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TWO NEW EXTREMELY HOT PULSATING WHITE DWARFS

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ABSTRACT

High-speed photometry of the extremely hot, nearly degenerate stars PG 1707+427 and PG 2131+066 reveals that they are low-amplitude pulsating variables. Power spectral analysis shows both to be multiperiodic, with dominant periods of 7.5 and 6.4–6.9 minutes, respectively. Together with the known pulsators PG 1159−035 and the central star of the planetary nebula Kohoutek 1-16, these objects define a new pulsational instability strip at the hot edge of the H-R diagram. The variations of these objects closely resemble those of the much cooler pulsating ZZ Ceti DA white dwarfs; both groups are probably nonradial *g*-mode pulsators. Evolutionary contraction of the PG 1159−035 variables may lead to period changes that would be detectable in as little as 1 year.

The optical and *IUE* spectra of the PG 1159−035 variables are characterized by absorption lines of C IV and other CNO ions, indicating radiative levitation of species heavier than helium. He II is also present in the spectra, but the hydrogen Balmer lines are absent. Effective temperatures near 10^5 K are required, and the He II 4686 Å profiles indicate log $g > 6$. These helium-rich pulsators form the hottest known subgroup of the DO white dwarfs.

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

I. INTRODUCTION

The Palomar-Green survey (Green 1977) of about one-quarter of the entire sky resulted in a list of some 3000 ultraviolet-excess objects, including a few very rare, luminous degenerates. One such object, PG 1159−035, is of particular interest not only because of its very high temperature and unusual composition (its optical spectrum being dominated by C IV absorption lines), but because it is a low-amplitude pulsating variable star (McGraw *et al.* 1979). A power spectrum computed from the light curve indicated dominant periods of 7.7 and 9.0 minutes.

Recently, two of us (Grauer and Bond 1984) discovered that the central star of the planetary nebula Kohoutek 1-16 is also a pulsating variable, with a dominant period of 28 minutes. Since the spectrum of K1-16 is very similar to that of PG 1159−035, we suggested that these objects were the first two members of a new class of extremely hot pulsators.

The PG survey has revealed several more objects whose spectra closely resemble those of PG 1159−035 and K1-16 (Green and Liebert 1979; Liebert, Green, and Wesemael 1983). In this paper we report that high-speed photometry of two of these stars shows that they are also pulsating variables, bringing the number of PG 1159−035 variables to four, and clearly demonstrating the existence of a new pulsational instability strip at the left-hand edge of the H-R diagram.

II. PHOTOMETRIC OBSERVATIONS

High-speed photometric observations of our two candidate stars were made in 1982 September and 1983 April with the No. 2 91 cm reflector at Kitt Peak National Observatory (KPNO), using the two-star photometer and data-reduction techniques described by Grauer and Bond (1981). Our photometer permits one to monitor a nearby comparison star simultaneously with the observations of the program star. Division by the comparison-star data then removes any effects of atmospheric extinction or transparency variations; a second-order extinction correction is also made in cases like the present ones where the variable star is significantly bluer than the comparison star. The value of the two-star technique, even at a good site like KPNO, is illustrated by the fact that sky transparency variations of up to about 10% were encountered (and removed) during three of the six photometric runs discussed here.

The two objects selected for photometric monitoring were PG 1707+427 and PG 2131+066. Their 1950 positions are, respectively, $17^{\mathrm{h}}07^{\mathrm{m}}14\overset{\mathrm{s}}{.}1$, $+42°44'45''$, and $21^{\mathrm{h}}31^{\mathrm{m}}39\overset{\mathrm{s}}{.}2$, $+06°37'34''$. Finding charts will be published by Green, Schmidt, and Liebert (1984). The comparison star for PG 1707+427 lies $39\overset{\mathrm{s}}{.}4$ east and $3'25''$ south of the variable, while the comparison star for PG 2131+066 lies $40\overset{\mathrm{s}}{.}3$ west and $5'45''$ north. The mean magnitude and color indices of PG 2131+066, from three measurements, are $V = 16.6$,

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1984ApJ...279..751B

TABLE 1

OBSERVING RUNS (KPNO No. 2 91 cm TELESCOPE)

