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TWO EXTREME EXAMPLES OF COMPACT PULSATORS: PG 1115+158 AND PG 1351+489

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ABSTRACT

We have discovered pulsations in the helium atmosphere (DB) white dwarfs PG 1115+158 and PG 1351+489 of a character unlike those seen before in any compact pulsators. Although they are typical in many ways, their differences stretch the boundaries of the observed pulsation properties of the compact pulsators.

The peak-to-peak amplitudes of the light curve variations, 0.11 mag for PG 1115+158 and 0.16 mag for PG 1351+489, are similar to those found in the two other known DB pulsators. The light curves of PG 1115+158 on different nights confirm a complexity and a range of periods which strongly resemble those of the previously known DB pulsators, but there is also evidence for periods which are the longest ever observed in a pulsating white dwarf.

In contrast, PG 1351+489 has the simplest light curve of any known variable white dwarf: it is dominated by a single period, 489.5 s and its harmonics. Unlike similar pulsators, essentially all of the observed modulation is confined to this single period, indicating the presence of an extremely efficient filter mechanism of unknown origin. The low frequencies observed in PG 1115+158 are anticipated by current theoretical models; the monoperiodic character of PG 1351+489 is both unanticipated and unexplained.

Subject headings: stars: individual (PG 1115+158, PG 1351+489)—stars: pulsation — stars: white dwarfs

I. INTRODUCTION

Our discovery of pulsations in the helium atmosphere white dwarfs PG 1115+158 and PG 1351+489 (hereafter referred to by the generic term DBV stars; see Sion *et al.* 1983) exploited the theoretical prediction that the He I surface partial ionization zone is responsible for the instability (Winget 1981; Winget *et al.* 1982*b*). This implied that the He I opacities should be near maximum for these stars, and therefore the He I absorption lines should be strong and broad. We used the optical classification spectra of the Palomar Green survey stars (Green, Schmidt, and Liebert 1986) to select DB white dwarfs with extremely broad He I lines for high-speed photometric observation.

We expect that the light curves of DBV stars will be rich with many different pulsation periods. These expectations are based on extensive study of their siblings, the DAV stars (pulsating hydrogen atmosphere white dwarfs, also called ZZ Ceti stars) (see Winget and Fontaine 1982 and references therein). Observationally, only a handful of the possible nonradial gravity modes are excited. As discussed in Winget and Fontaine (1982), the stratified layering of the star provides the needed filter: modes are selected by resonance conditions with both the thicknesses of the surface hydrogen layer and of the underlying helium layer and with the structure of the composition transition zone; the sharpness of the filter increases with the decreasing thickness of a compositional layer.

The DB stars are quite similar to the DAs but lack their thin ($\sim 10^{-4}$–10^{-14} M_*) outer layer of hydrogen. This led Winget *et al.* (1983) to expect that the DBVs would not be as strongly filtered as the DAVs and so would have many more pulsation modes present simultaneously.

The light curves of the first two DBVs discovered are consistent with this expectation, as is that of PG 1115+158. The light curve of PG 1351+489 is not.

Recently, Hansen, Winget, and Kawaler (1985) pointed out that, even including a filter mechanism, there should be long periods (up to 10,000 s) in the light curves of pulsating white dwarfs. No evidence for these has been reported, but our observing techniques (even at present) are not very sensitive to such periods because slow variations in sky brightness and transparency can mimic longer periodicities.

