1996ApJ...456..365G

THE ASTROPHYSICAL JOURNAL, 456:365–369, 1996 January 1

VARIATIONS OF β COMAE THROUGH A MAGNETIC MINIMUM

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Received 1995 January 17; accepted 1995 July 3

ABSTRACT

The dwarf star β Com = HR 4983 = HD 114710 (G0 V, $B-V = 0.57$) is close to the Sun in the H-R diagram, being only $\approx$260 K hotter. We present measurements done over several years of (1) the line depth ratios of V I λ6251.83 to Fe I λ6252.57 to establish the temperature, (2) the line bisectors as a measure of the star's granulation, (3) Ca II H and K emission as an indirect indicator of magnetic activity, and (4) the blue and visual magnitudes as an indication of the power output. All these parameters show a similar variation consisting of a broad minimum extending over approximately 5 years, but the minima do not occur at the same epoch. The magnetic signature leads the others in time. Time lags relative to the magnetic variation are 0.9 ± 0.3 yr for the photometric data, 2.9 ± 0.3 yr for the temperature, and 2.9 ± 0.5 yr for the granulation. A 1% variation in radius during the 5 yr interval is indicated.

Subject headings: stars: activity — stars: individual (β Comae) — stars: magnetic fields

1. BACKGROUND

The magnetic cycle–type variations of stars and the Sun are apparently major controllers of the atmospheric dynamics of cool stars. During the last solar 11 yr cycle, essentially every physical parameter that was measured showed some systematic pattern of variation. But understanding how and why these changes are occurring has proved to be difficult. Waiting through several more 11 yr cycles to obtain additional data must be done, but in the meantime, we can also glean information from other stars, many of which show magnetic cycle–type variations, some with clearly defined cycles, others showing more random variations. In many cases, the magnetic activity is stronger than on the Sun, and we might expect to see amplified versions of the solar events, or different phenomena altogether. Additional background material can be found in the previous papers of this series (Gray et al. 1992, hereafter Paper I [on σ Dra K0 V]; Gray & Baliunas 1993, hereafter Paper II [on τ Cet G8 V]; Gray 1994a, hereafter Paper III [on η Cep K0 IV]; Gray & Baliunas 1995, hereafter Paper IV [on ϵ Eri K2 V]).

The focus of this paper is β Com, a G0 main-sequence star some 8 pc away (Gliese 1969; Hoffleit 1982). No evidence has been found from astrometric studies or from precise radial velocity measurements for its being a binary (Heintz 1986; Campbell, Walker, & Yang 1988). The projected equatorial rotation velocity has been measured at 3.9 km s^{-1} (Gray 1984) and 4.3 km s^{-1} (Soderblom 1983). This value is not unusual for early G dwarfs, but it probably does indicate that β Com is younger than the Sun by approximately half a billion years. Complex rotational modulation of the H and K emission has been reported by Donahue & Baliunas (1992), which they interpret as evidence for differential rotation. The sense of the differential rotation is opposite that of the Sun. The periods they detected range from 11.4 to 13.5 days, again consistent with approximately double the solar rotation rate. An earlier study, based on fewer data, found similar results (Baliunas et al. 1985). In our study of β Com, we shall assume that our data sampling is sufficiently random and frequent to suppress any effects of the rotational modulation on timescales of several months or more.

Cayrel de Strobel et al. (1992), in their [Fe/H] catalog, list nine entries with a mean [Fe/H] of 0.152. Six of the nine entries have a temperature close to 6000 K, i.e., near the value we find below, and their mean is 0.145 ± 0.09. Taylor (1994), in a reanalysis of the [Fe/H] data, finds 0.14 ± 0.06. This slight metal enrichment relative to the Sun is consistent with β Com being somewhat younger than the Sun.

The H and K S index has a mean of $\approx$0.20 compared to the solar value of $\approx$0.17. Although this difference may seem small, β Com is situated significantly closer to the boundary between correlated versus anticorrelated behavior between photometric brightness and H and K emission variation, as delineated by Radick, Lockwood, & Baliunas (1990). The H and K variations over the longer timescales of decades do not show smooth cyclic behavior, but they are more irregular and in this regard similar to the younger and more active dwarfs.

We apparently have in the example of β Com a star rather similar to the Sun when it was $\approx$10% younger than now.

2. THE OBSERVATIONS

High-resolution, high signal-to-noise spectroscopic observations were done at the University of Western Ontario using the coude spectrograph of the 1.2 m telescope (see Gray 1986). The resolving power is approximately 10^5, and the signal-to-noise ratios are typically 300–500. We used the standard set of spectral lines, as shown in Figure 1 of Papers I and II. In the time span covered by the spectroscopy, 1986–1993, 84 exposures were measured.

