THE PULSATING NUCLEUS OF THE PLANETARY NEBULA LONGMORE 4

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ABSTRACT

CCD photometry shows that the central star of the planetary nebula Longmore 4 is a multiperiodic, nonradially pulsating variable. Its light curves show an amplitude that can reach 0.1 mag (peak to peak) and a strong periodicity near 31 min, but with considerable interference among numerous pulsation modes. Power spectra reveal nearly a dozen significant individual periods, lying in groups around 875, 1560, and 1850 s. The optical spectra of Lo 4 and K 1-16, the other known pulsating planetary nucleus, and of the four known pulsating GW Vir white dwarfs, are all dominated by features of He II, C IV, and O VI, indicating extremely hot ($T_{\rm eff} \gtrsim 10^5$ K), hydrogen-deficient, and carbon- and oxygen-rich surface layers. The apparent uniformity of the chemical compositions supports a pulsation mechanism proposed by Starrfield *et al.* involving cyclical ionization of carbon and/or oxygen. The longer oscillation periods of Lo 4 and K 1-16, along with the presence of planetary nebulae, is consistent with an evolutionary sequence in which they are the progenitors of pulsating GW Vir variables. In fact, continued photometric observations of Lo 4 should be capable of revealing the predicted decreases in the pulsation periods due to the star's rapid evolutionary contraction.

I. INTRODUCTION

The first pulsating central star of a planetary nebula, the nucleus of Kohoutek 1-16, was discovered by Grauer and Bond (1984). High-speed photometry of K 1-16 (which has received the variable-star designation DS Dra) shows it to be a multiperiodic nonradial pulsator, whose dominant pulsation periods lie near 1500 and 1700 s (Grauer and Bond 1984; Grauer *et al.* 1987a).

K 1-16 appears to be related closely to the GW Vir class of extremely hot, pulsating white dwarfs. Pulsations were discovered in GW Vir (PG 1159 − 035) by McGraw *et al.* (1979). PG 1159 − 035 is also the prototype of a spectroscopically defined group of DO white dwarfs, characterized by absorption and/or emission features of He II, C IV, and O VI, and an absence of Balmer absorption lines (Wesemael, Green, and Liebert 1985). High-speed photometry has revealed three additional pulsating members of the PG 1159 − 035 spectroscopic class (Bond *et al.* 1984; Bond and Grauer 1987), but several other PG 1159 − 035-type objects do not exhibit detectable pulsations (Grauer *et al.* 1987b; Demers *et al.* 1990). The pulsation periods of the GW Vir variables typically range from about 400 to 800 s.

The close spectroscopic similarities of K 1-16 and the GW Vir pulsators have been emphasized by Bond *et al.* (1984), Grauer and Bond (1984), and Sion, Liebert, and Starrfield (1985). The fact that all of these hot pulsators have spectra indicating hydrogen deficiencies and high abundances of carbon and oxygen in their surface layers is in agreement with a pulsation mechanism advocated by Starrfield *et al.* (1984,1985). Further support for the Starrfield *et al.* mechanism, which involves cyclical ionization of carbon and/or oxygen in the outer layers of the star, comes from recent non-LTE abundance analyses of four members of the PG 1159 − 035 spectroscopic class (two pulsators and two nonvariables) by Werner, Heber, and Hunger (1990). Carbon was found to be the dominant species in these objects, followed by helium and oxygen; the abundances of hydrogen and nitrogen were found to be very low, and the effective temperatures were found to range from 110 000 to 140 000 K.

As part of a photometric survey for additional pulsating planetary-nebula nuclei (PNNs), we observed three southern hydrogen-deficient PNNs whose spectra have been discussed by Méndez, Kudritzki, and Simon (1985) and Méndez *et al.* (1986). These are the central stars of Kohoutek 1-27, Longmore 3, and Longmore 4, which we will refer to as K 1-27, Lo 3, and Lo 4, respectively. None of these three PNNs show Balmer absorption, while K 1-27 shows He II absorption, and Lo 3 and Lo 4 show both He II and C IV absorption. Of the three, the spectrum of Lo 4 is most similar to those of the PG 1159 − 035 objects and K 1-16, showing conspicuous absorption features at C IV 4441, 4646, and 4658 Å, and at He II 4541 and 4686 Å.

