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A SPECTROSCOPICALLY PREDICTED NEW ZZ CETI VARIABLE: GD 165

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ABSTRACT

We report the discovery that the DA white dwarf GD 165, recently identified by Becklin and Zuckerman as possibly having a brown dwarf companion, is also a ZZ Ceti variable. The variability of GD 165 was previously predicted from the spectroscopic analysis of Bergeron *et al.*: GD 165 was found to have atmospheric parameters similar to other ZZ Ceti white dwarfs, namely an effective temperature near 13,000 K and a pure hydrogen atmosphere. The analysis of our two independent photometric observations shows brightness variations of up to 0.1 mag on time scales of 200–1800 s. Fourier analysis of the light curves indicates that, as is true in general for ZZ Ceti variables, multiple periodicities are present on both nights and the period structure of the star can change on a time scale of 2 days. In the first run, Fourier analysis shows a multiperiodic low-frequency spectrum, while on the second run, the low-frequency spectrum is dominated by an ~1800 s period, which is the longest period ever observed in a ZZ Ceti white dwarf. A high-frequency peak of variable amplitude corresponding to a period of 120 s is present in both runs as well. The time variability of the period structure is interpreted as interaction between pulsation modes, as is seen in other ZZ Ceti variables.

Subject headings: stars: individual (GD 165) — stars: pulsation — stars: white dwarfs

I. INTRODUCTION

Recently, Bergeron *et al.* (1990) have completed the analysis of a sample of 37 cool ($T_e < 13{,}000$ K) DA white dwarfs. Spectra obtained with the Steward Observatory 2.3 m reflector were used to determine effective temperatures, surface gravities, and especially helium abundances for all objects. Because helium becomes spectroscopically invisible below $T_e \sim 13{,}000$ K, its presence must be inferred from pressure effects exerted on the profiles of high Balmer lines. Since the gravitational settling time scale for helium and other heavy elements at these low effective temperatures is of the order of 10^1–10^3 yr (Paquette *et al.* 1986), in the absence of any competing mechanisms, DA white dwarfs are expected to have pure hydrogen atmospheres. The spectroscopic analysis of Bergeron *et al.*, however, has shown that the atmospheres of most cool DA white dwarfs below 12,000 K are contaminated by large amounts of helium. In several objects (e.g., G1–7, G67–23, PG 1237−028, GD 25, G117–25), helium is even the dominant constituent [$N(\mathrm{He})/N(\mathrm{H}) > 1$]. The presence of helium has been interpreted as evidence for convective mixing between a thin, superficial hydrogen layer with a deeper, more massive helium layer. The analysis also demonstrates the existence of a unique mixing temperature around $T_e \sim 11{,}500$ K for all objects. This last result is in complete agreement with the observed red edge of the ZZ Ceti instability strip and reinforces the suggestion of Winget and Fontaine (1982) that convective mixing of the stratified hydrogen and helium layers in the envelopes of DA stars could return these stars to stability. Furthermore, the spectroscopic sample included two well-known ZZ Ceti white dwarfs (GD 66 and G238–53). The analysis has shown that both stars have effective temperatures higher than $T_e \sim 11{,}500$ K and, most importantly, that they have pure hydrogen atmospheres. This result is consistent with our current understanding that ZZ Ceti white dwarfs represent an evolutionary phase *prior* to convective mixing.

In the Bergeron *et al.* sample, one other object, GD 165 (WD 1422+095, L1124-10), was found to have atmospheric parameters similar to other ZZ Ceti white dwarfs, namely, an effective temperature near 13,000 K and a pure hydrogen atmosphere (see also Daou *et al.* 1990). Since the pulsating ZZ Ceti stars represent an evolutionary phase through which *all* DA stars are expected to evolve in the course of their cooling (Fontaine *et al.* 1982; Greenstein 1982), the atmospheric parameters determined by Bergeron *et al.* (1990) indicate that GD 165 should also be a pulsating DA white dwarf. Previous attempts by McGraw (1977) had failed to detect any significant variability in the light curve of GD 165. However, the new spectroscopic evidence has led us to take a closer look at this bright ($V = 14.3$) DA white dwarf. We report in this *Letter* the discovery that GD 165 is indeed a ZZ Ceti variable.

