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MAGNETIC, PHOTOMETRIC, TEMPERATURE, AND GRANULATION VARIATIONS OF ξ BOOTIS A 1984–1993

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ABSTRACT

The magnetically active G8 dwarf star, ξ Boo A = HR 5544 = HD 131156 is studied for magnetic-cycle type variations over the 1984–1993 interval. We present measurements of Ca II H and K emission as an indirect indicator of magnetic activity, blue and visual magnitudes as an indication of the power output and temperature, line-depth ratios of V I λ6251.83 to Fe I λ6252.57 as a measure of temperature, and line bisectors as a measure of the star's granulation. The season means of all these parameters show the same pattern of variation with several irregular rises and falls, rather different from the relatively smooth variations seen for the Sun. As found for several other stars in previous studies, the magnetic signal leads the others in time. Time lags relative to the H and K index variation are 1.4 ± 0.4 yr for the photometric brightness, 1.5 ± 0.5 yr for the $b-y$ color index, 1.8 ± 0.3 yr for the line-depth ratio, and 2.1 ± 0.4 yr for the line bisectors. The ≈1.7 year temperature lag for ξ Boo A is close to the linear relation between lag and effective temperature found for the other stars that have been measured.

Subject headings: stars: individual (ξ Bootis) — stars: late-type — stars: magnetic fields

1. BACKGROUND

The influence of the solar magnetic cycle on the surface behavior of the Sun is profound. To broaden the base of observations beyond the isolated solar case, we are bringing together measurements of relevant physical parameters for stars roughly similar to the Sun. Our goal is to understand more completely the generation of magnetic fields in the Sun and other cool stars and how various physical phenomena are related to the magnetic fields.

In our previous studies, we delineated the year-to-year changes in magnetic activity, power output, temperature, and granulation for several cool stars, typically over a 10 yr time base. Most of the stars we studied do not show smooth continuous variations like the solar ones, but more chaotic behavior, and two of the stars showed little or no variation (η Cep and τ Cet). Rotational modulation is also detected in several cases. To date, a summary of these studies is as follows: σ Draconis K0 V (Gray et al. 1992), τ Ceti G8 V(Gray & Baliunas 1994), η Cephei K0 IV (Gray 1994a), ϵ Eridani K2 V (Gray & Baliunas 1995), and β Comae G0 V (Gray et al. 1996).

While it is remarkable enough that several normal dwarfs show sizable variations in the measured parameters, the discovery that the variations in brightness, temperature, and granulation *lag behind* the magnetic variation presents a challenging puzzle. The lag of variations in temperature behind those in the H and K emission is the most completely documented comparison (Gray 1994b), and a nearly linear relation is seen between this time lag and the effective temperatures of the stars studied to date. A lag of nearly 3 yr occurs for the G0 V star (β Com) compared to only 0.3 yr for the K2 dwarf (ϵ Eri). Although the number of stars that have been monitored spectroscopically is very limited, ξ Boo A adds one more consistent point to this relation. The interpretation of physical meaning of the phase lag is still a mystery, but its importance for understanding dynamo processes and the influence of magnetic fields in stellar atmospheres can hardly be doubted.

Long recognized as a binary star with a period of some 151 yr and a parallax of 0".148, ξ Boo has reasonably well determined masses of 0.85 and 0.72 $M_{\odot}$ (Strand 1943; Wielen 1962; Harris, Strand, & Worley 1963; Gray 1992). The spectral types are G8 V and K5 V (Abt 1981), and the magnitudes and colors are tabulated in Blanco et al. (1970) and Hoffleit (1982). The angular separation during recent years has been 7" as the secondary star passes through apastron. This is sufficiently large to prevent contamination of the primary star's spectrum by light from the secondary star, but both stars are included in photometric measurements. The precision radial velocity study of Campbell, Walker, & Yang (1988) shows no variations in excess of their ≈10 m s^{-1} measuring errors. The effective temperature of ξ Boo A, ≈5551 K (Gray 1994c), is reasonably well known, although the star does show discrepant behavior on temperature calibration curves using the $B-V$ color index (Gray 1994c; Fekel, Moffatt, & Henry 1986). Uncertainty in the absolute temperature does not preclude precise measurements of *variations* in temperature, as reported here. The star is slightly metal deficient, with [Fe/H] = −0.20 ± 0.08 (Cayrel de Strobel et al. 1992; Taylor 1994). The lithium line at λ6707 is known to be strong (Herbig 1965), a result we confirmed with observations from Western Ontario.