Date	Starting Time (UT)	Duration (hr)	Integration Time (s)	Sky Transparency
		PG 1707+427		
1982 Sep 22	3:23	2.12	5	8% variations
1982 Sep 23	4:38	1.30	5	10% variations
1983 Apr 14	8:53	2.70	5	Photometric
		PG 2131+066		
1982 Sep 21	5:27	1.05	5	Photometric
1982 Sep 22	6:04	2.42	5	Photometric
1982 Sep 24	7:53	1.19	5	10% variations

$B-V = -0.36$, and $U-B = -1.17$. Unfortunately, we were unable to obtain *UBV* measurements of PG 1707+427, but a scanner observation at Palomar Observatory gave $V = 16.7$.

Table 1 gives details of the observing runs. We used 5 s integrations in all cases, but the light curves presented below have been smoothed by summing the data into 50 s bins. In order to increase the count rate, we used no filter in front of our blue-sensitive EMI 9840 photomultiplier.

III. PULSATIONS OF PG 1707+427 AND PG 2131+066

a) *Light Curves*

The variability of PG 1707+427 was apparent at the telescope within a few minutes after the beginning of our first photometric run on 1982 September 22. Figure 1*a* illustrates the light curve obtained on this night; it is dominated by a pulsation with a period of 7.5 minutes that persisted throughout the 2.1 hr run, albeit with a diminished amplitude for several cycles around the middle of the run. The 7.5 minute pulsation was also present on the next night (not shown). However, on 1983 April 14, the character of the light curve was different, as shown in Figure 1*b*. Not only is the amplitude of the variations smaller, but they appear to be much more complex than in Figure 1*a*.

Variations of PG 2131+066 were also discovered on our first attempt. Figure 2*a* shows its light curve on 1982 September 21. Here a pulsation with a period of 6.9 minutes is apparent, and the amplitude of the variations was seen to build during the 1 hr run. Again, the character of the light curve is highly variable. On the next night, for example, a 2.4 hr run revealed the complex variations shown in Figure 2*b*. The behavior two nights later (not shown) was fairly similar to that in Figure 2*b*.

