. 2.—Periodogram of HR 1362. The solid line is the periodogram from the entire 11 yr data set; the dashed line is the resulting periodogram if we exclude the observations from 1988 and 1989, which show a comparatively small *V* amplitude. The arrows indicate the period which results in the greatest reduction of the sum of the squares of the residuals.

one by one to the data, is shown in Figure 2. A 335.0 ± 0.1 day period results in the greatest reduction of the sum of the squares of the residuals. Note that the standard deviation describes the precision of measuring the period according to our technique and does not necessarily imply the accuracy of the period. Clearly, this settles the ambiguity in the literature of whether an approximately 300 day period, or half of that, is the true photometric period. The second step was to fit a sinusoidal curve to the data by means of a truncated Fourier series to derive approximate seasonal amplitudes. These amplitudes are listed in Table 1 for $P = 335$ days and, as a comparison, for $\frac{1}{2}$ P. Note the monotonic decrease since the beginning of the observations in 1978. A phase plot of all seasons of data is given in Figure 3a (with $P = 335$ days) and Figure 3b (with $P = 167.5$ days). The symbols are the same as in Figure 1. Visual inspection of the two figures clearly favors the 335 day

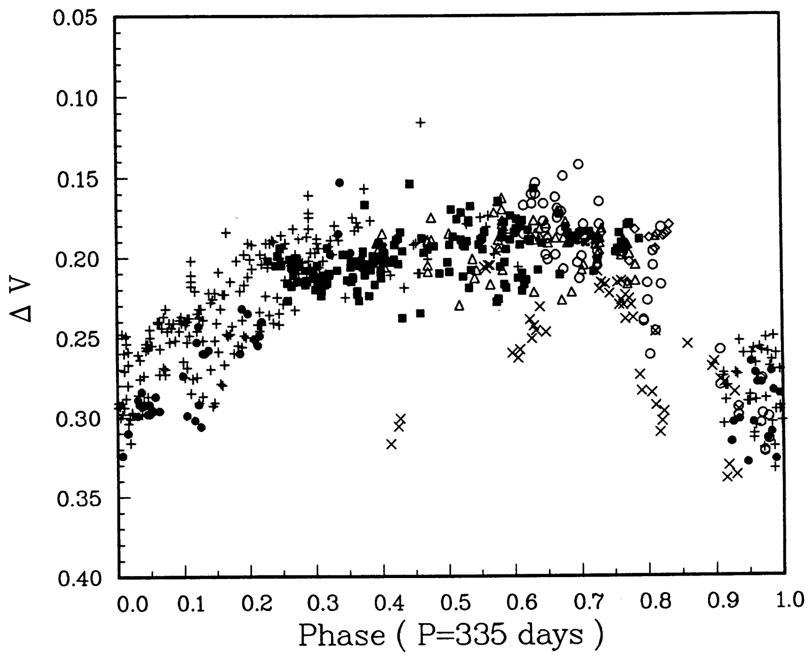

FIG. 3a

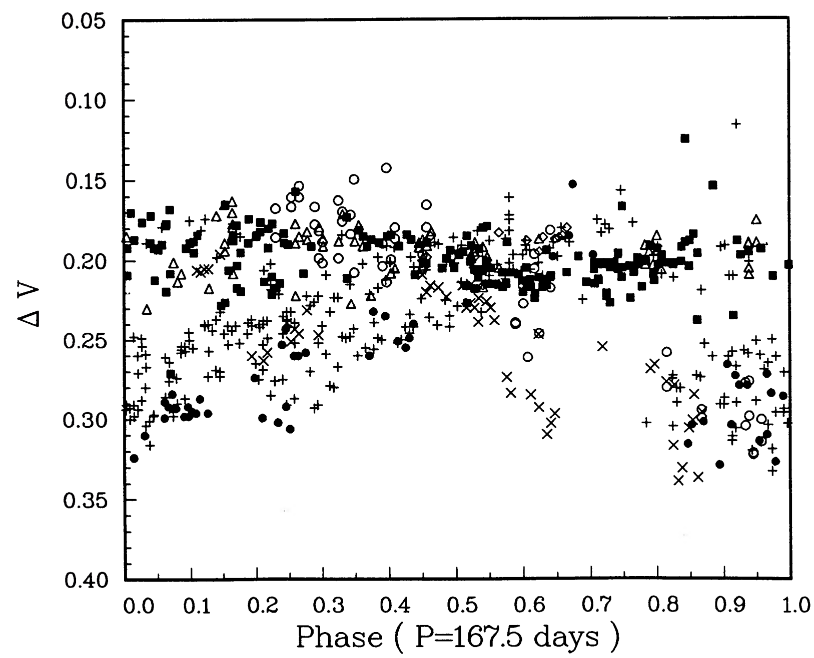

FIG. 3b

FIG. 3.—Light curves of HR 1362 from the entire data set phased together with (a) the 335 day period and, (b) with one-half of this period (167.5 days). The different symbols are again the same as in Fig. 1.

period because it produces a much tighter light curve and is therefore evidence for the reality of this period. The full V amplitude in Figure 3*a* is 0.091 ± 0.003 mag and the mean V light level (variable minus comparison) is 0.225 mag. Analogously, the full amplitude in Figure 3*b* is only 0.048 ± 0.004 mag. The scatter of ~ 0.05 mag in Figure 3*a* is certainly real and very likely due to intrinsic changes in the amplitude and possibly the period, as a result of evolving starspot geometry (compare with Fig. 1). Some points (*crosses*) differ noticeably from the mean in Figure 3*a* and possibly indicate a double-humped light curve shape in 1979. This might explain the ambiguity of earlier period determinations.

