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TWO NEW VARIABLE WHITE DWARFS: G185-32 AND G191-16[1]

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ABSTRACT

We report the discovery of two new ZZ Ceti variables, originally selected as candidates for variability on the basis of their $(G - R)$ colors. The star G191-16 is a stable, large-amplitude variable showing several periods and significant nonlinear effects in its light curve. The star G185-32 is a much smaller amplitude, multiply periodic variable. The period structures of both stars act as counter-examples to the accepted correlation for the ZZ Ceti variables between pulsation amplitude and period-structure complexity. The implication of this result with respect to the structure of hydrogen-rich white dwarf (DA) stars is discussed.

The results of our continuing survey for new ZZ Ceti variables, which uses Greenstein's multichannel colors as the selection criteria for candidate stars, are reviewed. Thus far, 10 ZZ Ceti stars are found in the range $-0.45 \leq (G - R) \leq -0.38$, and *no* constant DA dwarfs have yet been discovered in this interval. This implies that the ratio of constant to variable DA stars in the temperature range in which the variables occur is very much smaller than indicated by previous surveys.

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

I. INTRODUCTION

Systematic surveys for luminosity variations in white dwarfs have led to the discovery of a very homogeneous class of variable stars, the ZZ Ceti stars. These variables *all* have a DA spectral type, that is they show only Stark-broadened hydrogen absorption lines in their spectra, and all have colors near $(B - V) = +0.20$. The variations of these stars have been interpreted as nonradial gravity-mode pulsations (Warner and Robinson 1972; McGraw and Robinson 1975), and virtually all additional observations have supported this interpretation (see Robinson 1979; McGraw 1980).

The ZZ Ceti phenomenon corresponds to an evolutionary phase in the lifetime of a DA white dwarf (McGraw 1979). As a white dwarf cools, it eventually enters the temperature range from about 13,000 K to 11,000 K, in which variability is observed to occur. Because this temperature interval corresponds to the maximum of atmospheric opacity (Weidemann 1971) and the onset of efficient surface convection in the hydrogen-rich, high-gravity DA stars, it has been suggested that a partial ionization zone mechanism is responsible for the pulsational instability of the ZZ Ceti stars (McGraw 1977, 1979).

In order to understand more fully the mechanisms at work in the ZZ Ceti stars and to obtain the information about the structure of DA white dwarfs that is contained in the pulsations, additional observations are necessary. Recently, we have begun a high-speed photometric observing program designed to (1) discover new ZZ Ceti variables and (2) determine what fraction of DA stars become pulsationally unstable as they evolve through the temperature range in which the variables occur. Previous surveys (see McGraw 1977; Hesser, Lasker, and Neupert 1979, and references therein) have generally used a DA spectral type and $(B - V)$ colors near $+0.20$ as criteria for selecting ZZ Ceti candidates. These surveys led to the discovery of 12 firmly established ZZ Ceti stars. It was

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also found that both variable and constant stars seem to coexist in the interval $+0.15 \leq (B - V) \leq +0.25$ with a ratio of about one variable to three nonvariables (Robinson 1979).

Candidate stars for our survey are selected on the basis of a DA spectral type and $(G - R)$ color indices as defined by Greenstein (1976) from multichannel-scanner observations. While our sample is smaller than samples for previous surveys because of the limited number of stars with $(G - R)$ colors, our candidate stars gain the important advantage of having more homogeneous and accurate colors. The first result of our survey was the discovery of a new ZZ Ceti star, GD 385 (Fontaine *et al.* 1980). Extensive observations of the light curve of this variable showed it to have extremely interesting nonlinear and mode-coupling effects. In this paper, we present the discovery of and data on an additional two new ZZ Ceti variables. The star G191-16 appears to be a large-amplitude variable with a period structure somewhat more stable than usual for large-amplitude ZZ Ceti stars, while G185-32 is an erratic, small-amplitude pulsator. These two new variables differ from the other ZZ Ceti stars in that their period structures do not closely follow the empirical amplitude-complexity correlation (see Robinson 1979; McGraw 1980) found to hold for other ZZ Ceti variables. The $(G - R)$ colors for the two new variables are -0.44 and -0.42 respectively (Greenstein 1976).

The discovery of these two new variables brings the number of known ZZ Ceti stars in the color range $-0.45 \leq (G - R) \leq -0.38$ to a total of 10, that is, every ZZ Ceti with a measured $(G - R)$ color. *No* constant star has yet been found in this color interval. The implication of this result is that a high percentage of, and possibly all, DA white dwarfs become pulsationally unstable.