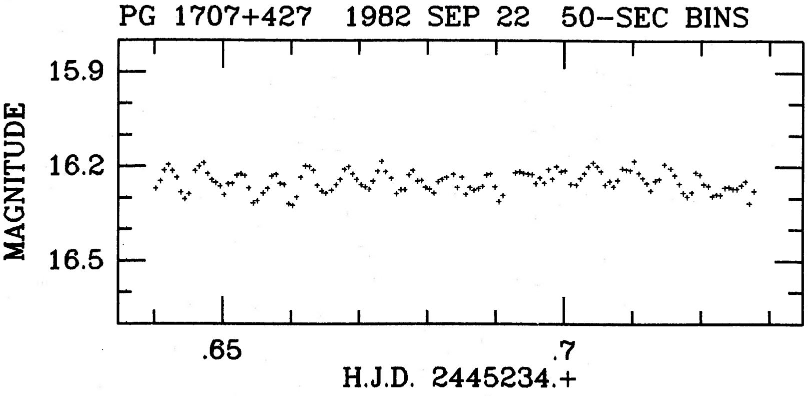

FIG. 1*a*

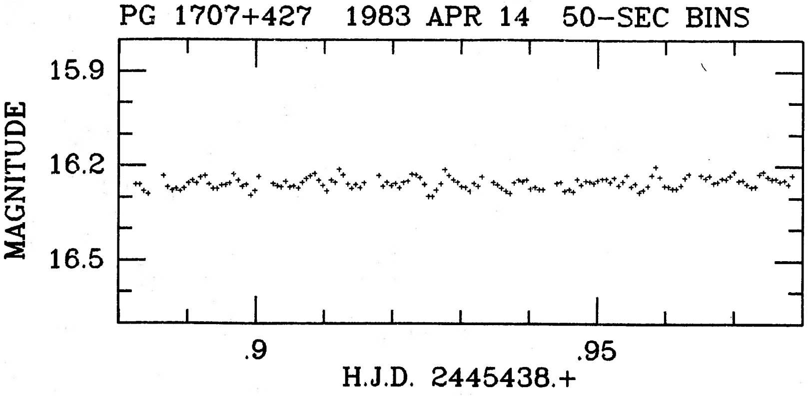

FIG. 1*b*

FIG. 1.—(*a*) Light curve of PG 1707+427 on 1982 September 22. The data, taken without a filter, have been converted to approximate *B* magnitudes, which are plotted against heliocentric Julian Date. The light curve is dominated by a pulsation with a period of 7.5 minutes. In Figs. 1 and 2, the original 5 s integrations have been combined into 50 s bins, and the intervals between ticks on the time axes are 0.01 day = 14.4 minutes. (*b*) Light curve of PG 1707+427 on 1983 April 14.

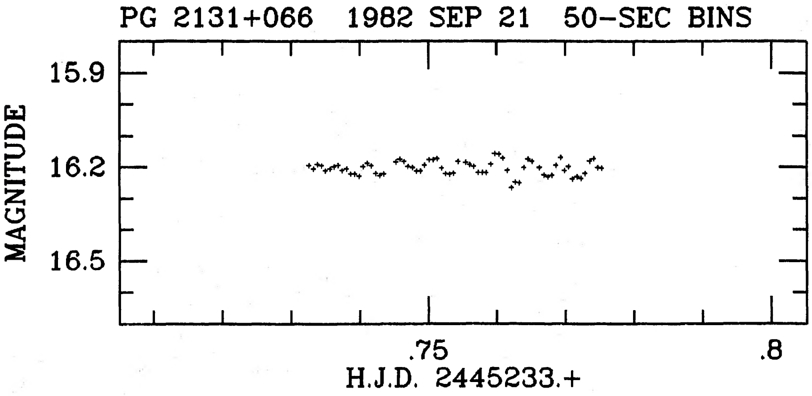

FIG. 2*a*

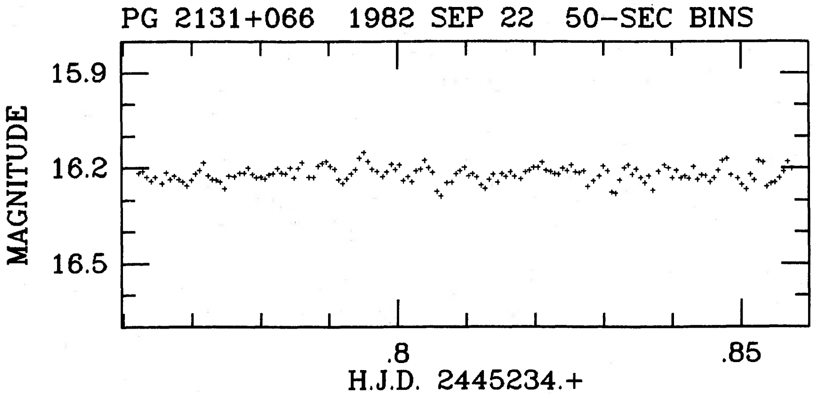

FIG. 2*b*

FIG. 2.—(*a*) Light curve of PG 2131+066 on 1982 September 21. A pulsation with a period of 6.9 minutes and a variable amplitude is present. (*b*) Light curve of PG 2131+066 on September 22.

b) *Power Spectra*

Complex light curves are perhaps best characterized by their power spectra, which we have calculated using the technique described by Deeming (1975). Figure 3*a* shows the power spectrum for the PG 1707+427 light curve of 1982 September 22 displayed in Figure 1*a*. There is a strong peak at 2.22 mHz, corresponding to the period of 7.5 minutes that obviously dominates the light curve. At least two other frequencies are also present at 2.03 and 3.00 mHz, but with much lower powers. The peak at 0.33 mHz is of doubtful significance; it may have been caused by a slight error in the adopted second-order extinction correction.

Figure 3*b* shows the power spectrum for PG 1707+427 on 1983 April 14, calculated from the light curve shown in Figure 1*b*. It is immediately apparent why the light curve has a more complex appearance than in Figure 1*a*: although the same three frequencies are present, their relative amplitudes are now quite different, so that a single frequency no longer dominates so completely. The oscillation near 2.0 mHz, as well as the strong peak at 2.22 mHz, are both much weaker than on 1982 September 22, while the 3.00 mHz frequency has nearly the same amplitude as before.

