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THE PERIODIC VARIABILITY OF THE PECULIAR A STAR HD 111133

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ABSTRACT

The period of the peculiar A star HD 111133 is 16.31 days. Maximum light coincides in phase with minimum longitudinal magnetic field. The strengths of the lines of the iron-peak elements vary and are greatest at maximum light. This star belongs to that subgroup of Ap stars in which the magnetic and rotation axes are nearly aligned.

I. INTRODUCTION

The magnetic field of HD 111133 (HR 4854) was discovered by Babcock (1958), who found a moderately strong negative field on each of two spectrograms. A series of Zeeman observations of HD 111133 was subsequently made by Preston, but the amplitudes of both the magnetic and spectrum variations proved to be rather small, and a convincing period could not be derived from the spectroscopic measurements alone. We therefore decided to make photometric observations of HD 111133, and by combining the resulting light curves with our own measurements of Preston's Zeeman spectrograms, we have derived the period of this star.

II. OBSERVATIONS

a) *Photometry*

Four-color *uvby* observations of HD 111133 were made with a 24-inch (61 cm) reflector at the Mauna Kea Observatory. The techniques of observation and reduction have been described elsewhere (Wolff and Wolff 1971). The primary comparison star was HD 109860, and we find that the colors of this star are

$$V = 6.37,\ b - y = +0.01,\ m_1 = +0.14,\ c_1 = 1.14\,.$$

These values incorporate the errors involved in transforming instrumental magnitude and color systems to the standard system, and the error may be as large as 0.04 mag for the transformation of y to V. The standard deviations of the transformed values of $b - y$, m_1, and c_1 are approximately 0.01, 0.015, and 0.015 mag, respectively. The constancy of HD 109860 was checked by measurements of HD 110951, which was observed on 14 nights.

The magnitude and color differences, in the sense HD 111133 − HD 109860, are given in table 1. From a comparison of the observations of HD 109860 and HD 110951, we estimate that the rms deviations in Δy and $\Delta(b - y)$ are approximately 0.003 mag, in Δm_1 and Δc_1 approximately 0.007. These differences can be used together with the colors given for HD 109860 to derive standard *uvby* colors for HD 111133. It should be noted, however, that line blanketing is greater in HD 111133 than in normal stars of the same temperature (Wolff 1967), and consequently the colors will not have the same meaning as they would for a normal star.

b) *Spectroscopic Observations*

Fourteen Zeeman spectrograms of HD 111133 were obtained by Preston with the coudé spectrograph of the 120-inch (305 cm) telescope. Two (ECZ 4966 and ECZ 5005)

TABLE 1

PHOTOMETRIC OBSERVATIONS OF HD 111133

J. D. ⊙	Phase	HD 111133 − HD 109860			
2440000+		Δy	Δ(b−y)	Δm_1	Δc_1
630.05	0.38	−0.013	−0.035	+0.039	−0.146
631.02	.44	− .004	.038	.045	.147
635.00	.68	− .010	.048	.056	.138
635.99	.74	− .009	.057	.072	.157
636.98	.81	− .020	.056	.076	.153
637.99	.87	− .018	.065	.082	.155
639.04	.93	− .018	.071	.091	.157
641.98	.11	− .019	.062	.082	.159
642.96	.17	− .008	.050	.064	.164
644.98	.30	− .009	.043	.057	.160
649.04	.54	− .001	.039	.049	.148
649.99	.60	− .005	.043	.053	.145
660.95	.27	− .011	.043	.054	.160
661.94	.34	− .007	.043	.052	.154
673.92	.07	− .024	.063	.087	.171
684.89	.74	− .015	.057	.076	.155
685.86	.80	− .014	.067	.085	.159
686.90	.87	− .017	.086	.117	.171
689.87	.05	− .019	.069	.092	.169
690.86	.11	− .019	.057	.079	.172
693.88	.29	− .007	.045	.057	.164
694.88	.35	− .009	.042	.052	.156
695.85	.41	+ .001	.046	.054	.156
696.84	.48	− .002	.037	.051	.162
698.86	.60	− .005	.047	.058	.148
754.79	.03	− .028	.064	.088	.167
755.76	.09	− .018	.063	.089	.176
757.76	.21	− .011	.051	.068	.172
758.77	.27	− .013	.044	.060	.166
760.77	.39	+ .003	.044	.052	.160
763.76	.58	−0.003	−0.043	+0.050	−0.142

