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THE PULSATING CENTRAL STAR OF THE PLANETARY NEBULA KOHOUTEK 1-16[1]

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ABSTRACT

High-speed photometry of the central star of the planetary nebula Kohoutek 1-16 shows it to be a low-amplitude pulsating variable. The dominant period is 28.3 minutes, with a semiamplitude that is usually about 0.01 mag. However, several additional periods sometimes appear in power spectra computed from our light curves, and on two occasions we witnessed a rapid drop into, or emergence from, a state in which no detectable variations were present. Such "mode switching" is typical of some of the ZZ Ceti-type white dwarf nonradial pulsators, but, at $T_{eff} > 80,000$ K, K1-16 is much too hot to be a ZZ Ceti variable. Spectroscopically and photometrically, the central star of K1-16 closely resembles the previously known hot pulsator PG 1159−035; these two objects represent a new pulsational instability mechanism for extremely hot degenerate or predegenerate stars. We predict that the evolutionary contraction of K1-16 will lead to a period decrease so rapid that it should be detectable over an interval of about 2 yr.

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

I. INTRODUCTION

The possibility of pulsational instabilities in the nuclei of planetary nebulae has been discussed from a theoretical standpoint by Stothers (1977) and Van Horn (1980). There have also been scattered observational reports of low-amplitude, short time scale oscillations of nonbinary central stars (Lawrence, Ostriker, and Hesser 1967; Alekseev 1973; Gilra *et al.* 1978; Patterson 1979*a*; Zhiljaev and Totochava 1980), but to the best of our knowledge the existence of such variations has never been conclusively established (e.g., Lasker and Hesser 1971). In some cases the reported variations may have been due to nebular contamination of the photometric measurements (e.g., Patterson 1979*b*).

In this paper we present observational evidence that, for the first time, clearly shows the central star of a planetary nebula to be a pulsating variable. This discovery is of particular interest not only because it demonstrates pulsational instability in a new region of the H-R diagram, but because it provides the most promising opportunity yet for the direct observation of stellar evolution.

II. PHOTOMETRIC OBSERVATIONS OF CENTRAL STARS

For the last several years, the writers have had underway a photometric survey of the central stars of planetary nebulae. The primary aim of the work has been to search for very close binaries, an effort in which we have been successful (Bond 1983; Grauer and Bond 1983). Our discovery of a pulsating central star was thus serendipitous.

The photometric observations have been made with 91 cm reflectors at Kitt Peak National Observatory (KPNO) and Louisiana State University (LSU) Observatory, using the two-star photometers and data-reduction techniques described by Grauer and Bond (1981). These photometers permit 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.

In selecting central stars for our survey, we have preferentially chosen objects in low surface brightness nebulae, for the observational reason that there are fewer photometric problems with the nebular background. One of the objects we chose was the 15th mag central star of Kohoutek 1-16, a faint planetary nebula discovered on Palomar Sky Survey prints by Kohoutek (1963). Hereafter, we will refer to the central star as "K1-16." The 1950 coordinates of the central star are $18^h21^m35^s$, $+64°20'30''$, and finding charts have been given by Kohoutek (1963), Perek and Kohoutek (1967), and Kaler (1981). The comparison star that was monitored simultaneously lies 60^s west and $6'31''$ north of K1-16; four *UBV* measurements of the comparison star at KPNO gave $V = 10.79$, $B-V = 0.39$, and $U-B = 0.01$. The mean magnitude and color indices of K1-16, also from four measurements, are $V = 15.04$, $B-V = -0.38$, and $U-B = -1.25$.

Preliminary observations of K1-16 in 1980 at KPNO and LSU revealed that it is a low-amplitude variable. In order to determine the nature of these variations, we obtained runs of several hours' duration on single nights in 1982 April (KPNO) and 1982 June (LSU), and on four nights at KPNO in 1982 September. We normally used integration times of 5 s; however, the light curves presented here have been smoothed by summing the data into 50 s bins. We used

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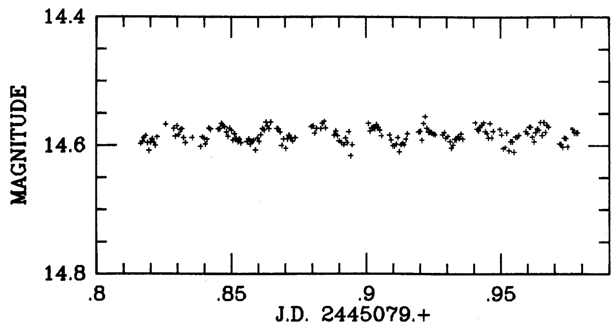

