THE ASTRONOMICAL JOURNAL VOLUME 111, NUMBER 6 JUNE 1996

A SURVEY FOR PULSATIONS IN O VI NUCLEI OF PLANETARY NEBULAE

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Received 1996 January 10; revised 1996 February 26

ABSTRACT

We present results of a CCD survey for pulsational variability in a sample of 29 hot, hydrogen-deficient planetary-nebula nuclei (PNNs) with "O VI" (early WC) or "PG 1159" spectra. We identify six PNNs, those of NGC 246, 1501, 2371-2, 2867, 5189, and 6905, as low-amplitude pulsating variables similar to K 1-16 and PG 1159−035 (GW Vir); this brings to 14 the number of PNNs and isolated white dwarfs now known to belong to this class. Time-series analyses show that the PNN pulsators tend to have longer pulsational periods (11.5 to 31 min) than their GW Vir white-dwarf counterparts, but within the PNNs there is little correlation between spectral subtype and pulsation period. Most (if not all) of the PNN pulsators have power spectra that are highly variable on time scales of months or less; this is in contrast to the GW Vir white-dwarf pulsators, whose power spectra generally vary only on time scales of years. The variable power spectra and low pulsation amplitudes suggest that the true fraction of pulsators among hot, hydrogen-deficient PNNs may be higher than found in our survey. © *1996 American Astronomical Society.*

1. INTRODUCTION

The nuclei of the planetary nebulae (PNe) K 1-16 and Lo 4 were found to be low-amplitude pulsating variable stars by Grauer & Bond (1984) and Bond & Meakes (1990). Power spectra show that the complex photometric variations which these stars exhibit are due to the presence of many individual pulsation modes, with typical periods near 30 min and amplitudes of $\lesssim 0.1$ mag. The length and multiplicity of the periods indicate an origin in nonradial *g*-mode pulsations. Both stars have extremely high temperatures ($T_{\rm eff} \gtrsim 100{,}000$ K), and show spectroscopic evidence for hydrogen deficiency and high abundances of carbon and oxygen.

The spectra and pulsational properties of these two planetary-nebula nuclei (PNNs) are very similar to those of the pulsating GW Virginis (PG 1159−035) stars. Like the pulsating PNNs, these objects are extremely hot (pre-)white dwarfs, characterized by low-amplitude ($\lesssim 0.1$ mag) variations occurring on timescales of several minutes (McGraw *et al.* 1979; Bond *et al.* 1984; Bond & Grauer 1987; Werner 1992). Since the GW Vir stars have shorter pulsation periods than the pulsating PNNs, and lack surrounding planetary nebulae, it is natural to suppose that they are the more evolved and more compact descendants of the K 1-16-type central stars.

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To explain the pulsations of these objects, Starrfield *et al.* (1984, 1985) proposed a mechanism involving cyclical ionization and recombination of C and/or O in the outer layers of hot, hydrogen-deficient white dwarfs. This suggestion implies the existence of a C−O pulsational instability strip, and leads to the expectation that other hot, hydrogen-deficient stars in the strip should be pulsators.

However, in spite of the spectroscopic similarities of the known pulsating PNNs and GW Vir variables, not all stars that have these spectroscopic characteristics are pulsators. Using high-speed photoelectric photometry, Grauer *et al.* (1987b) found that none of their 15 program stars (four hot H-deficient PNNs, three white dwarfs with PG 1159-type spectra, and seven other related objects) exhibited significant photometric variability. Moreover, Werner (1992, 1995) has identified two pairs of PG 1159-type white dwarfs with nearly identical spectra, yet one member of each pair pulsates and the other is observed to be stable. In fact, less than half of the spectroscopically identified PG 1159 white dwarfs appear to pulsate (Werner 1995).

Pulsations were discovered in the central star of K 1-16 by Grauer & Bond (1984) using photoelectric aperture photometry. This observational technique is suitable in cases where the PNN is located in a nebula of low surface brightness. However, when the surrounding nebula is bright, small guiding errors and variations in seeing make aperture photometry impossible. Thus previous searches for pulsations in PNNs have generally been limited to those lying in low-surface-brightness nebulae (although Hine 1988 did attempt a survey using special guiding techniques).

 0004-6256/96/111(6)/2332/17/$6.00

CCDs are ideal detectors for searching for variability in nuclei of bright PNe. The two-dimensional format records both the PNN and its surrounding nebula, allowing software apertures that enclose the star and define the background to be created after the fact. Moreover, because CCDs simultaneously measure the PNN, the sky, and several nearby comparison stars, differential photometry can be performed even under bright-sky and/or nonphotometric conditions.