From $UBV(RI)_C$ observations obtained by Lloyd-Evans and Koen (1987) between 1978 and 1981, and by the Vanderbilt APT in 1987–1988, we derive mean Johnson colors of $U-B = +0.572 \pm 0.011$ mag, $B-V = +0.909 \pm 0.010$, $V-R = +0.705 \pm 0.014$, and $V-I = +1.193 \pm 0.015$. Earlier values of $U-B$ and $B-V$ obtained by Cousins (1963) and by Lake (1964) are in excellent agreement with the present data. After correcting for interstellar reddening with $E_{B-V} = 0.03$ mag (Eggen and Iben 1989), these colors are more consistent with a spectral classification of G8 III-IV instead of the G8 IV: classification assigned by Cowley and Bidelman (1979). The $(R-I)_{KE}$ colors listed in Eggen (1978) and in Eggen and Iben (1989) (+0.31 mag and +0.282 mag, respectively), when transformed to the Cousins system, seem to be slightly too blue. Note that our $V-R$ and $V-I$ colors are slightly redder than expected from the spectral type, indicating a color excess toward the red and near-infrared wavelengths. Such color excesses are typical for chromospherically active stars (Fekel, Moffett, and Henry 1986). A more direct attempt to classify the spectrum has been made in Figure 4. A moderately high resolution (0.22 Å) red CCD spectrum of HR 1362, kindly provided by F. C. Fekel, is compared with the spectrum of the standard star κ Gem (G8 III, $v \sin i \sim 4$ km s^{-1}). The synthesized spectrum (*solid line*) fits the HR 1362 spectrum (*plus signs*) generally well, except for the luminosity-sensitive lines Ca I 6449.82/Co I 6450.18 Å, which indicate a luminosity class slightly less than III. A spectrum of β Aql, a G8 IV standard, generally fails to match the HR 1362 spectrum. A consistency test for the III–IV classification, as well as for our long photometric period, comes from our new $v \sin i$ determination of 2 ± 2 km s^{-1} (for a description of the method, see Fekel, Moffett, and Henry 1986). This $v \sin i$ value, when combined with the 335 day rotation period, results in a minimum radius of 13 $R_\odot$ (with the formal uncertainty of ± 13 $R_\odot$ introduced by the uncertainty of the $v \sin i$ measure). Unfortunately the star lacks a trigonometric parallax measure.

III. DISCUSSION

A constant radial velocity does not rule out a near pole-on orbit but, if it is rotational modulation that is being measured, then obviously the star cannot be pole-on. However, the star's axis of rotation may or may not be aligned with the orbit.