II. THE OBSERVATIONS

PG 1115+158 and PG 1351+489 were classified as DB white dwarfs on the basis of low-resolution SIT spectra (Green, Schmidt, and Liebert 1986). We observed the two objects with a standard McDonald Observatory high-speed, two-star photometer (Nather 1973) on the 2.1 m telescope at McDonald Observatory. All observations were made in unfiltered light using a blue-sensitive RCA 8850 photomultiplier tube. The light curve of the comparison star observed in the second channel of the photometer was used to verify that the sky was photometric but was not otherwise used in the data reduction process. Our reduction procedure has been described by Kepler *et al.* (1982). Table 1 is a summary of our observations.

a) PG 1115+158

The light curves of PG 1115+158 on the nights of 1985 March 22 and 23 (UT) are presented in Figure 1. The general morphology of the light curves is similar to that of the other known DBV stars, GD 358 and PG 1654+160 (Winget *et al.* 1982*a*, 1984): the pulses are sharply peaked with amplitudes of ~0.11 mag, and the light curve does not repeat on any time scale covered by the observations. Winget *et al.* (1982*a*) noted that the amplitudes of the variations in GD 358 were modulated at a period of 5400 s. Our longest run, 3012, suggests a similar effect, with a period of at least 8000 s; this modulation is too long to be resolved in our other runs.

We computed amplitude spectra (the square root of the power spectra) of all our light curves to search for periodicities

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TABLE 1

JOURNAL OF PHOTOMETRIC OBSERVATIONS

Run Number	Date (UT)	Integration Time (s)	Run Length (hr)
PG 1115+158			
2877..........	1984 Feb 6	10	2.9
2879..........	1984 Feb 28	5	1.9
3012..........	1985 Mar 22	10	4.7
3023..........	1985 Mar 24	10	3.0
PG 1351+489			
2957..........	1984 May 6	10	4.3
2958..........	1984 May 6	1	0.22
2961..........	1984 May 7	10	2.6
2962..........	1984 May 7	10	3.9
2976..........	1984 Jun 30	10	3.8
2978..........	1984 Jul 1	10	3.3
2979..........	1984 Jul 2	10	0.9
3006..........	1985 Feb 16	10	4.3
3007..........	1985 Feb 18	10	3.7
3015..........	1985 Mar 22	10	1.4
3019..........	1985 Mar 23	10	6.1
3025..........	1985 Mar 24	10	4.8
3072..........	1985 Jun 15	10	2.0
3077..........	1985 Jun 22	10	1.5
3080..........	1985 Jun 24	10	1.4

in the luminosity variations (Kepler *et al.* 1982). All the significant features in the amplitude spectra were confined to long periods; there were no periodicities present with fractional semi-amplitudes greater than 2×10^{-3} between 20 s and 100 s.

The low-frequency portions of the amplitude spectra of runs 3012 and 3023 on PG 1115+158 are shown in Figure 2. The features do not repeat from night to night, as Winget *et al.* (1984) also noted for PG 1654+160. The amplitude spectra have many peaks, and the shapes of several peaks suggest that they are severely underresolved. It is clear from both runs, however, that there are many significant peaks below 10 mHz and the main power is concentrated toward the lower frequencies, near 1 mHz; this pattern is very similar to both PG 1654+160, and GD 358.

The distinction of PG 1115+158 from the other DBVs—and even from any other pulsating white dwarf—is in run 3012: we see significant power around 0.4 mHz, a uniquely low frequency. Transparency variations can occur on this same time scale, so these peaks individually can be no more than suggestive of real variations in the star. However, this group of peaks has the same uniform frequency splitting exhibited by the group around 1.0 mHz. Similar uniform separation has been seen in at least six DAV stars and one other DBV star (Winget and Fontaine 1982; Winget *et al.* 1982*a*) and is interpreted as the signature of rotational splitting (Cox 1984).

