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THE VERY SLOW SPECTRUM, MAGNETIC, AND PHOTOMETRIC VARIATIONS OF HD 9996

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ABSTRACT

The Cr and Eu line intensities, magnetic field, and *UBV* photometric properties of the Ap star HD 9996 appear to vary in a period of 22–24 years. The phase relations between the various variable parameters are identical with those of well-known Ap stars with shorter periods. HD 9996 is also a single-line spectroscopic binary with a period of 273ᵈ2.

I. INTRODUCTION

We have accumulated evidence for extraordinarily slow spectrum, magnetic, and light variations of the Ap star HD 9996 (=HR 465), a Cr-Eu star (Osawa 1965) with a modest magnetic field (Babcock 1958). Bidelman (1967) called attention to the unusual strength of rare-earth lines on a 1960 September spectrogram (2 Å mm^{-1}) of HD 9996 which he used to make extensive line identifications. As a preliminary to the measurement of a series of Zeeman spectrograms obtained at Lick Observatory in 1966 and 1967 we tried to use Bidelman's (unpublished) line list and were surprised to find that the line strengths on our spectrograms bore no relation whatever to those estimated by Bidelman. This circumstance was all the more astonishing because all of our spectrograms, obtained from 1966 July through 1967 October, are much alike; there is no evidence of any marked changes in line strength in an interval of 15 months. In view of this result we continued observation to the present time and have examined all additional spectrograms of HD 9996 on file at the Hale Observatories. A journal of all spectroscopic observations is given in Table 1, together with their dates and other pertinent data. In this more extensive set of observations spectral variations *can* be detected, as illustrated in Figure 1 (Plate 4) in which comparison of spectrograms Ce 18038 and Ce 20155 shows that the Eu II line λ4435.58 has markedly weakened, the Cr lines have strengthened, and the number of weak lines has diminished between 1965 August and 1969 October. No high-dispersion spectrograms are available near the date of Bidelman's observation, but two 20 Å mm^{-1} spectrograms (Ce 15689 and Ce 15762), exposed primarily for the ultraviolet region λλ3100–3700, were obtained by S. Chandra in 1962 September. Comparison of these plates with repeat spectrograms of 1969 November, also reproduced in Figure 1, shows more pronounced changes in the spectrum. At the present time the spectral region λλ3500–3700 contains the strong lines of Cr II in *Revised Multiplet Table* multiplets 12 and 13, whereas in 1962 these lines were lost or inconspicuous in a forest of weak features most of which are blends at 20 Å mm^{-1} dispersion. Similar conclusions follow from the more familiar region near λ4250, but the spectrograms are greatly overexposed at this wavelength. The H- and K-lines of Ca II have weakened by a factor of at least 2 since 1962. From the above comparisons and from the fact that no spectrum variations can be found on time scales of a day, a week, a month,

