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PULSATIONAL MODE SWITCHING IN HD 161796

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ABSTRACT

Photometry of HD 161796 in 1980 shows a low-amplitude (0.08 mag in V) sinusoidal variability of period 43^{d}. Photometry of the previous year by Percy and Welch shows a variability of similar amplitude but with a 62^{d} period, while photometry in 1981 showed the star constant to a level of ± 0.005 mag or less for two months before breaking into oscillation again. Oscillations are neither built up nor damped, but appear at full amplitude immediately before and after cessation.

The two periods observed, having a ratio of 0.69, are interpreted as the fundamental and first overtone modes of radial pulsation. If this is correct, then HD 161796 is unique among known variables in switching modes; in other stars only one mode is present, or both are present simultaneously.

Petersen's (P_1/P_0) versus P_0 diagram strongly suggests that HD 161796 has a normal mass, i.e., is not a very old evolved star. This eventually leads to $M_{\mathrm{bol}} = -7.6$ and a distance of 8.3 kpc. On the other hand, if it is really a low-mass star, one arrives at $M_{\mathrm{bol}} = -5.6$ and a distance of 3.4 kpc. An application of the Barnes-Evans surface brightness method, although weak because of the star's low amplitude, indicates a distance of ~ 10 kpc, thus lending further support to the normal mass interpretation.

UBVRI data imply $E_{B-V} = 0.00$, not surprising in view of the star's galactic latitude of 31°.

The fairly large radial velocity (~ -53 km s^{-1}) of HD 161796 is shown to be accounted for by ordinary differential galactic rotation. It does not indicate any high-velocity star characteristic.

Because the blue edge of the Cepheid instability strip at its high luminosity end is poorly established, it is difficult to locate HD 161796 relative to the strip. Estimates place it between the blue edge and perhaps 1000 K hotter.

Subject headings: stars: individual — stars: pulsation — stars: supergiants

I. INTRODUCTION

HD 161796 is an early F supergiant that is of interest because it is distant, yet located at a galactic latitude of 31°. As such, it is often compared with another such supergiant, 89 Her. Both have been the subject of a detailed spectroscopic analysis (Searle, Sargent, and Jugaku 1963) which concluded that they are both of normal Population I composition and of high luminosity ($M_V \approx -6.4$ and -7.1, respectively). Others (Abt 1960; Burki, Mayor, and Rufener 1980; Divan 1961) have attributed an even higher luminosity to HD 161796, perhaps as much as $M_V = -9$, in the light of which it would be of interest to check the only existing spectral classification of F3 Ib for the star (Bidelman 1951).

89 Her has shown bizarre photometric behavior (Fernie 1981*a*), exhibiting a smooth, low-amplitude variability that at times abruptly ceases or gives way to random fluctuations and which may or may not be accompanied by radial velocity variations. This naturally suggested a photometric investigation of HD 161796, the results of which make up this paper, although at the start (mid–1980) I was unaware that others (Burki, Mayor, and Rufener 1980; Percy and Welch 1981) were already engaged on just such work. As it happens, ignorance has proved blissful; comparison of the present results with those of the other workers now shows HD 161796 to be unique among stars of its type.

II. OBSERVATIONS

All observations reported here were made with the 0.5 m reflector of the David Dunlap Observatory and a photon-counting photoelectric photometer with *UBVRI* filters (Fernie 1974). The observations were made differentially with respect to HR 6656, and typically each observation reported here is the mean of four or five differential ones. The internal standard errors of these means average 0.004 mag. HR 6656 was tied into the Johnson standard *UBVRI* system (see Table 1) in order to put the HD 161796 results on an absolute basis. In order to compare these data with those obtained by Percy and Welch, I also tied their comparison star, HR

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TABLE 1
PHOTOMETRY OF COMPARISON STARS

Star	V	$U-V$	$B-V$	$V-R$	$V-I$
HR 6656	5.033	0.082	0.042	0.050	0.011
HR 6641	6.513	...	0.078	...	...

6641, into the Johnson system; its parameters are also given in Table 1.

Table 2 contains the results for HD 161796. During the first season (1980) I was concerned only to see whether the star was variable at all, and in the interests of observing time, measurements were restricted to B, V. Only in the following season were observations extended to *UBVRI*.

