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GD 385: A NEW ZZ CETI VARIABLE

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ABSTRACT

We report the discovery of a new ZZ Ceti variable, GD 385, thus increasing the number of stars belonging to this class to a total of 13. On time scales of a month the luminosity variations of this star are dominated by a single period of about 256 s; however, the light curve may abruptly change its character on time scales on the order of days. Variations have, on several occasions, been virtually undetectable during an entire night's observing run. This behavior cannot be explained in terms of simple beating phenomena. We suggest that nonlinear coupling of pulsational energy among a large number of nonradial *g*-modes may account for the photometric behavior of GD 385.

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

I. INTRODUCTION

The ZZ Ceti stars are single, pulsationally unstable DA white dwarfs which occur in the restricted temperature range from about 10,500 K to 13,500 K on the white-dwarf cooling sequence. Their observational properties have recently been reviewed by Robinson (1979). The onset of pulsational instability in these stars is an evolutionary effect, analogous to that operating in Cepheid variables—as a DA white dwarf cools, it eventually enters the temperature range in which the variables occur. This temperature range is associated with the maximum of hydrogen opacity for white dwarfs (cf. Weidemann 1971), leading to the suggestion that a partial ionization zone mechanism is responsible for the pulsational instability of these stars (McGraw 1979). Of the DA white dwarfs in this temperature range which have been searched for pulsations, at least 25% are ZZ Ceti variables (Robinson 1979).

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Analysis of the light curves of the ZZ Ceti stars shows that these objects are multiperiodic variables with principal periods which occur in the approximate range 190–1200 s. The amplitudes of the variables range from about 0.01 to greater than 0.30 mag. The low-amplitude variables, those with $\Delta m \lesssim 0.1$, tend to have fewer and shorter periods. The large-amplitude variables, however, tend to have light curves which are complicated by the presence of harmonics of primary pulsation modes and nonlinear coupling between modes (McGraw 1978). The light curves of virtually all ZZ Ceti stars have power spectra that show frequency and amplitude variations. Beating between closely spaced pulsational frequencies has been successfully invoked to explain the nonstationary nature of the power spectrum of the light curve of R548 (Robinson, Nather, and McGraw 1976) and BPM 30551 (McGraw 1977*a*). For BPM 31594 (McGraw 1976) and GD 154 (Robinson *et al.* 1978), however, abrupt changes in the light curve were observed, and these cannot be explained in such simple terms.

In the present paper, we announce the discovery of a new ZZ Ceti variable. The new variable, GD 385 (L1357−4 = GR 394), shows a light curve that is

dominated by a single period during long intervals of time. However, drastic changes in the period structure and pulsation amplitude have also been observed in this star over time scales of the order of days. The pulsations may even completely disappear below detectability for several hours. Our observations of this star are presented in § II, where we also discuss the changing character of its light curve. In § III, we offer a tentative explanation for this behavior.

II. OBSERVATIONS AND ANALYSIS

In an effort to improve on the statistics of ZZ Ceti variables, we have embarked on a search program that complements the broader surveys that are based on Johnson *UBV* colors (cf. McGraw 1977*b* and Hesser, Lasker, and Neupert 1979). The present sample of stars makes use of Greenstein's (1976) multichannel color observations of white dwarfs. Greenstein's color index $G-R$ has been used as the effective temperature indicator for hydrogen-rich white dwarfs; therefore, our search concentrates on DA stars within a restricted range of $G-R$.

As part of this survey, GD 385 was found to be variable. Extensive observations of this star, spanning more than two observing seasons, were obtained at six different observatories. GD 385 was observed on two nights with the University of Western Ontario 1.22 m telescope, two nights with the Mount Wilson 1.52 m telescope, 10 nights with the McDonald Observatory 0.91 and 2.09 m telescopes, one night with the Multiple Mirror Telescope on Mount Hopkins, three nights with the Mont Mégantic 1.60 m telescope, and two nights with the Palomar 1.52 m telescope. The details of each run are given in Table 1. The McD data were obtained with the McDonald two-star photometer (Nather 1973), and the MP data with the Palomar star-sky photometer. The other observations were obtained with single-channel photometers. The various photomultipliers have either S-11, S-20, or bi-alkali responses. All runs were obtained in "white light," that is, with no optical filters. Additional observations by one of us (J. T. M.) have shown that GD 385 has Johnson's color indices $B-V=+0.19$, $U-B=-0.68$, which are quite typical of ZZ Ceti stars.

