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THE DEMISE OF MODE IDENTIFICATION IN THE PULSATING DA WHITE DWARF GD 66

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ABSTRACT

An analysis of new photometric and spectroscopic observations of the pulsating DA white dwarf GD 66 is presented. It is shown that the mode identification suggested by Dolez, Vauclair, and Chevreton is premature. The photometric data reveal the existence of several additional pulsation frequencies which do not fit with their model. Moreover, the 3.90 mHz peak seen in the Fourier spectrum of their light curve of GD 66 is shown to be an artifact of both insufficient time resolution and rotational splitting of the frequency of the dominant pulsation mode. It is not caused by the presence of an independent (different k value) pulsation mode as suggested. In addition, a comparison of model atmosphere calculations with the spectroscopic observations suggests that the surface gravity of GD 66 is quite normal ($\log g = 7.7^{+0.4}_{-0.2}$). This is in conflict with the model of the above authors which further requires a significantly larger surface gravity ($\log g \approx 8.45$) to account for the observed pulsation properties of GD 66.

Subject headings: stars: individual — stars: pulsation — stars: white dwarfs

I. INTRODUCTION

In a recent paper, Dolez, Vauclair, and Chevreton (1983, hereafter referred to as DVC) have reported the discovery of a new pulsating DA white dwarf, the ZZ Ceti variable GD 66. This is yet another star whose colors place it in an instability strip in which 100% of the DA white dwarfs so far observed are variable (Fontaine *et al.* 1982). More interestingly, DVC have tentatively identified actual pulsation modes in GD 66 by fitting the observed excited frequencies obtained by a Fourier analysis of its light curve with the theoretical pulsation frequencies of an envelope model of that star. The analysis of DVC suggests that three of the four observed frequencies (3.28, 3.66, and 3.90 mHz) correspond to three independent, nonradial pulsation modes with spherical harmonic index $l = 2$ and with consecutive radial wavenumber $k = 5$, 6, and 7. The fourth excited frequency, at 5.07 mHz, is identified with a mode with $l = 3$ and $k = 5$.

In order to achieve this fit, DVC had to make two basic assumptions which merit further consideration. First, they had to suppose that, somehow, the modes with the *largest* growth rates in their theoretical model of GD 66—a second group of resonant modes with k values around 14—are *not* excited in that particular star. In order to explain this discrepancy, DVC suggested that, perhaps, a nonlinear analysis would prove the higher k modes not to lead to significant luminosity variations in a model with parameters similar to the one they used. Second, DVC also had to assume a rather large mass for GD 66 ($M \approx 0.85\ M_{\odot}$). While this value is not implausible by any means, it is nevertheless at variance with the rather narrow range of masses of DA white dwarfs ($\langle M \rangle = 0.6 \pm 0.1\ M_{\odot}$) found by Koester, Schulz, and Weidemann (1979) and Weidemann and Koester (1984).

Rather than questioning the validity of the linear theory of nonradial stellar pulsations and assuming an unusual mass for GD 66, an alternative point of view is to reexamine the problem of mode identification in that star. Unfortunately, any attempt to identify unambiguously individual pulsation modes from Fourier spectra of light curves of ZZ Ceti variables remains highly risky. Indeed, from a theoretical point of view, there are so many parameters involved in the construction of a ZZ Ceti model (cf. Winget and Fontaine 1982) that mode identification may not be unique. The theoretical g-mode spectrum is so rich that a knowledge of the excited frequencies may not suffice. Furthermore, experience has shown that lengthy observations are required to decipher completely the light curve of a pulsating white dwarf. Detailed studies are necessary to reveal the frequencies of the most important pulsation modes in even the "simplest" ZZ Ceti pulsators such as R548 (Stover *et al.* 1980), L19−2 (O'Donoghue and Warner 1982), G117−B15A (Kepler *et al.* 1982), GD 385 (Kepler 1984), and G226−29 (Kepler, Robinson, and Nather 1983; McGraw *et al.* 1985). It thus would appear that the identification of modes in an intermediate-amplitude ZZ Ceti star such as GD 66, for which few observations are available, can be very difficult indeed.