Turning to PG 2131+066, we show in Figure 4*a* the power spectrum for the 1982 September 21 light curve. A strong peak is present near 2.5 mHz, corresponding to the 6.9 minute period that is obvious in Figure 2*a*; the low frequency resolution is due to the relatively short length of the photometric run. Figure 4*b* shows the power spectrum one night later, on 1982 September 22. This run was long enough to resolve the 2.5 mHz peak into frequencies of 2.42 and 2.59 mHz (6.9 and 6.4 minutes); the power in these peaks is considerably lower than on the previous night. The increased resolution also reveals that a number of other frequencies are present.

The central star of K1-16 occasionally shows no detectable variations (Grauer and Bond 1984). PG 1159−035 showed a 1 hr interval with no observable variations during a high-speed photometric run in 1979 (E. L. Robinson and D. E. Winger 1983, private communication). We suspect that PG 1707+427 also displays this phenomenon, since high-speed photometry of it on one night in 1979 revealed no variations (S. G. Starrfield 1982; private communication). Similar cessations of pulsation have also been observed in at least one ZZ Ceti-type DA white dwarf variable, GD 385. Fontaine *et al.* (1980) attributed this behavior to a switch to a large number of pulsation modes so that no variations in the integrated starlight are observable. However, more recently Kepler (1984), in a detailed study of GD 385, has found that the large variations in pulsation amplitude are due to beating between very closely spaced frequencies. Thus the amplitude variations