In this paper we report the results of a CCD survey for photometric variability in 29 hot, hydrogen-deficient PNNs. In Sec. 2, we list our targets and briefly discuss the spectral classification schemes that have been applied to these objects. In Secs. 3 and 4, we describe the observations and reduction procedures which allow us to perform relative photometry to $\lesssim 1\%$ accuracy, even when our targets are surrounded by high-surface-brightness nebulae. In Secs. 5 and 6, we discuss our power-spectral analyses, and present the results of our survey, including the identification of six new pulsating PNNs. Finally, Sec. 7 discusses and summarizes the results and suggests avenues for future research.

2. SPECTRAL CLASSIFICATIONS AND TARGET SELECTION

Spectral-classification schemes for central stars in planetary nebulae have evolved as more objects have been observed and as spectroscopic techniques have improved. The hottest hydrogen-deficient PNNs were assigned to the "O VI" type in the early classification scheme of Smith & Aller (1969), and the O VI spectroscopic class has been discussed more recently by Heap (1982) and Kaler & Shaw (1984). The class is defined by the presence of emission at O VI 3811–3834 Å, and this emission feature is present in the spectra of the pulsators K 1−16 (Grauer & Bond 1984) and Lo 4 (Werner *et al.* 1992). Lists of O VI PNNs have been given by Kaler & Shaw (1984) and Kaler *et al.* (1991).

More detailed classification schemes for hot, hydrogen-deficient PNNs have been devised by Heap (1982) and Méndez *et al.* (1986). Heap precedes the O VI type with a "WC," "C," or "C–N" type and a numerical subclass, with "C" and "N" denoting spectra that combine absorption lines with Wolf–Rayet WC- or WN-like emission features. Tylenda *et al.* (1993) have determined WC subclasses for a large number of PNNs (and they note that PNNs with nitrogen features are extremely rare). Méndez *et al.* suggest a sequence, presumably evolutionary as well as spectroscopic, that proceeds from WC-type spectra with strong emission lines, through the transition objects Abell 30 and Abell 78 (with absorption lines as well as strong emission lines), to "O-type" objects with predominantly absorption lines plus weak emission spectra. In this scheme, O(He) objects show only He II absorption, while K 1−16 and Lo 4, which also show C IV absorption, are called O(C).

More recently, Schönberner & Napiwotzki (1990) showed that several PNNs are spectroscopically indistinguishable from the PG 1159−035 white dwarfs (i.e., they have a broad He II and C IV absorption trough near 4686 Å , but lack strong O VI emission), and assigned them a spectral type of "PG 1159." Werner (1992) subdivided these stars (both with and without nebulae) into three subgroups based on the appearance of the He II-C IV trough. In his scheme, "lgE" (low-gravity emission) objects have relatively sharp absorption components underlying their He II and C IV emission (these are the objects called O(C) above), "E" (emission) objects have higher gravity, with a mix of absorption and emission near 4686 Å, and "A" (absorption) objects have a 4686 Å absorption trough with no emission. Finally, Napiwotzki & Schönberner (1991) and Napiwotzki (1992, 1993) have identified several PNNs that appear to be "hybrid" PG 1159 objects in the sense that they show Balmer absorption lines in addition to their characteristic PG 1159 features. These hybrids are denoted "O(H,C)" by Napiwotzki (1993).

Table 1 lists the names of the PNe whose nuclei were selected for monitoring in our survey, along with the Galactic-coordinate designations of their nebulae, the PNNs' (approximate) apparent magnitudes, and their spectral types. For completeness, the three previously known PNN pulsators, K 1−16, Lo 4, and the recently discovered RX J2117.1 +3412 are also included in the list. Most of this information has been taken from the *Strasbourg-ESO Catalogue of Galactic Planetary Nebulae* (Acker *et al.* 1992). Note that three objects, which we designate Lo 3, LoTr 4, and VV 47, are named Wray 17−1, ESO 320−28, and JnEr 1, respectively, by Acker *et al.* In addition, the central star of A 21 has also been called YM 29 in the literature, and Sh 2−68 has been called S 68 or YM 15.