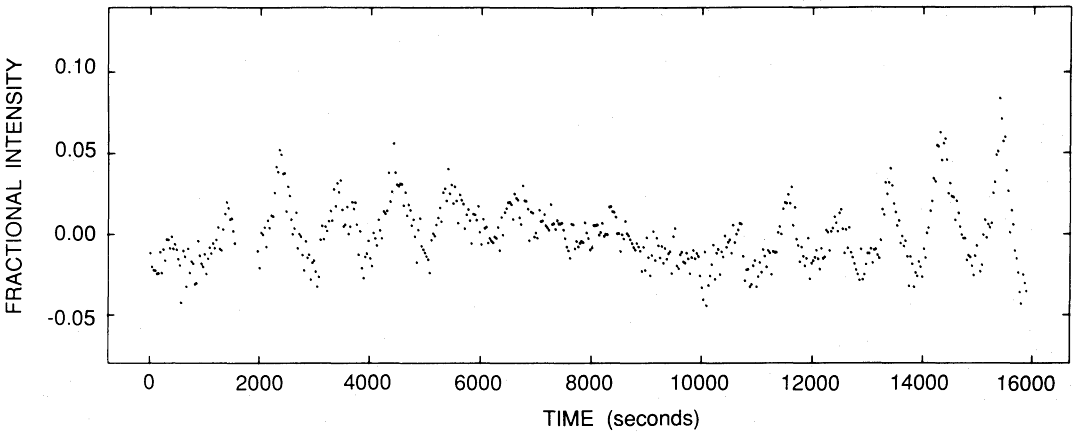

FIG. 1*a*

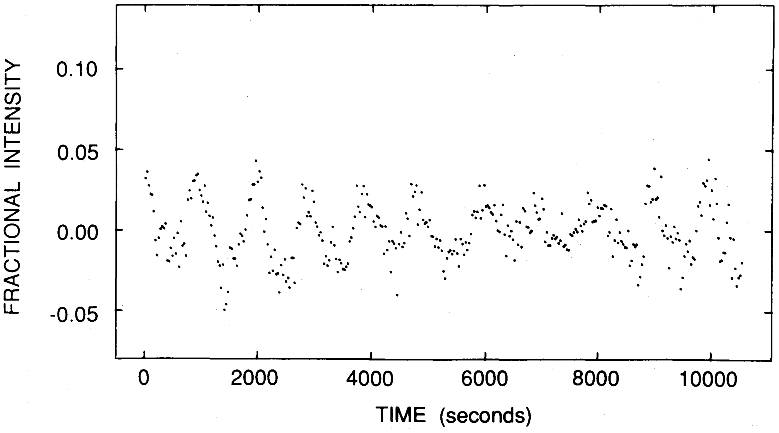

FIG. 1*b*

FIG. 1.—(*a*) PG 1115+158: the light curve from run 3012 on the night of 1985 March 22 (UT). The data were taken in 10 s bins but are displayed in 30 s bins. (*b*) PG 1115+158: the light curve from run 3023 on the night of 1985 March 23 (UT). The data are again displayed in 30 s bins but were taken in 10 s bins.

