Astron. Astrophys. 121, L 23–L 26 (1983)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

Identification of gravity modes in the newly discovered ZZ Ceti variable GD 66*

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Received March 1, accepted March 8, 1983

SUMMARY : We report the discovery of a new ZZ Ceti variable : GD66. The star was selected from spectrophotometric data obtained with the Hale Double Spectrograph. Its colors in the MCSP system place GD66 in the ZZ Ceti instability strip. Fast photometry obtained at the Haute Provence Observatory 1.93 m telescope confirms the variability of GD66. Four periods are identified with 304s, 273s, 256s and 197s periods. The main period at 273s has a 2% amplitude. The fact that the Fourier spectrum consists of three closely spaced frequencies separated from a fourth frequency, lead us to a tentative identification of the observed modes. The periods and the effective temperature ($T_e \cong 10500$ K - 11000 K) also suggest that GD66 is a massive white dwarf ($M \gtrsim 0.85\ M_\odot$) with a large mass hydrogen outer layer ($M_H/M > 10^{-11}$). A stratified DA model, computed with these parameters, has its most $l = 2$ unstable gravity modes at 267s (k=5), 281s (k=6), 303s (k=7), and its most $l = 3$ unstable mode at 195s (k=5), in good agreement with the observed periods. However, the higher k resonant modes at 524s (l=2, k=14) and at 374s (l=3, k=14), predicted by the linear theory, are not observed.

Keywords : White dwarfs, ZZ Ceti stars, Fast photometry, Mode identification.

I - INTRODUCTION

Statistics on ZZ Ceti stars rely on the small number of DA white dwarfs known to be variable. The total number of firmly established ZZ Ceti variables is of seventeen at the present time as discussed by Winget and Fontaine (1982). In their statistical analysis of the ZZ Ceti stars, Fontaine et al. (1982) show how the use of the Greenstein's (G-R) color index conducted to the discovery of a number of new variables : GD 385 (Fontaine et al., 1980), G 191-16 and G 185-32 (McGraw et al., 1981), G 226-29 (McGraw et al., 1983), G 255-2 (Vauclair et al., 1981). They conclude that probably all DA white dwarfs in the (G-R) color interval -0.45 < (G-R) < -0.38 are variables. Greenstein (1982) used the Oke and Gunn (1983) absolute flux scale recalibration of his MCSP data do determine the new location and width of the ZZ Ceti instability strip as -0.41 < (G-R) < -0.29. When compared to Shipman's (1977) model atmospheres, this revision makes the instability strip somewhat cooler than was previously thought, with a blue edge at about 11700 K and a red edge at about 10700 K. In the new (G-R) interval, Greenstein (1982) finds that 60% - 80% of the DAs are variable. From a theoretical point of view, the new determination of the instability strip favors the conclusion that the ZZ Ceti variability is due to the K-mechanism in the hydrogen partial ionization zone, as found independently by Dolez and Vauclair (1981), Winget et al. (1982) and Starrfield et al. (1982). The K-mechanism acting in the helium partial ionization zone produces a much bluer edge as demonstrated by Dziembowski and Koester (1981) and by Dolez and Vauclair (1981) (hereafter DV). The presently available linear non-adiabatic stability analyses predict that DA white dwarfs are unstable to non radial gravity modes in a temperature interval which varies slightly from one analysis to another, but which corresponds well enough to the observed range.

At the present stage of our understanding of the ZZ Ceti variables some important points are still unclear :

1) are all DAs in the instability strip really variable ?

2) the blue and red edges of the instability strip should be determined precisely enough to help further theoretical studies (on convection-pulsation coupling for instance).

These questions point towards the need of better statistics and temperature determination in and around the instability strip.

This led two of the authors (G.V. and N.D.) to obtain reliable spectrophotometry for a number of DA white dwarfs, to get a larger sample of ZZ Ceti candidates. The results of this investigation, conducted at the Hale 5 m Telescope, with the Double Spectrograph of Oke and Gunn (1982) equiped with two CCD cameras, will be described in a forthcoming publication. A few ZZ Ceti candidates have been selected from this sample and observed for short period variability. We report in this Letter on the discovery of the new ZZ Ceti variable GD66.