FIG. 1*a*

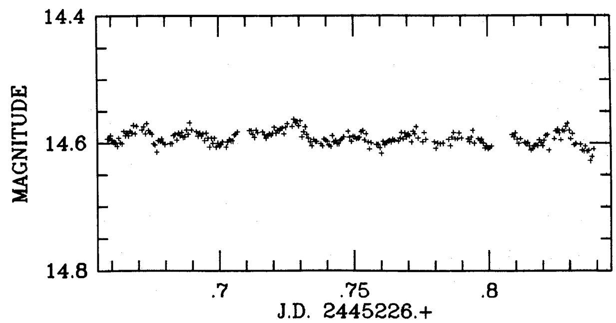

FIG. 1*b*

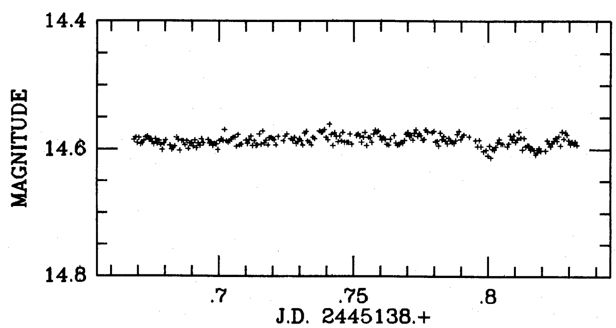

FIG. 1*c*

FIG. 1.—(*a*) Light curve of the central star of K1-16 on 1982 April 20. *B* magnitudes are plotted against heliocentric Julian Date. In Figs. 1*a*–*c*, the original integrations have been combined into 50 s bins, and the intervals between ticks on the time axes are $0^{d}.01$ = 14.4 minutes. The light curve shows a sinusoidal pulsation with a period of 28 minutes. (*b*) Light curve of K1-16 on 1982 September 14. The data in Figs. 1*b*–*c* were obtained with no optical filter in order to increase the count rate, and the data have been converted to approximate blue magnitudes. The 28 minute pulsation is still present, but the variations are distinctly nonsinusoidal. (*c*) Light curve of K1-16 on 1982 June 18, obtained with the LSU Observatory 91-cm reflector. The central star showed no detectable variations for the first 3 hr, then suddenly resumed the 28 minute oscillation.

either the *B* filter of the *UBV* system, or, to increase the counting rate, no filter at all in front of our blue-sensitive EMI 9840 photomultiplier.

III. PULSATIONS OF THE CENTRAL STAR OF K1-16

a) *Light Curves*

The variability of the nucleus of K1-16 was shown very clearly on 1982 April 20, during a 3.9 hr run. Figure 1*a* illustrates the light curve on this night. The data, taken through a *B* filter, have been converted to magnitudes, using the known *B* magnitude of the comparison star. During this run, K1-16 exhibited essentially sinusoidal variations, with a semiamplitude of about 0.01 mag and a period of about 28 minutes. We do not doubt the reality of the variations. The sky conditions were photometric. Other comparably faint central stars that we have monitored with the same equipment have never shown such variations. A variable amount of nebular contamination cannot produce variations with a period this long, since we always correct the telescope pointing every few minutes. Finally, the relative gains of the two photomultipliers were measured regularly and found to be constant to within a few thousandths of a magnitude.

The variations shown in Figure 1*a* could, in principle, be due to motion in an extremely short-period binary system. We favor the alternative of pulsations because the variations showed a quite different character on other nights, and even disappeared altogether on occasion. Figure 1*b* shows the light curve on 1982 September 14. On this night the variations had nearly the same amplitude as in Figure 1*a*, but now the pulsations appear to be more complex. Nevertheless, the 28 minute period still dominates, and in fact the cycle count can be maintained unambiguously over the 21 hr gap between a run on September 13 and this run. On the next night, September 15, however, the 28 minute pulsation was not present.