The G8 III-IV classification of HR 1362 is most consistent with a stellar mass of 2 $M_\odot$ (X, Y, Z = 0.70, 0.28, 0.02; Maeder

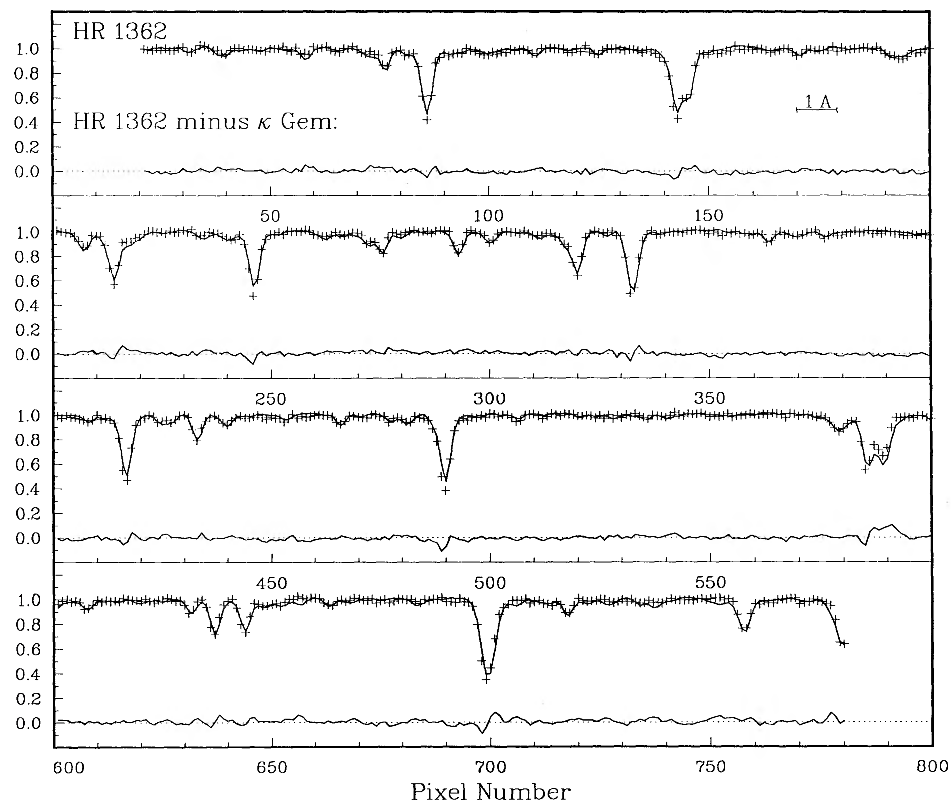

FIG. 4.—A moderately high resolution (0.22 Å) CCD spectrum of HR 1362 obtained with the KPNO coudé feed telescope (plus signs) is compared with the G8 III standard κ Gem (*full line*). The lower curve is the difference spectrum: HR 1362 minus κ Gem. The wavelength range is $\sim$6385 Å–6475 Å. Note that the luminosity-sensitive line ratio Ca I 6449.82/Co I 6450.18 Å of HR 1362 (at pixel numbers 585 and 590, respectively) is too large for a luminosity class III classification but too small if compared to the G8 IV standard β Aql (not shown).

and Meynet 1988), placing the star at the end of the horizontal-branch evolution at an age of $\sim 1.7 \times 10^9$ yr. It is therefore in a stage of internal (radial) redistribution of mass caused by the rapid decrease of the thickness of the H-burning shell shortly before the He flash. Together with the rapid increase of the stellar radius, this causes a rapid spin-down of the star. There has been modeling of the rotational velocity during the evolution of cool giants (Rutten and Pylyser 1988) assuming complete (radial) exchange of angular momentum, i.e., rigid-body rotation. For a discussion of the validity of this assumption see Endal and Sofia (1979). This assumption might not be valid in the case of HR 1362. The zone where the dynamo mechanism is supposed to work (presumably at the bottom of the convection zone in accordance with the solar picture) might rotate more rapidly than the surface layers. If we assume that a dynamo model must obey the empirical rotation versus activity relation, we could speculate that the (surface) rotation period in this relation needs to be replaced by the rotation period of the layers where the dynamo is active. For HR 1362, this rotation period at the bottom of the convection zone would then be more around 10 days than 335 days. It is interesting to note that, on the basis of his X-ray flux versus rotation relation, Walter (1981) predicted a (surface) rotation period of 13^{+13}_{-6} days, in good agreement with the hypothetical 10 day value from the Ca II H and K versus rotation relation.