This is confirmed in the present paper in which we report on the results of new photometric and spectroscopic observations that demonstrate that the mode identification suggested by DVC for GD 66 is premature. In the next section, we summarize our analysis of ~13 hr of photometric observations of GD 66 and compare our results with those of DVC. In § III, we combine spectroscopic data with model atmosphere calculations to derive an estimate of the surface gravity of GD 66. Finally, in the last section, we briefly examine the implications of our analysis.

II. THE PHOTOMETRIC EVIDENCE

a) Observations

Light curves of GD 66 were obtained with the new Mount Wilson dual-channel photometer attached to the 2.5 m Hooker telescope. Details of this instrument will be appropriately

TABLE 1

MOUNT WILSON PHOTOMETRIC OBSERVATIONS OF GD 66

Run Number	Date (UT, 1983)	Start Time (UT)	Sampling Time (s)	Total Number of Data Points	Resolution (mHz)
MWD 09	Nov 2	10:37	13	670	0.11
MWD 12	Nov 3	8:32	13	598	0.13
MWD 16	Nov 4	8:22	13	1258	0.06
MWD 18	Nov 5	6:30	13	1014	0.08

reported by its designers elsewhere, but a brief description is in order here. The dual-channel photometer is a computer-controlled, photon-counting device that incorporates remote television viewing and guiding. The instrument was operated in a continuous monitoring mode in which short, independent observations—equally spaced in time—are stored on a disk file. A high-precision clock insures the integrity of the measurements. An aperture plate containing three holes with the same dimensions is repeatedly moved back and forth in front of the two Fabry windows at a chosen frequency. In the first part of the cycle, the target star is measured in channel one while the sky is simultaneously monitored in channel two. The aperture plate is then moved, and, this time, channel one measures the brightness of a (different) sky patch while channel two measures the star for a second independent observation. This cycle is then continuously repeated. The whole apparatus can be rotated through 180° to ensure that the two sky patches are not contaminated by faint field objects. The time spent for one independent observation thus consists of the time the counter gates are actually open, the time necessary for television guiding, and the transit time for the motion of the aperture plate. The brightness of the target star determines the ratio of television viewing to net integration time. For GD 66, we chose 13 s as the total sampling time for one measurement. Of those, 7 s were spent for actual integration, 2.5 s were spent for television guiding in the integration mode ($\Delta t = 1.2$ s) to visualize at least two independent images, and the rest was lost in the transit and positioning of the aperture plate. No filters were used to maximize the photon detection rate. With an aperture size of 7″, the RCA 31034 A phototubes gave a star-to-sky ratio of about 2 for our particular target star, a 15.6 mag object. One important advantage of the system is that it allows the *simultaneous* measurements of star and sky combined with continuous television guiding.

We have obtained four independent light curves for GD 66. The details are summarized in Table 1. A portion of the light curve for run MWD 16 is shown in Figure 1. Each dot is the mean of two 13 s integrations corresponding to the two different positions of the aperture plate. This procedure allows, of course, for the different sensitivities of the two photomultipliers. The light curve is dominated by a quasi period of about 300 s and exhibits peak-to-peak variations that can be as large as ~0.1 mag. The mean pulse shape is distinctly nonsinusoidal. The light curve is quite reminiscent of that of the southern ZZ Ceti variable BPM 30551 (McGraw 1977*a*). As in the latter case, there is an obvious beat pattern, although it is not as pronounced here.

b) *Analysis of the Light Curves*

Power spectra for each of the light curves were computed. We show in Figure 2*a* and 2*b* the low-frequency part of the power spectrum of runs MWD 16 and MWD 18, respectively, our longest light curves. From a frequency of about 8 mHz to a Nyquist frequency of 38.5 mHz, the power spectrum is totally flat. The peaks at 9.3 mHz (Fig. 2*a*) and 9.4 mHz (Fig. 2*b*) are artificial tracers corresponding to 1% of the mean intensity of