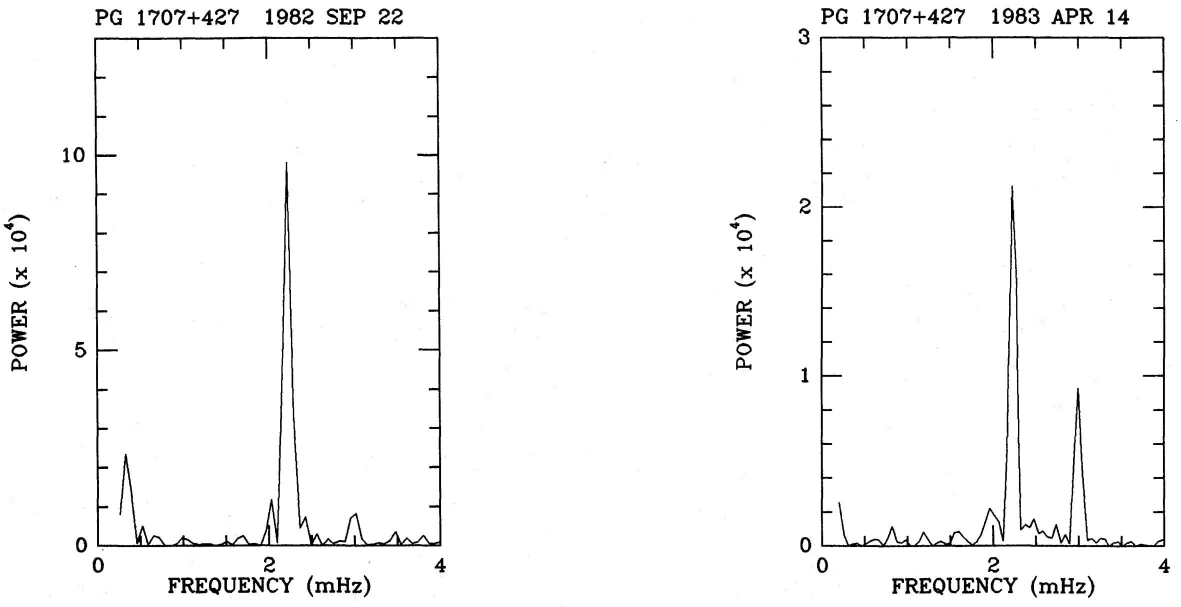

FIG. 3*a*

FIG. 3*b*

FIG. 3.—(*a*) Power spectrum of the PG 1707+427 light curve of Fig. 1*a*. It is dominated by a peak at 2.22 mHz, corresponding to a 7.5 minute period. The power is defined as the square of the mean fractional semiamplitude; hence, the semiamplitude of the 7.5 minute pulsation on 1982 September 22 was 0.033 mag. Several other frequencies (e.g., 2.03 and 3.00 mHz) were also present, but with much smaller amplitudes. (*b*) Power spectrum of PG 1707+427 on 1983 April 14 (see Fig. 1*b*). Now the amplitudes of the 2.03 and 2.22 mHz pulsations are much lower, while that of the 3.00 mHz oscillation is nearly the same as on 1982 September 22.

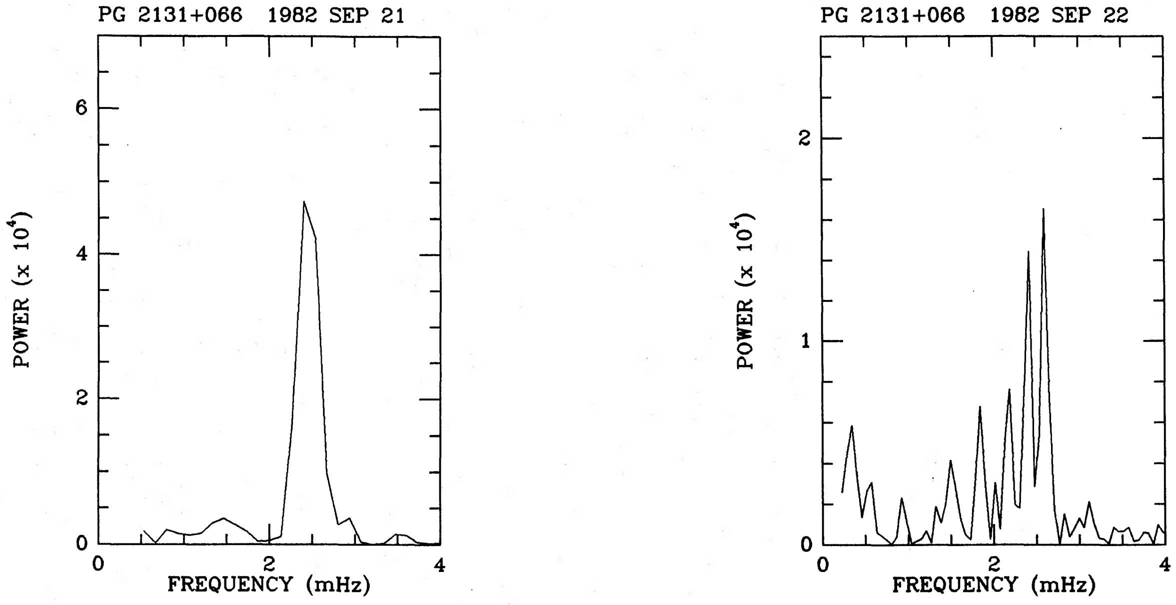

FIG. 4*a*

FIG. 4*b*

FIG. 4.—(*a*) Power spectrum of PG 2131+066 on 1982 September 21 (see Fig. 2*a*). A broad peak near 2.5 mHz dominates; its breadth is due to the relatively short duration of the photometric run. (*b*) Power spectrum of PG 2131+066 on 1982 September 22 (see Fig. 2*b*). Now a number of new frequencies are present, dominated by 2.42 and 2.59 mHz (6.9 and 6.4 min).

in the PG 1159−035 pulsators may also be due to beating rather than mode-switching.

c) *The Three Instability Strips for Degenerate Stars*

The ZZ Ceti variables are DA white dwarfs that are believed to be nonradial *g*-mode pulsators (Chanmugam 1972; Robinson 1979). Because the pulsation periods of the PG 1159−035 variables are likewise much longer than the fundamental radial periods of the stars, and because of their similar photometric behavior, we suggest that these objects are also *g*-mode pulsators. Starrfield, Cox, and Hodson (1980) and Starrfield *et al.* (1983) in theoretical investigations of PG 1159−035, have suggested that the nonradial pulsations may be driven by partial ionization of carbon and/or oxygen.