II. PHOTOMETRIC OBSERVATIONS AND REDUCTIONS

We carried out photometric monitoring of K 1-27, Lo 3, and Lo 4 with the 0.9 m telescope at Cerro Tololo Inter-American Observatory (CTIO) during an observing run in 1988 February. The RCA 5 CCD was used behind a BG 38 filter, which maximizes the detection rate by providing a broad blue bandpass. We obtained sequences of 60–90 s exposures, and the fields were chosen so that one or more nearby comparison stars were also present in the frames. This allowed us to compensate for any changes in atmospheric transparency or sky background by calculating differential magnitudes between the PNN and the comparison star(s); moreover, the two-dimensional images allowed accurate subtraction of the contribution of the surrounding nebulae. By reading out only part of the chip, we were able to reduce the time between the end of one exposure and the beginning of the next to ~14 s. At the $f/13.5$ focus of the telescope, the CCD pixels project to $0\farcs49 \times 0\farcs49$ on the sky.

K 1-27 was observed on one night for 3.0 hr, and Lo 3 on two nights for 2.4 and 1.8 hr, respectively. None of these runs revealed any significant periodic variations, and we will

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not discuss these two objects further; details of the null results will be published elsewhere.

Lo 4, however, proved to be a new pulsating variable, and is the subject of this paper. We obtained data on five photometric nights during 1988 February. Table I presents a log of the CCD observations.

The field surrounding Lo 4 contains two convenient comparison stars; Table II presents accurate coordinates for Lo 4 and its comparison stars (determined to an accuracy of about $\pm 0''.8$ using the Space Telescope Science Institute's Guide Star Astrometric Support Package) along with approximate (± 0.05 mag) magnitudes and colors determined at CTIO by direct comparison with five standard stars chosen from Landolt (1983). The planetary nebula was discovered independently by Longmore (1977) and Holmberg *et al.* (1977, in which the object is designated ESO 263-PN02); finding charts showing the nebula and its central star are provided by Longmore (1977) and West and Schuster (1980).

After debiasing and flatfielding the CCD frames, we extracted small "postage stamps" surrounding Lo 4 and its comparison stars, using the CDPHOT software written at the National Optical Astronomy Observatories by B. Goodrich. This procedure provides a substantial reduction in the amount of data taken from the telescope, and also enables a valuable "quick look" at the photometry in near real-time.

The final data reduction was carried out at the Space Telescope Science Institute, using several DAOPHOT routines (Stetson 1987). The procedure that was used involved determining the centroid of each stellar image, and then carrying out aperture photometry. By determining differential magnitudes between the two comparison stars for various values of the radius of the star aperture, we found that the smallest scatter was generally obtained for a 6-pixel diameter (corresponding to a diameter of $3''.0$ projected onto the sky). The FWHM of the stellar seeing profiles was typically $1''.5$. The sky background (and, in the case of Lo 4 itself, the small contribution from the surrounding nebula) was determined from an annulus surrounding, and well outside, the stellar profile.

To improve the signal-to-noise ratio for the final differential magnitudes, we calculated the difference in magnitude between Lo 4 and the *sum* of the intensities of the two comparison stars for each CCD observation. Because of the broad bandpass of the BG 38 filter and the substantial difference in color between Lo 4 and the comparison stars, we removed trends with airmass from each night's data (using the same second-order extinction coefficient for all nights).