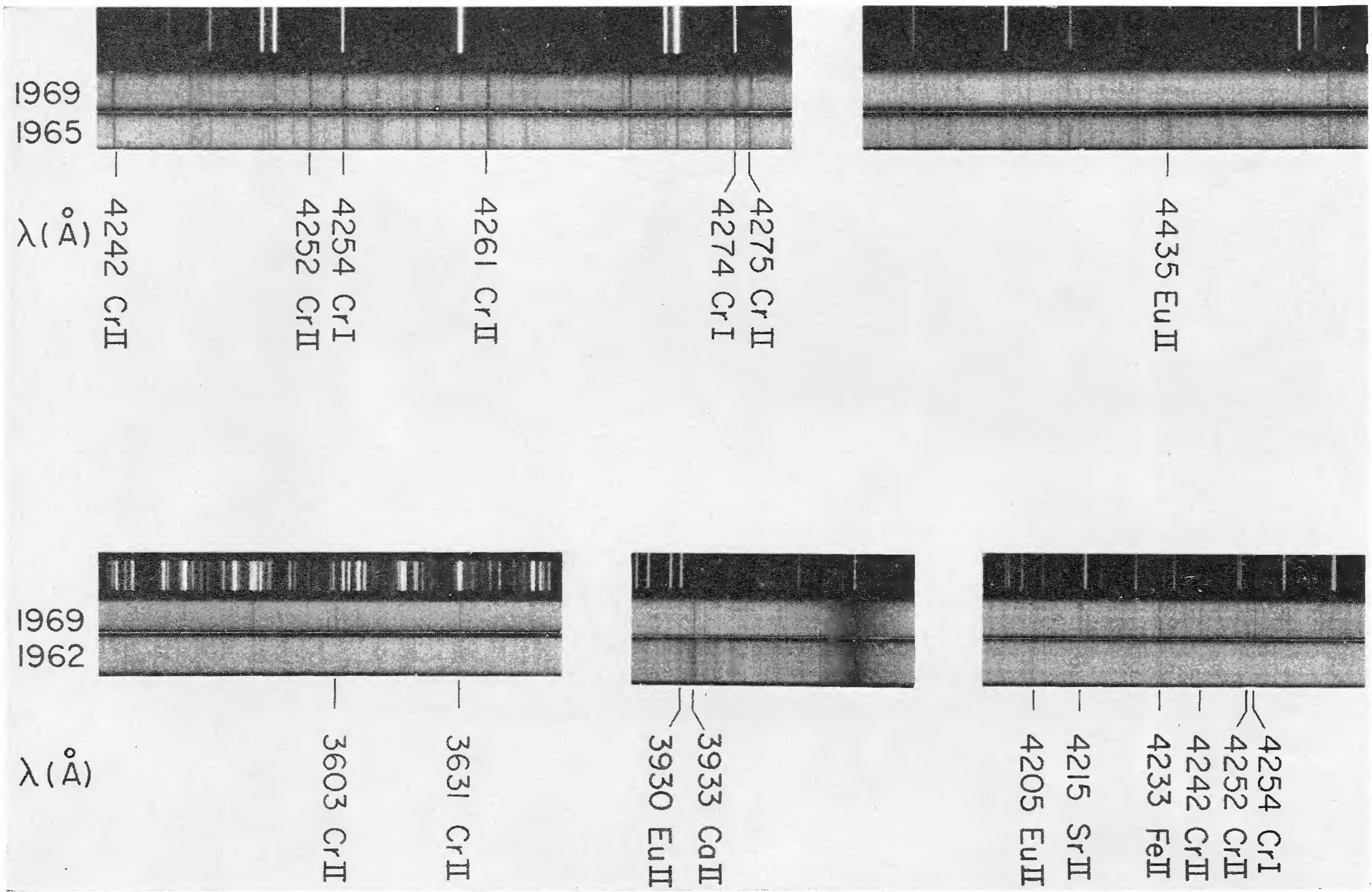

FIG. 1.—*Top*, reproductions of portions of two 4.3 Å mm^{-1} spectrograms of HD 9996 obtained in 1965 (Ce 18038) and 1969 (Ce 20155). Between 1965 and 1969 the Eu II line λ4435.58 became much weaker whereas the lines of Cr II near λ4250 became stronger. *Bottom*, reproductions of portions of 20.9 Å mm^{-1} spectrograms obtained in 1962 and 1969. All Cr lines were much stronger in 1969, but Eu II λλ3930.50 and 4205.05 and the K-line of Ca II were stronger in 1962.

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or a year in 1966–1967 (see Table 1), we conclude that the weakening of the rare-earth lines and the strengthening of the Cr lines probably occurred monotonically from 1960 through 1969.