II - OBSERVATIONS AND ANALYSIS

1) Spectrophotometry : GD66 (WD 0517 + 304), a proper motion star from the Lowell Survey (Giclas, Burnham and Thomas, 1980), is a DA white dwarf (Wickramasinghe et al., 1975) with UBV photometry from Eggen (1968) : V=15.6, B-V=+.22, U-B=-.59. The absence of MCSP data (Greenstein, 1976) together with a B-V close to the colors of known ZZ Ceti variables, led us to put GD66 on our observing list with the Hale DBSP. We obtained a 700s integration on October 10, 1982 with the red CCD camera alone as a consequence of a temporary failure of the blue camera. The grating was tuned to cover the wavelength range 4000 Å < λ < 8800 Å. The absolute calibration of the colors is based on Oke-Gunn subdwarf G star standards, AB79 system. The only missing standard MCSP color is U at 3571 Å. Other colors (B, G, V, R, I as defined by Greenstein, 1976) may be measured directly on the ∿ 6 Å resolution spectrum,

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* Based on observations made at the Hale 5 m Telescope, of the California Institute of Technology ; and at the Haute Provence Observatory (CNRS).

allowing the construction of color indices (G-R), (V-I) and of the mean color index which measures the slope of the Paschen continuum $\Delta P=1/2\ |(G-R)+(V-I)|$. Both color indices $(G-R)=-.31$ and $\Delta P=-.36$, determined with an error of about .03, put GD66 well inside the range of colors for the ZZ Ceti variables ($-.41 < (G-R) < -.29$; $-.47 < \Delta P < -.32$). Comparison with Shipman's (1977) or Koester's (1978) model atmospheres for DA white dwarfs suggests an effective temperature of about $10500\ K < T_e < 11000\ K$, for log g = 8.

2) Fast Photometry : GD66 was subsequently observed at the Haute Provence Observatory, with the fast photometer, described by Vauclair and Bonazzola (1981) and Vauclair, Dolez and Chevreton (1981), at the Cassegrain focus. The Fast Fourier Transform (FFT) analysis procedure has been described in the above cited papers. A first run of ∿ 100 mn was obtained on November 9, 1982. The FFT showed a noisy spectrum, due to the variations of the sky transparency during the night. However, four frequencies had statistically significant amplitudes at 3.28, 3.61, 3.94, 5.08 millihertz (mHz). With a resolution of .32 mHz, this gives periods of 304 ± 14s, 276 ± 12s, 253 ± 10s and 196 ± 6s. The observation was repeated on January 15, 1983 in much better conditions. We obtained a 177 mn run which confirms the discovery of the variability. The improved frequency determination (resolution .18 mHz) and noise level, allows a good measure of the amplitudes. The light curve is shown on figure 1. The total run covers almost 40 periods of the main 273s period. The Fourier spectrum, shown in figure 2, presents well separated peaks. A summary of the analysis is presented in table 1. A statistical analysis of the data has been made as in Vauclair and Bonazzola (1981). The signal/noise ratio (S/σ) allows a measure of the probability p for a peak at a given frequency to be due to noise. None of the four frequencies detected in the spectrum may be attributed to noise. The amplitude of the main mode reaches 2% of the mean stellar intensity (I_f/I_*). A third confirmation run was made on January 16, 1983. Interrupted after 51 mn, due to observing conditions getting bad, this run provides a .65 mHz resolution only. However, we still find the four identified frequencies in the Fourier spectrum with amplitudes comparable to the ones reported in table 1. The 3.90 mHz low amplitude ($I_f/I_* = .005$) peak is present on the three independant observations, from which we conclude that it is a true excited mode.

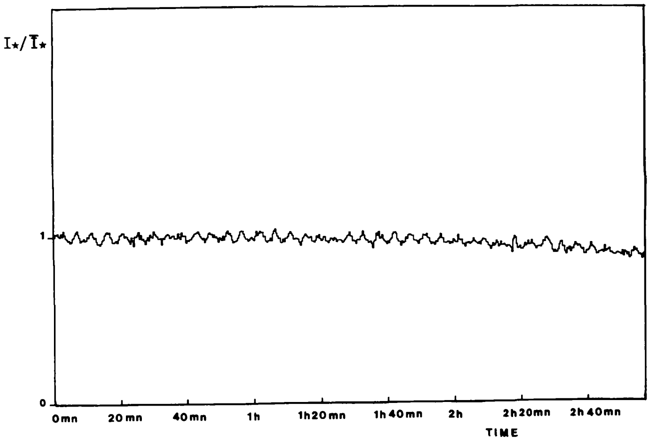

Figure 1 : Light curve of GD66, run of January 15, 1983, Haute Provence Observatory. The light curve is normalized after sky substraction, refraction is not substracted.