We have observed two examples of the actual appearance or disappearance of the 28 minute pulsation. Figure 1*c* shows a 3.9 hr run obtained with the LSU telescope on 1982 June 18. For the first 3 hr, no detectable variations were present. Then the pulsations suddenly began and, in less than one 28 minute period, built up to the full amplitude observed on other nights. On 1982 September 24 (not shown), K1-16 underwent about one cycle at full amplitude; then the pulsation amplitude rapidly became much smaller, and by the end of the run, the pulsations had nearly disappeared.

b) *Power Spectra*

We have further investigated the light curves described above by calculating power spectra using the technique described by Deeming (1975). Figure 2*a* shows the power spectrum for the light curve of 1982 April 20 displayed in Figure 1*a*. There is a strong peak at 0.589 mHz, corresponding to a period of 28.3 minutes; no harmonics or other frequencies are present above the noise level, confirming the visual impression that the variations that night were essentially sinusoidal.

Figure 2*b* shows the power spectrum of the 1982 September 14 light curve of Figure 1*b*. Here again the 0.589 mHz peak dominates; however, five or more new frequencies have appeared, giving rise to the distinctly nonsinusoidal light curve.

IV. DISCUSSION

a) *Similarity to ZZ Ceti Variables*

The ZZ Ceti variables are DA white dwarfs believed to be undergoing nonradial *g*-mode pulsations (Chanmugam 1972; Robinson 1979 and references therein). The photometric behavior of K1-16 is strikingly similar to that of GD 385, a ZZ Ceti variable that has been extensively observed by

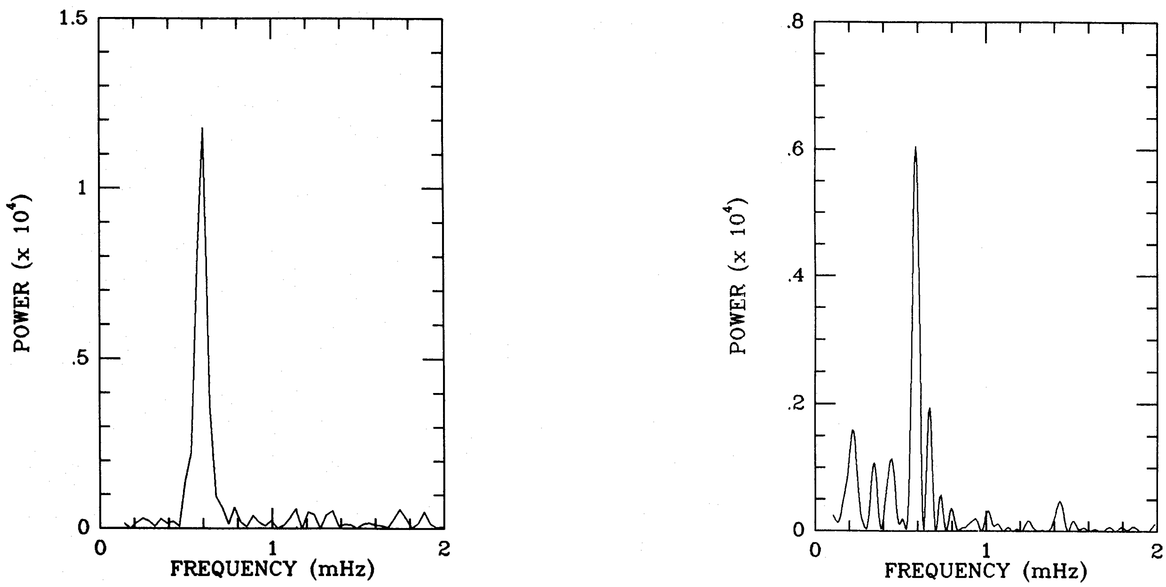

FIG. 2*a* FIG. 2*b*

FIG. 2.—(*a*) Power spectrum of the light curve of Fig. 1*a*. It is dominated by a single peak at 0.589 mHz, corresponding to a pure sinusoid with a 28.3 minute period. The power is defined as the square of the fractional semiamplitude; hence the semiamplitude of the pulsation on 1982 April 20 was 0.012 mag. (*b*) Power spectrum of the light curve of Fig. 1*b*. Now several additional frequencies are present, corresponding to the nonsinusoidal light curve.

Fontaine *et al.* (1980). On 15 nights, GD 385 exhibited one strong period (4.3 minutes). On two nights, several additional periods were present, and on three nights, no variability at all was detected.