The objects listed in Table 1 represent all but five of the O VI and related hot, hydrogen-deficient PNNs that were known to us as of the early 1990's. We attempted four further objects, NGC 6302, IC 1297, IC 2003, and Th 2−A, but they proved to be too faint for useful observations (i.e., their central stars are fainter than about 17th–18th mag), and we have been unable to date to obtain observations of the nucleus of NGC 6578. About half a dozen additional early WC candidates were noted more recently by Tylenda *et al.* (1993), but we likewise have been unable to obtain observations to date. We also note that the PNN-like field O VI star Sanduleak 3 has been shown to be a pulsating variable (Bond *et al.* 1991), but without a surrounding nebula. This object will be described in a separate paper.

3. OBSERVATIONS AND REDUCTIONS

Our survey observations were obtained between 1986 November and 1994 March with CCD cameras on the 0.9- and 1.5-m telescopes at Kitt Peak National Observatory (KPNO) and Cerro Tololo Inter-American Observatory (CTIO). Each photometric run consisted of a series of short CCD exposures (ranging from 45 to 300 s), with a 10- to 20-s deadtime between each image, depending on the area of the chip that was read out. Observing logs, including the telescope and detector characteristics, are given in Tables 2 and 3, with Table 2 containing those stars which exhibited no significant variability and Table 3 listing our newly discovered pulsating variables. Most of our data were obtained during bright-time runs, often extending through the night of full moon.

In order to suppress the nebular emission and decrease the atmospheric extinction color terms, many of the observations were made through a Strömgren y filter or a 279 Å full-

TABLE 1. Central stars and spectral classifications.

Name	PN G	m_v	Spectrum	Reference
(a) Program Stars Observed in our CCD Photometry Program				
NGC 246	118.8−74.7	11.96	O VI	SA69
			C 3/O VI	H82
			O(C)	MMHK86
			PG 1159/lgE	W92
NGC 650-1	130.9−10.5	15.9	PG 1159	N91
			PG 1159/E	N93
			hgO(C)	N93
NGC 1501	144.4+06.5	14.39	O VI	SA69
			WC 4/O VI	H82
			WC early	MMHK86
			WC 4	TAS93
NGC 2371-2	189.1+19.8	14.85	O VI	SA69
			WC 3:/O VI	H82
			WC early	MMHK86
NGC 2452	243.3−01.0	17.71 *B*	O VI	SA69
			WC 3	H82
NGC 2867	278.1−05.9	16.62 *B*	O VI	SA69
			WC 3	H82
NGC 5189	307.2−03.4	14.92 *B*	O VI	SA69
			WC 2	H82
NGC 5315	309.1−04.3	14.40	WC 4	MMHK86,TAS93
NGC 6369	002.4+05.8	15.94	WC 4	TAS93
NGC 6751	029.2−05.9	15.45	WC 4-N 4/O VI	H82
			WC 4 (str. N)	MMHK86
			WC 4	TAS93
NGC 6905	061.4−09.5	15.7	O VI	SA69
			WC 2/O VI	H82
			WC 3	MMHK86,TAS93
NGC 7026	089.0+00.3	14.20	O VI	SA69
			WC 2/O VI	H82
			WC 3	MMHK86
NGC 7094	066.7−28.2	13.68	"hybrid"	N92
			O(H,C)	N93
IC 1747	130.2+01.3	15.4	O VI	SA69
			WC 4/O VI	H82
			WC 4	MMHK86
A 21	205.1+14.2	15.99	PG 1159	N92
			PG 1159/A:	W92
			PG 1159/E	N93
			hgO(C)	N93
A 30	208.5+33.2	14.38	O VI	SA69
			C 3-N 2/O VI	H82
			A 30-78 (str. N)	MMHK86
			Of-WR(C)	M91
A 43	036.0+17.6	14.75	"hybrid"	N92
			O(H,C)	N93
A 78	081.2−14.9	13.21	O VI	SA69
			C 3-N 2/O VI	H82
			A 30-78 (str. N)	MMHK86
			Of-WR(C)	M91
Ba 1	171.3−25.8	18.7 *B*	O VI	KSK90
He 2-55	286.3+02.8	17.4	WC 3	M91,TAS93
IsWe 1	149.7−03.3	16.56	PG 1159	SN90
			O(C)	M91
			PG 1159/A:	W92
			PG 1159/A	N93
			hgO(C)	N93
Jn 1	104.2−29.6	16.13	PG 1159	K87,SN90
			O(C)	M91
			PG 1159/A:	W92
			PG 1159/E	N93
			hgO(C)	N93
K 1-27	286.8−29.5	16.7	O(He)	MMHK86
Lo 3	258.0−15.7	···	O(C)	MMHK86
LoTr 4	291.4+19.2	···	O(He)	M91