Measurements of the chromospheric activity were done at Mount Wilson using 1 Å bands centered on the cores of the Ca II H and K lines (see Baliunas & Vaughan 1985). Individual measurements have photometric errors ≈2%, and typically three observations were made per night.

Photometric observations were made at the Lowell Observatory (Lockwood & Skiff 1988) in the blue (4720 Å) and the yellow (5510 Å). Individual measurements have errors of 2.5 mmag. The number of observations per year ranged from 11 in 1987 to 32 in 1988, and the average number per year was 22.

3. MEASUREMENTS OF TEMPERATURE

The line depth ratios of the two lines shown in Figure 1 are used to measure the temperature. The V I line varies much more rapidly with temperature than does the Fe I line, and near the temperature of *β* Com, the sensitivity amounts to some 49 K per 1% change in the depth ratio. We use the calibration derived in an earlier study (Gray & Johanson 1991). The depths of the lines are taken to be the minima of parabolae fitted to the lowest three points in each profile. Continua are set to ≈0.1% by eye. Automatic scaling to a reference exposure, using precisely the same sections of continuum, produced virtually identical results. The average mean error from a single exposure is 19 K. The average error on the season mean (which is primarily what we are concerned with here) is 5.5 K. This is a statement of our measuring precision. The actual effective temperature scale is much less certain. These errors are somewhat larger than the numbers given in earlier papers of this series because of the decreased sensitivity of line depth ratio to temperature. The measuring precision for *β* Com is not significantly different than for previous analyses. A more complete discussion of temperature errors is given in Paper I.

Given the complex nature of the variations demonstrated by this star (see below), it is worth remembering that we cannot be absolutely certain that the line depth ratio is measuring temperature changes. There is no doubt about the change of line depth ratio with spectral type across a sample of many stars. But for small changes in line depth ratio, one cannot completely rule out subtle alterations in the structure of a star's photosphere.

The nature of the deduced temperature changes can be seen in panels Figures 2*c* and 3*c*. Values for individual exposures are shown in the first figure, while season means shown in the

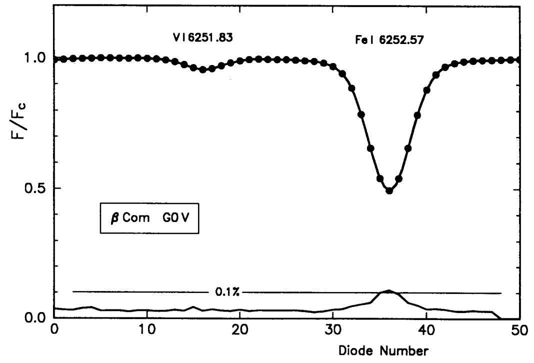

FIG. 1.—The ratio of the depth of the vanadium line to the iron line is used as a temperature index. The rms errors of this average spectrum, incorporating 84 exposures, are shown at the bottom of the plot with a vertical magnification of 100 times.

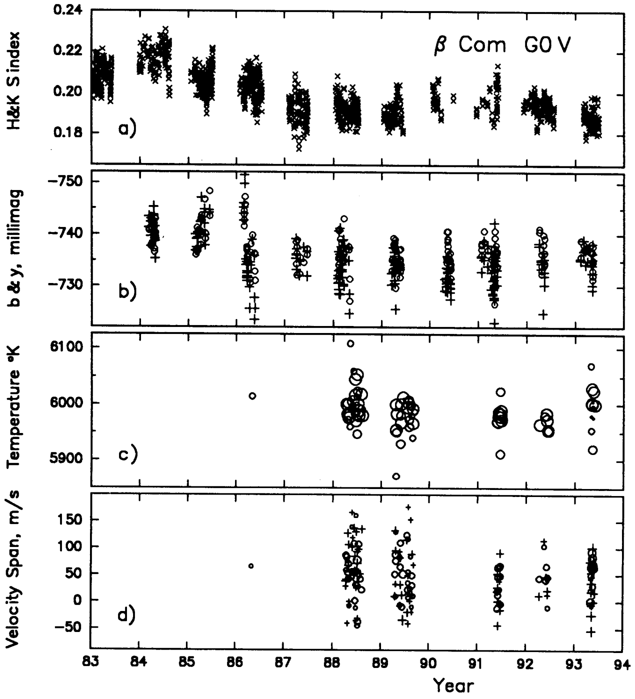

FIG. 2.—The complete set of individual measurements is shown here as a function of time. Each panel shows a different variable, as labeled, and a minimum is discernible in each. In (*b*), plus signs represent the *b* magnitudes and open circles represent the *y* magnitudes with a 59 mmag zero offset. In (*d*), plus signs are velocity spans between F/F_c = 0.55–0.85, while open circles are velocity spans between F/F_c = 0.70–0.95. Larger symbols in (*c*) and (*d*) denote higher weight observations.