III. DISCUSSION

The 1980 observations describe a low-amplitude sine curve with considerable precision (rms deviation of an individual point = 0.006 mag). This light curve was followed through more than three cycles of ~6 weeks each, and I emphasize that on such a time scale there is no doubt as to the period: consecutive cycles unfold as one watches. A least-squares solution of the V magnitudes gave

$$V = 7.091 - 0.034 \cos[2\pi(\mathrm{JD} - 2{,}444{,}463.21)/43.15].$$
$$\pm 0.002 \pm 0.003 \qquad \pm 0.61 \quad \pm 0.63$$

The $B-V$ data showed a similar sine curve, a least-squares solution for which gave

$$B - V = 0.489 - 0.014 \cos[2\pi(\mathrm{JD} - 2{,}444{,}462.56)/42.03].$$
$$\pm 0.002 \pm 0.003 \qquad \pm 1.56 \quad \pm 1.62$$

The errors of the parameters are somewhat larger in $B-V$ because the semiamplitude of the variation is only 1/100 of a magnitude, but it is clear that the phase and period of the two quantities do not differ significantly. This is worth emphasizing because there are some peculiar F supergiants, notably the R CrB stars, in which there are significant phase differences between light and color curves (Alexander *et al.* 1972). The weighted mean of the periods is $43^{\mathrm{d}}.00 \pm 0^{\mathrm{d}}.38$.

The 1980 data, phased according to the above parameters, are shown in the center and lower panels of Figure 1.

The data of Percy and Welch (1981) were obtained in 1979 and are shown plotted against time in Figure 4 of their paper. Again, at least for the later two-thirds of their run, a well-defined sine curve is present. Close

TABLE 2
PHOTOMETRY OF HD 161796

HJD	V	$U-V$	$B-V$	$V-R$	$V-I$
2,444,408.641 ...	7.100	...	0.503	...	...
421.653 ...	7.058	...	0.472	...	...
423.666 ...	7.059	...	0.479	...	...
430.642 ...	7.094	...	0.493	...	...
433.631 ...	7.106	...	0.494	...	...
438.619 ...	7.129	.	0.501	...	...
444.620 ...	7.117	...	0.498	...	...
451.622 ...	7.085	...	0.473	...	...
459.621 ...	7.065	...	0.469	...	...
460.613 ...	7.057	...	0.479	...	...
489.577 ...	7.125	...	0.500	...	...
493.551 ...	7.112	...	0.508	...	...
498.545 ...	7.080	...	0.480	...	...
521.522 ...	7.101	...	0.497	...	...
536.526 ...	7.086	...	0.481	...	...
801.635 ...	7.063	0.724	0.460	0.398	0.652
807.609 ...	7.084	0.733	0.462	0.400	0.664
808.611 ...	7.082	0.734	0.459	0.411	0.659
815.609 ...	7.076	0.755	0.465	0.402	0.664
817.600 ...	7.072	0.729	0.460	0.418	0.674
834.578 ...	7.077	0.722	0.451	0.400	0.638
871.589 ...	7.077	0.724	0.460	0.407	0.670
886.518 ...	7.100	...	0.458	...	...
891.521 ...	7.125	0.738	0.464	0.413	0.674
908.486 ...	7.087	0.763	0.469	0.419	0.678
912.475 ...	7.064	...	0.470	...	...
921.468 ...	7.047	...	0.435	...	...

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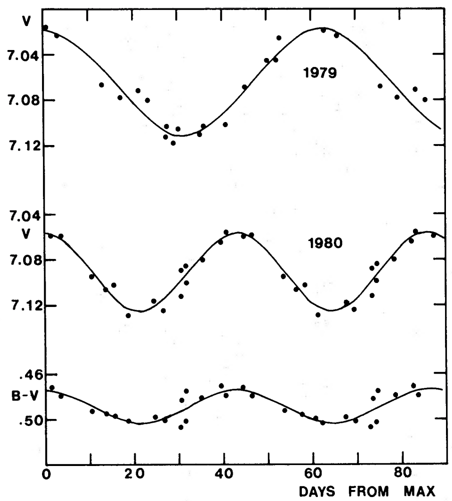

FIG. 1.—Light and color curves of HD 161796 in two seasons. The upper curve is that obtained by Percy and Welch in 1979, the lower two those obtained in 1980. Phases are shown in terms of days past maximum light to emphasize the difference in period between the 1979 and 1980 results. Note also that the 1980 color curve is in phase with the corresponding light curve, unlike some types of peculiar F supergiants.