TABLE 1. (continued)

M 3-30	017.9−04.8	17.9 *B*	O VI	KS84
			WC early	MMHK86
PB 6	278.8+04.9	17.6	O VI	KSFI91
			WC 3	TAS93
Sh 2-68	030.6+06.2	16.0 *B*	"hybrid"	NS91
			hgO(H,C)	N93
VV 47	164.8+31.1	16.83	PG 1159	LFGG88
			O(C)	M91
			PG 1159/E:	W92
(b) Previously Known Pulsating PNNs				
K 1-16	094.0+27.4	15.08	PG 1159	GB84
			hgO(C)	MMHK86
			O(C)	M91
			PG 1159/lgE	W92
Lo 4	274.3+09.1	16.6	O(C)	MMHK86
RX J2117.1+3412	080.3−10.4	13.2	PG 1159/lgE	MWP93

References for Table 1: The following coding is used for references: GB84 (Grauer & Bond 1984); H82 (Heap 1982); K87 (Kaler 1987); KS84 (Kaler & Shaw 1984); KSFI91 (Kaler *et al.* 1991); KSK90 (Kaler *et al.* 1990); LFGG88 (Liebert *et al.* 1988); M91 (Méndez 1991); MMHK86 (Méndez *et al.* 1986); MWP93 (Motch *et al.* 1993); N91, N92, N93 (Napiwotzki 1991, 1992, 1993); NS91 (Napiwotzki & Schönberner 1991); SN90 (Schönberner & Napiwotzki 1990); SA69 (Smith & Aller 1969); TAS93 (Tylenda *et al.* 1993); W92 (Werner 1992).

width-half-maximum (FWHM) filter centered at 5279 Å; both these filters effectively exclude the bright nebular [O III] line at 5007 Å, while transmitting the stellar continuum at slightly longer wavelengths. For objects embedded within relatively low-surface-brightness nebulae, we chose to improve our throughput by observing through a broadband *B*, *V*, BG 38, or $CuSO_4$ filter. Each star was typically monitored for several hours on two or three different nights, although a few of the more difficult objects were only observed once. As Table 3 shows, several objects for which pulsations were detected were observed more intensively thereafter.

Since each time sequence typically consisted of over 100 individual CCD frames, a frame-extraction routine was used at the telescope to reduce the data volume to a manageable size. After debiasing and flatfielding the individual CCD images, we chose a set of comparison stars for each PNN, and extracted from each frame a set of 32×32 pixel regions surrounding each star. Typically, at least three comparison stars were chosen for each object, although in a few cases, only one or two suitable stars fell within our CCD field. These "postage stamps" were then moved into a new set of "packed" pictures, in which each image contained the extracted regions from 16 individual frames, arranged in a time sequence. The Universal Times of the exposures were recorded by the KPNO and CTIO data systems to the nearest second (plus a constant offset, which we always measured by direct reference to broadcast signals).

Photometric reductions were accomplished using a combination of routines from IRAF and DAOPHOT (Stetson 1987). For objects located in relatively faint, or bright but uniform nebulae, we measured the PNN and comparison-star magnitudes (with an arbitrary zero point) using the point-spread-function (PSF) fitting algorithms of DAOPHOT. A fitting radius of order half the stellar FWHM was found to provide the highest photometric accuracy. This small "aperture" also enabled us to monitor objects with nearby stellar companions (such as NGC 246) with no fear of photometric contamination.

For several of the PNNs, direct PSF measurements could not be performed, due to bright asymmetrical nebulae. For these objects, we modeled, and then subtracted, the surrounding nebulae from each image. To do this, the PSF of each individual frame was estimated from the comparison stars, and the frames with the sharpest PSFs were summed together. The PSF and comparison star magnitudes for the resulting template image were then calculated, and the sky background removed using the modal sky as determined from the regions surrounding the comparison stars. A model for the nebula was then created by repeatedly guessing the magnitude of the PNN, using the star-subtraction algorithm of DAOPHOT to remove the hypothesized central star, and viewing the results on an image display.