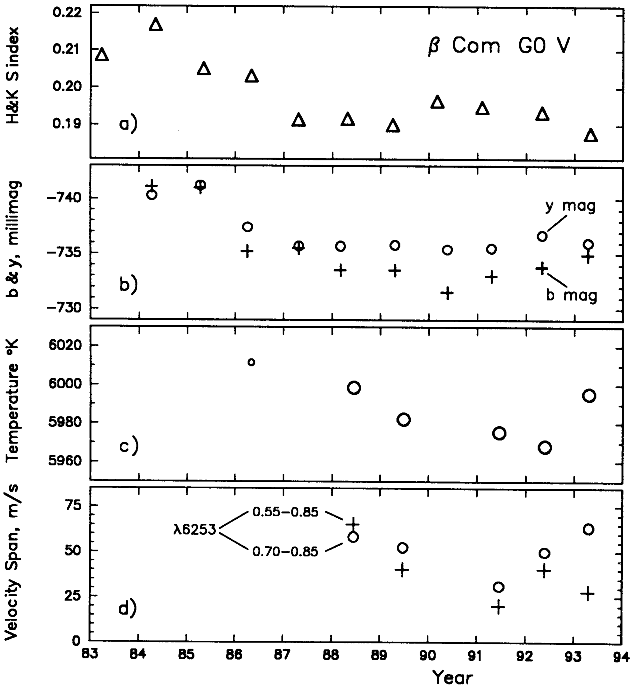

FIG. 3.—Same as Fig. 2, but with each observing season's data averaged. Notice the greater decline in the blue light compared to the yellow light in (*b*). Two velocity spans are shown in (*d*) for the values of F/F_c as labeled.

second. We see a broad minimum spanning the years of measurement with an excursion of ≈ 30 K.

4. MEASUREMENTS OF GRANULATION

The implicit correlation of rise velocities with hotter temperatures of granules and fall velocities with cooler temperatures of intergranular areas produces asymmetries in spectral lines, and these asymmetries are reduced only by a factor of about 2 by integration over the disk of the star. Granulation asymmetries were first discovered in stellar lines a decade and a half ago (Gray 1980, 1981), and several studies have subsequently been published (e.g., Gray 1982, 1988; Dravins 1987). The line bisector has come to be the usual tool for asymmetry analysis. The information we seek is contained in the shape of the bisector. We do not know the absolute position of stellar line bisectors because of the radial velocity of the star as a whole.

Figure 4 shows the line bisectors of $\lambda 6252.57$ for the individual exposures. Their mean is shown on the right. Some of the scatter is observational error, some is caused by year-to-year variations, and some may arise from rotational modulation. Bisector errors (horizontal in the plot) increase toward the top and bottom of the bisector because they are largely photometric errors (vertical in the plot) divided by the slope of the line profile (Gray 1983, 1988). The velocity span for β Com is substantially larger than for the Sun, but it still fits into the well-known general pattern of change in bisectors across the H-R diagram (Gray 1988, 1992 [Fig. 18.16]). The β Com mean bisector differs systematically in shape from its solar counterpart. Solar bisectors have roughly a C shape because the largest blueward shifts occur near the center of the bisector. In the case of β Com, the bottom of the C shows more blueshift than the solar case, presumably because the contrast of the granulation structure in β Com is still significant at the higher photospheric levels where the cores of the lines are formed.

The season averages and their errors are shown in Figure 5. They are positioned arbitrarily in order of year. Variations in shape are seen. Since lower points on a bisector correspond to higher photospheric layers, one way to interpret the data is to decode blueward shifts as a measure of the vigor of granulation with height. In the 1988 season, granulation was the most vigorous, penetrating well into the higher layers of the photosphere (strong blueshift in the core). By the 1991 season, the granulation had become generally weaker (smaller blueshifts everywhere). And by 1993, the granulation was again showing increased virgo in deep and intermediate layers. On the other hand, some solar measurements (Brandt & Solanki 1990) indicate a complex interaction between magnetic field and line bisectors, and so such a simple interpretation should be treated with caution.