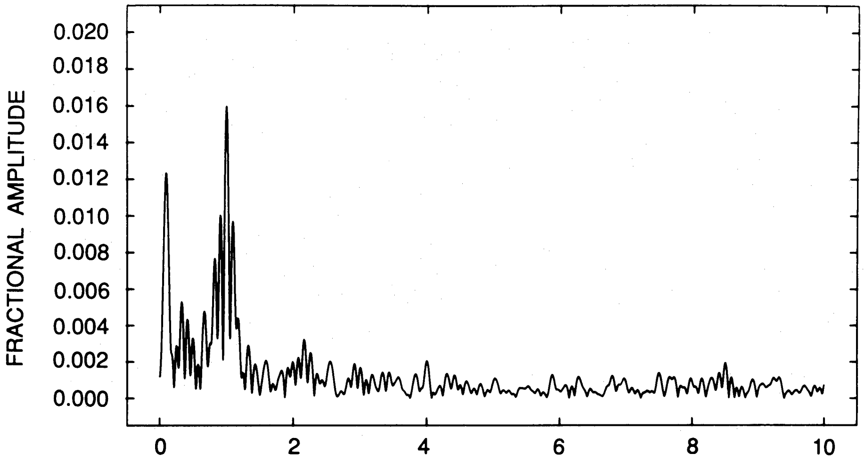

FIG. 2*a*

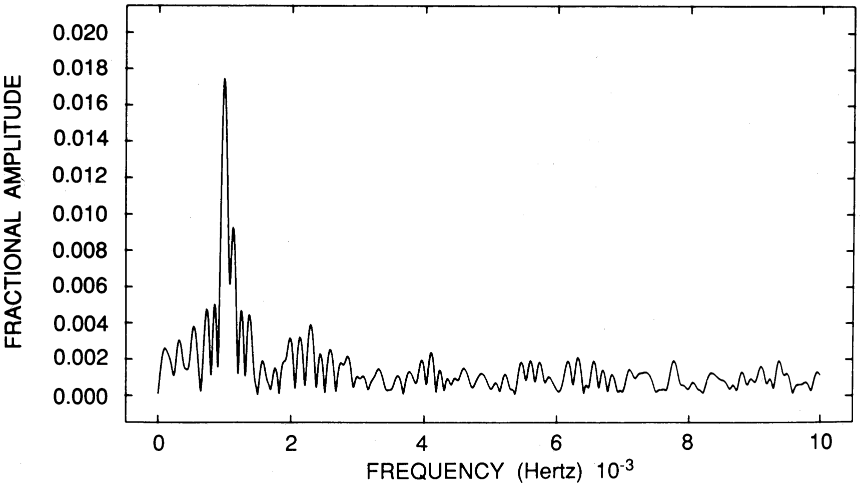

FIG. 2*b*

FIG. 2.—(*a*) PG 1115 + 158: the amplitude spectrum of the light curve from run 3012. (*b*) PG 1115 + 158: the amplitude spectrum from run 3023.

b) *PG 1351+489*

Figure 3 displays portions of the light curve of PG 1351+489 on the nights of 1984 May 6 and 7 (UT). Unlike the other three known DBV stars, the light curve of PG 1351+489 is dominated by a single period of ~490 s. The peak-to-peak amplitude of the pulses is ~0.16 mag, very similar to the maximum amplitudes in the light curves of the other three DBV stars: 0.11 mag in PG 1115+158, 0.18 in PG 1654+160, and 0.30 in GD 358.

Figure 4 shows the amplitude spectra of the light curves from Figure 3. They are remarkably stable; compare them with the average amplitude spectrum (Fig. 5) derived from the seven longest runs available (See Table 1). Unlike those of the other DBVs, its amplitude spectra are unusually simple. They are dominated by a single peak, ν_0, at 489.5 s and its harmonics—the first and second are present well above the noise level. The amplitudes of all these peaks are constant to within the 15%–20% limits imposed by our present observing techniques. The main peak showed an amplitude of 0.06 ± 0.01 in all runs.

Both amplitude spectra also show a peak near 333 s, corresponding to $1.47\nu_0$, and in Figure 4*a* there are also significant peaks at $2.47\nu_0$ and $3.47\nu_0$. All of these small peaks vary in amplitude; the largest, at $1.47\nu_0$, varies from 0.009 mag down to 0.001 mag, our limit of detection. Although all these peaks were not present in all runs, their frequencies were the same whenever they could be detected. It seems most likely that the frequencies are always present, but often fall below the limit of detectability because of their modulation in amplitude.

The unusual stability and simplicity of the light curve of PG 1351+489 allows us to construct an average pulse shape for the variation, by the co-addition of a contiguous series of pulses folded on the pulse period of 489.5 s. We folded all of the data from the seven longest runs to obtain seven individual averages, which we then added together to derive the grand average pulse shape shown in Figure 6. The small, amplitude-modulated periodicities will have no discernable effect on this pulse shape; they are widely spaced in frequency, and sufficient data are available for co-addition so their effects are averaged out. Thus the pulse shape shown in Figure 6 (in which two complete cycles are plotted for clarity) is an accurate description of the periodic luminosity variations in the star. This average pulse is sharply peaked, and takes 70 s (one seventh of a cycle) longer to fall than to rise.