When a satisfactory model for the nebula *sans* PNN was found, (i.e., when the resultant image had neither a "hole" nor a "spike" at the location of the central star), we were ready to perform photometry. The comparison stars of each CCD frame were used to determine the translation, scaling, and smoothing needed to align and match the model nebula with that of the program frame. After this was done, the model nebula was subtracted from the CCD image, and simple aperture photometry was performed on the naked PNN with an aperture diameter of the order of the FWHM. Simulations on our objects show that relative photometry performed in this way should, in general, be accurate to better than 0.01 mag. Figure 1 demonstrates this technique by displaying NGC 2867 with and without its nebula.

In principle, of course, there could be a real nebular hole or spike at the location of the central star. If so, the error introduced by our technique would be a nearly constant, but slightly seeing-dependent, offset in the differential magnitudes. To guard against this possibility, as well as any other systematic error introduced by the complex backgrounds surveyed in this program, we regressed all our derived differential PNN magnitudes against their corresponding seeing measurements. When a correlation with the FWHM was found,

TABLE 2. Observing log—non-pulsators.

Object	UT Date	Telescope	CCD	Pixel Size (″)	Length (hr)	Exp. (s)	Filter	A_{max} (mmag)
NGC 650-1	1989 Oct 10	KP#1 0.9	RCA3	0.86	4.05	300	*B*	3.3
	1989 Oct 11	KP#1 0.9	RCA3	0.86	1.01	420	*B*	11.5
NGC 2452	1991 Jan 3	CT 1.5	Tek4	0.50	3.01	250	*y*	17.5
	1991 Jan 4	CT 1.5	Tek4	0.50	2.18	250	*y*	21.8
NGC 5315	1991 Jan 10	CT 0.9	Tek4	0.44	1.12	120	*y*	6.3
	1991 Jan 14	CT 0.9	Tek4	0.44	2.93	120	*y*	3.3
NGC 6369	1994 Mar 26	CT 0.9	Tek1K2	0.40	2.37	90	BG 38	10.2
	1994 Mar 27	CT 0.9	Tek1K2	0.40	3.78	90	BG 38	6.9
NGC 6751	1989 May 20	KP#1 0.9	RCA3	0.86	2.45	90	*y*	3.5
NGC 7026	1989 Oct 11	KP#1 0.9	RCA3	0.86	3.03	240	*y*	7.9
	1990 Dec 5	KP 0.9	Tek1K	0.76	2.90	200	*y*	5.7