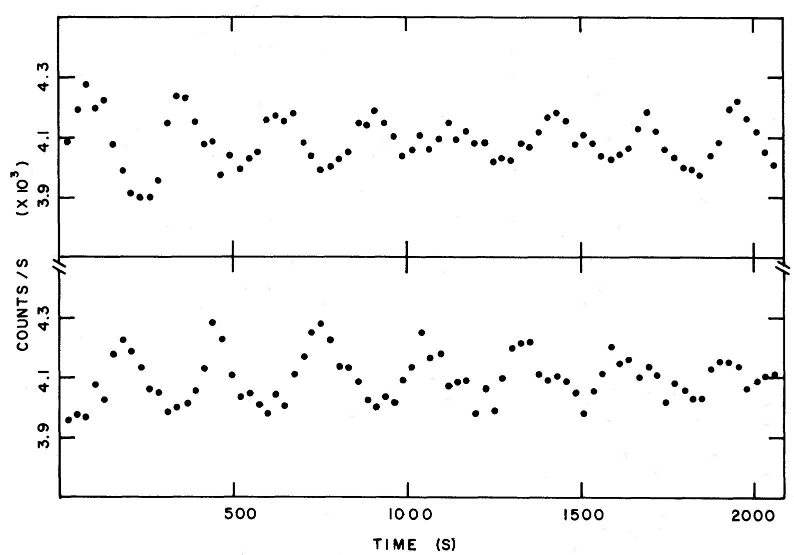

FIG. 1.—Segment of the light curve of GD 66 (run MWD 16), expressed in detected photons per second corrected for atmospheric absorption. The abscissa is given in seconds. The light curve is continuous, starting at upper left, and each point is the mean of two 13 s integrations.