III. DISCUSSION

We now have a total of four known DB variables, and a crude relative temperature sequence for the hot DB white dwarf stars (see Liebert *et al.* 1986). With these observations we can begin to see an outline of an empirical DBV instability strip emerging. The work of Liebert *et al.* (1986) includes all

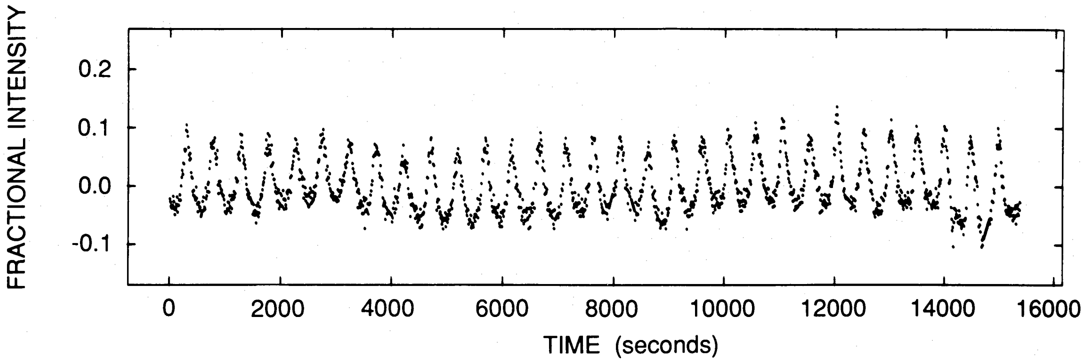

FIG. 3*a*

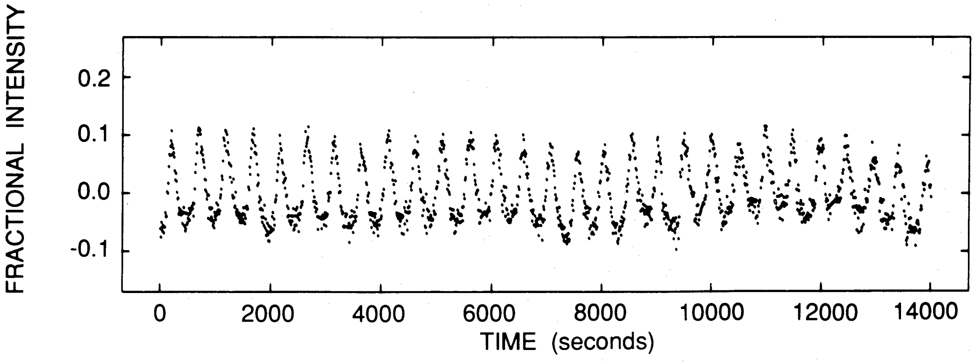

FIG. 3*b*

FIG. 3.—(*a*) PG 1351 + 489: the light curve from run 2957 on the night of 1984 May 6 (UT). The data are in 10 s bins. (*b*) PG 1351 + 489: the light curve from run 2962 on the night of 1984 May 7 (UT). The data are in 10 s bins.

four known DBV stars and six stars with no detectable variability in the range of periods and amplitudes of the other pulsating white dwarfs. These authors have shown that the variables form a homogeneous spectroscopic group clustered between ~25,000 K and 28,000 K[2] near the He I opacity maximum.

Of the four known DB variables, three show the pulsational behavior expected from the simple theoretical models of Winget *et al.* (1983). These models were constructed with the assumption that the helium-atmosphere white dwarfs are just like their hydrogen-atmosphere counterparts but with the thin outer layers of hydrogen removed. This implies that the resonance effects (due to mode trapping) which arise from the presence of thin outer envelope layers will not be nearly as important for the DBV stars since the surface helium layers should be thicker than the hydrogen layers (Winget and Fontaine 1982). In turn, this implies that the filter mechanism in the DBV stars will have a broad " bandpass " and a wealth of periods should be present. This is in agreement with the observations for three of the four DBV stars.