Thus three pulsational instability strips are now known observationally for stars descending the white-dwarf cooling track. In order of decreasing effective temperatures, they are (1) the PG 1159−035 strip that we have been discussing; (2) the DB instability "strip" (which as yet contains only one known star), driven by helium partial ionization (Winget *et al.* 1982*a*), and (3) the DA (ZZ Ceti) strip, driven by hydrogen partial ionization (Winget *et al.* 1982*b* and references therein).

d) *Detectability of Evolutionary Period Changes*

As first pointed out by McGraw *et al.* (1979), PG 1159−035 variables are believed to be in a state of rapid evolutionary contraction, raising the possibility of "real-time" observation of stellar evolution through the resultant decrease in pulsation period. Grauer and Bond (1984) have shown that, over an interval of as little as one month, the prospects for such a measurement in the case of K1-16 are very promising because of its extremely rapid contraction. We will now discuss prospects for detecting period changes in the less rapidly evolving PG 1159−035 variables.

Winget, Hansen, and Van Horn (1983) have predicted that the rate of period decrease for PG 1159−035 variables will be of order $\dot{P}/P \approx -10^{-6}$ yr^{-1}. We can estimate how long it will take to detect such a period change by referring to the technique used by Kepler *et al.* (1982) to place exceedingly stringent limits on $\dot{P}/P$ for the ZZ Ceti variable G117−B15A. Their method consists of measuring the phase shift in observed times of maximum for the dominant period (3.6 minutes in the case of G117−B15A). Over an interval of 5 yr, they were able to set an upper limit, $|P/P| < 10^{-8}$ yr^{-1}, from the lack of a detectable phase shift. Since the phase shift increases with the square of the observing interval, it would take one-tenth as long to detect a period change 100 times more rapid; but since the typical periods of the PG 1159−035 variables are twice those of G117−B15A, we arrive at an estimate that about 1 yr would be required to detect the phase shift for a typical PG 1159−035 variable.

If the variable were to switch out of its dominant mode during this 1 yr interval—a possibility raised by the pulsation disappearance seen in several of the PG 1159−035 variables, but perhaps an unlikely one in the light of Kepler's (1984) work—then the phase information would be lost. We would be forced to measure the periods at such epochs as they are present, and look for secular changes. Referring again to Kepler