During 15 runs the light curve exhibited a periodic behavior with a period of about 256 s. All these light curves were quite similar to that of run 2287 shown in Figure 1. The light curve shows sharp maxima and broad minima and has a peak-to-peak amplitude of about 0.05 mag which appears to be constant. The low-frequency part of the Fourier spectrum of run 2287 is shown in Figure 2. To a Nyquist frequency of 167 mHz, corresponding to a period of 6 s, the power spectrum is flat except for two peaks at about 3.9 and 7.8 mHz. The peak at 9 mHz corresponds to an artificial signal inserted into the data string at a frequency with essentially no power from the star. It has an amplitude of 1% of the mean intensity of the star and, thus, calibrates the power axis. The measured FWHM of the three peaks corresponds exactly to the calculated resolution ($R=0.21$ mHz) which is determined by the length of the run. This implies that, to within spacings $\sim\frac{1}{2}R$, the spectral lines are not blends of closely spaced frequencies. Also, it is clear that the 7.8 mHz line is the first harmonic of the 3.9 mHz line, to well within the resolution of the spectrum. The nonsinusoidal appearance of the light curve corresponds to the presence of the harmonic.

TABLE 1

JOURNAL OF OBSERVATIONS OF GD 385

Run Number	Date	Start Time ($JD_{\odot}$ 2,440,000+)	Telescope (m)	Integration Time (s)	Number of Points
UWO20	1977 May 14	3277.860924	UWO 1.22	10	125
UWO26	1977 Jun 9	3303.819212	UWO 1.22	10	480
MW21	1978 Jun 3	3662.846805	MW 1.52	20	504
MW31	1978 Sep 8	3759.651953	MW 1.52	20	413
2287	1978 Sep 9	3760.730262	McD 2.09	5	951
2294	1978 Sep 10	3761.653947	McD 2.09	10	316
2296	1978 Sep 10	3761.754174	McD 2.09	10	338
2299	1978 Sep 11	3762.643716	McD 2.09	5	800
2308	1978 Sep 14	3765.708383	McD 2.09	10	525
LC101	1978 Sep 17	3763.666682	McD 2.09	3	1799
2318	1978 Sep 30	3781.711543	McD 0.91	10	304
LC210	1978 Nov 20	3832.566641	McD 0.91	5	1000
2329	1978 Nov 27	3839.568110	McD 0.91	10	560
2335	1978 Nov 30	3842.549639	McD 0.91	5	682
0020	1979 Jun 25	4049.789018	MMT	1	6390
MM02	1979 Jun 27	4051.702130	MM 1.60	20	210
MP01	1979 Sep 14	4130.721806	MP 1.52	20	224
MP04	1979 Sep 15	4131.667639	MP 1.52	20	364
MM04	1979 Sep 16	4132.566689	MM 1.60	20	210
MM05	1979 Sep 17	4133.530903	MM 1.60	20	112

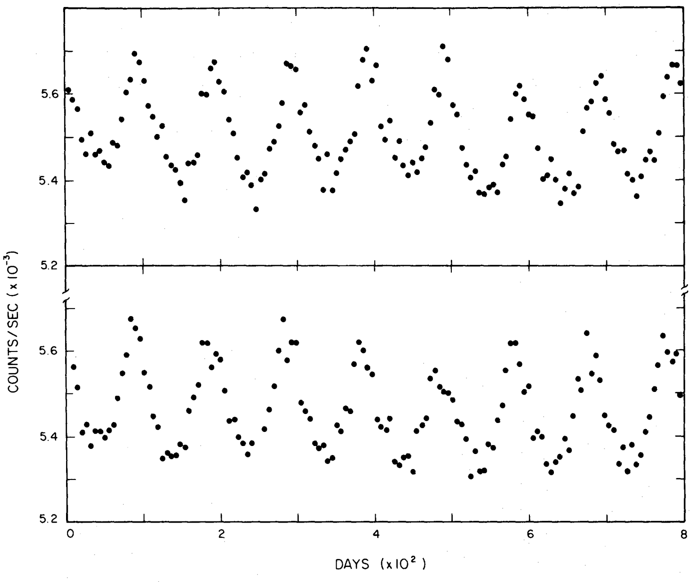

FIG. 1.—The light curve of GD 385, run 2287, expressed in detected photons per s reduced to outside the atmosphere. The light curve is continuous starting at upper left, and each plotted point is the mean of three 5 s integrations.