Surface features and rotational modulation of ξ Boo A have been studied in some detail (Noyes et al. 1984; Baliunas et al. 1985; Toner & Gray 1988; Gray 1988). Variations in line asymmetries and temperature showed the main photospheric feature to be rather difficult from sunspots or starspot, and the name "starpatch" was adopted for it. The rotational period from this feature was 6.43 ± 0.01 days in the epoch around 1986. Some of these same data are used here. The Lowell Observatory photometry showed that the star grew ≈1.5% fainter, and the Mount Wilson H and K measurements showed stronger emission, during the starpatch transit of the disk (see Gray 1988, Figs. 7-16 and 7-17 for 6.43 day phase diagrams). Earlier studies found some evidence for a 10.15 day period (e.g., Rucinski 1980).

The average H and K *S* index is ≈0.45, placing ξ Boo A at the upper boundary of activity in dwarfs (Lockwood 1994). Interpretation of the ultraviolet spectral region with chromosphere-coronal models was done by Ayres et al. (1983) and Jordan et al. (1987). Radio observations at 6 cm (Gary & Linsky 1981) resulted only in upper limits of detection. Spectral line profiles in the red have also been analyzed for rotation, macroturbulence, and granulation parameters (Gray 1984a; Toner & Gray 1988. Magnetic fields have been sought or studied by Boesgaard, Chesley, & Preston (1975), Robinson, Worden, & Harvey (1980), Marcy (1981), Borra, Edwards, & Mayor (1984), Gray (1984b), Gondoin, Giampapa, & Bookbinder (1985), Marcy & Basri (1989), Saar (1990), and Linsky et al. (1994). Typically 1–2 kG fields are found over a substantial fraction of the star's surface.

2. THE OBSERVATIONS

The observations were done with the same equipment and procedures discussed in the previous papers of this series, and the reader is referred to those papers for additional details. In brief, measurements of the chromospheric emission in the H and K lines were done at Mount Wilson (Baliunas & Vaughan 1985), with individual measurements having photometric errors ≈2%. The measurements start in 1967, but we are concerned here primarily with those from 1982 onward since photometric and spectroscopic monitoring did not start until the 1980s. Typically, three independent measurements of the empirical *S* parameter were taken per night. Starting with the 1982 season, the number of nights ξ Boo A was observed was 112, 57, 91, 89, 99, 43, 69, 43, 13, and 14. On one night in 1984, 374 measurements were taken for rotational modulation studies. Scatter around the season means is almost entirely from rotational modulation.

Photometric observations were made at the Lowell Observatory (Lockwood & Skiff 1988) in the blue (4720 Å) and the yellow (5510 Å), with individual measurements having average errors of ≈2.5 mmag. HD 129972 and HD 132146 are the nonvariable comparison stars. Nearly identical variation is seen in both bandpasses and with both comparison stars, but a small systematic variation can still be seen in the $b - y$ color index, as described below. Both stars are included in the measuring diaphragm, and with a visual magnitude difference ≈2.0, about 15% of the light is contributed by the K5 companion. Variations in the companion star, if they occur, might cause additional "noise" or systematic deviation in the photometry.

Spectroscopic observations were done with the University of Western Ontario coude spectrograph (Gray 1986) at a resolving power of approximately 10^5, and signal-to-noise ratios of typically 300–500. Table 1 gives the number of exposures per year and related information. There is considerable range in the amount and quality of the data from one year to the next, a result of competing demands for telescope time, dome and telescope maintenance, and the weather. The large number of exposures in 1986 was taken for the rotational modulation study. A weight is assigned to each exposure according to its quality, mainly signal-to-noise ratio.

TABLE 1

SPECTROSCOPIC OBSERVATIONS

Year	N^a	$\sum W^b$	$\langle W \rangle^c$
1984......	5	0.89	0.18 ± 0.13
1985......	17	1.88	0.11 ± 0.09
1986......	43	18.11	0.42 ± 0.34
1987......	7	6.96	0.99 ± 0.70
1988......	3	3.05	1.02 ± 0.22
1991......	10	7.30	0.73 ± 0.34
1992......	2	0.72	0.36 ± 0.28
1993......	5	3.53	0.71 ± 0.31

[a] Number of exposures.