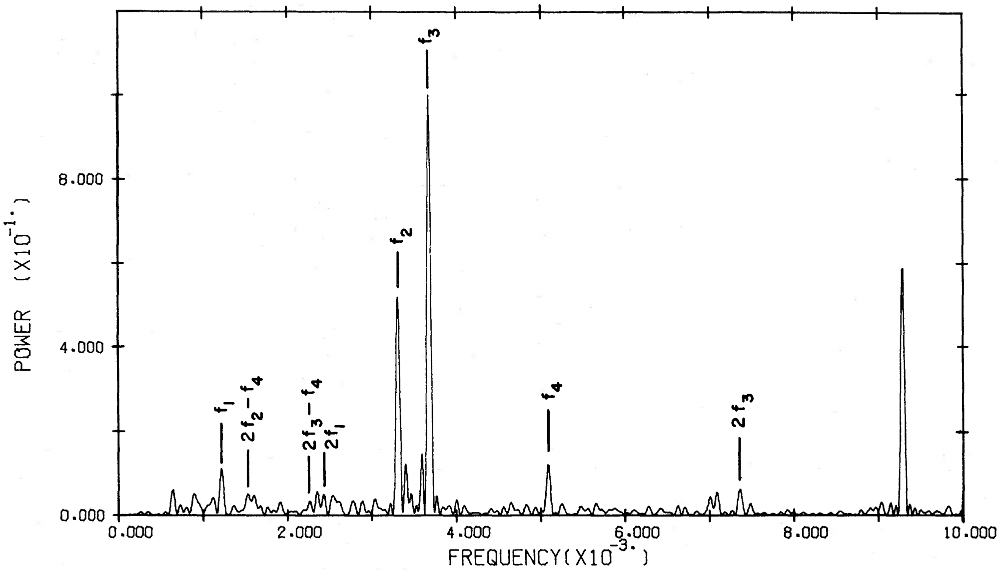

FIG. 2*a*

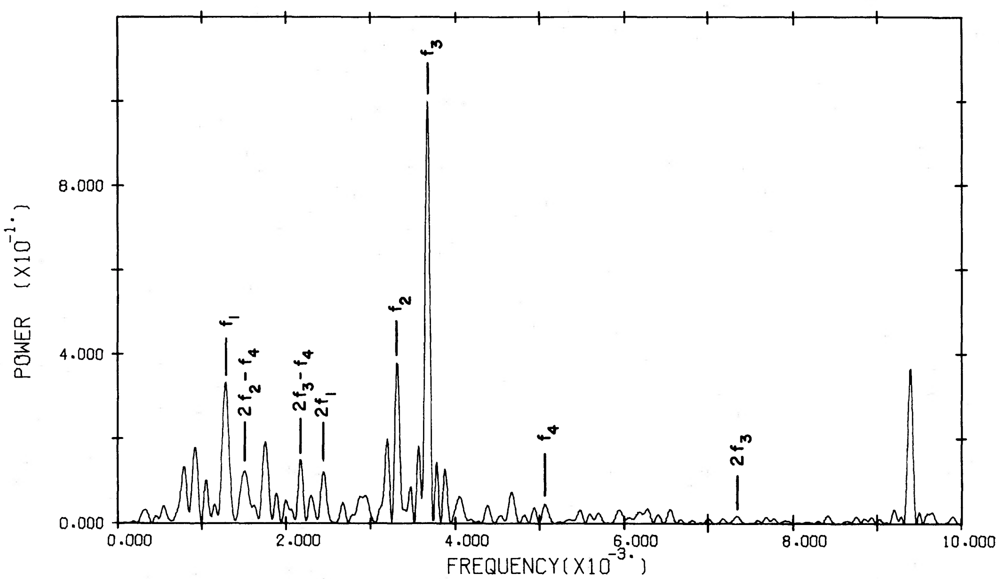

FIG. 2*b*

FIG. 2.—(*a*) Low-frequency part of the power spectrum of the light curve of GD 66 calculated from the data of run MWD 16. The peak at 9.3 mHz is an artificial tracer with an amplitude of 1% of the mean intensity of the star. The eight frequencies common to all of the runs are indicated. (*b*) Same as (*a*), but for run MWD 18. The artificial tracer is at 9.4 mHz.

the star; they serve to calibrate the vertical axis. For run MWD 16, the power spectrum is dominated by two peaks at 3.68 mHz and 3.32 mHz, respectively. These are responsible for the quasi period of ~300 s easily observable in the light curve of GD 66. There are, however, a number of much smaller but nevertheless significant peaks which give the overall spectrum a somewhat complicated appearance. The spectrum for run MWD 18 is also dominated by the same two main peaks, although the photometric activity seems to have increased in that case as evidenced by the smaller relative amplitude of the 1% tracer. As in run MWD 16, the 3.32 mHz peak has kept an amplitude comparable to that of the tracer. However, the main peak at 3.68 mHz is now substantially higher. In addition, a number of low-frequency peaks showing significant power have appeared. Some of these could be due to noise, but others must be real, making the spectrum of run MWD 18 a complicated one.

We have searched for and found eight excited frequencies that correlate very well among the Fourier spectra of our four independent observations. In general, these are the frequencies showing the most power. Their values are given in Table 2, where we also list the resulting average frequencies (and corresponding average periods) computed assuming a weight proportional to the total length of the run. Assuming the existence of four basic frequencies, $f_1 = 1.23$ mHz, $f_2 = 3.32$ mHz, $f_3 = 3.68$ mHz, and $f_4 = 5.08$ mHz, the other four can be explained in terms of linear combinations of those (see Table 2 and Figs. 2*a* and 2*b*). Other combinations could possibly be valid. Such relationships are quite typical of moderate- to large-amplitude

TABLE 2

COMMON FREQUENCIES IN THE POWER SPECTRA OF GD 66

Fourier Component	MWD 09 (mHz)	MWD 12 (mHz)	MWD 16 (mHz)	MWD 18 (mHz)	Frequency (mHz)	Period (s)
f_1	1.221	1.221	1.221	1.268	1.234	810.4
$2f_2$-f_4	1.540	1.540	1.540	1.502	1.530	653.6
$2f_3$-f_4	2.263	2.235	2.263	2.169	2.233	447.8
$2f_1$	2.432	2.404	2.432	2.441	2.430	411.5
f_2	3.315	3.334	3.315	3.315	3.318	301.4
f_3	3.681	3.700	3.681	3.681	3.684	271.4
f_4	5.089	5.089	5.089	5.071	5.084	196.7
$2f_3$	7.362	7.352	7.362	7.362	7.360	135.9

ZZ Ceti stars (cf. McGraw 1977*b*). It is interesting to note that the peak at 7.36 mHz ($2f_3$) is probably *not* the first harmonic of the dominant peak because the former should have been smaller in run MWD 16 than in run MWD 18. The situation may be analogous to the case of GD 385 for which Kepler (1984) suggests that parametric resonance could excite a mode with twice the frequency of the mode with the largest amplitude.

c) Comparison with the Results of DVC

Our results show a first difference with those of DVC in the sense that we have found at least eight excited frequencies in the power spectrum of GD 66, whereas they found only four. The frequencies f_2, f_3, and f_4 are in common and, interestingly, f_1, $2f_1$, and $2f_2$-f_4 appear to be also present in the power spectrum shown by DVC, although these are hidden by the noise (see their Fig. 2). At first sight, it would appear that our finding that there are at least four low-frequency (<2.5 mHz) components in the light curve of GD 66 would support DVC's interpretation because they theoretically expected—but did not find in their data—low-frequency, high radial order modes. However, the expected frequencies of their most unstable, high k modes at 1.91 mHz and 2.67 mHz are nowhere near the observed low frequencies (cf. Table 2). It thus appears that the luminosity variations of GD 66 are considerably more difficult to explain than anticipated by DVC.