In § II, we present our observations of G191-16 and G185-32 and, in § III, we discuss the pulsational properties of these variables and the implications of discovering a large number of variables in a restricted color range.

II. OBSERVATIONS

Our survey is a collaborative effort that involves high-speed photometric observations obtained at several observatories. In the course of this survey, G191-16 and G185-32 were found to be ZZ Ceti variables. Observations of these two stars were obtained with the Palomar 1.52 m telescope (MP), the Mont Mégantic 1.60 m telescope (MM), and the 4.48 m equivalent-aperture Multiple-Mirror Telescope on Mount Hopkins (MMT). The photometers used for these observations are computer-controlled, photon-counting devices. They are, however, "single-star" instruments; thus, nearby stars in the field of the variable are monitored both before and after each run to ensure that the night remains photometric. Real-time display of the data as they are collected allows us to discriminate with a high degree of confidence between variations intrinsic to the star and those caused by transparency variations or possible guiding errors. Where there is any question of the quality of the data, they are simply discarded and not used in our analyses. All observations were made in "white light," using various photomultipliers having either S-11, S-20, or bi-alkali responses. The journal of observations of G191-16 and G185-32 is given in Table 1.

The top panel of Figure 1 shows a segment of the light curve of G191-16 obtained in run 0054. The light curve of this star exhibits variations which can exceed 0.3 mag peak to peak. The arrival time of peaks of individual pulses is not strictly periodic, but a quasi-period of about 865 s can be derived from the light curve. Individual pulses typically show a rapid rise to a sharp maximum followed by a slower decline to a broad minimum—behavior characteristic of large-amplitude ZZ Ceti stars. Power spectra of the light curve obtained in each run were calculated to examine the period structure in detail.

Low-frequency spectra calculated for runs 0041b and 0054 are shown in Figures 2*a* and 2*b* respectively. From a frequency of about 6 mHz to a Nyquist frequency of 0.167 Hz, the power spectrum is flat, indicating no photometric activity in the light curve of the star. Each spectrum is dominated by a peak near 1.133 mHz. The first two harmonics of this signal are always present with significant power. In addition, significant power can occur at other frequencies. Examples are the two peaks at about 1.5 and 1.7 mHz in Figure 2*b*. When additional signals appear in the power spectra of the light curve of this star, small-amplitude peaks corresponding to linear combinations of the 1.13 mHz peak and the additional signals also appear, typically at the limit of significance. The lowest-frequency peak in Figure 2*a* at about 0.2 mHz is due to incomplete removal of extinction and is not a real signal associated with the star.

Small shifts in the frequency of the primary peak, on the order of 0.06 mHz, may occur. Confirmation of the reality of these shifts will require further observations, as they tend to be of the same size as the frequency resolution in the power spectrum. However, the largest shifts tend to occur when additional signals are present in the light curve. The power in each peak is definitely variable, as indicated in Figure 2.

The period structure of G191-16 is unique among ZZ Ceti variables because it is remarkably simple for such a large-amplitude variable. It has been noted repeatedly (see Robinson 1979; McGraw 1980) that there is an apparent correlation between the amplitude of the pulsation and the complexity of the power spectrum derived from the light curve. The sense of the correlation is that large-amplitude variables have complex power spectra. The star G29-38, for example, a ZZ Ceti with an amplitude also about 0.3 mag, has a spectrum indicating significant power at about 20 different frequencies. In addition, the power, and the frequencies at which it appears, are rapidly variable with time (McGraw and Robinson 1975). The simplicity and relative stability of the period structure of G191-16 appear to act as a counterexample to this correlation.

The observed period structure of the second new variable, G185-32, also appears to contradict the amplitude-complexity correlation but in the opposite sense. The lower panel of Figure 1 shows the segment of

TABLE 1

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Run	Date (UT)	Start Time ($JD_\odot$ 2,440,000+)	Telescope	Integration Time(s)	Total points
		G 191-16			
MP 03	Sept.15, 79	4131.5792	MP	20	179
MP 06	Sept.16, 79	4132.5611	MP	20	379
MP 11	Sept.17, 79	4133.5736	MP	20	197
0036	Oct. 14, 79	4160.893578	MMT	4	1084
0037	Oct. 14, 79	4160.954277	MMT	3	1730
0041 a	Oct. 15, 79	4161.807775	MMT	3	1253
0041 b	Oct. 15, 79	4161.854804	MMT	3	3716
MM 09	Nov. 1 , 79	4178.7208	MM	20	609
0054	Feb. 11, 80	4280.601429	MMT	5	1959
		G 185-32			
MM 06	Oct. 31, 79	4178.4775	MM	20	180
0083	May 18, 80	4377.902856	MMT	5	1169
MP 17	May 18, 80	4377.9375	MP	20	138
0090	May 19, 80	4378.935843	MMT	4	709
0094	May 20, 80	4379.924422	MMT	5	739
MP 26	May 20, 80	4379.8847	MP	20	282
0100	June 8, 80	4398.943214	MMT	5	437