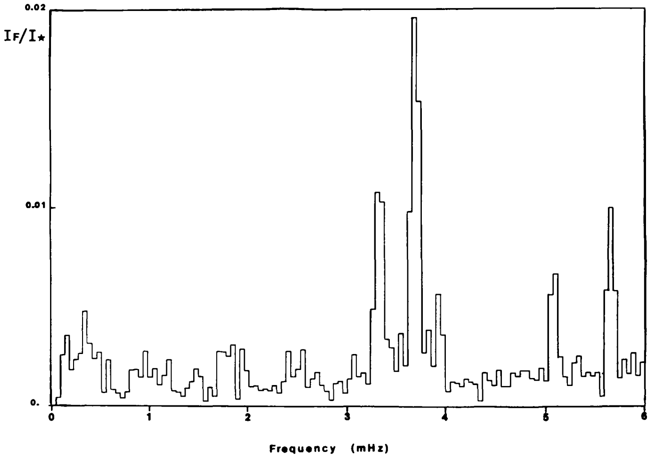

Figure 2 : Low frequency part of the Fourier transform modulus of the light curve shown in figure 1. The amplitude, expressed as a fraction of the mean stellar intensity (I_F/I_*) is plotted vs frequency in mHz (10^{-3} Hz). The data exhibit four frequencies at 3.28 mHz, 3.66 mHz, 3.90 mHz and 5.07 mHz. The peak at 5.65 mHz is a 1% amplitude tracer added to the data.

FREQUENCIES IN THE FOURIER SPECTRUM OF GD66

F mHz	P s	S/σ	I_F/I_*	P
3.28 ± .09	304 ± 8	14	.010	$7\ 10^{-17}$
3.66 ± .09	273 ± 7	28	.020	0
3.90 ± .09	256 ± 6	6.8	.005	$6\ 10^{-3}$
5.07 ± .09	197 ± 4	8.4	.006	$2\ 10^{-5}$

Table 1

3) Mode identification : The Fourier spectrum of GD66 exhibits a characteristic behaviour : three closely spaced frequencies, around the main frequency at 3.66 mHz, are well separated from a fourth one at 5.07 mHz. We want to take advantage of this behaviour to discuss the identification of modes in GD66. We may think of two possible interpretations, based on the theory of trapped modes (Winget, Van Horn, Hansen, 1981):

1) The four modes belong to the same spherical harmonic l, the isolated mode is a low k order, while the three close frequencies have much higher radial order k corresponding to a second set (harmonics) of modes trapped in the hydrogen layer.

2) The three close frequencies are modes of same l corresponding to close values of k, while the fourth one corresponds to a different value of l.

Let us consider these two interpretations in turn :

The first possible interpretation implies two sets of resonant modes trapped in the hydrogen layer : such resonant modes are described in Winget, Van Horn, Hansen (1981) and Dolez (1981). As an example selected from Dolez (1981), an hydrogen rich model ($M_H/M = 3.2\ 10^{-11}$, $T_{eff} = 11000$ K) has its most unstable l=4 gravity modes for k=12 (period of 374s) and k=5 (197s). These two modes are trapped in the hydrogen layer, the first one being in some way an harmonic of the second one. The period ratio is close to 2. The resonant modes found by Winget, Van Horn, Hansen also have period ratios close to integer numbers : 2, 3, 4.... This is easily understood as the subsequent trapped modes have eigenfunctions with one, respectively two, three...

maxima in the hydrogen layer. In GD66 the period ratio (1.38) seems too far from the expected resonance values, and do not support that interpretation.

We consider now the second possible interpretation. It is known from theoretical linear stability analysis of gravity modes in DA white dwarfs that, in a given model, the radial order k of the most unstable modes does not depend much on the spherical order l (DV). This is related to the fact that the onset of instability occurs near the Lamb frequency of the driving zone, which has the same l-dependence than the frequencies of the modes themselves, and to the fact that trapped modes of various l must have similar vertical structure (ie, a node at the same location near the bottom of the hydrogen layer), which implies the same value of k as this structure does not depend much on l for low values of l. Consequently, trapped modes corresponding to two different spherical order l and l', and the same k value, will have their frequencies in the ratio $(l(l+1)/l'(l'+1))^{1/2}$. Let us consider the frequencies of table 1 and assume that the modes at 3.28 mHz, 3.66 mHz, 3.90 mHz belong to harmonic l, while the 5.07 mHz mode corresponds to harmonic l' : one finds a good fit with l=2 and l'=3 ; the theoretical ratio is then 1.41, in close agreement with the ratio of the observed frequencies 5.07/3.66=1.38. Other values of l and l' would also fit the observed frequency ratios ; for instance l=4, l'=6 gives a ratio of 1.45, and the frequency ratio 5.07/3.28=1.54 is close to the value obtained with l=3, l'=5 (1.58). These two last possibilities would imply odd or even modes invisibility, which can be explained only by a proper orientation of the star rotation axis. Moreover we can probably exclude these higher spherical harmonics due to the rapid decrease of the luminosity variation visibility with increasing l. The best fit is l=2, l'=3, all modes with l>3 being invisible. If this interpretation is correct, we want to show that one may deduce important stellar physical parameters.