In addition, the light curve of PG 1115 + 158 gives evidence for longer period pulsations than previously seen in white dwarfs. These peaks around 0.4 mHz are expected by theory (Hansen *et al.* 1985) but are not easily detected with our present observing techniques. Only the characteristic signature of rotational splitting—the repeat of a uniform frequency splitting seen in a higher frequency group—gives weight to their presence in the star. Only carefully calibrated extended coverage observations from multiple sites can confirm their existence. It is also extremely important to determine if the amplitude spectra of this object and of the other two complex DBV stars can be completely resolved or if they are inherently unstable. The answer must also await extended observations from multiple observing sites—a project now under active pursuit.

The light curve of PG 1351 + 489 clearly show that the photometric properties of the DBVs are not all the same, and therefore the models must be improved to take these differences into account. Its well-defined pulse shape will serve as a motivation to future attempts to construct nonlinear models of the light curves of these objects.

Although PG 1351 + 489 has an amplitude and pulse shape quite typical of all the other DBVs, and the large-amplitude DAV stars as well, the essentially monoperiodic character of its light curve sets it apart from all other pulsating white dwarfs, placing it in sharp contrast with the other DBV stars in particular. Some filter mechanism is acting to enhance the effects of one single period relative to all the others; if the mechanism is due to mode trapping, then it implies that there must be a very thin outer layer in PG 1351 + 489. Spectroscopically, only helium is seen, so this thin outer layer must be helium. Thus the light curve of this object implies that at least some DBs have helium layers considerably thinner than the value of 10^{-2} suggested by pre–white dwarf evolutionary calculations. These helium layers may be very thin compared to those in DA stars, and perhaps they are as thin as the DAs hydrogen layer. This points to a possible difference in the mass loss at the planetary nebular ejection stage between DA and DB stars.

In other ways as well, PG 1351 + 489 seems more like some

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[2] This temperature range is based on the model atmospheres of Wesemael (1981) and the IUE temperature scale as discussed by Liebert *et al.* (1986). If the optical temperature scale of Koester *et al.* (1985, and references therein) is adopted these numbers would be 2000–3000 K cooler.