the light curve of G185-32 obtained during run 0094. The variations of this star are much more erratic than those of G191-16 and the peak-to-peak amplitude is less than 0.02 mag. However, a quasi-period of about 200 s can be associated with the light curve of this star. Figures 3*a* and 3*b* show the low-frequency power spectra of the light curve calculated for runs 0090 and 0094 respectively. There are always several significant peaks in the spectrum, though the frequencies and amplitudes of some of the peaks are variable. The primary peak, which always recurs within the resolution of the spectrum, is at about $f_0 = 4.65$ mHz. Additional signals which are always present occur at about 7.07 mHz, which is very nearly $3f_0/2$, and at about 14.13 mHz, which is very nearly $3f_0$. The first harmonic of f_0 is never present with significant power. The structure of the power spectrum changes from

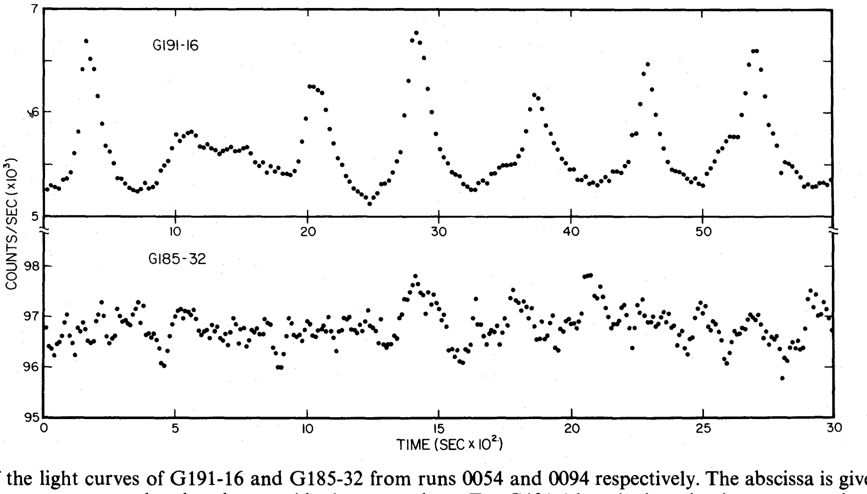

FIG. 1.—Segments of the light curves of G191-16 and G185-32 from runs 0054 and 0094 respectively. The abscissa is given in seconds, and the ordinate is expressed in counts per second, reduced to outside the atmosphere. For G191-16, each plotted point corresponds to a 30 s measurement, and, for G185-32, each point is a 10 s measurement.

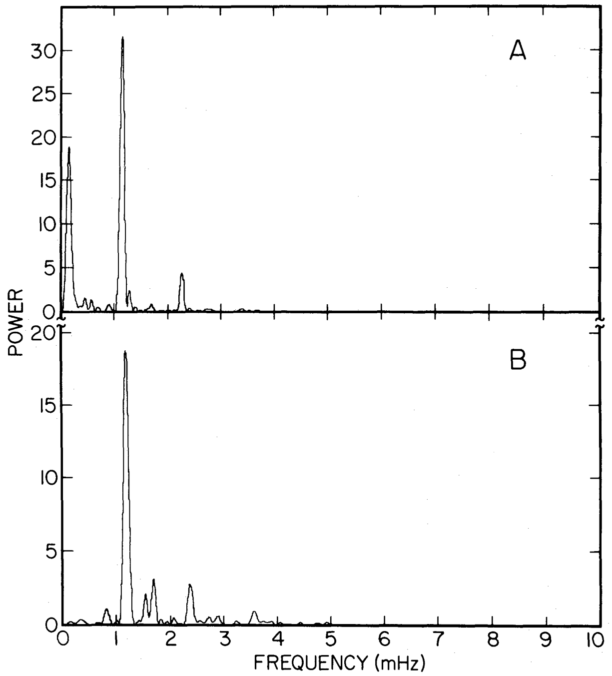

FIG. 2.—Power spectra calculated from segments of the light curve of G191-16 obtained in (*a*) run 0041b and (*b*) run 0054. All spectra shown in this paper have been normalized so that the power is directly comparable. The half-amplitude in magnitudes, Δm, of a sinusoidal signal in these spectra is given by $\Delta m = 2.5 \log \{1 + [2P(f)/N\Delta t]^{1/2}\}$, where $P(f)$ is the power at the frequency, f, of the sinusoidal signal, N is the number of points in the transform, and Δt is the sampling interval. Note the differing power levels but relative frequency stability from run to run. The low-frequency peak at about 0.2 mHz corresponds to incomplete removal of atmospheric extinction and is not significant.