II. THE SPECTRUM, MAGNETIC, AND PHOTOMETRIC VARIATIONS OF HD 9996

a) *Spectrum Variations*

Eye estimates of line intensities for all available spectrograms are given in Table 1. Line strengths were estimated relative to two "standard" spectrograms, ECZ 5373 (8.2 Å mm^{-1}, 1966 November 23) and ECZ 5406 (4.1 Å mm^{-1}, 1966 November 26) on a Boller and Chivens spectrocomparator. The zoom microscopes of this comparator greatly facilitated matching of the 8–10 Å mm^{-1} plates and the various 4 Å mm^{-1} dispersions that are indicated in the second column of Table 1. Two intensities are given

TABLE 1

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Plate No. (1)	Dispersion (Å mm^{-1}) (2)	Date (U.T.) (3)	J.D. (2400000+) (4)	Relative Line Strength: Eu (5)	Relative Line Strength: Cr (6)	V_{rad} (km sec^{-1}) (7)	H_e (gauss) (8)
V1661	38	1936 November 26	28498.7	Str.	Wk.	− 6.2	...
V2108	38	1937 November 21	28858.7	Str.	Wk.	− 0.5	...
γ 21513	78	1938 November 5	29207.8	...	...	+10.8	...
Ce 5413	10	1948 November 10	32865.7	0.55	1.0	− 6.1	...
Ce 5446	10	1948 November 23	32878.7	0.80	1.05	− 7.9	−1180
Ce 5501	10	1948 December 19	32904.7	0.85	1.2	− 5.6	−1700
Ce 5783	10	1949 July 19	33116.9	0.70	1.15	− 6.0	− 990
Ce 6063	10	1949 December 6	33256.6	0.50	1.1	+ 4.4	−1140
Pb 2860	4.5	1956 September 26	35742.9	1.35	1.0	+12.0	+ 140
Ce 15689	20.9	1962 September 13	37920.8	≥1.5:	≤0.4	+ 8.0	...
Ce 15762	20.9	1962 September 27	37934.9	≥1.5:	≤0.4	...	...
Ce 18038	4.3	1965 August 17	38989.9	1.35	0.85	+ 2.4	...
Ce 18052	10	1965 August 19	38991.9	...	...	+ 3.9	...
ECZ 5095	8.2	1966 July 27	39334.0	1.0	0.95	+ 0.6	+ 30
ECZ 5105	8.2	1966 July 31	39338.0	1.0	1.0	+ 0.4	+ 400
ECZ 5127	4.1	1966 August 2	39339.9	1.15	0.9	− 0.7	+ 420
ECZ 5144	4.1	1966 August 5	39343.0	1.05	1.05	− 1.8	+ 440
ECZ 5157	4.1	1966 August 6	39344.0	...	...	− 1.5	+ 430
ECZ 5254	4.1	1966 October 2	39400.8	...	...	− 6.3	+ 200
ECZ 5273	4.1	1966 October 4	39403.0	1.2	1.0	− 6.4	+ 330
ECZ 5373	8.2	1966 November 24	39453.7	1.0	1.0	− 6.2	0
ECZ 5398	8.2	1966 November 26	39455.8	1.2	1.0	− 5.5	+ 230
ECZ 5406	4.1	1966 November 27	39456.6	1.0	1.0	− 5.9	+ 270
ECZ 5415	4.1	1966 November 30	39459.6	...	...	− 5.9	+ 270
ECZ 5473	4.1	1967 January 2	39492.6	1.0	0.95	− 3.6	+ 260
ECZ 5840	4.1	1967 August 18	39721.0	...	...	− 6.0	− 60
ECZ 5924	4.1	1967 August 26	39729.0	1.0	1.0	− 5.6	+ 270
ECZ 6088	4.1	1967 October 13	39776.9	1.0	1.0	− 2.6	+ 130
Pb 10687	4.5	1968 August 16	40084.9	0.90	1.05	+ 3.4	...
Pb 11250	4.5	1969 August 26	40459.9	0.90	1.05	− 5.7	...
Ce 20083	20.9	1969 October 1	40495.9	...	...	...	...
Pb 11405	4.5	1969 October 30	40524.6	0.85	1.0	− 7.1	...
Ce 20155	4.3	1969 November 21	40546.8	0.8	1.2	− 6.5	...
Ce 20181	20.9	1969 November 23	40548.8	...	...	− 7.0	...
Ce 20201	4.3	1969 November 24	40549.9	0.8	1.2	− 7.2	...
Ce 20204	4.3	1969 December 21	40576.6	...	...	− 3.8	...