	1990 Dec 6	KP 0.9	Tek1K	0.76	2.52	180	*y*	5.6
NGC 7094	1989 Oct 10	KP#1 0.9	RCA3	0.86	4.54	60	*B*	1.3
IC 1747	1988 Nov 30	KP#1 0.9	RCA3	0.86	6.18	180	*y*	6.5
	1989 Sep 21	KP#1 0.9	Tek2	0.77	1.66	180	*y*	5.9
	1989 Sep 22	KP#1 0.9	Tek2	0.77	2.75	150	*y*	5.3
A 21	1986 Nov 23	KP#1 0.9	RCA1	0.86	4.30	45	*B*	5.8
	1994 Mar 24	CT 0.9	Tek1K2	0.40	2.00	90	BG 38	5.3
	1994 Mar 25	CT 0.9	Tek1K2	0.40	2.49	90	BG 38	6.2
A 30	1990 Apr 11	KP#1 0.9	Tek2	0.77	4.38	75	*B*	2.2
	1990 Apr 14	KP#1 0.9	Tek2	0.77	3.25	90	*B*	3.4
A 43	1989 May 23	KP#1 0.9	RCA3	0.86	3.42	120	*B*	3.5
A 78	1989 Sep 21	KP#1 0.9	Tek2	0.77	3.01	60	*B*	1.9
	1989 Sep 22	KP#1 0.9	Tek2	0.77	1.04	60	*B*	1.4
Ba 1	1989 Sep 22	CT 0.9	RCA5	0.49	2.08	300	BG 38	14.7
	1989 Oct 7	KP#1 0.9	RCA3	0.86	2.39	180	*B*	10.1
	1991 Jan 4	CT 1.5	Tek4	0.50	2.17	250	BG 38	6.4
	1991 Jan 14	CT 0.9	Tek4	0.44	2.00	250	BG 38	6.2
He 2-55	1991 Jan 5	CT 1.5	Tek4	0.50	2.31	180	BG 38	8.9
	1991 Jan 15	CT 0.9	Tek4	0.44	2.36	180	BG 38	5.7
IsWe 1	1989 Oct 12	KP#1 0.9	RCA3	0.86	2.02	150	*B*	4.4
	1990 Dec 2	KP 0.9	Tek1K	0.76	4.86	90	BG 39	5.6
	1990 Dec 4	KP 0.9	Tek1K	0.76	5.45	120	$CuSO_4$	3.4
Jn 1	1988 Oct 18	KP#1 0.9	RCA3	0.86	4.27	90	$CuSO_4$	2.4
	1990 Nov 28	KP 0.9	Tek1K	0.68	3.77	60	$CuSO_4$	4.0
K 1-27	1988 Feb 25	CT 0.9	RCA5	0.49	2.96	60	BG 38	3.3
	1991 Jan 12	CT 0.9	Tek4	0.44	2.75	90	BG 38	2.1
Lo 3	1988 Feb 27	CT 0.9	RCA5	0.49	2.24	75	BG 38	6.2
	1988 Mar 1	CT 0.9	RCA5	0.49	1.82	75	BG 38	7.7
	1989 Jan 21	CT 0.9	RCA5	0.49	4.08	90	BG 38	3.5
	1991 Jan 10	CT 0.9	Tek4	0.44	1.88	90	BG 38	2.9
LoTr 4	1988 Feb 25	CT 0.9	RCA5	0.49	1.98	90	BG 38	5.6
M 3-30	1989 Sep 19	CT 0.9	RCA5	0.49	1.25	200	BG 38	16.3
PB 6	1991 Jan 7	CT 1.5	Tek4	0.50	4.42	250	BG 38	9.0
	1994 Mar 23	CT 0.9	Tek1K2	0.40	4.96	250	*y*	9.0
Sh 2-68	1990 Apr 15	KP#1 0.9	Tek2	0.77	0.80	180	*V*	8.6
VV 47	1987 Dec 27	KP#1 0.9	RCA1	0.86	2.07	45	*B*	15.3
	1989 Apr 10	KP#1 0.9	Tek1	0.77	3.66	90	$CuSO_4$	4.0
	1990 Nov 28	KP 0.9	Tek1K	0.68	3.20	75	$CuSO_4$	4.1
	1990 Dec 5	KP 0.9	Tek1K	0.76	3.81	85	$CuSO_4$	5.2