Let us now assume that the three close frequencies of GD66 have successive radial order k, as suggested by DV (ie, they are the three modes closest to the resonant value). For a given l, theoretical results show that the frequency f, for successive modes, are regularly spaced as Δk/k, provided k is large enough. We note however that for the most unstable modes, the spacing of the frequencies is smaller than Δk/k (see DV, table 1). The observed periods in GD66 gives for the 3.28 mHz and 3.66 mHz modes a ratio Δf/f = 1/10 which suggest k ≅ 8 or 7. Such a low value of k, together with the value of the periods, give some indication on the possible structure of the star :

1) The hydrogen content of the star must be large enough to allow such low radial order modes to be trapped. The results of DV suggest a value of M_H/M larger than 10^{-11}.

2) A frequency of 3.66 mHz for a l=2, k=7 mode implies a mass of the star higher than the models discussed in DV : the frequency is proportional to $(GM/R^3)^{1/2}$, which is roughly M for a white dwarf.

Using these values, we constructed models of white dwarfs with $M = 0.85\ M_\odot$, $M_H/M = 6.4\ 10^{-11}$ and several temperatures ranging from 10000 K to 11000 K as a guess for GD66. The models and their non-radial pulsations are computed as in DV. The growth rates of modes l=2 and l=3 are presented in fig. 3 for the model at 11000 K. Their periods are listed in table 2. The configuration of unstable modes aroud k=5, 6, 7 is very similar to the observations, and we remark that the frequency ratio of l=2 and l=3 modes for k=5 is 267/195, equal to the observed value (1.38). For l=2 the spacing Δf/f between k=7 and k=6 (1/13) is bigger than between k=6 and k=5 (1/19), in agreement with observational data (respectively 1/9 and 1/15). However the spacing between the observed frequencies is larger than in the model, which suggest a lower value of the radial order k of the excited modes (or may be a lower excitation rate, which could lead to the same effect as discussed above) : if we adopt k=4, 5, 6 or k=3, 4, 5 we have to make a correction to the overall mass of the star to fit the frequencies (this would give respectively $M \cong 0.79\ M_\odot$ and $M \cong 0.75\ M_\odot$), and assume a higher hydrogen content to trap the right modes.

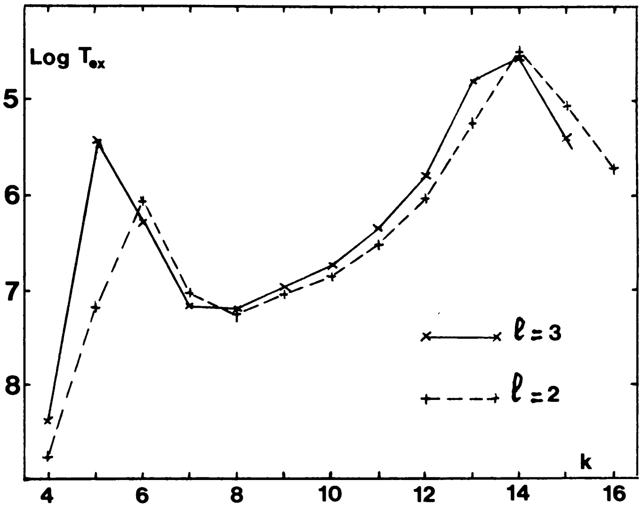

Figure 3 : Growth rates of l=2 and l=3 gravity modes. The growth rates ($T_{ex}=1/\sigma$) in seconds, is plotted on a logarithmic scale as a function of k for l=2 and l=3, in a model of DA white dwarf ($M = 0.85\ M_\odot$, T_e= 11000 K, $M_H/M = 6.4\ 10^{-11}$). Modes with small k radial orders (k=5, 6) have one maximum in the hydrogen driving zone while modes large k (k=14) have two maxima. They are trapped in the hydrogen outer layers. Only the k low modes are identified in GD66.