inspection, however, reveals the startling fact that the period is quite different from that of my 1980 data, although the amplitude is much the same. Converting the data of Percy and Welch to absolute values through the HR 6641 figures given in Table 1, a least-squares solution gives

$$\begin{aligned} V = 7.064 &- 0.046 \cos\,[2\pi(\mathrm{JD} - 2{,}444{,}071.38)/62.46] \\ \pm 0.003 &\pm 0.004 \qquad\qquad\qquad\qquad \pm 0.84 \quad \pm 2.34. \end{aligned}$$

The rms deviation of an observational point is 0.009 mag. It is uncertain whether the differences in zero point and amplitude between the Percy-Welch 1979 results and my 1980 results are significant. In the case of the amplitudes, probably not. My tie-in of the two comparison stars to the Johnson system was done with the same equipment at the same time, and, in effect, the difference in V between the two stars was determined differentially with a standard error of only 0.004 mag. Thus, the difference in the zero points probably is significant. There is no doubt, however, that the two periods are different. The Percy-Welch data, assembled on the $62^{\mathrm{d}}.5$ period, are shown in the upper panel of Figure 1.

The results of the 1981 season offered yet another surprise. As can be seen from Table 2, for some two months between JD 2,444,807 and JD 2,444,871, the star was nonvariable right down to a level of ± 0.005 mag, i.e., the measuring error. Thereafter it broke into oscillation again, but the season concluded before a period could be established. However, enough of the cycle was observed to show that this very first cycle after constancy was at full amplitude; the star does not build up its amplitude gradually. Likewise, unpublished observations by Percy and his co-workers show the star was in full oscillation immediately before the interval of constant light. This abrupt transition from one state to another was also found in 89 Her (Fernie 1981*a*). Finally, one may note that the magnitude at constant light was $V = 7.078 \pm 0.002$, which is intermediate between the zero points of the 1979 and 1980 data.

As I have noted elsewhere (Fernie 1981*b*), when discussing stars bordering the main instability strip it seems one must always consider the possibility that such stars can sometimes be variable and sometimes nonvariable. Rather than a black-and-white situation of variable/nonvariable, it seems there exists a continuum running from never variable through sometimes variable to always variable. An examination of this continuum in terms of stellar properties might prove fruitful.

If HD 161796 oscillates in only two periods, either 62^{d} or 43^{d}, then the most obvious explanation is that the star sometimes oscillates in its fundamental mode (62^{d}) and sometimes in the first harmonic (43^{d}), because the ratio of these periods ($= 0.688 \pm 0.026$) is close to that expected theoretically for such a situation. We return to this shortly, but note first that if this interpretation is correct, then HD 161796 is unique among Cepheid-like variable stars studied so far. Others are known to have both modes excited simultaneously, but so far as I know, none has been observed to switch from one to the other. However, mode-switching has been observed in early-type nonradial pulsators like 53 Per, ι Her, and 10 Lac (Smith 1978).

In the light of this conclusion it is disconcerting that Burki, Mayor, and Rufener (1980) found from a radial velocity study of HD 161796 during 1978 and 1979 that it showed a period of $\sim 54^{\mathrm{d}}$. I have reanalyzed their velocity data by the discrete complex Fourier transform method of Deeming (1975). I verify that there is a definite peak in the power spectrum at $\sim 54^{\mathrm{d}}$, but I find also strong subsidiary peaks at 43^{d} and 62^{d}. Now because their data cover more than one season, there is an alias frequency of one reciprocal year which can interfere with the frequencies corresponding to the 43^{d} and 62^{d} periods. Given that $\nu_{62} = 0.0161$, $\nu_{43} = 0.0233$, $\nu_{54} = 0.0185$, and $\nu_{365} = 0.0027$, we see that

$$\nu_{43} - 2\nu_{365} = \nu_{54}\,,$$

and

$$\nu_{62} + \nu_{365} = \nu_{54}\,.$$

I therefore suggest that the apparent period of 54^{d} is not physically real but is an alias. Its apparent strength in the power spectrum arises from its being a double alias.

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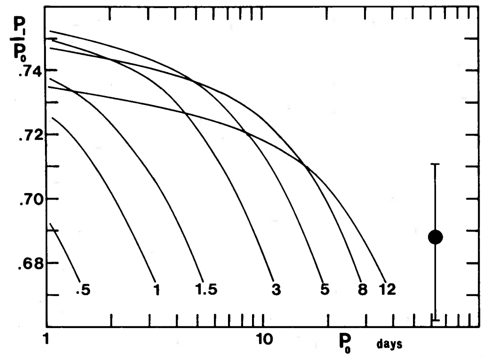

FIG. 2.—The ratio of first harmonic period to fundamental period determined theoretically by Petersen as a function of mass and fundamental period. The numbers at the foot of each curve indicate masses in solar units. The point for HD 161796 on the diagram is in the lower right.