III. LIGHT CURVES AND POWER SPECTRA

Figure 1 shows the CCD light curves obtained for Lo 4 on the five nights in 1988 February. Each curve is labeled with the integer part of the Heliocentric Julian Date, and the differential magnitudes are plotted against the fractional part of the H.J.D. The light curves typically show a periodicity near 31 min and a peak-to-peak amplitude of up to 0.1 mag. However, there is considerable variability in the amplitude. For example, just after the beginning of the run on 1988 February 29 (H.J.D. 2447220) the pulsations nearly vanished for about two cycles of the 31 min period. This is typical behavior for a multiperiodic variable, and is due to destructive interference between individual, simultaneously present pulsation modes.

In order to characterize the light variations in more detail, we used power-spectral analysis. Each night's data were normalized to a mean intensity of unity, and then all of the data were combined into a single dataset with, of course, large gaps between the five nights. A power spectrum was calculated for the combined data, using a fast-Fourier-transform algorithm written by R. L. White.

The power spectrum is plotted in Fig. 2(a), and it is clear that there is significant power in the vicinity of 0.54 mHz (period 1850 s), in agreement with the appearance of the light curves described above. However, the power spectrum shows a complicated structure due both to additional periodicities in the data, and to the alias structure (or window function) introduced by the large gaps in the time series. (There is no significant power outside the frequency range plotted in the figure.)

In order to deconvolve the window function from the power spectrum, we used the CLEAN algorithm of Roberts, Lehár, and Dreher (1987). CLEAN is an iterative procedure that at each step finds the frequency of the highest peak in the power spectrum and removes a small fraction of this power and its aliases from the power spectrum (using the known window function). The iterations are continued until all of the remaining power is below some preselected value. The "clean" spectrum is then constructed from the components that were selected at each iteration.

Figure 2(b) shows the resulting spectrum that we obtained by CLEANing the power spectrum of Fig. 2(a). The clean spectrum contains a large number of individual frequencies, which account for the complex behavior of the light curves.

The statistical significance of the peaks in the power spectra was assessed as follows. We randomly reassigned the observed data points among the times of observation, calculated a new power spectrum, and noted the peak power. This procedure was repeated for a total of 200 times, so that we obtained 200 power spectra of data with the same noise characteristics as the original data, but with any real periodicities destroyed by the scrambling. Any peak in the power spectrum of the original data that was higher than 99% of the highest peaks in the spectra of the randomized data was considered significant with greater than 99% confidence.

Each time we identified one or more frequencies with greater than 99% confidence, we removed (or "prewhitened") these frequencies from the data (since real periodi-

TABLE I. Log of CTIO 0.9 m CCD observations.

Date	Starting UT	Run duration (hr)	Integration time (s)
1988 February 24	3:59:38	2.54	90
February 26	6:31:06	2.40	75
February 27	4:23:05	4.65	75
February 28	7:36:53	3.60	75
February 29	8:38:38	4.31	75

TABLE II. Lo 4 positions and magnitudes.

Star	α_{1950}	δ_{1950}	V	$B-V$
Lo 4	$10^h03^m43^s.43$	$-44°06'55''.9$	16.6	-0.16
Comparison 1	$10^h03^m42^s.61$	$-44°08'12''.6$	15.44	$+0.65$
Comparison 2	$10^h03^m39^s.81$	$-44°08'12''.4$	15.63	$+1.08$