Periods in seconds of gravity modes near the maximum instability in a theoretical model with $0.85\ M_\odot$, 11000 K, $M_H/M = 6.4 \times 10^{-11}$: the most unstable modes are underlined.

k	4	5	5	7..........	13	14	15
l=2	267	281	303		503	524	545
l=3	195	201	222		363	374	394

Table 2

This interpretation, however encounters some difficulties : First, as fig. 3 shows, the theory predicts a second set of excited modes trapped in the hydrogen layer, at a higher value of k (k ≅ 14), which are the harmonics of the first resonant modes around k=5. These modes are not observed, although their growth rates are even higher than those discussed above. We computed cooler models (T = 10500 K and T = 10000 K) with same characteristics, and it appears that the low k resonant modes get more excited, while the high k modes get less excited ; nevertheless they cannot be suppressed by a reasonable change of temperature, and we know that the continuum flux distribution of GD66 does not indicate a temperature much below 10500 K. We know of no mechanism which could inhibit this harmonic set of trapped modes, but we should keep in mind that the modes have been calculated in the limit of a linear analysis, and does not include the perturbation of the convective flux.

Some insight about this problem can be obtained from Brickhill (1983) who discuss the amplitude of the oscillations in ZZ Ceti stars. The origin of the greater growth rates of the k=14 modes, compared to the k=5 modes, in our models, cannot be found in a greater input of energy through the driving mechanism, but rather in the lower kinetic energy of the pulsation. This point is discussed by Brickhill (1983), who concludes that the growth rate is not the more useful indication of large luminosity variations at the surface, and prefers the ratio of the excitation in the driving zone to the damping in the layers below. This could explain the non-visibility of high k-order resonant modes in GD66.

Secondly, if our analysis gives good results on this individual star, GD66, it seems to be in contradiction with the statistical study of Winget, Fontaine (1982) which suggests a period-temperature correlation : cool ZZ Ceti seem to have longer periods than hot ZZ Ceti. Our present analysis cannot explain this, and if we think of a switch from the first set of trapped modes (low k) to the second set (high k, longer periods), it seems to work exactly the opposite way.

III- CONCLUSIONS :

Spectrophotometry of GD66 obtained with the Hale Double Spectrograph places the star in the observed instability strip for ZZ Ceti variables. Fast photometry performed at the Haute Provence Observatory confirms that GD66 is indeed a ZZ Ceti variable. Four excited modes have been detected, corresponding to the periods of 304s, 273s, 256s and 197s. The light curve is dominated by the 273s period with a 2% amplitude. A discussion on possible mode identification leads to the following prefered solution : the three periods at 256s, 273s, 304s could be l=2 gravity modes of low radial order (k $\approx$ 4, 5, 6) while the fourth one at 197s could be a l=3, k $\cong$ 5 mode. The rather low k orders, and the corresponding short periods observed in this cool ZZ Ceti variable ($T_e \cong$ 10500-11000 K) point towards GD66 having a large mass hydrogen envelope ($M_H/M > 5.10^{-11}$) and the possibility of having a total mass of about 0.8 $M_\odot$, somewhat larger than the accepted average value of 0.6 $M_\odot$ for DA white dwarfs (Koester, Schulz, Weidemann 1979). A theoretical model computed to fit GD66, with 0.85 $M_\odot$, 11000 K, $M_H/M = 6.4\ 10^{-11}$ has its most unstable gravity modes at 267s, 281s, 303s (l=2, k=5, 6, 7) and 195s (l=3, k=5) in good agreement with the observations. However it exhibits a second set of resonant modes at 524s (l=2, k=14) and 374s (l=3, k=14) which are not observed. However our analysis is limited to linear perturbation theory, not even including the perturbation of the convective flux. Furthermore the implicit assumption on which the discussion relies is that the largest amplitude observed does correspond to the mode of highest growth rate found by linear theory. The calculations of Brickhill (1983) suggests that a fully non-linear stability analysis, still to be undertaken, could lead to different conclusion in the general case.

Acknowledgements

The observations of GD66 with the Hale Double Spectrograph were obtained in collaboration with Pr. Jesse Greenstein who provided some of his observing-time allocation. We are also grateful to the director of the Hale Observatory, G. Neugebauer, for hospitality. We wish to thank Dr. B. Oke, Mrs. B. Zimmermann and Mr. F. Harris for teaching us how to use the Double Spectrograph and the data reduction programs. N.D. and G.V. acknowledge grants from the French Ministère des Relations Extérieures and the CNRS. We thank the technical staff of the Haute Provence Observatory for their assistance.

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