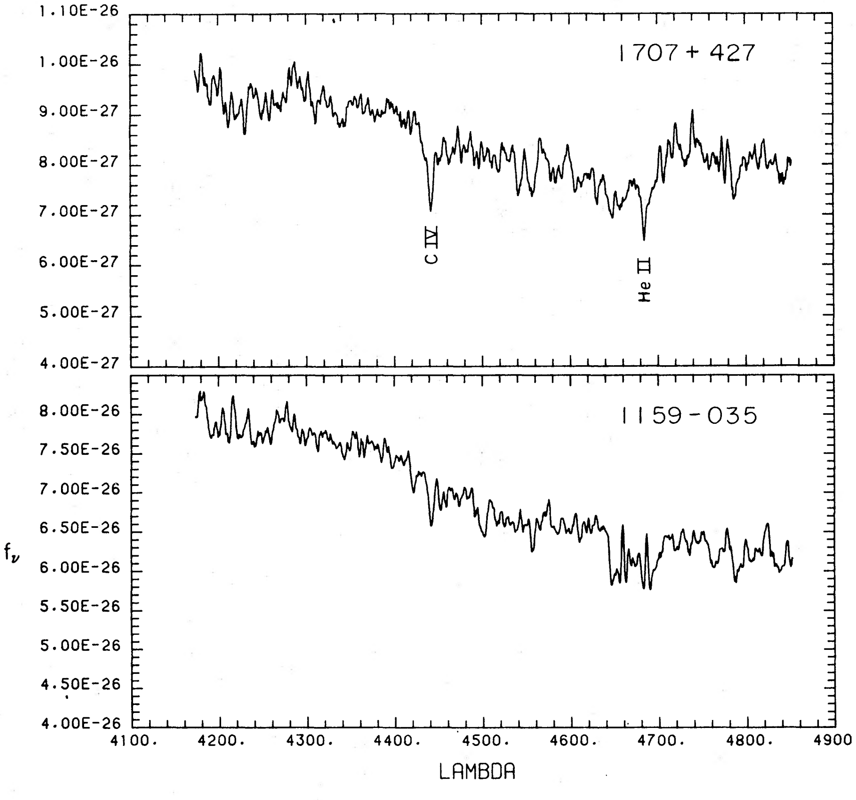

FIG. 5.—KPNO IIDS spectra of the hot pulsators PG 1707+427 and PG 1159−035. The strongest absorption lines are due to C IV and He II. Emission cores are present in C IV 4658 Å and He II 4686 Å in PG 1159−035.

1984ApJ...279..751B

et al. (1982), we find that they were able to measure the period of G117−B15A to an accuracy of about ±0.05 s from observations made over several hours with a large telescope. For a PG 1159−035 variable with a period about twice as long, the attainable accuracy would be about ±0.1 s. With $\dot{P}/P \approx -10^{-6}$ yr^{-1}, a change of 0.1 s requires about 200 yr, and thus would not be measurable over a human lifetime. If a pulsation were coherent over several weeks, so that the period could be determined to, say, ±0.001 s, the period measurement would be capable of revealing the predicted period change in just a few years.

Intensive photometric observations of the PG 1159−035 variables will be necessary in order to detect the predicted period changes. We urge that these observations be made because of the exciting possibility of direct observation of stellar evolution.

IV. OPTICAL AND ULTRAVIOLET SPECTROSCOPY

The PG 1159−035 stars form a small, spectroscopically distinct class among the objects found in the PG survey. Summed KPNO 2.1 m IIDS spectra of PG 1707+427 and PG 1159−035 are shown in Figure 5, while Fig. 6 shows a single Steward 2.3 m Reticon spectrum of PG 2131+066. A KPNO spectrum of the central star of K1-16 has been illustrated by Grauer and Bond (1984).

As shown in Figures 5 and 6, the distinguishing spectroscopic characteristics of this class include a trough-like region covering approximately 4650–4680 Å and blending into He II 4686 Å. This depression is due to blending of several CNO lines that are difficult to identify individually at low resolution, but include strong C IV 4658 Å. Other C IV lines present in the spectra are 4441 Å and probably 4798 Å, lines seldom seen in subdwarf O spectra. Higher dispersion spectra of several objects in this class (Wesemael, Green, and Liebert 1983) show that the wings of He II 4686 Å are so broad that they can be fitted only with models with log $g > 6$. Sharp emission cores in the He II 4686 Å and C IV 4658 Å lines are present in our spectrum of PG 1159−035, and in higher resolution spectra of other members of the class.