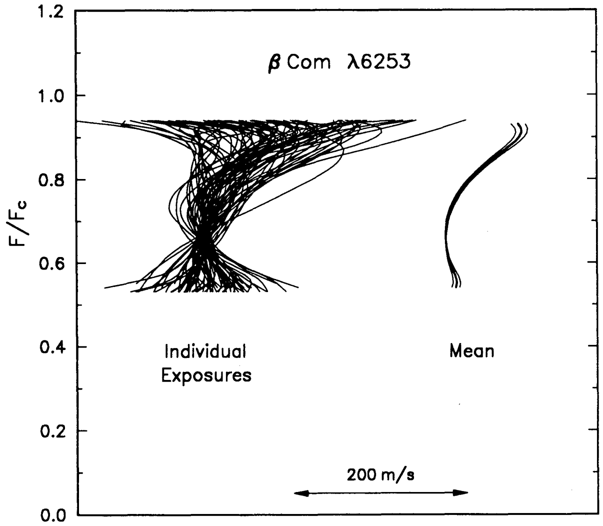

FIG. 4.—The bisectors of Fe I $\lambda 6253$ for the individual exposures are shown on the left. Their mean is shown on the right. The lighter lines bracketing the mean bisector indicate the standard deviations on the mean. There is no absolute zero point to the velocity scale, and only the shapes of the bisectors are being considered.

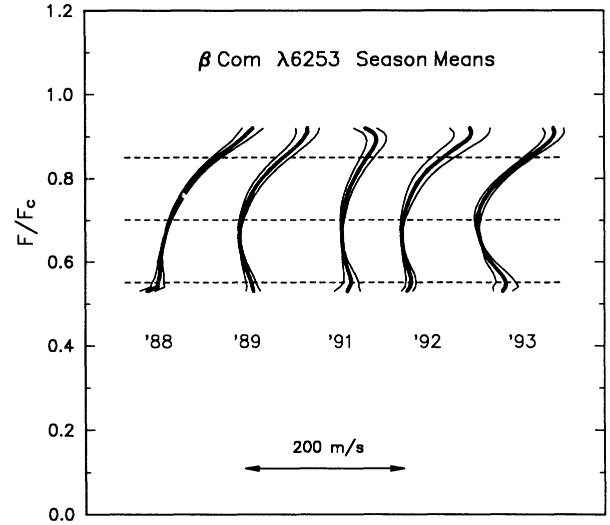

FIG. 5.—Mean bisectors of $\lambda 6253$ are shown for each observing season (*heavier lines*). The standard deviations on mean bisectors are shown by the thinner lines. Horizontal dashed lines show the levels at which the velocity spans were computed.

We selected three levels in the $\lambda 6253$ profile to measure velocity spans, as shown by the dashed lines in Figure 5. The velocity difference between the points at $F/F_c = 0.55$ and 0.85 is a measure of the granulation in higher photospheric layers; the velocity difference between $F/F_c = 0.70$ and 0.85 is a measure for the deeper layers. In Figure 2*d*, these velocity spans are plotted as plus signs and open circles, respectively. The corresponding season means are shown in Figure 3*d*.

The velocity span parameters show a broad dip that mimics the one seen in the temperature variations.

5. MEASUREMENTS OF MAGNETIC ACTIVITY

The magnetic signal is indicated indirectly by the chromospheric emission we monitored in the H and K lines. We use the S index here; it has the fewest correction factors applied to it, e.g., basal corrections for the nonmagnetic component of emission, or normalization to the bolometric flux of the star. In Figures 2*a* and 3*a* we show the individual and season mean observations. The broad dip is clearly delineated. The drop ($\Delta S \approx 0.025$) from 1984 to 1989 is the largest variation seen for β Com since monitoring began in 1966. The ΔS variation of ϵ Eri (which is one of the most chromospherically active stars) studied in Paper IV is only 1.5 times larger.

6. PHOTOMETRIC MEASUREMENTS

The b and y photometry are indicative of the power output of the star. The b and y data are shown in Figures 2*b* and 3*b*, in which a broad dip can be seen. Both the blue and the yellow magnitudes show the dip, but they are not identical. As can be seen in the figures, especially in Figure 3*b*, the blue flux drops more than the yellow flux. We also formally subtracted the two to form a color index. It shows a general reddening, i.e., a cooling, by ≈5 mmag during the major portion of the time window of our study, in at least qualitative agreement with the temperature measurements discussed above. The color index errors are too large to make a more definitive statement.