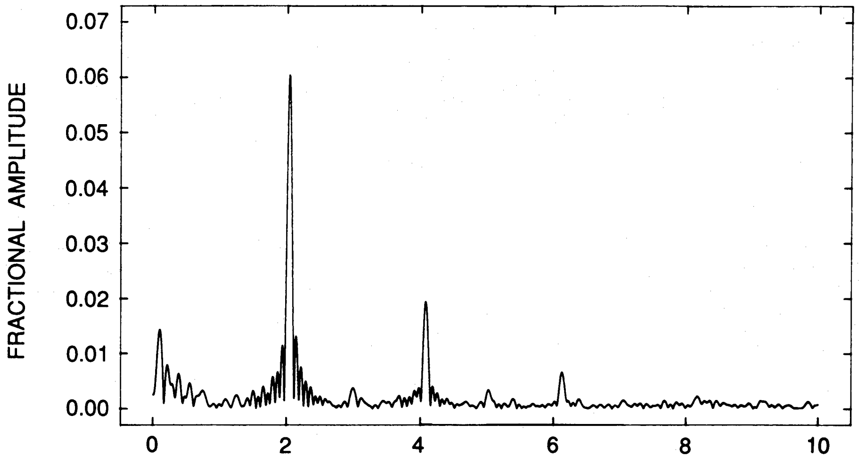

FIG. 4*a*

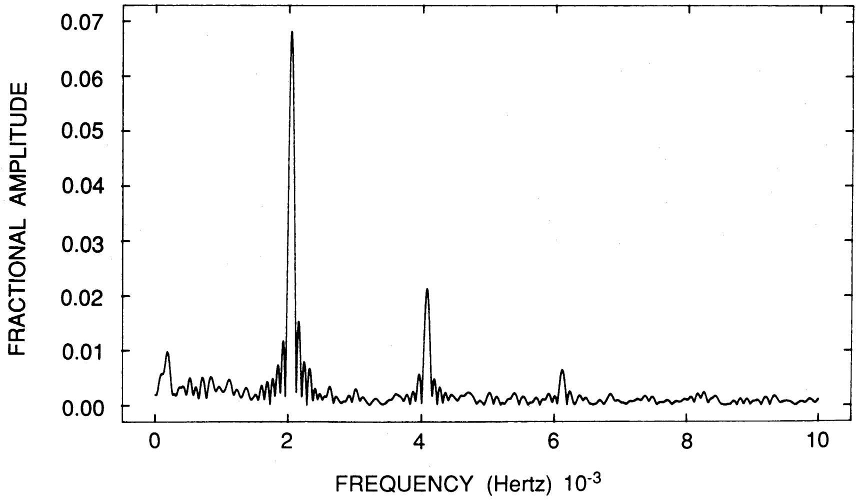

FIG. 4*b*

FIG. 4.—(*a*) PG 1351+489: the amplitude spectrum of the light curve from run 2957. (*b*) PG 1351+489: the amplitude spectrum from run 2962.

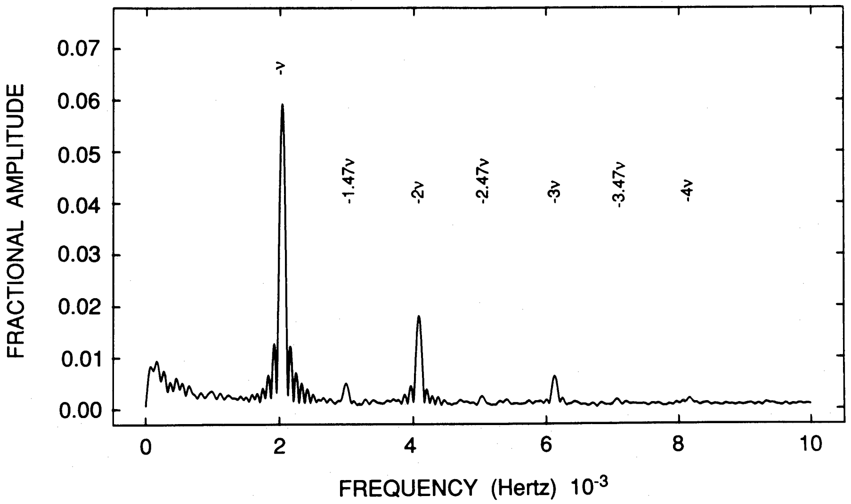

FIG. 5.—PG 1351+489's average amplitude spectrum from the seven longest runs (see Table 1). Each run was truncated to 11,570 s, its power spectrum computed, then all the power spectra were averaged together, and finally the square root of that average power spectrum gave the average amplitude spectrum.

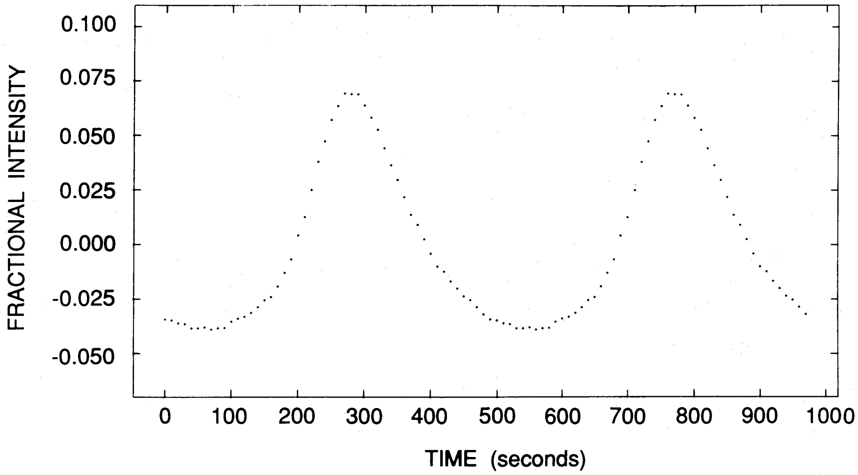

FIG. 6.—PG 1351+489: the average pulse shape. The seven longest runs were folded individually at the 489.5 s period and then averaged together, weighted by the run lengths.