are at a dispersion of 4 Å mm^{-1}, the remainder at 8.2 Å mm^{-1}. Approximately 80 unblended lines, mostly due to Fe and Cr, were used to determine the value of the effective longitudinal magnetic field, H_e, for each plate. The probable errors in H_e are typically ±80 gauss. The results are given in table 2. The last column of table 2 gives the radial velocity V_R for each spectrogram.

To test for spectrum variability, the equivalent width W was measured for each of the lines used to determine H_e. The plate ECZ 4940 was arbitrarily chosen as the standard plate. For each line i on each of the other spectrograms j we then obtained the quantity

$$\Delta \log (W/\lambda)_{j,i} = \log (W/\lambda)_{j,i} - \log (W/\lambda)_{4940,i} . \quad (1)$$

The value of $\Delta \log (W/\lambda)_{j,i}$ is independent of line strength, provided that all the lines lie on a portion of the curve of growth where the slope is constant. In fact, all of the lines measured are of comparable strength so that this condition is very nearly satisfied. We then averaged the values of $\Delta \log (W/\lambda)_{j,i}$ over i to obtain for each element and state of ionization the quantity $\langle \Delta \log (W/\lambda) \rangle_j$. These average values for Cr I, Cr II, Fe I, and Fe II are given in table 3. The other elements present in HD 111133 are typically represented by fewer than half a dozen unblended spectral lines, and the scatter in the values of $\langle \Delta \log (W/\lambda) \rangle_j$ is so large as to mask any periodic spectrum variability.

TABLE 2

EFFECTIVE MAGNETIC FIELDS OF HD 111133

Plate ECZ	JD$_\odot$ 2430000+	Phase	H_e (gauss)	V_R (km s^{-1})
4156.......	8841.72	0.73	− 870	+17.9
4266.......	8897.87	0.17	− 910	18.3
4909.......	9239.79	0.14	− 980	18.2
4940.......	9244.77	0.44	− 460	19.4
4966.......	9247.74	0.63	− 870	18.5
4983.......	9250.81	0.81	−1100	17.7
5005.......	9253.78	0.00	−1400	18.0
5018.......	9279.76	0.59	− 430	19.9
5080.......	9313.68	0.67	− 760	17.1
5109.......	9338.69	0.20	−1060	20.0
5149.......	9343.68	0.51	− 280	19.0
5380.......	9454.04	0.27	− 630	19.2
5394.......	9455.06	0.34	− 660	18.4
5425.......	9460.02	0.64	− 750	18.4
5426.......	9460.06	0.64	− 510	18.0
5472.......	9492.02	0.60	− 560	+16.8

TABLE 3

SPECTRUM VARIATIONS IN HD 111133

Plate ECZ	Phase	⟨Δ log (W/λ)⟩ Cr I	Cr II	Fe I	Fe II
4909........	0.14	+0.07	+0.13	+0.08	+0.07
4925........	0.38	−0.05	+0.03	+0.01	−0.05
4940........	0.44	0.00	0.00	0.00	0.00
4966........	0.63	−0.12	−0.02	−0.12	−0.07
4983........	0.81	+0.16	+0.20	+0.10	+0.08
5005........	0.00	+0.08	+0.15	+0.07	+0.04
5018........	0.59	−0.02	+0.08	−0.03	−0.01
5080........	0.67	−0.03	+0.08	−0.02	−0.01
5109........	0.20	+0.09	+0.15	+0.09	+0.05
5149........	0.51	−0.06	+0.01	−0.08	−0.06
5380........	0.27	+0.12	+0.18	+0.12	+0.11
5394........	0.34	+0.06	+0.08	+0.03	+0.04
5425........	0.64	−0.01	+0.07	−0.01	−0.02
5426........	0.64	−0.01	+0.09	−0.04	−0.04
5472........	0.60	+0.03	+0.10	−0.04	+0.04