It might be added that a least-squares analysis of the only portion of the radial velocity data to show anything like a clear velocity curve gave a period of $43^{d}_{.}2 \pm 2^{d}_{.}0$.

Assuming that the 62^{d} and 43^{d} periods correspond to the fundamental and first harmonic modes allows further interesting conclusions to be drawn. Petersen (1973) has studied theoretically how this period ratio P_1/P_0 varies as a function of P_0 and mass. Figure 2 is almost a reproduction of his Figure 1, and shown on it is the point for HD 161796. It seems clear that even if the curves are uncertain (Petersen, for example, notes they are sensitive to chemical composition), HD 161796 must have a mass close to the evolutionary mass of a normal luminous *F* supergiant. A formal extrapolation in Figure 1 gives a mass of $\sim 20\ \mathfrak{M}_\odot$ or more, but this is quite uncertain because the curves are so highly nonlinear. The Becker, Iben, and Tuggle (1977) evolutionary mass-luminosity relation for Cepheids predicts $\mathfrak{M} = 16.4\ \mathfrak{M}_\odot$ for the luminosity of HD 161796 derived below. A discussion of Cepheid evolutionary masses by Cox (1980) indicates $\mathfrak{M} = 13.2\ \mathfrak{M}_\odot$.

If its mass is normal, then HD 161796 very likely obeys the very tight correlation between period and radius for classical Cepheids. From a survey of many recent Cepheid radius determinations in the literature, I find this to be

$$\log \frac{R}{R_\odot} = \underset{\pm 0.011}{1.174} + \underset{\pm 0.011}{0.678} \log P,$$

which is almost identical to the theoretical relation found by Cogan (1978). Using $P = 62^{d}_{.}5$, this gives a mean radius of $246 \pm 8\ R_\odot$ for HD 161796.

Table 3 gives a mean magnitude and colors for HD 161796, obtained by simply averaging the five-color data in Table 2 for the interval during which the star did not vary. If it is of normal composition, as found by Searle, Sargent, and Jugaku (1963), $B-V$ and $R-I$ may be used to find E_{B-V} (Fernie 1982). The result, on the scale of Parsons and Bell (1975), is $E_{B-V} = -0.02$, which is not significantly different from $E_{B-V} = 0.00$. This then allows an estimate of the star's effective temperature: with $(B-V)_0 = 0.46$, the calibration by Flower (1977) gives $T_e = 6370$ K, while the calibration by Böhm-Vitense (1981) gives 6170 K. I adopt $T_e = 6300 \pm 150$ K.

TABLE 3

MEAN PARAMETERS FOR HD 161796

V	$U-V$	$B-V$	$V-R$	$V-I$
7.08 ...	0.74	0.46	0.41	0.66

With this temperature and the previously determined mean radius of 246 $R_\odot$, one obtains $\log(L/L_\odot) = 4.93 \pm 0.04$, or $M_{\text{bol}} = -7.59 \pm 0.11$. In turn, this yields $M_V = -7.5 \pm 0.2$ and a distance of 8.3 ± 0.8 kpc.

Suppose, however, that there is some error in the basic assumptions underlying these results and that HD 161796 is really a low mass star with $\mathfrak{M} \approx 1$ or $2\ \mathfrak{M}_\odot$. Then the radius may be estimated from the $P\sqrt{\rho} = Q$ relation, although a difficulty arises through Q being a steep and poorly known function of $\mathfrak{M}/R$ when the latter ratio is small (Cogan 1970). An estimate is $R \approx 100 \pm 20\ R_\odot$. This then leads to $M_{\text{bol}} = -5.6 \pm 0.4$ and a distance of 3.4 ± 0.5 kpc.

In principle, the Barnes-Evans surface brightness method (Barnes, Evans, and Moffett 1978) would give an independent estimate of the distance and so allow a choice between the alternatives above. The very low amplitude of HD 161796, however, greatly weakens the determination. Nevertheless, I have carried out the calculation using the approach detailed in Fernie (1977) and using $B-V$ instead of $V-R$ because the latter was only measured during the nonvariable phase. At this color ($B-V = 0.46$) this should not introduce any appreciable error (Barnes, Evans, and Moffet 1978). The result is a distance of 10 ± 1 kpc, which clearly supports the normal mass interpretation rather than the low mass interpretation.