While GD 385 showed a behavior very similar to that of run 2287 during most of the observing runs, its photometric activity was considerably reduced on at least three occasions: runs MW21, 2335, and MP01. No obvious variability could be seen by direct inspection of these light curves. This was confirmed by the Fourier analysis that was performed for these runs. For example, Figure 3 shows the low-frequency power spectrum of GD 385 for run MP01. The largest peak at 6.8 mHz corresponds to the 1% tracer. Clearly, if the other peaks are at all significant, the variability has reached a considerably lower level of intensity. In effect, the star does not pulsate with any significant amplitude.

At other times, however, the light curve of GD 385 can contain a large number of frequency components of significant power. This was the case in runs UWO26 and MM02. Along with the 3.9 mHz frequency, several other frequencies were also excited with large amplitudes. Although the spectra of runs UWO26 and MM02 are quite different, several frequencies are common to both. Thus the new ZZ Ceti star GD 385 appears to have at least three "states": (1) most of the time its luminosity variations are dominated by a single frequency around 3.9 mHz; (2) the star may stay quiet for a few hours or more; or (3) it may pulsate with several frequencies excited in a manner quite typical of large amplitude ZZ Ceti stars.

We have summarized our spectral analysis of 18 runs in Figure 4, where we show the power of the largest peaks for each run versus the frequency. The vertical axis of each panel has been calibrated in terms of a 1% tracer which has the power indicated in the figure. Thus comparisons can be made directly between various runs. For example, the spectral features of runs MW21, 2335, 0020, and MP01 all have

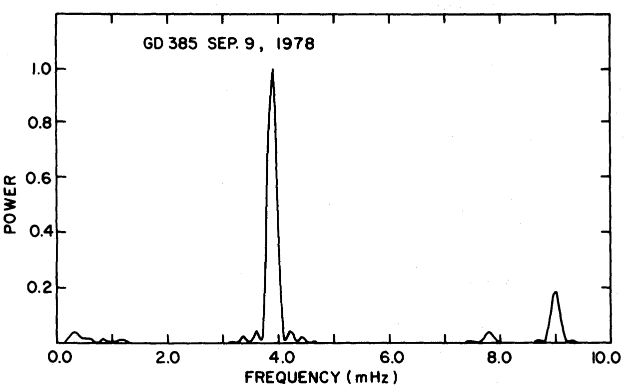

FIG. 2.—Low-frequency power spectrum of run 2287. The high-frequency part does not show spectral features with any significant power. The peak at 9 mHz is a tracer with an amplitude of 1% of the mean intensity of the star.

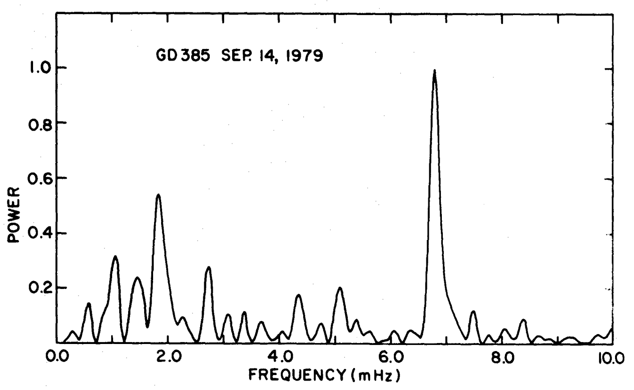

FIG. 3.—Low-frequency power spectrum of run MP01. The 1% tracer at 6.8 mHz completely dominates the spectrum, indicating low photometric activity.