III. THE PERIOD OF HD 111133

The technique described by Lafler and Kinman (1965) was applied to the photoelectric observations of HD 111133 in order to derive a preliminary period. The best period, based on the photometry alone, is $P = 16.23$ days. The maximum error in this value permitted by the observations is about ± 0.15 days. It is true of every Ap star analyzed to date that the magnetic and light variations are either in phase or in antiphase. If we apply this additional condition to the observations of HD 111133, then we find that the allowed periods are, in days, 16.12, 16.21, 16.31, and 16.41. Of these, a period of 16.31 days provides a somewhat better representation of the magnetic-field variations. Therefore, we adopt the elements

$$\mathrm{JD}_{\odot}\,(\text{maximum light}) = 2440640.2 \pm 0.8 + 16.31E \pm 0.03\,. \tag{2}$$

The errors indicated are the maximum errors allowed by the data.

If this were a spurious period because observations were made only once a night and approximately at the same time each night, then the most probable true periods, in days, would be 1.06 and 0.94. These periods were eliminated by observations made during an interval of 8 hours on each of two consecutive nights during 1971 April. The variation observed on each night was less than 0.005 mag.

The observations, plotted according to the ephemeris given by equation (2), are shown in figures 1–3. As these figures show, maximum light coincides in phase with minimum magnetic field. The lines of the iron-peak elements Cr I, Cr II, Fe I, and Fe II vary in phase and reach their maximum strength at approximately phase zero. The amplitude of the spectrum variations is rather small; the ratio of maximum to minimum equivalent width is about 1.4. The radial velocity is variable with a total range of slightly more than 2 km s^{-1}. Velocity maximum occurs approximately at phase 0.35 and velocity minimum at phase 0.8. Within the errors in measurement, velocities derived for individual elements vary in the same way, and the spectrum and radial-velocity variations are in quadrature, as predicted by the rigid-rotator model.

IV. DISCUSSION

The observed rotational velocity, $v_e \sin i$, of HD 111133 is 10 km s^{-1} (Preston 1971*a*). Adopting the rigid-rotator model and substituting $P = 16.31$ days into the period-line-width relation for Ap stars (Preston 1970*a*),

$$P(\text{days}) = 160 v_e^{-1}(\text{km s}^{-1})\,, \tag{3}$$

we find that $v_e = 9.8$ km s^{-1}. The value of sin i is evidently nearly equal to unity. This conclusion would be altered only if the radius of HD 111133 were significantly different

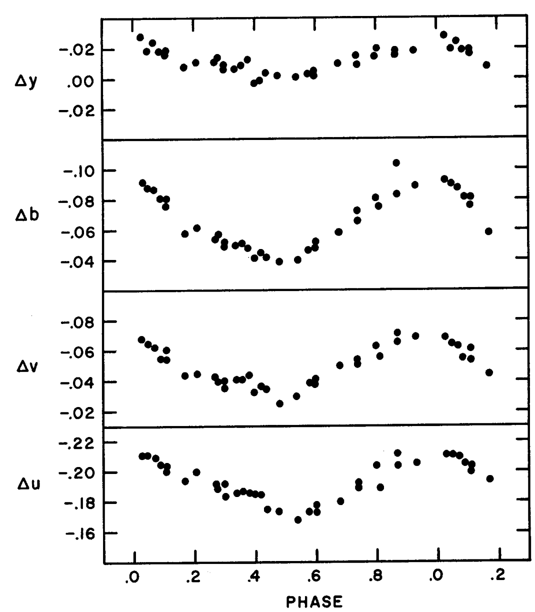

FIG. 1.—Light variation of HD 111133 plotted according to the ephemeris $\mathrm{JD}_{\odot}$ (maximum light) = 2440640.2 + 16.31*E*.