[b] Sum of the exposure weights for the season.

[c] Mean weight/exposure and rms scatter around mean.

3. MAGNETIC ACTIVITY

We use the measured H and K *S* index as an indicator of magnetic activity, its linkage being through the chromospheric enhancement caused by the magnetic activity. Figure 1 shows the season means of *S* for all available observations. Except possibly for the last two seasons, the observations are sufficiently numerous to reasonably average away the rotational modulation. Remaining uncertainty in the season means is ≈0.001. This is negligibly small, compared to stochastic outbursts, e.g., flares, that are likely to occur on such a magnetically active star. The size of the variation always remains small compared to the range of *S* index seen for dwarf stars.

Underlying the shorter timescale variations seen in Figure 1,b there may be a sweeping decline from ≈1970 to ≈1985, followed by the beginning of a general rise. If this broad variation arises from the magnetic-cycle of this star, its period is 25–30 yr. Another decade or two of observation will be needed to establish this point.

Overlying the possible slow variation are significant changes from year to year and over 3 or 4 yr timescales. These are the features we focus on in this study. The H and

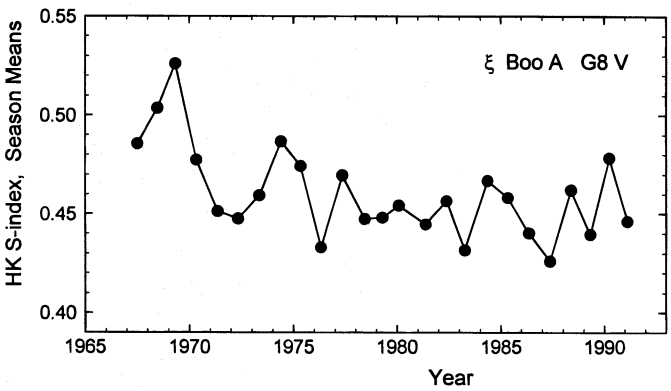

FIG. 1.—The season mean values of the Ca II H and K line index, *S*, is shown as a function of time. We are concerned primarily with the section starting in 1984.

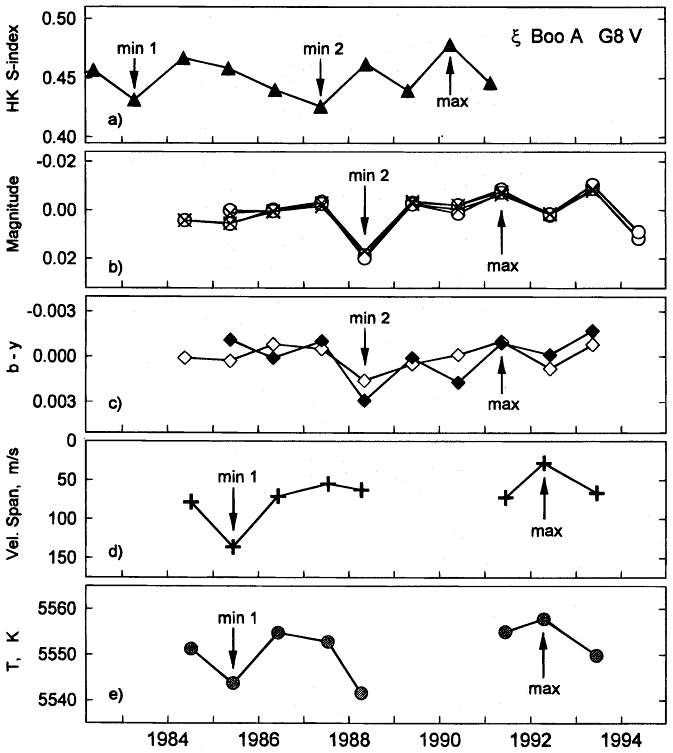

FIG. 2.—Season means of the five observed parameters are shown as a function of time. The labeled maxima and minima are discussed in the text.

K S index for the time frame of our other observations is replotted in Figure 2a.