More importantly, we have found no evidence that there exists a pulsation mode in GD 66 with a frequency of 3.90 mHz. By contrast, the model proposed by DVC is characterized by a $l = 2$, $k = 7$ mode at that frequency. An examination of our four power spectra indicates that there is only some nonrepetitive structure around that particular frequency. For example, the Fourier spectrum of our longest light curve (run MWD 16, Fig. 2*a*) shows that there is no significant power at ~3.90 mHz. Only the power spectrum of our *shortest* run (MWD 12) shows an important peak at 3.88 mHz, well separated from the main peak at 3.70 mHz. A blowup of the spectral region in the immediate vicinity of this main peak (f_3) is shown in Figure 3. The upper curve gives the power spectrum of the light curve of GD 66 for run MWD 12. Note that the curve has been shifted vertically for better visualization. As in Figures 2*a* and 2*b*, the power of the main peak is normalized to one. A significant feature of the curve is the presence of a peak at 3.52 mHz with comparable power to that of the 3.88 mHz peak. The noteworthy characteristic of these two peaks is that they are *exactly* equidistant from the main peak, at ± 0.18 mHz on each side of f_3.

One could perhaps interpret this particular structure as being due to the simultaneous presence of three different pulsation modes. Indeed, DVC suggest that the 3.70 mHz and 3.88 mHz features are due to two different pulsation modes with the same l value but with consecutive values of k. The 3.52 mHz peak is not seen in their spectrum. We believe instead that the structure of the upper curve of Figure 3 is better explained in terms of both inadequate time resolution and rotational splitting. This is indeed strongly suggested by the following analysis.

The lower curve of Figure 3 shows the power spectrum of the light curve of GD 66 for run MWD 18 in the immediate vicinity of f_3 (see Fig. 2*b*). This run is our second longest (3.7 hr) and corresponds to an epoch for which the photometric activity of GD 66 seems to have been relatively intense as noted previously. We find an interesting pattern of five equally spaced peaks (within the measurements errors) with an average spacing of 0.104 mHz as indicated by the arrows. This structure is very similar to that found by McGraw (1977*a*) in BPM 30551; we previously pointed out also how the light curves of

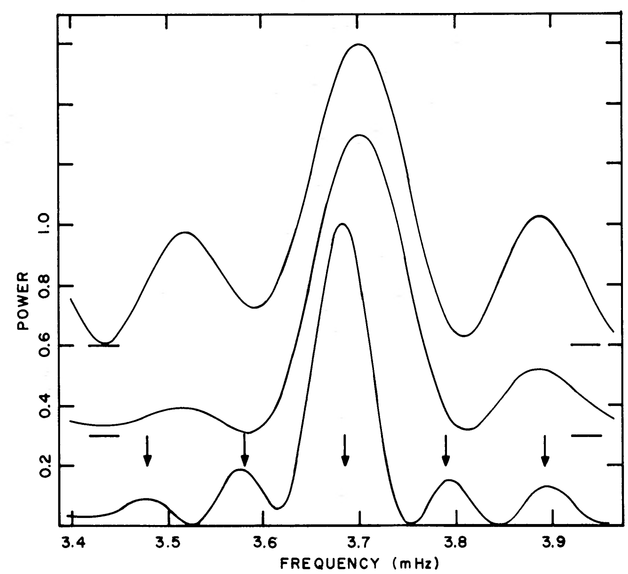

FIG. 3.—Power spectra of the light curve of GD 66 in the immediate vicinity of the dominant pulsation peak. The vertical scale is the same as in Figs. 2*a* and 2*b*. The upper curve represents the power spectrum for run MWD 12, our shortest one. The lower curve shows the power spectrum of the light curve of run MWD 18. It is characterized by five equally spaced frequency peaks as indicated by the arrows. The middle curve is also a power spectrum for run MWD 18, but with a degraded frequency resolution obtained by considering only a segment of the light curve equal in length to the light curve of run MWD 12 (2.2 hr). Note that the curves have been displaced vertically by 0.3 power unit to facilitate their visualization.