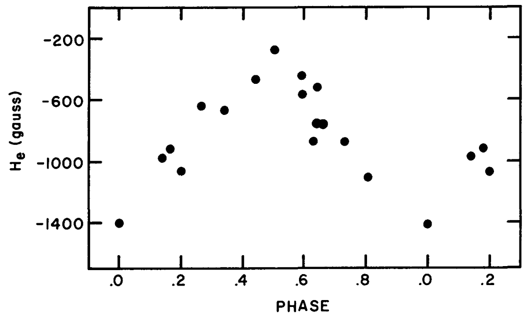

FIG. 2

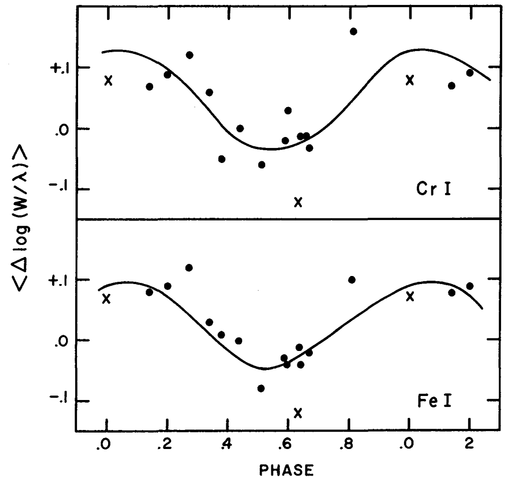

FIG. 3

FIG. 2.—Magnetic variation of HD 111133.

FIG. 3.—Spectrum variations of HD 111133. The filled circles and crosses denote measurements of spectrograms with dispersions of 8.2 Å mm^{-1} and 4 Å mm^{-1}, respectively.

from the average value for Ap stars. It is unlikely that this is true, since the surface gravity of HD 111133 is the same as for Ap stars of similar effective temperature (Wolff 1967). Since the value of sin i is close to unity, a large fraction of the surface of HD 111133 is observable. Unless the remainder of the surface is radically different from the portion that we see, the rare-earth elements are decidedly less abundant than in such Ap stars as β CrB and 78 Vir. The three strongest Eu lines in Ap stars of similar temperature are λλ3907.10, 4129.73, and 4205.05. The last of these three lines in HD 111133 is blended; the equivalent widths of the first two are less than 30 mÅ. Lines of Nd II (10) are probably present, but again the equivalent widths do not exceed 30 mÅ. The elements Ce and Gd are apparently not present.

The fact that the magnetic field of HD 111133 does not reverse sign puts stringent limits on the value of α, the angle, measured at the center of the star, between the line of sight and the positive magnetic pole. For a dipolar magnetic field, the observed longitudinal field H_e will be negative only if α is larger than 90°. There is evidence that magnetic fields in Ap stars can be better represented by a dipole offset along its axis from the center of the star (Wolff and Wolff 1970; Preston 1970*b*). If the offset is in the direction of the negative pole, then the positive field at the surface of the star is weakened, and H_e may be negative for values of α that are less than 90°. However, even for an offset that is as large as six-tenths of the radius of the star, H_e will be negative only if α is greater than 80° (Preston 1970*b*). The condition that α be larger than 80° can be satisfied in a star that is seen approximately equator-on only if the magnetic and rotation axes are very nearly aligned. Preston (1971*b*) has suggested that β, the angle between the magnetic and rotation axes, is preferentially either large (~80°) or small (~20°) and that there is a real deficiency of intermediate values of β. The star HD 111133 is another example of an Ap star in which β is close to zero.

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