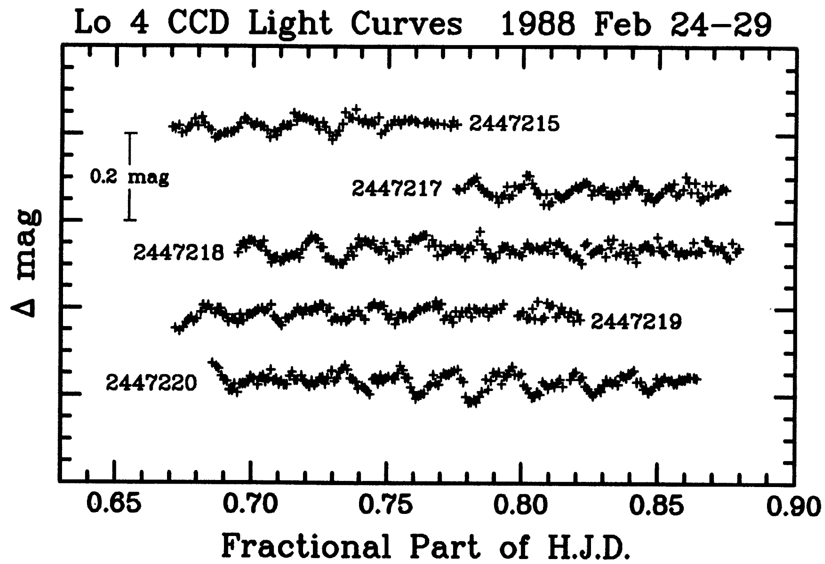

FIG. 1. CCD light curves of the pulsating central star of Longmore 4, obtained on five nights in 1988 February with the CTIO 0.9 m telescope. Each light curve is labeled with the integer part of the Heliocentric Julian Date, and the differential magnitudes are plotted against the fractional part of the H.J.D. and have been arbitrarily displaced vertically; the interval between ticks on the horizontal axis is 0.01 day = 14.4 min. The light curves typically show periods near 31 min, but with considerable beating between numerous individual modes.

cities add spurious "noise" to the scrambled data), and repeated the procedure to see if additional significant periodicities were present. This process converged to the 11 frequencies listed in Table III, which we thus regard as present in the time-series photometry with greater than 99% confidence.

Since, in general, the frequencies of peak power do not lie on the grid points, we determined their precise values by fitting 3-point parabolas in the vicinity of each of the high points in the clean spectrum of Fig. 2(b). A reasonable estimate for the accuracy of the frequencies listed in column 1 of Table III is the change in frequency that would produce a relative phase shift of 0.05 cycle over the 5.2-day data length, i.e., ± 0.0001 mHz. This corresponds to a period accuracy of ± 0.3 s for the strong periods near 1850 s. This estimate was confirmed by injecting tracer signals of known frequen-