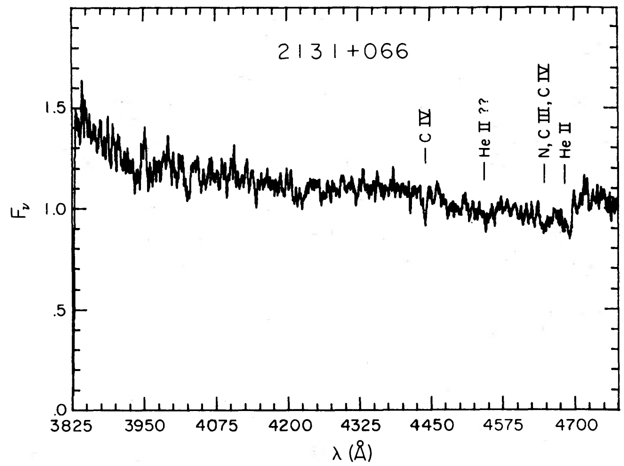

FIG. 6.—Steward Reticon spectrum of PG 2131+066

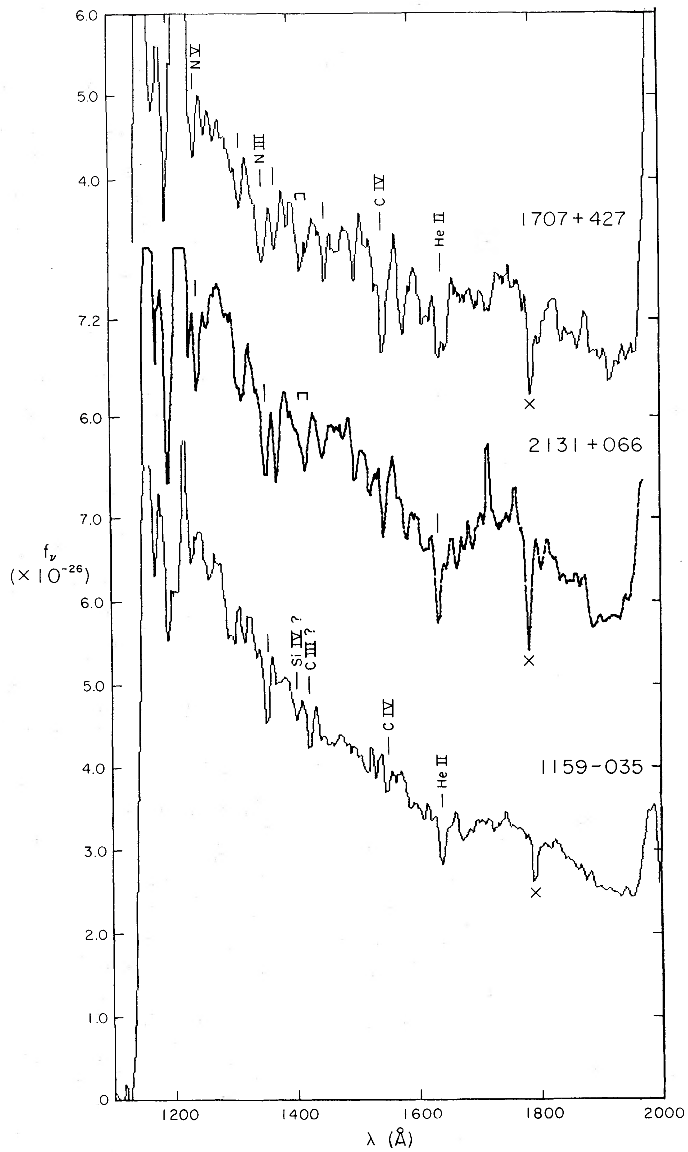

FIG. 7.—Short-wavelength *IUE* spectra of the three PG pulsating variables. The "X" symbol denotes a reseau mark that is not a real absorption line.

Wesemael *et al.* (1983) propose that the PG 1159−035 stars are the hottest subgroup of the helium-rich DO white dwarfs. They are also the only DO stars that normally show lines of elements heavier than helium in their optical spectra. Very high effective temperatures ($\sim 10^5$ K) are required by the absence of He I lines, the weakness of He II 4686 Å, and the near-absence of He II "Brackett" transitions. The Balmer lines are not seen, but at very high temperatures this does not give a strong constraint on the hydrogen abundance.

In Figure 7 we display short-wavelength, low-dispersion *IUE* spectra of the three known hot pulsators from the PG survey. The following features may be noted. He II 1640 Å appears at a strength commensurate with the 4686 Å strength at these high temperatures and gravities. C IV 1550 Å is strong in all objects, and N V 1240 Å is present in our two new pulsating stars, though not convincingly in the prototype. Other possible identifications include Si IV, C III, and N III. Long-wavelength *IUE* exposures yielded few detected absorption features.

The rich ultraviolet metallic spectrum in a class of high-gravity objects is not unexpected, following recent theoretical work on radiative levitation of selected ions (Fontaine and Michaud 1979; Vauclair, Vauclair, and Greenstein 1979; Alcock and Illarionov 1980). The ions identified here include some of the most likely cases to be supported in a helium-rich atmosphere against gravitational and thermal diffusion processes. A number of these ions have recently been found to be present as much weaker absorption lines in high-dispersion *IUE* spectra of hot DA and DO stars (Sion, Guinan, and Wesemael 1982; Bruhweiler and Kondo 1983), and have been attributed to outflowing winds. These lines are so strong in the PG 1159−035 variables that it is reasonable to attribute them to the photospheres.

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