4. PHOTOMETRIC VARIATIONS

Variations in b and y magnitude we take to be a measure of the power fluctuations of the star. Season mean photometry is shown in Figure 2b, and it is important to remember that both the primary and secondary components of the binary are measured together. The mean of each magnitude was set to zero. Circles are for the blue magnitude, crosses are for the yellow magnitude, and the two curves for each bandpass are for the two comparison stars. The excellent agreement illustrates the integrity of the data. Significant year-to-year variations are seen, with a slight secular rise during the 1985–1994 time window.

Color indices formed by subtracting the two magnitudes to form $b - y$ show a noisy but significant variation, as depicted in Figure 2c. The two curves here are for the two comparison stars, and their differences allow us to estimate the photometric errors.

5. GRANULATION

Asymmetries of spectral lines arise from granulation and other photospheric velocity fields (Gray 1980, 1981, 1982, 1988; Gray & Toner 1985; Dravins 1987). Figure 3 shows the asymmetries for Fe I $\lambda6253$, as delineated by the line bisectors, with individual exposures on the left, and their mean on the right. (Experience has shown $\lambda6253$ to be one of the best and most stable lines for bisector work, and it has been used consistently throughout this series of papers.) The mean bisector for ξ Boo A is not at all typical of other late G dwarfs that have been measured, but it shows a much stronger granulation signature, one more typical of late F or early G dwarfs. This is consistent with the earlier study of line broadening (Gray 1984a), in which anomalously large macroturbulence was found.

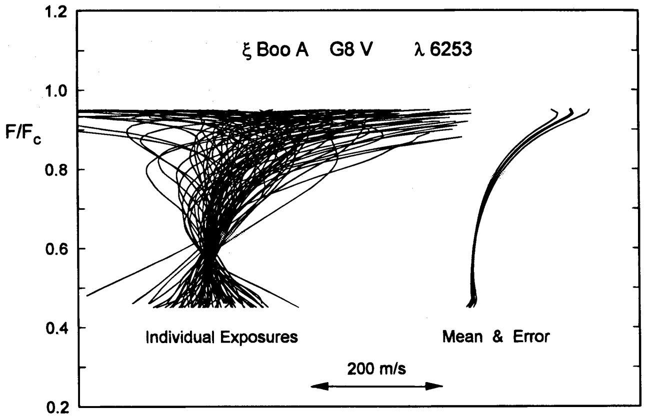

FIG. 3.—Bisectors for the Fe I spectral line $\lambda6253$ are shown on the left for 92 exposures. Their mean is shown on the right. About half the scatter arises from rotational modulation, and the other half arises from observational errors. The thin lines on either side of the mean show the standard deviation of the mean; this includes the rotational modulation.

Asymmetries in spectral lines can also arise from gross surface features such as starspots and starpatches, and modulation of the line bisector occurs as rotation carries the feature across the disk of the star (e.g., Toner & Gray 1988; Gray 1988). About half the scatter of the individual bisectors in Figure 3 arises from rotational modulation. Therefore, it becomes important to know the rotational phase of the observations and if or how the season means are affected by the times of sampling. Figure 4 shows the phases of the spectroscopic observations for the 6.43 day period found in the earlier study. For the combined data set, the phase coverage is very complete (*top*). For the 1986 season, the phases are well covered. This is the season when the rotational modulation was observed intensively. To help judge the nature of any biases in other years, the rotational variation in velocity span of the line bisector is shown at the bottom of Figure 4. There we see that the more extreme variations occur near phases ≈ 0.2 and ≈ 0.5.

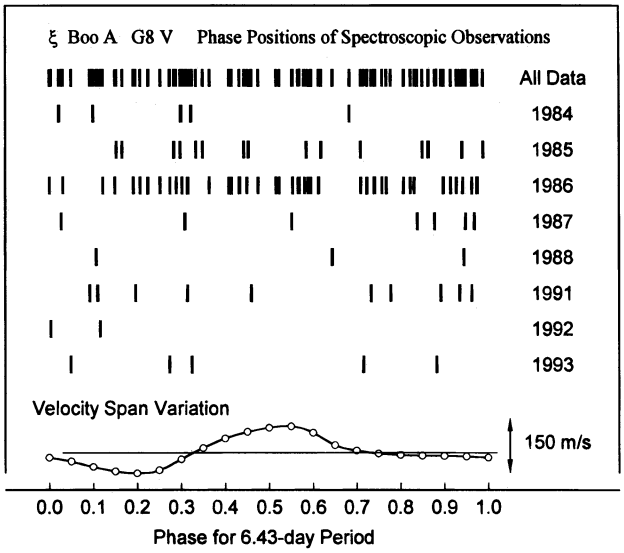

FIG. 4.—The phases of the spectroscopic exposures are shown for the 6.43 day rotation period. The variation in bisector velocity span (Toner & Gray 1988) is shown at the bottom. The most extreme deviations occur near phases 0.2 and 0.5.