An aspect that might cause hesitation in accepting HD 161796 as a normal Population I supergiant is its radial velocity of about -53 km s^{-1}. This approaches the canonical high-velocity star figure of -63 km s^{-1}, and with $l = 77°$, one envisions HD 161796 as having a mostly radial motion through the Galaxy, its observed velocity reflecting mostly the Sun's circular motion around the Galaxy. This, however, is to reckon without the star's large distance from the Sun. The standard formula for radial velocity due to differential galactic

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rotation, viz.,

$$V_r = -2A(R - R_{\odot})\sin l \cos b,$$

gives $V_r = -63 \pm 12$ km s^{-1} for $A = 13 \pm 2$ km s^{-1} kpc^{-1} and $R - R_{\odot} = 2.9 \pm 0.3$ kpc. ($R - R_{\odot}$ is much less uncertain than either galactocentric distance individually.)

Thus, apart from the extraordinary height of 4300 pc above the galactic plane, there is little if anything to suggest that HD 161796 is anything other than a normal Population I supergiant.

Searle, Sargent, and Jugaku (1963) concluded that it is just possible that HD 161796 reached its present position as a "runaway" star from the galactic plane. The present study, however, has assigned the star an absolute magnitude ~ 1 mag brighter. This has more than doubled the star's height above the plane and halved its age, making it much less probable that it is a runaway star. The problem of its origin then becomes part of a larger problem, since Greenstein and Sargent (1974) have found that more than one-fourth of faint blue stars in the galactic halo are normal B stars. HD 161796 has presumably evolved from one such star (see also Tobin and Kilkenny 1981).

Finally, it would be interesting to know the location of HD 161796 in the H-R diagram relative to the Cepheid instability strip. In fact, this is quite uncertain because the location of the strip at its most luminous end is quite uncertain. For example, the theoretical blue edge of the strip determined by Iben and Tuggle (1975) is shown in their Figure 1, and, depending on choice of helium abundance and mass-luminosity relation, HD 161796 would appear to be some 1000 K hotter than the blue edge corresponding to the star's luminosity. This result is based on Cox-Stewart opacities. However, Carson and Stothers (1976) give results based on Carson opacities, and their Figure 3 suggests (although with some extrapolation) that in this case HD 161796 might lie on or much closer to the blue edge. Given all the uncertainties, one can only conclude that the star is probably not far from the blue edge of the Cepheid instability strip.

IV. SUMMARY

1. HD 161796 sometimes shows sinusoidal variations of light and color which can have one of two distinct periods: 62^d or 43^d, with amplitudes in V of 0.08 mag, the same in each case. On other occasions the star has been constant in light to within the observational error of ± 0.005 mag for 2 months at a time. Oscillations seem not to be damped out nor gradually built up, but cease or appear abruptly at full amplitude.

2. The two periods, having a ratio of 0.69 ± 0.03, are interpreted as being the fundamental and first harmonic modes of the star's pulsation. If this is correct, HD 161796 is the only "Cepheid" known to show mode switching.

3. Petersen's diagram of P_1/P_0 versus P_0 strongly suggests that HD 161796 must have a normal Population I mass. It therefore very likely obeys the Cepheid period-radius relation, and a radius of 246 $R_{\odot}$ is derived.

4. The $B - V$ and $R - I$ colors of the star indicate it has zero reddening, and its color then implies $T_e = 6300$ K. This then leads to a luminosity of $\log(L/L_{\odot}) = 4.93$ or $M_{\rm bol} = -7.6$, and so to a distance of 8.3 kpc.

5. This distance receives support from an application of the Barnes-Evans technique, which makes a low-mass case (~ 1–2 $\mathfrak{M}_{\odot}$, leading eventually to a distance of ~ 3 kpc) much less likely.

6. The quite large radial velocity of HD 161796 is shown to be entirely accounted for by differential galactic rotation of a Population I object. The velocity does not indicate a Population II characteristic.

7. The height of HD 161796 above the galactic plane is now estimated to be 4300 pc, which, together with a reduction in the star's age (i.e., increased luminosity) compared to some earlier estimates, makes it quite unlikely that the star originated in the galactic plane. The problem of its origin then is akin to that of the many faint high-latitude Population I B stars.

8. Partly because of its high luminosity it is difficult to locate HD 161796 in the H-R diagram vis-à-vis the Cepheid instability strip. Most likely it is not far from the blue edge.

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