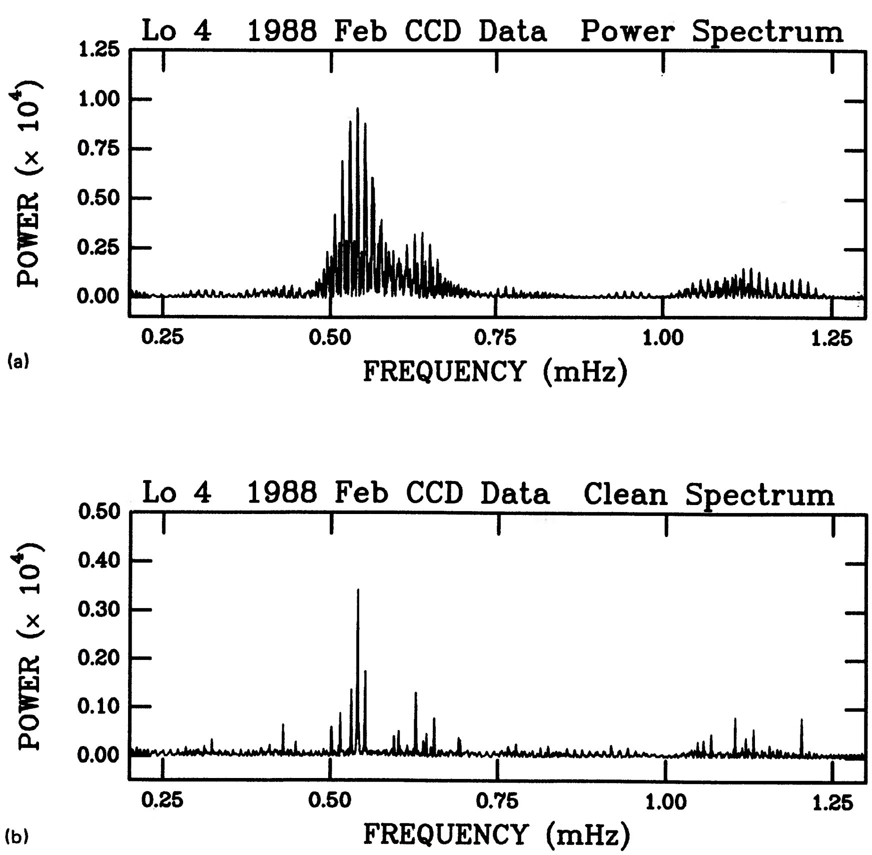

FIG. 2. (a) Power spectrum (square of the fractional amplitude) for the combined five nights of CCD time-series photometry for Lo 4. The complicated alias structure is due to the large gaps in coverage between the nights. (b) Power spectrum with the alias structure removed by the CLEAN algorithm. Most of the power lies in groups of individual frequencies near 0.54 mHz (period 1850 s), 0.64 mHz (1560 s), and 1.14 mHz (875 s). As discussed in the text, at least 11 of the highest peaks appear to represent statistically significant individual periodicities in the time-series photometry.

TABLE III. Pulsation modes in Lo 4.

Frequency (mHz)	Period (s)	Fractional semi-amplitude
0.43006	2325.3	0.0025
0.50180	1992.8	0.0025
0.51482	1942.4	0.0030
0.53097	1883.4	0.0037
0.54042	1850.4	0.0058
0.54262*	1842.9	0.0026
0.55209*	1811.3	0.0042
0.62717	1594.5	0.0036
0.65511	1526.4	0.0028
1.10365	906.1	0.0029
1.20344	831.0	0.0028

*Possible one-day aliases of neighboring strong peaks.

cy into the data, calculating the power spectrum, and CLEANing it; the input frequencies were recovered to within the stated accuracy.

With a power spectrum as complicated as that of Lo 4, there is a real danger that CLEAN will spuriously assign some power to aliases of strong frequencies. This may indeed have happened in our analysis, since the components identified by CLEAN at 0.53097 and 0.54262 mHz (1883.4 and 1842.9 s) and at 0.54042 and 0.55209 mHz (1850.4 and 1811.3 s) are nearly separated by the one-cycle-per-sidereal-day spacing of 0.01161 mHz.

IV. DISCUSSION

a) Spectral Classification and the Driving Mechanism for Pulsating Pre-Degenerates

The hottest, hydrogen-deficient PNNs are assigned to the "O VI" type in the spectral-classification scheme devised by Smith and Aller (1969). Discussions of the general properties of the class have been given by Heap (1982) and Kaler and Shaw (1984). The characteristic feature of O VI objects is the appearance in emission of the O VI 3811–3834 Å doublet. The doublet is weakly present in emission in the spectrum of the pulsating PNN K 1-16 [as can be seen in the spectrum published by Grauer and Bond (1984), although the feature is not labeled], allowing the assignment of K 1-16 to the O VI class.

Heap (1982) and Méndez *et al.* (1986) have pointed out the wide variety of individual spectra among O VI nuclei, and have proposed more detailed spectral-classification schemes for hydrogen-deficient PNNs. In the classification of Méndez *et al.*, they suggest a sequence that proceeds from WC-type spectra with strong emission lines, through the transition objects Abell 30 and 78, to "O-type" objects with mixed absorption and emission spectra. The scheme differentiates between O-type objects like K 1-27 that show only He II absorption, called O(He), and objects like Lo 3, Lo 4, and K 1-16 that also show C IV absorption, called O(C). Existing spectra do not cover the region of the O VI doublet in Lo 4, but Méndez *et al.* (1985) predict that O VI emission will be found to be present.