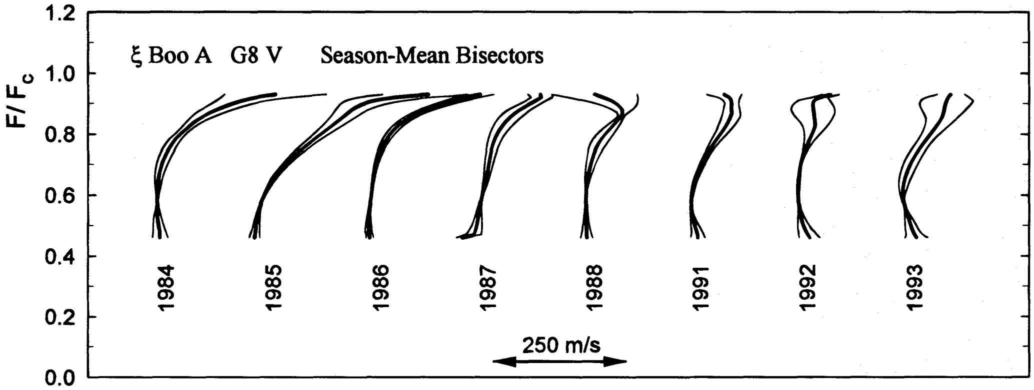

FIG. 5.—The means of bisectors for each season show significant differences. The heavy lines are the mean bisectors; the light lines are the standard deviations of the means, including rotational modulation. The velocity spans plotted in Fig. 2*d* are measured between $F/F_c = 0.55$ and 0.85.

Inspection of the phases for individual years shows that for most years these phases were sampled roughly equally, so that their extreme deviations will essentially average out. The 1987 season is an exception, with an observation at phase 0.552 that is not balanced with one in the phase interval around 0.2. Even this situation turns out to be only slightly perturbed, however. The season mean with the point included is 54.8 m s^{-1} compared to 56.6 m s^{-1} without it. Such a small difference is well within the errors of measurement for these data.

The nature of the season-to-season variations is shown in Figure 5. As a measure of the vigor of the granulation, we use the span in velocity over which the bisectors extend between 55% and 85% of the continuum level. From Figure 5 or Figure 2*d*, we can see that the velocity span is largest in the 1985 season. We shall see below, when discussing the time lags of various phenomena, that this corresponds to a magnetic minimum. The general correspondence of velocity span with magnetic variation (as presented below in Figure 7) may indicate a global suppression of granulation by the stronger magnetic fields. Suppression of bisector blueshifts for this same spectral line in the solar spectrum is seen in magnetic areas on the (resolved) solar disk (Brandt & Solanki 1990).

6. TEMPERATURE VARIATIONS

The ratio of line depths for the two lines shown in Figure 6 is temperature dependent, and the calibrations published previously (Gray & Johanson 1991) have been used here to derive the temperature variations. In order to be strictly consistent with previous papers in this series, we have chosen not to include other line-depth ratios (Gray 1994c). Most of the observed scatter around season means arises from rotational modulation. As with the granulation measurements in the previous section, the season averages are expected to retain minimal bias from rotational variations. Estimated errors for the season mean temperatures range from a low for the 1986 data of ≈1.5 K to a high for the 1992 data of ≈4 K.