for each spectrogram: one for Eu II based on λλ4205.05 and 4435.58 and one for several Cr II lines near λ4250. The K-line of Ca II varies in phase with the Eu II lines, whereas Sr II varies in phase with Cr. The results shown in Figure 2, *a* and *b*, confirm the variations indicated in Figure 1 and show in addition that Eu II was weak and Cr II strong on the Mount Wilson spectrograms of 1948 and 1949. Because the observations of 1965–1969 rule out any period shorter than about 10 years, we are inclined to believe that extrema of the Eu and Cr variations occurred near 1950 and that the spectrum of HD 9996 is once again approaching this state. The freehand curves drawn through the 1948–1969 data in Figure 2, *a* and *b*, suggest a period of 22–24 years.

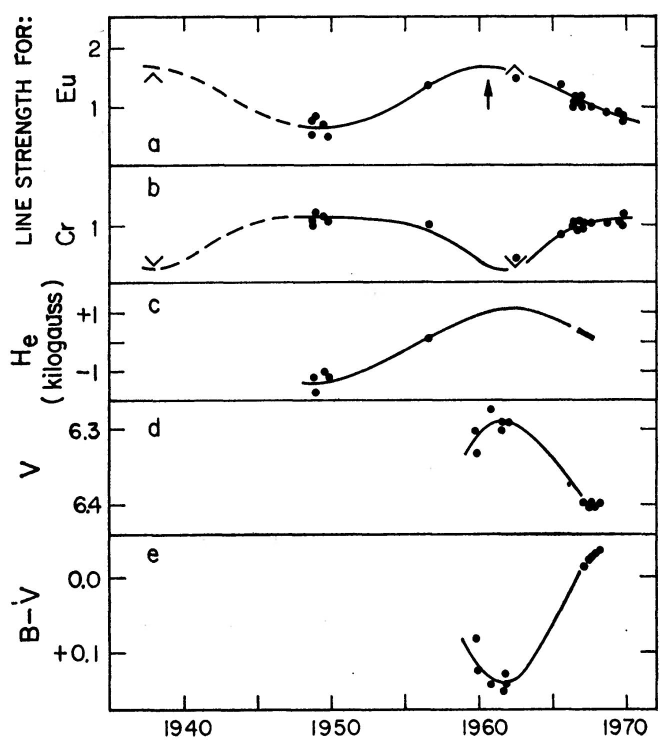

FIG. 2.—Line strength versus time for (*a*) Eu II lines and (*b*) Cr lines. The symbols ∧ and ∨ for 1938 and 1962 denote approximate lower and upper limits, respectively. Arrow denotes the date of Bidelman's spectrogram when rare-earth lines were very strong and numerous. (*c*) Magnetic-field observations. *Dots*, observations by Babcock. Inclined bar at 1967 denotes the slope in Fig. 3 that is discussed in the text. (*d*) and (*e*) show, respectively, the changes in *V* and *B* − *V* that are indicated by observations of Abt and Golson (1959–1961) and Stępień (1967–1968).

One additional bit of information supports the above conclusion. Two *V*-series prism spectrograms (dispersion ~40 Å mm^{-1}) of HD 9996 were obtained at the Mount Wilson 60-inch telescope by G. Stromberg in 1937 and 1938. Fortunately, Chandra also obtained a high-quality 40 Å mm^{-1} spectrogram with the X-spectrograph of the 60-inch telescope in 1962 September. Comparison of these spectrograms indicates that the Eu II lines at λλ3930, 4205, and 4435 were as strong and the Cr lines were as weak in 1937–1938 as they were in 1962. These results would be expected for a period of 22–24 years, as indicated by the curves in Figure 2, *a* and *b*.