The spectral classification thus establishes the remarkable similarity of Lo 4 and K 1-16, the other known pulsating PNN. Moreover, both of these objects are quite similar spectroscopically to the four known pulsating GW Vir white dwarfs. Indeed, it would be quite natural to extend the spectral sequence of hydrogen-deficient PNNs defined by Méndez *et al.* (1986) by appending the PG 1159 − 035 class of hot non-PNNs.

The close similarity of the spectra (and therefore of the chemical compositions) among all of these hot pulsating predegenerate stars provides strong circumstantial support for the cyclical-ionization pulsation mechanism proposed by Starrfield and his collaborators, as described in Sec. I, since the mechanism requires hydrogen-deficient, carbon- and oxygen-rich outer layers.

An obvious prediction is that additional hot, hydrogen-deficient PNNs will prove to be pulsating variables. A forthcoming paper (Ciardullo and Bond 1990) will describe a successful search for pulsators among the O VI class.

b) Future Observations: Period Spacings and Period Changes

It appears likely that there is an evolutionary sequence connecting the two pulsating PNNs and the class of GW Vir white dwarfs. Lo 4 and K 1-16 would represent progenitor objects, still surrounded by visible planetary nebulae and having relatively long pulsation periods. As their evolution proceeds, the planetary nebulae will dissipate, and the contraction of the star will produce a trend toward the shorter pulsation periods observed in the four GW Vir pulsators. The evolution toward smaller radii and larger surface gravities apparently also leads to a reduction in the stellar mass-loss rate, since the O VI feature seen in emission in K 1-16 is very weak, or in absorption, in GW Vir stars, as shown by Sion *et al.* (1985).

In fact, the evolutionary timescales for PNNs and their descendant hot white dwarfs (e.g., Schönberner 1983) are so short that detectable changes in the pulsation periods should be occurring. Indeed, an evolutionary change has already been detected in one of the pulsation periods of GW Vir itself, with a timescale of $\sim 10^6$ yr (Winget *et al.* 1985; Kepler 1990). For higher-luminosity PNNs, the timescales are generally expected to be much shorter (e.g., Kawaler, Hansen, and Winget 1985; Kawaler 1987), making the detection of period changes easier in principle.

We are continuing to obtain photometry of Lo 4 in an attempt to detect the evolutionary change in the pulsation periods. The practical requirements for such a detection, however, are formidable; one must have sufficient data both to resolve the pulsation modes fully and to eliminate false identifications of alias periods as true periods, and the star must possess one or more modes that are always present in the power spectra. The problem may ultimately require photometry from several observing sites that are well-separated in longitude.

With sufficient amounts of data, it may also be possible to carry out mode identification for the individual frequency components, as discussed by Kawaler (1987,1988) and Kawaler and Hansen (1989). In particular, these authors point out that one expects a characteristic period spacing for consecutive radial overtones of g modes with the same degree l, have found that GW Vir itself exhibits a uniform period spacing, and have used the resulting determination of l and the value of the period spacing to infer the mass of GW Vir to very high accuracy. We conducted an analysis of the nine strongest periods found in Lo 4 (omitting the two possible one-day aliases identified in the footnote to Table III), using the technique described by Kawaler (1988), and find apparently highly significant period spacings of 8.5 and 36.3 s. However, we regard this analysis as premature until we have obtained considerably more data and have identified the modes with more confidence.

V. SUMMARY

CCD photometry of the central star of the planetary nebula Lo 4 shows it to be a multiperiodic pulsator. Both its spectrum (dominated by features of He II and C IV) and its pulsation periods are very similar to those of the other known pulsating central star, K 1-16.

The hot, pulsating GW Vir white dwarfs also exhibit hydrogen-deficient, carbon-rich compositions. The apparent commonality of such compositions among all of the known hot, pre-degenerate pulsators strongly supports a pulsation mechanism based on cyclical ionization of carbon and/or oxygen.

Future observations may reveal the predicted rapid evolutionary contraction of Lo 4, through the resulting decrease in the pulsation periods.

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