GD 66 and BPM 30551 are similar. The most probable explanation for this particular pattern is that the dominant mode at 3.68 mHz has been rotationally split; the five peaks correspond to modes with the same l and k values but with different m values. If true, it implies a rotation period of about 2.7 hr for GD 66 (this estimate neglects the constant C_{kl} in the equations of Brickhill 1975).

Consider now the following numerical experiment. We degrade the resolution of the lower curve of Figure 3 by computing the power spectrum of a *segment* of the light curve of run MWD 18. This segment is made up of the first 598 out of the 1014 data points available in order to have the same time resolution as in run MWD 12. The result of this operation is shown by the middle curve of Figure 3. In addition to a slight shift of the main peak from 3.68 mHz to 3.70 mHz, we now obtain two new "modes" at ± 0.18 mHz on each side of the dominant peak, in perfect agreement with the upper curve. We take this as very strong evidence against the existence of an independent (different k value) pulsation mode at ~ 3.90 mHz as suggested by DVC.

Our data show evidence that the mode (3.68 mHz) with the largest amplitude is split by rotation in run MWD 18 and in run MWD 12 (in the later case rotational splitting is coupled with inadequate resolution). We do not see any other patterns of equally spaced frequency components around the other peaks in our Fourier spectra as could be expected. A plausible explanation is that these other modes have amplitudes that are somewhat too small to reveal such components. Similarly, in runs MWD 09 and MWD 16, even the main peak does not show convincing structure to support the idea of rotational splitting. Again, however, the amplitude of the dominant mode may be too small. Indeed, we note that the amplitude of the 1% tracer in the normalized Fourier spectra of runs MWD 09 and MWD 16 is significantly larger than that in runs MWD 12 and MWD 18. This implies, as stated before, a lower photometric activity in the former cases.

III. THE SPECTROSCOPIC EVIDENCE

a) Observations

As part of an ongoing investigation of the properties of cool ($T_e \lesssim 11{,}000$ K) DA white dwarfs and their relationship to ZZ Ceti variables (cf. Lacombe 1985), GD 66 was observed with the blue-sensitive Reticon system attached at the Cassegrain focus of the Steward Observatory 2.3 m telescope on 1982 October 11. This observation precedes the discovery of variability in that object by DVC. The total exposure time was 32 m long; this is sufficiently long to cover several pulsation cycles and, therefore, to ensure that the resulting time-averaged spectrum is meaningful. Details of our observational procedure can be found in Lacombe *et al.* (1983).

b) Spectroscopic Analysis

In order to derive atmospheric parameters for GD 66 based on the spectroscopic observations, LTE model atmosphere calculations were carried out for DA white dwarfs in the temperature range of the ZZ Ceti stars (Lacombe 1985). These calculations, based on the ATLAS program, consist of 18 models, of pure hydrogen composition, in the range $9500 \leq T_e \leq 12{,}000$ K and $7.5 \leq \log g \leq 8.5$. For these models, detailed synthetic spectra of the gravity-sensitive Hδ line, for which both good wavelength coverage and good S/N ratio is available, were calculated. Because of the crowding of the hydrogen lines near the series limit, care was taken to include both the Hγ and the Hϵ line opacities in the line profile calculations of Hδ. This guarantees that the depression of the continuum level in the wings of Hδ caused by the presence of the neighboring hydrogen lines is properly accounted for. The continuum level in our spectra was consistently set at -65 Å and $+100$ Å from the line center.

The optimal effective temperature and surface gravity combination was obtained through a two-dimensional least-squares fitting technique. This numerical procedure yields the following parameters for GD 66: $T_e = 10{,}800 \pm 400$ K, $\log g = 7.7^{+0.4}_{-0.2}$. The resulting fit is displayed in Figure 4.