II. OBSERVATIONS AND ANALYSIS

High-speed photometry of GD 165 was obtained on 1989 May 8 and 10 UT, using the Catalina single-channel photon-counting photometer attached to the Mount Lemmon 1.5 m telescope. This photometer includes an offset guider and was used with an RCA 31034A photomultiplier tube. As this was our first experience with this telescope for high-speed photometric observations, prior to observing we visually checked for periodic drive errors and found none, with an upper limit peak-to-peak amplitude of 2″. Nonetheless, relatively large apertures of 25″.6 and 34″ were used to minimize any possible drive or guiding errors. On the first night, no optical filter was used, but on the second night a $CuSO_4$ filter was inserted to enhance the signal-to-noise ratio of the blue star relative to sky. The nights on which we observed GD 165 appeared photometric, and virtually continuous offset guiding on a nearby field star ensured that GD 165 remained centered in the aperture to within 2″. Seeing was estimated as 2″–3″ on both nights. The journal of observations is presented in Table 1.

Our observing procedure was to observe GD 165 continuously but to move the telescope to the same nearby blank field position to sample the sky brightness. The sky was sampled every 1500–2000 s for approximately three complete integrations or about 15–30 s of time. In reducing the light curves, a spline-interpolated sky curve was subtracted from

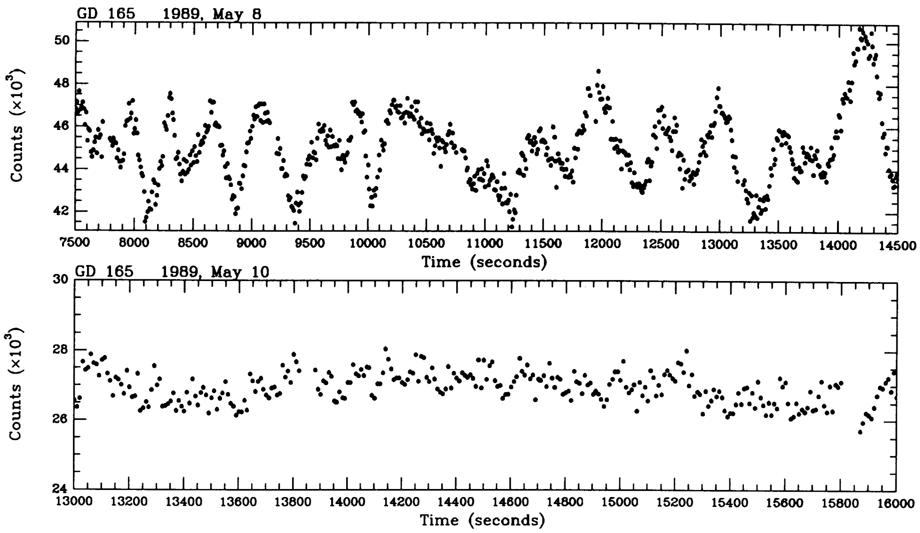

FIG. 1.—Portions of the light curves of GD 165 for our two independent runs. In both panels, each point represents a 10 s integration. The difference in the mean counts of both light curves is due to the use of a $CuSO_4$ filter on the second night.

each light curve. Portions of the resulting light curves obtained on the two nights, approximately corrected for atmospheric extinction using a spline fit to the data, are displayed in Figure 1. A simple examination of the entire light curve shows that GD 165 can exhibit variations larger than 0.1 mag, but at other times can have an amplitude much less than this. A typical time scale of variation is 500 s.