of the DAVs than its DBV siblings. For example, GD 154 (Robinson *et al.* 1978), G 191-16 (McGraw *et al.* 1981), and BPM 31594 (O'Donoghue 1986) exhibt light curves dominated by a single strong periodicity and its harmonics, with much smaller peaks near $1.5^{+}\nu_0$. Periodicities are also detected at $2.53\nu_0$ and $3.53\nu_0$ in GD 154. These similarities may just be a numerological coincidence but more likely reflect an underlying physical connection. Theoretical investigation into the nature of this connection will have to await the adequate development of nonlinear theory to mode-interactions.

PG 1351+489, because of its pulsational simplicity, is a prime candidate to monitor for period stability. The mean time of pulse arrival can be determined, on a single long night's run, to an accuracy of 1 s—sufficiently accurate to require corrections to the data for the motion of the barycenter of the solar system.

We thank Jim Liebert and Richard Green for providing us with finder charts for PG 1115+158 and PG 1351+489 and for help in selecting candidates from the classification spectra. We also thank Matt Wood for his help in taking some of the data and especially for suggesting the average pulse shape measure, and Butler Hine for his help with the data reduction. We thank Carl Hansen and E. L. Robinson for many helpful discussions.

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REFERENCES

Cox, John P. 1984, *Pub. A.S.P.*, **96**, 577.
Green, R. F., Schmidt, M., and Liebert, J. 1986, *Ap. J. Suppl.*, **61**, 305.
Hansen, C. J., Winget, D. E., and Kawaler, S. D. 1985, *Ap. J.*, **297**, 544.
Kepler, S. O., Robinson, E. L., Nather, R. E., and McGraw, J. T. 1982, *Ap. J.*, **254**, 676.
Koester, D., Vauclair, G., Dolez, N., Oke, J. B., Greenstein, J. L., and Wiedemann, V. 1985, *Astr. Ap.*, **149**, 423.
Liebert, J., Wesemael, F., Hansen, C. J., Fontaine, G., Shipman, H. L., Sion, E. M., Winget, D. E., and Green, R. F. 1986, *Ap. J.*, **309**, 230.
McGraw, J. T., Fontaine, G., Dearborn, G. S. P., Gustafson, J., Lacombe, P., and Starrfield, S. G. 1981, *Ap. J.*, **250**, 349.
Nather, R. E. 1973, *Vistas Astr.*, **15**, 524.
O'Donoghue, D. 1986, in *Advances in Helio-Asteroseismology*, ed. D. Grough (Cambridge: Cambridge University Press), in press.
Robinson, E. L., Stover, R. J., Nather, R. E., and McGraw, J. T. 1978, *Ap. J.*, **220**, 614.
Sion, E. M., Greenstein, J. L., Landstreet, J., Liebert, J., Shipman, H. L., and Wegner, G. 1983, *Ap. J.*, **269**, 253.
Wesemael, F. 1981, *Ap. J. Suppl.*, **45**, 177.
Winget, D. E. 1981, Ph.D. thesis, University of Rochester.
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. 142.
Winget, D. E., Robinson, E. L., Nather, R. E., and Balachandran, S. 1984, *Ap. J.* (*Letters*), 279, L15.
Winget, D. E., Robinson, E. L., Nather, R. E., and Fontaine, G. 1982*a*, *Ap. J.* (*Letters*), **262**, L11.
Winget, D. E., Van Horn, H. M., Tassoul, M., Hansen, C. J., and Fontaine, G. 1983, *Ap. J.* (*Letters*), **258**, L33.
Winget, D. E., Van Horn, H. M., Tassoul, M., Hansen, C. J., Fontaine, G., and Carroll, B. W. 1982*b*, *Ap. J.* (*Letters*), **251**, L65.

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