In a recent progress report on the photometry of 40 suspected variables presented at the 10th Fairborn-Smithsonian-IAPPP meeting in Tucson, Arizona, Hooten and Hall (1989) reported HD 181943, an apparently single star (Balona 1987) of spectral type G8 IV with Ca II H and K emission (Bidelman and MacConnell 1973), to exhibit *V* light variations with a full amplitude of 0.145 mag and a period of 385 days. If this period is correct, we might have another system with properties similar to HR 1362.

We are grateful to E. Derman, O. Demircan, and F. Özeren for sending us a preprint of their work and to F. C. Fekel for providing a spectrum of HR 1362. We also wish to thank F. M. Walter for comments on his X-ray observations of HR 1362. This project was supported by NASA grant NAG 8-111.

REFERENCES

Balona, L. A. 1987, *South Africa Astr. Obs. Circ.*, **11**, 1.
Bidelman, W. P., and MacConnell, D. J. 1973, *A.J.*, **78**, 687.
Boyd, L. J., *et al.* 1985, *Inf. Bull. Var. Stars*, No. 2696.
Cousins, A. W. J. 1963, *M.N.A.S., So. Africa*, **22**, 58.
Cowley, A. P., and Bidelman, W. P. 1979, *Pub. A.S.P.*, **91**, 83.
Derman, E., Demircan, O., and Özeren, F. F. 1989, *Pub. A.S.P.*, **101**, 677.
Durney, B. R., and Robinson, R. D. 1982, *Ap. J.*, **253**, 290.
Duvall, T. L., Jr., and Harvey, J. W. 1984, *Nature*, **310**, 19.
Eggen, O. J. 1978, *Ap. J.*, **222**, 203.
Eggen, O. J., and Iben, I. Jr. 1989, *A.J.*, **97**, 431.
Endal, A. S., and Sofia, S. 1979, *Ap. J.*, **232**, 531.
Fekel, F. C., Moffett, T. J., and Henry, G. W. 1986, *Ap. J. Suppl.*, **60**, 551.
Gray, D. F. 1988, *Lectures on Spectral-Line Analysis: F, G, and K Stars*, (Ontario: The Publisher), p. 5–1.
Griffin, R. F. 1972, *M.N.R.A.S.*, **155**, 449.
Hooten, J. T., and Hall, D. S. 1989, in *Remote Access Small Telescopes*, ed. D. S. Hayes and R. M. Genet (Mesa: Fairborn Press), in press.
Knobloch, E., Rosner, R., and Weiss, N. O. 1981, *M.N.R.A.S.*, **197**, 45P.
Lake, R. 1964, *M.N.A.S. So. Africa*, **23**, 136.
Lloyd-Evans, T., and Koen, M. C. J. 1987, *South Africa Astr. Obs. Circ.*, **11**, 21.
Maeder, A., and Meynet, G. 1988, *Astr. Ap. Suppl.*, **76**, 411.
Nicolet, B. 1978, *Astr. Ap. Suppl.*, **34**, 1.
Rutten, R. G. M., and Pylyser, E. 1988, *Astr. Ap.*, **191**, 227.
Schröter, E. H. 1985, *Solar Phys.*, **100**, 141.
Simon, T., and Fekel, F. C. 1987, *Ap. J.*, **316**, 434.
Strassmeier, K. G., and Hall, D. S. 1988, *Ap. J. Suppl.*, **67**, 453.
Strassmeier, K. G., Fekel, F. C., Bopp, B. W., Dempsey, R. C., and Henry, G. W. 1990, *Ap. J. Suppl.*, in press.
Walter, F. M. 1981, *Ap. J.*, **245**, 677.
Walter, F. M., and Bowyer, S. 1981, *Ap. J.*, **245**, 671.

WILLIAM S. BARKSDALE: Barksdale Observatory, 633 Balmoral Road, Winter Park, FL 32789

DOUGLAS S. HALL and KLAUS G. STRASSMEIER: Department of Physics and Astronomy, Dyer Observatory, Vanderbilt University, Nashville, TN 37235

GREGORY W. HENRY: Center of Excellence in Information Systems, Tennessee State University, 330 10th Avenue N., Nashville, TN 37203-3401

ANTHONY T. JUSICK: Department of Physics, Stetson University, DeLand, FL 32720