Power spectral analysis of the light curves was done to investigate the period structure in more detail. The power spectra of the two runs are shown in Figure 2. High resolution in the power spectrum results from the long observing time of several hours. The peak at 9 mHz corresponds to an artificial signal introduced to calibrate each spectrum and represents 1% of the mean amplitude. The high-frequency portion ($f > 10$ mHz) of the power spectra of both light curves is completely featureless up to the Nyquist frequency and is not displayed in Figure 2. To ensure that the sky subtraction has not introduced any significant period structure, we have also performed the Fourier analysis on the raw light curves and found no significant differences in the power spectra.

The power spectrum of GD 165 can change dramatically on a time scale of only 2 days. In the first run, the power spectrum is dominated by many low-frequency peaks with amplitudes of the order of 1%. Except for a peak at 8.3 mHz (120 s), no significant peaks are found at frequencies larger than 5 mHz. In the second run, most of these low-frequency peaks have disappeared, and the low-frequency portion of the Fourier spectrum is almost completely dominated by a single peak at 0.55 mHz (1820 s), which can readily be identified in the light curve. This periodicity in the light curve of GD 165 is the longest ever observed in a ZZ Ceti white dwarf. The previous longest period is 1186 s, found in GD 154 (Robinson *et al.* 1978). Several higher frequency peaks at 0.76, 1.15, 1.29, 1.54, 4.17, and 8.31 mHz (periods of 1316, 870, 775, 649, 240 and 120 s, respectively) are found in common in both runs, although at different amplitudes. Some of the peaks are probably harmonics of more fundamental frequencies, but the absence of simple integer relationships among them suggests that most of them are independent modes. We note also that

TABLE 1

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Date (1989 UT)	Integration Time (s)	Filter	Aperture	Total Observing Time (s)
May 8……	5	Clear	25″6	14570
May 10……	10	$CuSO_4$	34.0	24670

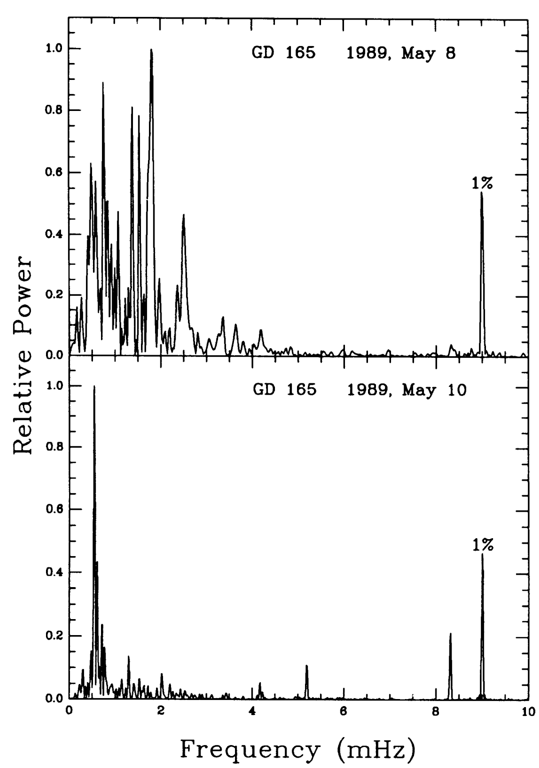

FIG. 2.—Power spectra of GD 165 derived from the two light curves. The peak at 9 mHz corresponds to an artificial signal introduced to calibrate the spectrum and represents 1% of the mean amplitude.

the 8.31 mHz peak has increased in amplitude in the second run, and a significant peak at 5.20 mHz (193 s) has emerged.