As Fontaine *et al.* point out, the disappearance of the pulsations of GD 385 cannot have been due to a simple beat phenomenon between two closely spaced frequencies, since this would require a continuously varying pulsation amplitude that was not observed on the other nights. This argument applies with even greater force to K1-16, where, as we have shown, we actually saw the 28 minute pulsation build up to full amplitude in less than one cycle.

Fontaine *et al.* suggested that GD 385 undergoes "mode switching"; that is, it can switch from its usual 4.3 minute mode either to a situation where several modes are present (giving several prominent frequencies in the power spectrum) or to a situation where so many modes are present (or the modes are of such high orders) that no detectable variations are observed. The same phenomenon appears to occur in K1-16. Other examples of mode switching in ZZ Ceti white dwarfs have been discussed by McGraw (1976) and Robinson *et al.* (1978).

b) *The PG 1159−035 Variables*

In spite of its very similar photometric behavior, K1-16 definitely cannot be classified as a ZZ Ceti variable: its *UBV* colors, and the fact that it excites a planetary nebula, show it to be much hotter than the ~11,000–13,500 K effective temperature range of the ZZ Ceti stars (Fontaine *et al.* 1982; Greenstein 1982). Kaler (1981, 1983) has determined that $T_{\rm eff} > 80{,}000$ K for K1-16, using the Zanstra method.

K1-16 is probably closely related to the known pulsating variable PG 1159−035, an extremely hot white dwarf (or pre-white dwarf) that was found to exhibit short time scale variations by McGraw *et al.* (1979). Observations on a single night in 1979 showed a semiamplitude of 0.01 mag—similar to that of K1-16—and dominant frequencies of 1.86 and 2.17 mHz (corresponding to periods of 9.0 and 7.7 minutes). The optical, ultraviolet, and soft-X-ray energy distribution of PG 1159−035 indicates an effective temperature of 100,000–170,000 K (Wegner *et al.* 1982; McGraw, quoted by Winget, Hansen, and Van Horn 1983). There is no detectable nebulosity surrounding PG 1159−035, suggesting that if it did eject a planetary nebula, it was sufficiently long ago that the nebula has now dissipated. Its shorter pulsation periods may also indicate that PG 1159−035 is more evolved and compact than K1-16.

The optical spectrum of PG 1159−035 is nearly unique in showing only C III–IV and He II absorption lines, several of which have a sharp emission core (McGraw *et al.* 1979; Green and Liebert 1979). The lack of Balmer absorption lines may imply a hydrogen-deficient composition.

Figure 3 shows an optical spectrum of the central star of K1-16, obtained by H. E. B. with the KPNO 2.1 m reflector and the image dissector scanner. A 4″ diaphragm was used to suppress the nebular emission lines. The strongest absorption line is C IV 4441 Å. Also probably present are He II 4541 Å and C IV 4658 Å. He II 4686 Å, curiously, is only marginally present, suggesting that it may be filled by an emission component as in PG 1159−035. No hydrogen lines are present. Thus the optical spectrum of the central star of K1-16 is remarkably similar to that of PG 1159−035. We feel secure in classifying K1-16 as the second member of what has now become the PG 1159−035 class of hot pulsating variables.

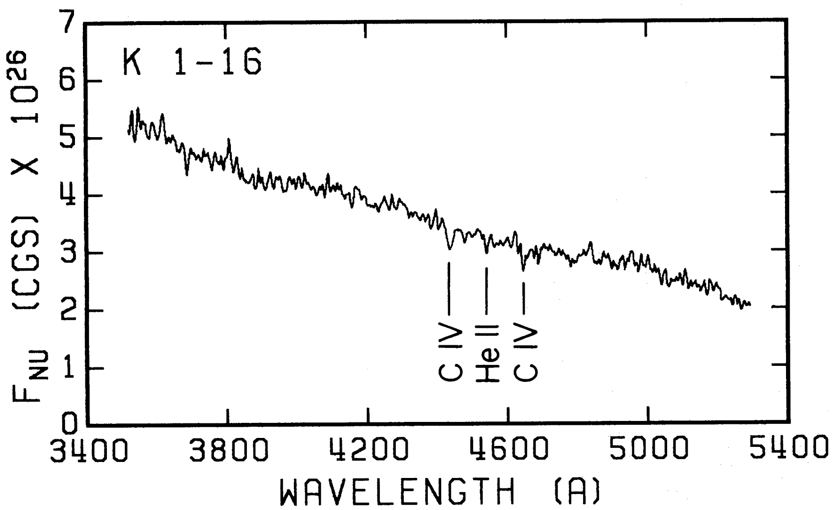

FIG. 3.—Kitt Peak IIDS scan of the central star of K1-16, with spectral resolution of 7 Å˙ The only definite features present are the C IV and He II absorption lines marked.