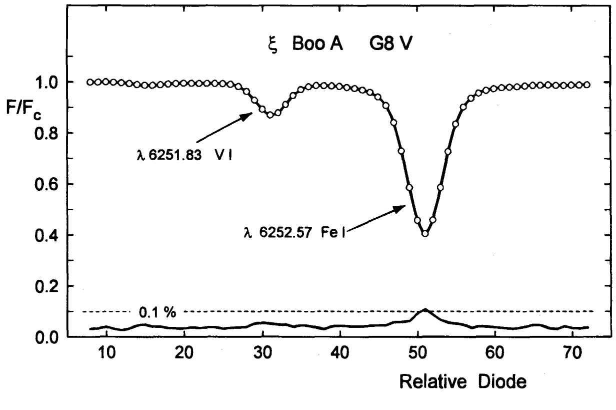

FIG. 6.—The ratio of the depths of these two spectral lines is used as a temperature indicator. The spectrum shown is the average of the 92 exposures. At the bottom is shown the error of this mean on a 100 times magnified scale.

The temperature excursion from the 1986–1987 seasons to the 1988 season is ≈12 K (Fig. 2*e*). A 12 K temperature change implies $\Delta(b-y) \approx 0.0022$, after correction for the light of the secondary star, according to the observed slope of temperature versus color index along the main sequence. This is to be compared to the observed change in Figure 2*c*, averaged over both comparison stars of $\Delta(b-y) \approx 0.0025$, i.e., reasonable agreement. This supports the premise that the line-depth ratio does indeed measure temperature and not some other change in atmospheric structure.

7. THE PHASE SHIFTS

Because of the chaotic nature of the year-to-year fluctuations shown by ξ Boo A, the pattern of the variation is less easily identified than for other stars studied in previous papers of this series. However, a careful inspection of Figure 2 reveals that each variable does go through approximately the same pattern of variation, but at different times, i.e., they are phase shifted in time. Some points of correspondence are indicated in Figure 2. The variation in the magnetic signature occurs first, as with all previous stars studied.

The photometric, granulation, and temperature curves of Figure 2 were each shifted along the time axis to match (by eye) the magnetic variation, as shown in Figure 7. The solid curve here has no special significance, and its purpose is merely to guide the eye through the profusion of symbols. The resulting time lags are given in Table 2. Taken at face value, they indicate the time order of occurrence to be (1) H and K index, (2) *b* and *y* magnitudes, (3) $b-y$ color index, (4) line-depth ratio temperature, and (5) bisector velocity span. The errors are sufficiently large, however, such that time-lag differences between color index and temperature, or between velocity span and temperature, are not significant. Previous studies, especially the one for β Comae, showed granulation and temperature to vary in phase, and the same is probably true for ξ Boo A.

Although the general pattern of maxima and minima can be seen in the four variables, the detailed shapes of the time