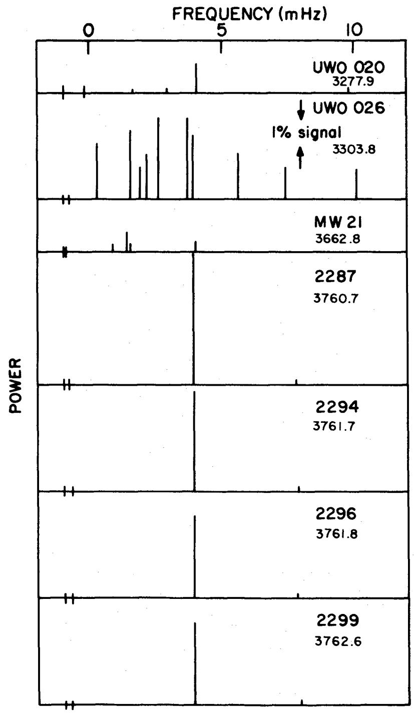

FIG. 4*a*

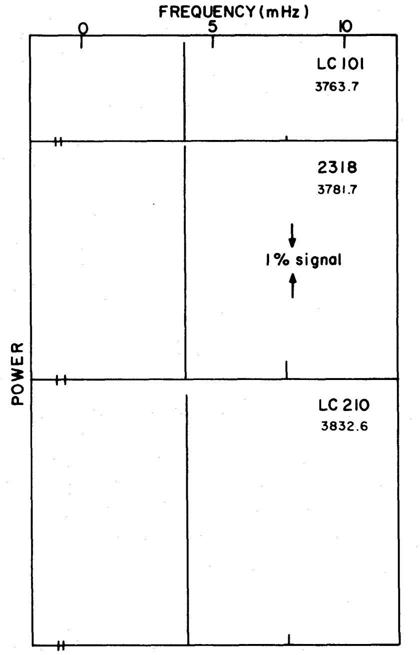

FIG. 4*b*

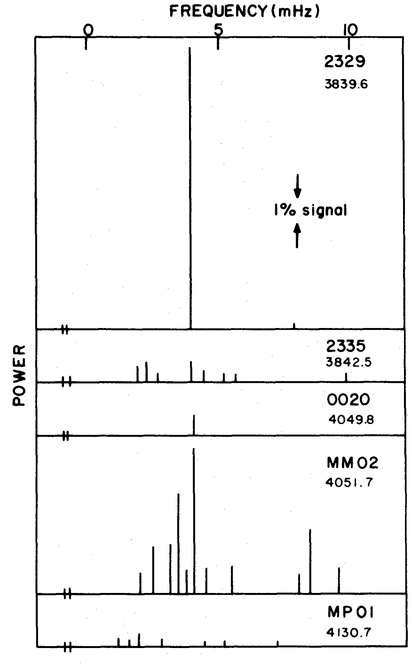

FIG. 4*c*

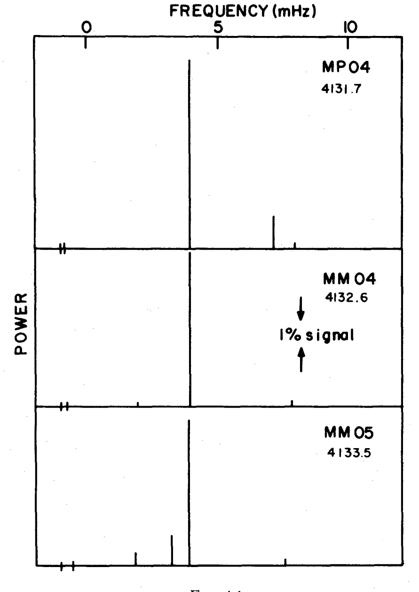

FIG. 4*d*

FIG. 4.—Schematic Fourier spectra of 18 runs. The power is represented by a vertical bar at the appropriate frequency. All panels have been calibrated with respect to a 1% signal which has the amplitude indicated by the vertical arrows. Only the largest peaks have been plotted. The two small vertical bars on the left-hand side give the resolution.

amplitudes that are less than the 1% tracer, indicating low photometric activity. By contrast, run 2329 shows the peak with the largest power.

We have also searched for common frequencies in the various runs and calculated for each of these frequencies one-half the peak-to-peak amplitude in magnitudes, Δm, which can be expressed for GD 385 as

$$\Delta m = 2.5 \log \left\{ 1 + \left[1.01 \times 10^{-4} \frac{P}{P(\mathrm{sig})} \right]^{1/2} \right\}, \quad (1)$$

where P and P(sig) are, respectively, the power of a spectral feature and the power of the 1% signal as given in Figure 4. The results are given in Table 2, where the resolution R of each run is also listed. The most common frequency is around 3.9 mHz; this single frequency completely dominates the power spectrum of GD 385 for most of the runs. Its first harmonic at 7.8 mHz is also frequently present. Beside those two, six other frequencies are also found to correlate between some of the runs. This is more than coincidence and must be taken as an indication that these modes are preferably excited in the various pulsational states of GD 385. These additional frequencies tend to be harmonics and linear combinations of the two or three frequencies containing the most power. This effect has been previously noted to occur in several intermediate to large amplitude ZZ Ceti variables (McGraw and Robinson 1975; Robinson and McGraw 1976; McGraw 1978).