Finally, the vertical arrow in Figure 2, *a*, marks the date of Bidelman's observation, which must have been made very nearly at Eu II maximum. This explains why Bidelman's impression of the spectrum differed so greatly from our initial one and from that of Babcock (1958).

b) *The Magnetic Variation*

The magnetic data are even more fragmentary than the spectrum-variation data. Five measurements by Babcock and those from the Lick spectrograms are listed in Table 1 and are plotted in Figure 2, *c*. The Lick observations are plotted as an inclined bar on the basis of Figure 3 which shows the Lick results on an expanded time scale. The data points represent means for groups of 4 Å mm^{-1} observations near J.D. 2439342, 402, 471, and 740 (*filled circles*) and two groups of 8 Å mm^{-1} observations near J.D. 2439336 and 454 (*open circles*). The systematic difference between the 4 and the 8 Å mm^{-1} data may be accidental or it may be due to other effects discussed by Preston (1969*a*). The slope of the straight line drawn through the 4 Å mm^{-1} data points is -0.60 gauss day^{-1}. We would have ignored this result were it not for the more convincing data for slow ***spectrum*** variations from 1962 through 1969. The schematic curve in Figure 2, *c*,

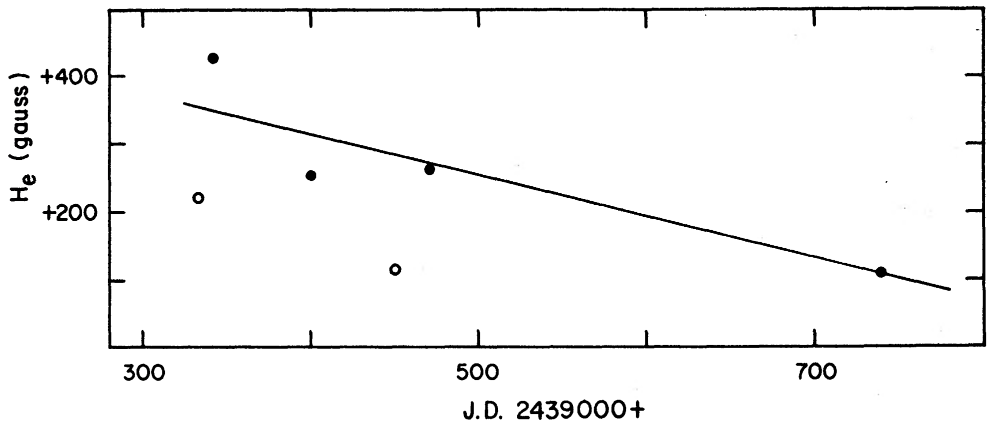

FIG. 3.—Effective magnetic field versus Julian Date for Lick observations made in 1966 and 1967. Each data point represents the mean of two or more observations. *Filled circles*, results obtained from 4.1 Å mm^{-1} spectrograms; *open circles*, those from 8.2 Å mm^{-1}. Straight line through the 4.1 Å mm^{-1} data points is discussed in the text.

has a range of about 2 kilogauss. If we represent it crudely by a sine wave with period 22 years (≈ 8000 days), viz.,

$$H_e \sim 1000 \sin \frac{2\pi t}{8000}, \tag{1}$$

then the magnitude of the rate of change is given by

$$\left|\frac{dH_e}{dt}\right| \sim \left|\frac{\pi}{4} \cos \frac{2\pi t}{8000}\right| \lesssim 0.78 \text{ gauss day}^{-1}. \tag{2}$$

Thus the admittedly poor "observed" slope for the 1966–1967 observations is in reasonable agreement with expectations for its location on the descending branch of a 22-year sinusoidal variation of H_e.

c) *The Photometric Variations*

The evidence for photometric variations rests entirely on a comparison between sets of observations made by Abt and Golson (1962) in 1959–1961 and by Stępień (1968) in 1967–1968. Comparison of these data, as in Figure 2, *d* and *e*, shows that between 1960 and 1968 the visual brightness of HD 9996 declined by about 0.1 mag and its $B - V$ color index decreased by a similar amount. There is no certain variation in $U - B$. The data are not well distributed in time, but the observed changes are unusually large for an Ap star and are undoubtedly real.