c) *Pulsation Mechanism*

The ZZ Ceti DA-type pulsators are generally believed to be driven by their hydrogen partial ionization zones (Winget *et al.* 1982*b* and references therein). Recently, a second instability strip has been discovered (both observationally and theoretically) for the hotter DB white dwarfs, and it is believed that in this case the driving is due to helium partial ionization (Winget *et al.* 1982*a*).

The class of PG 1159−035 variables demonstrates that at least a third instability strip exists for even hotter (pre-)degenerates. Starrfield, Cox, and Hodson (1980) and Starrfield *et al.* (1983) have shown theoretically that very hot pre-white dwarfs are indeed unstable to nonradial pulsations; the driving is due to partial ionization of carbon and/or oxygen. This appears to be the most plausible mechanism for the PG 1159−035 variables, although Starrfield *et al.* point out a possible difficulty that these objects may be even hotter than the calculated blue edge of the instability strip for the observed long periods.

d) *The Possibility of Detecting Evolutionary Period Changes*

Perhaps the greatest importance of our discovery of the pulsations of K1-16 lies in the opportunity it affords for direct observation of the change in its pulsation period due to evolutionary contraction. Winget, Hansen, and Van Horn (1983) have already pointed out this possibility for PG 1159−035, but the rate of period decrease for K1-16 should be even more rapid. The expected rate for K1-16, $\dot{P}$, may be estimated crudely as follows. If the change is due primarily to the decreasing radius of the star, then, for the *g*-modes, the period decrease is given by $\dot{P}/P \approx \dot{R}/R$, where R is the stellar radius (see Winget, Hansen, and Van Horn 1983). Kaler (1983) finds $\log L/L_{\odot} > 2.5$ for K1-16. At $\log L/L_{\odot} \approx 2.5$ on the evolutionary tracks of Schönberner (1981) or Iben *et al.* (1983) for planetary nuclei of 0.6 $M_{\odot}$, we find $\dot{R}/R \approx -3 \times 10^{-4}$ yr^{-1}. At higher luminosities, or higher stellar masses, the theoretical contraction time scale is even shorter.

An evolutionary change this rapid ($|P/\dot{P}| \approx 3.3 \times 10^3$ yr) could be detected in an astonishingly short time under favorable circumstances. The observed time of maximum for the 28 minute pulsation will exhibit a phase shift (relative to times of maximum predicted for a constant period) that grows as the square of the elapsed time. For the predicted rates. Starrfield, Cox, and Hodson (1980) and Starrfield *et al.* to 30 s, an easily measurable amount from data of high quality, in only 30 days! This powerful technique has been exploited by Stover *et al.* (1980) and Kepler *et al.* (1982) to place exceedingly stringent limits on $\dot{P}$ for two ZZ Ceti variables in which the same dominant frequency is always present, so that unambiguous cycle counting is possible.

Unfortunately, as we have shown above, the 28 minute pulsation of K1-16, unlike that of the white dwarfs studied by Stover *et al.* and Kepler *et al.*, sometimes disappears because of mode switching. Our tentative conclusion from our rather scattered observations is that the dominant 28 minute period is continuously present for intervals of only a few days before it disappears; when it reappears, it probably does so at a random phase, making the phase shift measurement outlined above impossible. Thus it seems that we must attempt to detect the period change by measuring the period itself at several different epochs. Our data for 1982 September 13 and 14 show that the 28 minute oscillation can persist on the same ephemeris for at least 24 hr, over which interval we believe the period can be determined to ± 1 s from data of high quality. For a $|P/\dot{P}|$ of 3.3×10^3 yr, the period should change by 1 s in 2 yr. Note that the accuracy with which the period can be determined increases with elapsed time, so if the pulsations at a given epoch are coherent for more than 1 day, the period change could be measured in even less than 2 yr.

The central star K1-16 provides a unique laboratory for "real time" study of stellar evolution, and we urge intensive observations over the next few years in order to exploit this extraordinary opportunity.

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