III. DISCUSSION

Our observations show that the period structure of GD 385 can change dramatically on short time scales, on the order of days. For example, from 1978 September 9 to November 27 (9 runs) the power spectrum of the light curve stayed remarkably stable, being dominated by a single peak at 3.9 mHz (see Fig. 4). Over this period of time we derived a value of $Q \gtrsim 10^7$, indicating that this frequency was very stable. The power represented by the peak varied somewhat, but was always greater than 0.02 mag (cf. Table 2). Three days later, however, the star appeared to have virtually stopped varying with detectable amplitude. During run MP01 the star did not show luminosity variations and would have been classified as "constant" had it been observed on this occasion only. During runs obtained on the three succeeding nights, however, the star had returned to its state of nearly sinusoidal oscillations at a frequency of 3.9 mHz with $\Delta m \gtrsim 0.025$.

This behavior cannot be explained solely in terms of simple beating phenomena that occur in some of the other ZZ Ceti stars. If the process producing the changes in the period structure of GD 385 were a beat mechanism, we should have seen appreciable amplitude modulation of the spectral feature at 3.9 mHz both before and after the "quiet" phase. Further,

TABLE 2

COMMON FREQUENCIES IN THE POWER SPECTRA OF GD 385

$JD_\odot$ (2,440,000+)	Run	R (mHz)	f (mHz)	Δm (mag)
3277.9	UWO20	0.80	4.053	0.011
3303.8	UWO26	0.21	3.906	0.017
3662.8	MW21	0.10	4.028	0.007
3760.7	2287	0.21	3.906	0.024
3761.7	2294	0.32	3.906	0.021
3761.8	2296	0.30	3.900	0.019
3762.6	2299	0.25	3.912	0.019
3763.7	LC101	0.19	3.910	0.021
3781.7	2318	0.33	3.900	0.032
3832.6	LC210	0.20	3.925	0.033
3839.6	2329	0.18	3.906	0.035
3842.5	2335	0.30	3.906	0.009
4049.8	0020	0.16	3.906	0.009
4051.7	MM02	0.24	3.967	0.025
4130.7	MP01	0.22	4.053	0.002
4131.7	MP04	0.14	3.967	0.029
4132.6	MM04	0.24	3.906	0.026
4133.5	MM05	0.45	3.845	0.025
			⟨3.933⟩	
3277.9	UWO20	0.80	1.611	0.005
3303.8	UWO26	0.21	1.563	0.018
3662.8	MW21	0.10	1.538	0.007
4130.7	MP01	0.22	1.453	0.005
			⟨1.541⟩	
3303.8	UWO26	0.21	1.880	0.012
3842.5	2335	0.30	1.850	0.009
4051.7	MM02	0.24	1.868	0.010
4130.7	MP01	0.22	1.831	0.008
4132.6	MM04	0.24	1.941	0.005
4133.5	MM05	0.45	1.831	0.008
			⟨1.867⟩	
3303.8	UWO26	0.21	2.588	0.019
3842.5	2335	0.30	2.588	0.006
			⟨2.588⟩	
3303.8	UWO26	0.21	3.687	0.019
4051.7	MM02	0.24	3.638	0.010
			⟨3.663⟩	
3842.5	2335	0.30	4.346	0.007
4051.7	MM02	0.24	4.419	0.011
4130.7	MP01	0.22	4.346	0.005
			⟨4.370⟩	
3303.8	UWO26	0.21	5.615	0.014
3842.5	2335	0.30	5.566	0.006
			⟨5.591⟩	
3277.9	UWO20	0.80	7.813	0.003
3760.7	2287	0.21	7.796	0.005
3761.7	2294	0.32	7.837	0.005
3761.8	2296	0.30	7.806	0.004
3762.6	2299	0.25	7.916	0.005
3763.7	LC101	0.19	7.800	0.005
3781.7	2318	0.33	7.751	0.009
3832.6	LC210	0.20	7.778	0.007
3839.6	2329	0.18	7.800	0.005
4049.8	0020	0.16	7.813	0.002
4051.7	MM02	0.24	7.935	0.009
4131.7	MP04	0.14	7.935	0.005
4132.6	MM04	0.24	7.788	0.006
			⟨7.829⟩	