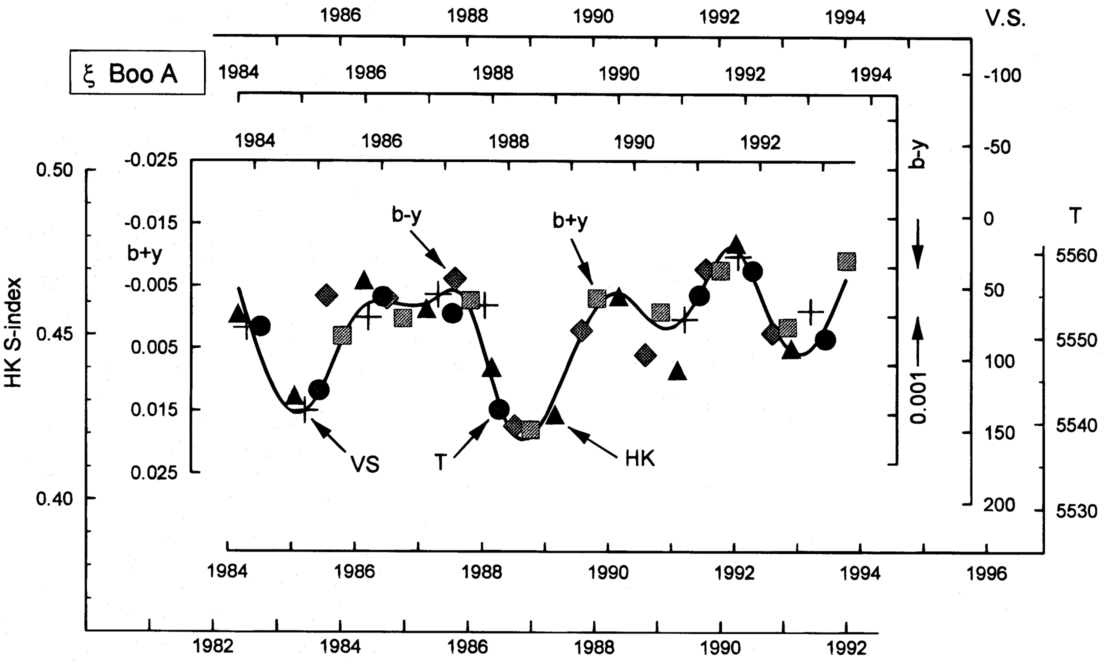

FIG. 7.—The five variables are shown here as a function of time with time lags introduced to match each of the others to the H and K variation. The solid line is put in to guide the eye. Each of the five sets of symbols is labeled, and there is a coordinate axis for each variable. Vertical scaling and shifts are arbitrary, but horizontal shifts give the time lags.

variations may show some differences (Figure 7). We must bear in mind that the parameters being plotted are signatures of different physical characteristics, and there is no reason to expect *linear* relations to exist among them. Therefore, the detailed shape of the variations may truly differ from one variable to the next. Further, the one-point-per-season sampling is not frequent enough to adequately delineate details for the more rapid variations. Even so, the 1984 photometric points do not seem to show "min 1" in Figure 2. Perhaps this can be attributed in some way to 1984 being the start-up year of the monitoring program, or possibly to variation of the secondary component of this binary whose light is included, or it may arise simply from statistical errors of measurement. Other apparent differences include the smooth decline from 1984 to 1987 of the *S* index compared to a more constant value followed by a sudden drop going into "min 2" for the other variables. The spectroscopic data may also show differences in shape around 1988, with velocity span not coming down into "min 2" as quickly as the temperature. Although we point out these subtle differences, we readily admit that they border on the errors of measurement and may not be real.

The time lags seen here for ξ Boo A are consistent with those found for other stars (Gray 1994b). In Figure 8, we show the position of ξ Boo A on the time lag versus effective temperature relation. The larger point is for the better determined temperature curve using line-depth ratios, while the smaller one is for the less well determined color index curve. With so few data, we do not know if the strong activity of ξ Boo A affects its position in this plot relative to less active stars, but apparently any such deviation is not large. The physical reason for such time lags is currently unknown, but the reader is referred elsewhere for some thoughts on the issue (Spruit 1991, 1994; Gray 1994b).

TABLE 2

TIME LAGS FOR ξ BOOTIS A

Variable	Lag Error (yr)
H and K	0.00 (Reference)
$b+y$	1.36 ± 0.4
$b-y$	1.54 ± 0.5
T	1.77 ± 0.3
Velocity span	2.07 ± 0.4

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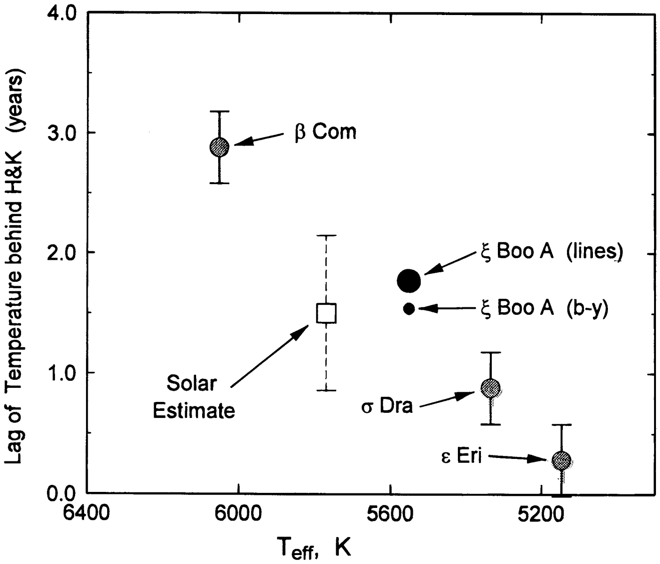

FIG. 8.—A summary of the time lags of temperature variation behind H and K variation is shown. The values for ξ Boo A determined in this paper are shown for temperature from the line-depth ratio (*large dot*) and for the color index (*small dot*). The errors of these determination are ≈0.3 yr for the large dot and ≈0.5 yr for the small dot.

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