7. THE PHASE SHIFTS

The astute reader will have noticed by now that the minima in Figures 2 and 3 do not occur at the same time, and in fact, the magnetic changes come first, trailed by the photometric changes, and still later come the temperature and granulation changes. A more complete comparison is shown in Figure 6. Here we use the average of *b* and *y* magnitudes and the average of the two velocity spans shown in the previous figures. The ordinates of the panels in Figure 6 have been arbitrarily scaled, and the time axes are shifted to give the best match as judged by eye. Within the errors of observation, each variable follows the same shape curve. Taking the H and K timescale as the reference, we estimate the photometric variation to come 0.9 ± 0.3 yr later, the temperature to lag by 2.9 ± 0.3 yr, and the granulation to lag by 2.9 ± 0.5 yr. There is some evidence that these kinds of phase shifts are systematically smaller in cooler stars (Gray 1994b).

This remarkable result has several implications. Since the pattern of H and K variation is not periodic, we can be fairly certain that the magnetic variation really does occur first, i.e., we are not viewing magnetic field lagging by *more* than half a cycle. This implies that magnetic changes may be *driving* the others. Naturally there remains the possibility that some other physical variable is driving all our measured quantities.

Second, we can see no phase difference between temperature and granulation changes. This is what might be expected with convection so intimately related to temperature and its gradient. But until we understand the reason for the temperature and bisector variations, even this should not be taken for granted.

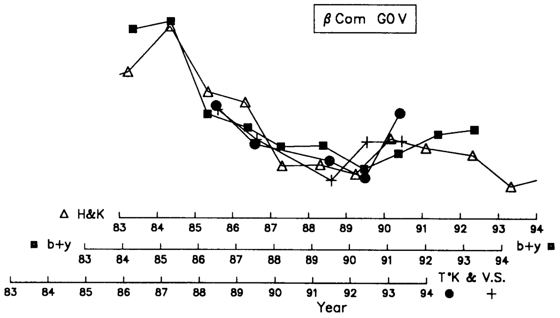

FIG. 6.—Each of the four parameters, H and K *S* index, *b* and *y* photometry, temperature, and velocity span are compared here by introducing translations in the abscissa to place their minima in the same position. The amount of phase shift in years can be read from the displacements of the abscissa scales.

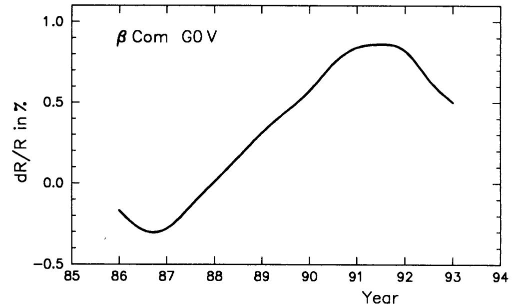

FIG. 7.—Our data predict a small systematic change in radius, ≈1%, across the time interval of the observations.

Third, the photometric and temperature changes cannot result from a simple "puncturing" of the photosphere by partially transparent magnetic flux tubes, since that would result in no phase differences. Apparently the interaction is more complex and involves thermal and possibly dynamical timescales. A proper understanding of the processes should allow us to deduce these timescales from the phase lags. Specifically, we may be able to deduce the effective depth at which certain surface variables are controlled.

Model photosphere calculations indicate that the photometric *y* magnitude can be expected to vary with the 3.9 power of the temperature. For our purposes, it is sufficiently accurate to approximate this with the fourth power, as with the luminosity dependence, and compute the expected change in radius given by $dR/R = \frac{1}{2} dL/L - 2\,dT/T$. We used the variation in *b* and *y* for dL/L, but in fact, the first term is small compared to the second, and the temperature change accounts for almost all the predicted radius change. Consequently, the changes in radius are essentially in antiphase with the changes in temperature. Using smooth curves drawn through the photometry and the temperature plots, the deduced radius change is shown in Figure 7. A growth of slightly more than 1% from 1987 to 1992 is indicated. If the radius of β Com is typical of a G0 dwarf (Gray 1992, Chapter 15 and Appendix B), 1% amounts to about 8600 km. Changes of this order might arise from any number of physical effects, including a change in efficiency of convection, changes in the expanse of the hydrogen ionization zone, changes in opacity in the envelope below the surface, or magnetic pressure, but it is too large to be accounted for by changes in the photospheric opacity.

The velocity of the stellar surface during the 4 years of expansion is ≈7 cm s^{-1}, about 2 orders smaller than errors of current techniques (McMillan et al. 1992; Larson et al. 1993).

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