there is some evidence in the data (cf. Table 2) that the power at 3.9 mHz is actually greatest in run 2329, the run obtained three days before the pulsation amplitude decreased to an undetectable level. This is, of course, the exact opposite of what we expect of a beat phenomenon operating on a time scale of days. The increase in pulsation amplitude from run 2299 to run 2329 suggests that a "critical amplitude" phenomenon may be involved, and we suggest the following scenario: of the large number of g-modes available in a white dwarf (cf. Cox 1976), because of the specific structure of the envelope of this star, only the mode corresponding to a frequency $f_0 = 3.9$ mHz is initially excited in the driving region. The pulsation amplitude then increases at the growth rate appropriate for this mode. During this phase the star shows the 256 s periodicity corresponding to frequency f_0 as observed in 15 of our runs. At some point the amplitude must be limited by nonlinear effects. In contrast to radially pulsation modes. These additional modes are not directly driven by the exciting region but are simply fed by the f_0 mode. Consequently, the total (constant) pulsation modes. These additional modes are not directly driven by the exciting region but are simply fed by the f_0 mode. Consequently, the total (constant) pulsational energy available in the star is shared by an increasing number of modes. The amplitude of the f_0 mode then decreases and other frequencies begin to show significant power. This may be the phase that we see in runs UWO26 and MM02. Eventually, as the amplitude of the f_0 mode drops below the critical value for nonlinear coupling, the other modes must disappear. At this point the energy may be shared by a very large number of modes, all having low amplitudes. This may correspond to the "quiet" phase of GD 385 represented by runs MW21, 2335, and MP01. As the other modes disappear, the energy may again be pumped into the f_0 mode and the process may repeat.

These suggestions based on our observations of GD 385 are in qualitative agreement with the theoretical discussion of Dziembowski (1979). In particular, for a model with log $T_e = 4.08$, $M = 0.6\ M_{\odot}$, and surface composition $X = 0.7$, $Z = 0.03$, he derives growth rate of $\sim 10^{-6}$ for low-order g-modes with periods of about 200 s. This rate implies that the time necessary for the amplitude of the f_0 mode to increase by about 0.01 mag is about 1 month. This time scale is in remarkable (fortuitous?) agreement with the "growth rate" observed for the f_0 mode of GD 385 during the 1978 September 9 to November 27 interval. Additionally, Dziembowski points out from a theoretical viewpoint that nonlinear coupling between modes should indeed provide the amplitude-limiting mechanism for ZZ Ceti variables and that the coupling time scales should be on the order of 1 day.

If the scenario suggested on the basis of our observational data holds true, the correspondence between the observed time scales and those predicted theoretically assures that GD 385 will be an important variable. For example, if the time scale over which the power spectrum changes considerably corresponds to the growth rate of the pulsation mode, it may be possible to *measure* the complex eigenfrequency of the f_0 mode. Further observations of this star should allow us to follow the time scales of "mode coupling" in detail. These data would be important observational constraints against which to test the theory of nonlinear nonradial stellar pulsations.

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REFERENCES

Cox, J. P. 1976, *Ann. Rev. Astr. Ap.*, **14**, 247.
Dziembowski, W. 1979, *IAU Colloquium No. 53, White Dwarfs and Variable Degenerate Stars*, ed. H. M. VanHorn and V. Weidemann (Rochester, N.Y.: University of Rochester), p. 359.
Greenstein, J. L. 1976, *A.J.*, **81**, 823.
Hesser, J. E., Lasker, B. M., and Neupert, H. E. 1979, *Ap. J. Suppl.*, **40**, 577.
McGraw, J. T. 1976, *Ap. J. (Letters)*, **210**, L35.
———. 1977*a*, *Ap. J. (Letters)*, **214**, L123.
———. 1977*b*, Ph.D. thesis, University of Texas at Austin.
———. 1978, *Proc. 4th Goddard/Los Alamos Conf., Current Problems in Stellar Pulsational Instabilities.*
———. 1979, *Ap. J.*, **229**, 203.
McGraw, J. T., and Robinson, E. L. 1975, *Ap. J. (Letters)*, **200**, L89.
Nather, R. E. 1973, *Vistas in Astronomy*, **15**, 91.
Robinson, E. L. 1979, *IAU Colloquium No. 53, White Dwarfs and Variable Degenerate Stars*, ed. H. M. VanHorn and V. Weidemann (Rochester, N.Y.: University of Rochester), p. 343.
Robinson, E. L., and McGraw, J. T. 1976, *Proc. 3d Los Alamos Conf., Solar and Stellar Pulsations.*
Robinson, E. L., Nather, R. E., and McGraw, J. T. 1976, *Ap. J.*, **210**, 211.
Robinson, E. L., Stover, R. J., Nather, R. E., and McGraw, J. T. 1978, *Ap. J.*, **220**, 614.
Weidemann, V. 1971, *IAU Symposium No. 42, White Dwarfs*, ed. W. Luyten (Dordrecht: Reidel), p. 81.

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