III. HD 9996 AS A SPECTROSCOPIC BINARY

Babcock (1958) concluded, on the basis of two greatly discordant radial velocities, that HD 9996 must be a spectroscopic binary. This conclusion is confirmed by the radial velocities in Table 1. A period of 273ᵈ2 leads to the velocity curve shown in Figure 4. A freehand curve drawn through the 4, 8, and 10 Å mm^{-1} data points gives a good representation of the radial velocities derived from Chandra's 1962 ultraviolet spectrogram and the three 40 Å mm^{-1} spectrograms obtained by Stromberg. The shape of the curve corresponds to an eccentricity $e \sim 0.4$ and a longitude of periastron near 0°. A more precise determination of the orbital elements was not attempted because of the poorly determined shape of the velocity maximum.

The spectrum, magnetic, and photometric variations of HD 9996 evidently are not coupled to the orbital motion; a gravitational interaction between the components would not be expected in a main-sequence binary with a separation of ~1 a.u.

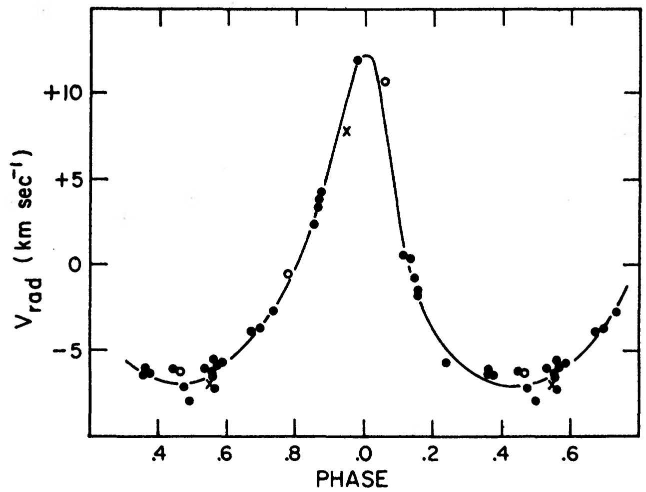

FIG. 4.—Radial-velocity curve of HD 9996 that is obtained for a period of 273ᵈ2. *Filled circles*, *crosses*, and *open circles* denote velocities from spectrograms with dispersions 4–10, 20, and 40 Å mm^{-1}, respectively. Curve is a freehand representation of the velocity variation.

IV. DISCUSSION

The data discussed in the preceding sections, though inadequate in many respects, lead to a consistent picture of spectrum, magnetic, and photometric variations that are identical with those of other Ap stars. The Eu and Cr lines vary in antiphase as is the case in virtually all Cr-Eu stars; the Eu lines are strongest when the star is reddest, as is the case for HD 221568 (Osawa 1967), 73 Dra (Preston 1967; Stępień 1968*a*), and α^2 CVn (Pyper 1969); and, insofar as we can determine, the extrema of all variable quantities appear to coincide in time (phase), as is the general rule. If the variations are not periodic, then the behavior of HD 9996 is unprecedented. However, in view of previous experience with Ap stars, particularly recent experience with apparently intractable cases, e.g., 21 Per (Preston 1969*b*) and 78 Vir (Preston 1969*a*), it seems more likely that the variation *will* prove to be periodic. From this point of view the behavior of HD 9996 is extreme but not unprecedented, since Babcock (unpublished) has found a magnetic period of 6.7 years for HD 187474.

The arguments in favor of the rigid-rotator model for periodic Ap stars have been reviewed elsewhere recently (Preston 1970), and they need not be repeated here. In apposition to those arguments it was recognized that the occurrence of two stars brighter than magnitude 6.5 with rotational velocities less than 0.1 km sec^{-1}, as would be the case for HD 187474 and HD 9996, is statistically incompatible with the rotational-velocity distribution functions of any known groups of stars on the upper main sequence, including the Ap stars themselves. Incompleteness will make the comparison even more difficult because there has been no systematic search for Ap stars with variations on time scales of years. Therefore, if the rigid-rotator model is to be reconciled with very slow variations such as that reported here for HD 9996, a powerful mechanism of rotational deceleration must be operative for at least *some* of the Ap stars.

We wish to thank Dr. W. P. Bidelman for sending us his unpublished line identifications for HD 9996. We also thank Miss Sylvia Burd for her careful measurements of radial velocity and Zeeman effect.

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