III. DISCUSSION

According to temperature-sensitive photometric colors quoted in McCook and Sion [1987; $(B-V) = +0.14$, $(b-y) = +0.065$], GD 165 is located near the blue edge of the ZZ Ceti instability strip (Fontaine *et al.* 1985), in agreement with the effective temperature determined independently from spectroscopy (Daou *et al.* 1990). The spectroscopic and photometric integration times thus far used for GD 165 have not been long enough to properly average over one full pulsation cycle. Therefore, the effective temperature determined from both analyses is probably not correctly time-averaged. In particular, the estimated temperature is at odds with the period-luminosity trend observed in other ZZ Ceti stars as discussed by Winget and Fontaine (1982) and more recently by Wesemael, Lamontagne, and Fontaine (1986). The trend is such that the hotter objects tend to have shorter dominant periods. Our discovery of a mode with a period of ~ 1820 s in a star which is apparently near the empirical blue edge of the ZZ Ceti instability strip certainly is at variance with this trend. As mentioned, however, properly time-averaged spectroscopic and photometric data are required if this single exception to the period-luminosity trend for ZZ Ceti stars is to be confirmed.

The light curves obtained on GD 165 show a highly variable period structure. Because we observed with a single-channel photometer, we must consider the fact that atmospheric transparency variations contributed to the structure in the light curve. While we cannot fully discount this possibility, the nights appeared photometric, and care was taken during offset guiding to ensure that the star remained well centered in a relatively large aperture. We have also checked for the presence of a nearby faint companion to GD 165 which, if placed on the edge of our aperture, could have modulated the light curve. The nearest star appears on the POSS E print and lies $\sim 60''$ from GD 165, which is about 4 times the radius of our largest aperture. This star, near the limit of the POSS print, is incapable of producing modulation of 10% of the mean light, as observed. The possible brown dwarf companion to GD 165 recently discovered by Becklin and Zuckerman (1988) is but $5''$ away, was always fully contained in our aperture, and is too faint to produce the modulation amplitude observed. Additionally, the data on May 8 and 10 UT were obtained using two different data acquisition systems. The first run was obtained using the standard Catalina Photometer data acquisition system; the second, with a system developed at the University of Texas and used in the Whole Earth Telescope (WET) campaign (Nather 1989).

The power spectra derived from the two runs are different from each other, principally in that the spectrum from the first night's run contains much more low-frequency power in the range 0–5 mHz. The low-frequency period structure is far simpler in the second run. Time-dependent power spectra are, however, common among ZZ Ceti stars. Variable power spectral features, but with smaller amplitudes, have been reported, for example, in G185–32 (McGraw *et al.* 1981), where spectral peaks have been observed to change in both amplitude and frequency from run to run. For G185–32 the effect was attributed to one or more of (1) real changes in the period structure of the star, (2) beating effects between closely spaced pulsation modes, or (3) nonlinearity of the pulsations.

At higher frequency, a peak at about 8.3 mHz is present in both runs on GD 165. This peak has variable amplitude, but it is present even when the light curve is relatively quiescent. For historical reasons, this periodicity requires discussion. In 1977, this star was reported to be constant (McGraw 1977). This claim was based upon three photometric observations obtained with the 0.7 m telescope at Sutherland, South Africa. The first run had a duration of about 5200 s, while the latter two had lengths of about 2700 s and 2000 s. Spectral analysis of the first run showed low-frequency power and a significant peak at 8.3 mHz (120 s period). The subsequent two runs also showed this peak. Even in the presence of these significant results, the star was declared constant because the rotation period of the worm gear in the telescope drive was 2 minutes, a period which appeared in four other light curves among the 27 light curves obtained during 1975–1976 on the basis of which the stars were declared nonvariable. The absence of low-frequency variations in the two shorter runs is marginally consistent with McGraw having observed GD 165 during episodes of destructive interference (beating) among multiple pulsation modes. The presence of the 120 s periodicity, which recurs in our present data, we interpret as a potentially real signal, but we point out the difficulty in discovering and confirming periods in a perfectly legitimate period range for which there are potential external causes.

New data for other ZZ Ceti candidates have recently been obtained with this same telescope but using the three-channel photometer of the WET campaign which allows simultaneous monitoring of two stars while continuously guiding on an offset field star. In more than 10 light curves which we acquired with this instrument, we never found a periodicity of 120 s. We did, however, discover peaks at 240 s in some light curves, especially those of field stars very far off-axis which were somewhat vignetted. This period corresponds to the 4 minute rotation period of the worm gear in the drive of the Mount Lemmon 1.5 m telescope.