night to night, especially at lower frequencies, indicating either that the pulsations of the star can change somewhat in both frequency and amplitude, or that, in a single run, we have not observed all of the periods (including beat periods resulting from closely spaced pulsation periods) present in the light curve of this star.

The period structure of this star is unique in two respects with respect to other ZZ Ceti variables. This star has the most complex period structure of the small-amplitude ($\Delta m \leq 0.03$) variables. Past experience indicates that small-amplitude variables have simple, stable period structure (see McGraw 1980). The star G185-32, with its complex and unstable period structure, thus acts as a small-amplitude counterexample to the amplitude-complexity correlation noted above.

The second unique feature of the period structure is that the first harmonic of the primary signal is absent while power at about $3f_0/2$ and $3f_0$ appears. Increasing complexity of the period structure of ZZ Ceti variables has been ascribed to increasing nonlinearity of the pulsations (see McGraw 1980). This normally implies that the first harmonic of the primary signal is the first additional signal to appear for nonlinear pulsations, with other harmonics being common, as well. Power at $3f_0/2$ and $3f_0$ implies either that pulsation modes with frequencies near these are being excited, or that the star can effectively suppress the first harmonic of a nonlinear pulsation while exciting the second and first "odd-half" harmonics.

Alternatively, the behavior of the light curve of G185-32 could perhaps be explained by nonlinear pulsation modes with a relatively large number of surface nodes. Such modes, if they also have a large number of radial nodes, could have periods in the observed range, be distinctly nonlinear, and still produce a small-amplitude light curve. While this appears unlikely because the dominant frequency near 4.65 mHz tends to favor a low number of surface nodes (Brickhill 1975), we cannot exclude this possibility at this time.

III. DISCUSSION

Our current survey has resulted in the discovery of two new ZZ Ceti stars, thus bringing the number of confirmed members of this class to 15. The period structures of both stars act as counterexamples to the amplitude-complexity correlation considered to exist for ZZ Ceti variables. This correlation is explained in terms of increasing nonlinearity of the nonradial g-mode pulsations of these stars. Small-amplitude variables are considered to be basically linear pulsators wherein only the (multiple) excited modes are present, while large-amplitude variables are considered to be highly nonlinear pulsators, the light curves of which contain harmonics and periods resulting from nonlinear coupling between the multiple primary pulsation modes. This correlation would be very strong indeed if DA dwarfs were identical mechanical

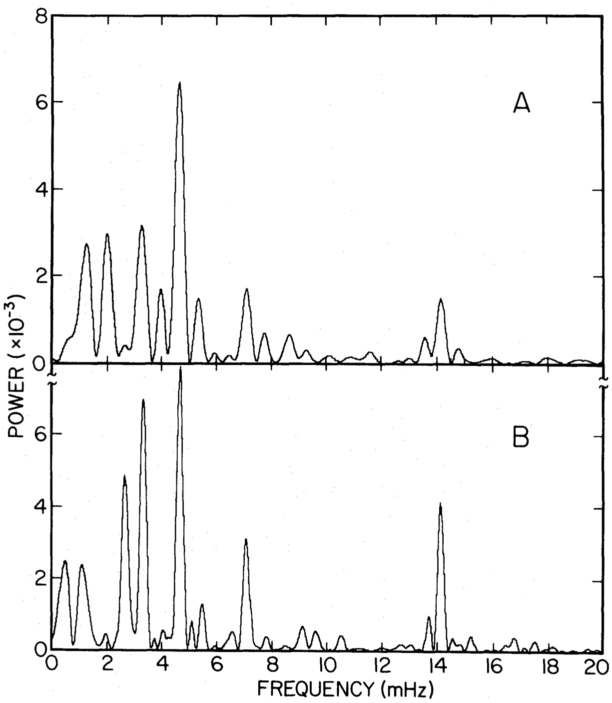

FIG. 3.—Power spectra of the light curve of G185-32 calculated from the data of (*a*) run 0090 and (*b*) run 0094. The peaks in these spectra, especially those at low frequencies, change in both amplitude and frequency from run to run.