Our spectroscopic effective temperature determination is in excellent agreement with the DVC estimate of 10,500 K $< T_e <$ 11,000 K, using the measured $G-R$ color of -0.31 ± 0.03 and based on unpublished Koester models and on the temperature scale of Shipman (1977). The use of the more recent Shipman (1979) scale yields $T_e = 10{,}800 \pm 300$ K. This result is further substantiated by our own set of theoretical multichannel colors which is based on the models of Lacombe (1985). These make use of the standard mixing length theory (ML 1—see Fontaine, Tassoul, and Wesemael 1984). More interestingly, our log g determination suggests that the surface gravity of GD 66 is quite normal or, at the very least, is not unusually large. The mass required by DVC in their mode identification ($M = 0.85\ M_\odot$) corresponds to $\log g = 8.45$ in the carbon sequences of Lamb and Van Horn (1975) and Winget, Lamb, and Van Horn (1985). Our surface gravity estimate strongly suggests that such a large value can probably be excluded for GD 66. This is in line with the results of Schulz and Wegner (1981) and Weidemann and Koester (1980, 1984) which suggest that field DA white dwarfs at $\log g \approx 8.45$ are genuinely rare.

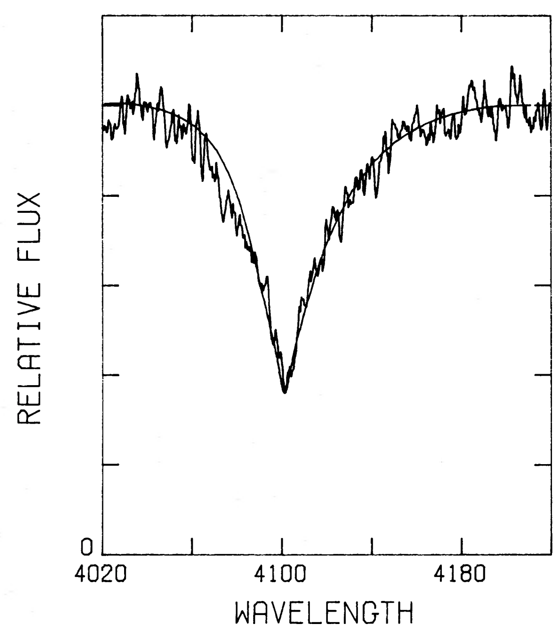

FIG. 4.—The Hδ line in GD 66, together with our optimal fit ($T_e = 10{,}800$ K, $\log g = 7.7$). The spectral resolution of the data is ~ 2.3 Å, and the theoretical spectra have been degraded to that value. The continuum level is set at -65 Å and $+100$ Å from the line center.

IV. CONCLUSION

The evidence presented in this paper strongly suggests that the mode identification put forward by DVC for the pulsating white dwarf GD 66 is incorrect. More detailed photometric observations indeed reveal that GD 66 pulsates in, at least, twice as many modes as inferred by DVC. The additional modes are not explained by their model. Moreover, the suggestion that the frequency peaks at 3.28 mHz, 3.66 mHz, and 3.90 mHz (observed in the power spectrum of their light curve of GD 66) correspond to three different pulsation modes with the same l value and consecutive k values, is not supported by the present analysis. In particular, the 3.90 mHz feature is, rather, explained in terms of rotational splitting of the main pulsation mode (thus corresponding to the same l and k values but with the m degeneracy removed). In addition, a detailed model atmosphere analysis of new spectroscopic observations strongly suggests that the surface gravity of GD 66 is quite normal. This result is in further conflict with DVC's model which requires a higher than average stellar mass ($M \approx 0.85$ $M_{\odot}$), and consequently surface gravity ($\log g \approx 8.45$), to account for the observed pulsation frequencies.

In the light of our results, we reaffirm Winget's (1981) conclusions that it is still premature to attempt identifying actual pulsation modes in ZZ Ceti stars by simply comparing the observed pulsation frequencies with theoretically expected frequencies. As discussed in § I, such an identification may not be unique considering the uncertainties involved in modeling ZZ Ceti stars and additional difficulties, such as the unknown angle between the symmetry axis of the pulsator and the line of sight. Yet, mode identification remains the key factor if we are to take full advantage of recent theoretical investigations of the pulsation properties of ZZ Ceti stars to probe the interiors of white dwarfs (Winget and Fontaine 1982). At the moment, we still do not know what modes are excited in the best studied ZZ Ceti stars—the linear pulsators for which the light curves have been completely deciphered. The possibility that detailed analyses of time-resolved spectrophotometry could lead to a determination of l as well as a determination of the pulsation frequencies is currently under investigation by Saumon *et al.* (1985) for the case of the large-amplitude variable G29−38.

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