We conclude that this star is indeed a ZZ Ceti variable, though the period structure of this star will take additional work to define. The case of GD 165 represents the first prediction of the variability of a DA white dwarf from a spectroscopic determination of the effective temperature and atmospheric abundance. This confirmation of that prediction indicates that our global picture of the cessation of pulsations at the onset of convective mixing when the layered H/He structure of these stars is perturbed is essentially correct. The discovery of pulsations in GD 165 strengthens our confidence in both (1) our current understanding of the evolutionary status of ZZ Ceti white dwarfs and (2) the spectroscopic diagnostics developed by Bergeron *et al.* (1990) to infer the atmospheric abundances of cool DA white dwarfs.

The discovery of pulsations in this star takes on additional interest because GD 165 is the possible companion to a brown dwarf star. Recently, Becklin and Zuckerman (1988) have discovered a low-temperature companion to GD 165, which has been identified as a brown dwarf candidate. The object has been resolved with very sensitive infrared imaging techniques. Their result indicates that the brown dwarf companion is located about 120 AU from the white dwarf, with an estimated effective temperature of ~ 2100 K and a mass between 0.06 and 0.08 $M_{\odot}$. At such a large distance, with a corresponding orbital period of ~ 1600 yr, it is very unlikely that the brown dwarf has any observable effects on the period structure of GD 165. It is also interesting to note that GD 165 represents the second

ZZ Ceti white dwarf to have a possible brown dwarf companion. The first one, G29–38, was reported by Zuckerman and Becklin (1987) on the basis of a photometric infrared excess relative to a single white dwarf energy distribution.

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REFERENCES

Becklin, E. E., and Zuckerman, B. 1988, *Nature*, **336**, 656.
Bergeron, P., Wesemael, F., Fontaine, G., and Liebert, J. 1990, *Ap. J. (Letters)*, **351**, L21.
Daou, D., Wesemael, F., Bergeron, P., Fontaine, G., and Holberg, J. B. 1990, *Ap. J.*, submitted.
Fontaine, G., Bergeron, P., Lacombe, P., Lamontagne, R., and Talon, A. 1985, *A.J.*, **90**, 1094.
Fontaine, G., McGraw, J. T., Dearborn, D. S. P., Gustafson, J., and Lacombe, P. 1982, *Ap. J.*, **258**, 651.
Greenstein, J. L. 1982, *Ap. J.*, **258**, 661.
McCook, G. P., and Sion, E. M. 1987, *Ap. J. Suppl.*, **65**, 603.
McGraw, J. T. 1977, *Ap. J. (Letters)*, **214**, L123.
McGraw, J. T., Fontaine, G., Dearborn, D. S. P., Gustafson, J., Lacombe, P., and Starrfield, S. G. 1981, *Ap. J.*, **250**, 349.
Nather, R. E. 1989, in *IAU Colloquium 114, White Dwarfs*, ed. G. Wegner (New York: Springer), p. 109.
Paquette, C., Pelletier, C., Fontaine, G., and Michaud, G. 1986, *Ap. J. Suppl.*, **61**, 197.
Robinson, E. L., Stover, R. J., Nather, R. E., and McGraw, J. T. 1978, *Ap. J.*, **220**, 614.
Wesemael, F., Lamontagne, R., and Fontaine, G. 1986, *A.J.*, **91**, 1376.
Winget, D. E., and Fontaine, G. 1982, in *Pulsations in Classical and Cataclysmic Variable Stars*, ed. J. P. Cox and C. J. Hansen (Boulder: University of Colorado), p. 46.
Zuckerman, B., and Becklin, E. E. 1987, *Nature*, **330**, 138.

Note added in proof.—Recent observations obtained by P. Bergeron, G. Fontaine, J. T. McGraw, and R. L. Lamontagne in 1990 January using the Montreal three-channel photometer have confirmed the variability of GD 165, in particular the 120 s and 193 s periods.

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