systems because nonlinearity would then depend *only* upon the mode and amplitude of the pulsation. That is, the mass, temperature, and composition of individual stars would not affect the observed nonlinearity of a pulsation mode. The fact that the correlation is as strong as it is indicates that, in fact, the DA dwarfs *are* remarkably similar. Because period structures of G191-16 and G185-32 do not closely follow the correlation, they indicate that there is indeed a limit to the similarity of DA dwarfs. Equivalently, they indicate current extremes to a finite "width" of the amplitude-complexity correlation, a significant contribution to which probably arises from differing structures among DA stars.

The major differences (and similarities) of the structure of DA white dwarfs made discernible by using g-mode pulsations as probes of the interiors of these stars occur in the outer envelopes. This is simply because the eigenfunctions of g-modes attain appreciable amplitude only in the envelopes of DA stars (Brickhill 1975; Dziembowski 1979). The fact that widely differing periods are excited in various white dwarfs is an indication of differing envelope structure. In recent papers, Winget, Van Horn, and Hansen (1981) and Dziembowki and Koester (1981) have investigated the properties of g-mode pulsations in DA models with layered envelope structure. Because one expects envelopes of DA dwarfs to be highly layered as a result of elemental diffusion (Fontaine and Michaud 1979), these models more closely approximate "real" DA stars than the homogeneous models analyzed previously. These recent studies have shown that the layered envelope may act as a mechanical filter for g-modes. Robinson (1979; see also Robinson *et al.* 1978) has pointed out that, in a *homogeneous* star, it is unlikely that a single g-mode, g_k, could be excited without exciting adjacent modes, g_{k-1} and g_{k+1}, where k is basically the number of radial nodes associated with the pulsation mode. The filtering capability of the more realistic, layered models suggests how isolated modes can appear, thus removing a major problem in identifying unequivocally the pulsations of ZZ Ceti stars as nonradial g-modes.

The complex power spectrum of G185-32 may then indicate a relatively homogeneous atmosphere so that damping from the deep interior is reduced, and mode coupling occurs in spite of the small amplitude. Conversely, the structure of G191-16 would seem to be quite efficient at preventing all but a single pulsation mode from being excited.

When additional observations of these and other ZZ Ceti variables, coupled with refined theoretical models, allow identification of which nonradial g-modes are excited in DA stars, we shall be able to determine quantitatively to what extent the structures of these stars are similar. Ultimately, we shall be able to measure the thickness of the hydrogen and helium layers of these stars by comparing the depth of the layers to the radial wavelengths of the excited modes.

TABLE 2

COLORS OF ZZ CETI STARS

Star	$(B-V)$	$(G-R)$
BPM 30551	+0.17	
ZZ Ceti	+0.20	−0.43
BPM 31594	+0.21	
HL Tau-76	+0.20	−0.39
G38-29	+0.16	−0.42
G191-16	+0.03:	−0.44
GD 99	+0.19	
G117-B15A	+0.20	−0.45
GD 154	+0.18	−0.43
L19−2	+0.25	
R808	+0.17	−0.38
G207-9	+0.17	
G185-32	+0.17	−0.42
GD 385	+0.19	−0.43
G29-38	+0.20	−0.43

Perhaps the most important result of this paper is the fact that, in the color range $-0.45 \leq (G-R) \leq -0.38$, 10 ZZ Ceti stars, that is, all ZZ Ceti stars with measured $(G-R)$ colors, have thus far been discovered, whereas *no* constant stars have been found in this range. These stars, with their $(G-R)$ colors, are listed in Table 2. Confirmation of this trend by further observations will have several important consequences. The implication is that the vast majority, *and perhaps all*, of the DA white dwarfs go through an instability phase during their cooling lifetimes. If true, this implies that any theory attempting to explain the ZZ Ceti phenomenon must treat it as a natural result of the evolution of white dwarfs. In particular, it implies that, independent of progenitor mass and composition or the evolution to the DA sequence, by the time all DA stars cool to about 13,000 K, they are sufficiently similar, at least in the envelopes, to support pulsations. The observational statistics of pulsators on the DA cooling sequence are discussed in detail by Fontaine *et al.* (1981). If the current promising trend in theoretical modeling of the variables continues, we may ultimately be able to investigate the structure of individual DA dwarfs and apply the knowledge of their structure to the structure and evolution of white dwarfs in general.

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