Note for Table 2: Telescopes are abbreviated as follows: CT 0.9 (CTIO 0.9-m telescope); CT 1.5 (CTIO 1.5-m); KP#1 0.9 (KPNO No. 1 0.9-m); KP 0.9 (KPNO 0.9-m [formerly KPNO No. 2 0.9-m]).

we used a straight-line fit to remove the trend from the data. Even when the seeing varied by factors of 2 or 3, this correction was only a few millimagnitudes at most.

4. DATA ANALYSIS

The procedures described above produced a time series of relative magnitude measurements for each PNN and its comparison stars. To prepare these data for a power-spectrum analysis, we first made sure that none of the reference stars used for comparison were variable by examining their light curves with respect to each other. Those few stars that were suspected of variability were excluded from the reductions. Next, magnitude differences between the PNN and the sum of intensities of the non-variable comparison stars were calculated. These differential magnitudes are extremely insensitive to variations in atmospheric transparency, and useful data were obtained even on nights with as much as $\sim$3 mag of clouds.

Because our comparison stars were usually redder than

TABLE 3. Observing log—pulsators.

Object	UT Date	Telescope	CCD	Pixel Size (″)	Length (hr)	Exp. (s)	Filter
NGC 246	1989 Sep 23	CT 0.9	RCA5	0.49	3.23	60	*B*
	1989 Sep 24	CT 0.9	RCA5	0.49	1.15	45	*B*
	1990 Jun 18	CT 0.9	Tek4	0.44	1.56	90	*B*
NGC 1501	1987 Dec 29	KP#1 0.9	RCA1	0.86	2.42	90	λ5279
	1987 Dec 30	KP#1 0.9	RCA1	0.86	4.82	75	λ5279
	1988 Jan 2	KP#1 0.9	RCA1	0.86	3.20	75	λ5279
	1988 Sep 30	KP#1 0.9	RCA1	0.86	1.85	120	λ5279
	1988 Nov 27	KP#1 0.9	RCA3	0.86	9.18	90	λ5279
	1988 Nov 28	KP#1 0.9	RCA3	0.86	11.66	75	λ5279
	1988 Nov 29	KP#1 0.9	RCA3	0.86	11.54	75	λ5279
	1989 Oct 8	KP#1 0.9	RCA3	0.86	6.39	75	λ5279
	1989 Oct 9	KP#1 0.9	RCA3	0.86	6.32	75	λ5279
	1989 Oct 15	KP#1 0.9	RCA3	0.86	6.68	75	λ5279
	1989 Oct 16	KP#1 0.9	RCA3	0.86	5.66	75	λ5279
	1989 Oct 21	KP#1 0.9	RCA3	0.86	2.41	75	λ5279
	1990 Jan 1	KP#1 0.9	Tek2	0.77	9.25	60	λ5279
	1990 Jan 2	KP#1 0.9	Tek2	0.77	10.03	60	λ5279
	1990 Nov 29	KP 0.9	Tek1K	0.76	11.12	120	λ5279
	1990 Nov 30	KP 0.9	Tek1K	0.76	11.61	90	λ5279
	1990 Dec 3	KP 0.9	Tek1K	0.76	6.23	90	λ5279
	1990 Dec 6	KP 0.9	Tek1K	0.76	5.68	90	λ5279
	1990 Dec 7	KP 0.9	Tek1K	0.76	5.86	90	λ5279
NGC 2371-2	1987 Dec 29	KP#1 0.9	RCA1	0.86	1.93	90	λ5279
	1989 Oct 12	KP#1 0.9	RCA3	0.86	2.55	120	*B*
	1989 Oct 13	KP#1 0.9	RCA3	0.86	2.26	120	*B*
	1989 Oct 14	KP#1 0.9	RCA3	0.86	2.58	120	*B*
	1990 Apr 10	KP#1 0.9	Tek2	0.77	4.11	60	*B*
	1990 Apr 12	KP#1 0.9	Tek2	0.77	4.09	90	*B*
	1990 Apr 13	KP#1 0.9	Tek2	0.77	2.81	60	*B*
	1990 Apr 16	KP#1 0.9	Tek2	0.77	3.75	60	*B*
NGC 2867	1991 Jan 6	CT 1.5	Tek4	0.50	5.67	250	*y*
	1994 Mar 21	CT 0.9	Tek1K2	0.40	5.10	240	*y*
	1994 Mar 22	CT 0.9	Tek1K2	0.40	5.24	240	*y*
NGC 5189	1988 Mar 1	CT 0.9	RCA5	0.49	2.18	90	*y*
	1990 Jun 8-9	CT 0.9	Tek4	0.44	5.01	75	BG 38
	1991 Jan 12	CT 0.9	Tek4	0.44	1.96	90	BG 38
NGC 6905	1989 May 24	KP#1 0.9	RCA3	0.86	0.83	180	*y*
	1989 May 25	KP#1 0.9	RCA3	0.86	3.50	180	*y*
	1989 May 26	KP#1 0.9	RCA3	0.86	3.23	180	*y*
	1989 May 26	CT 0.9	RCA5	0.50	1.60	150	*y*
	1989 May 27	CT 0.9	RCA5	0.50	0.42	75	BG 38
	1989 May 29	CT 0.9	RCA5	0.50	2.85	75	BG 38
	1989 May 30	CT 0.9	RCA5	0.50	1.82	75	BG 38
	1989 Jun 2	CT 0.9	RCA5	0.50	2.03	75	BG 38
	1989 Sep 26	CT 0.9	RCA5	0.50	0.96	75	BG 38
	1989 Oct 7	KP#1 0.9	RCA3	0.86	3.04	120	*y*
	1989 Oct 12	KP#1 0.9	RCA3	0.86	4.25	45	*B*
	1989 Oct 16	KP#1 0.9	RCA3	0.86	3.73	45	*B*
	1989 Oct 21	KP#1 0.9	RCA3	0.86	1.31	45	*B*
	1990 Dec 4	KP 0.9	Tek1K	0.76	1.64	90	*B*

Note for Table 3: Telescopes are abbreviated as in Table 2.

the hot PNNs, our broad-band observations generally contained a significant color term due to differential atmospheric extinction. To correct for this, we regressed our differential magnitudes against airmass, and used a linear fit to remove the trend; when we had data on the same object on more than one night, a mean coefficient was used. Even after this procedure, however, a few of our light curves still displayed slow, low-amplitude changes over a time scale of several hours, of rather uncertain origin. Where present, these were removed by arbitrarily fitting a low-order polynomial to the data. Finally, we computed nightly power spectra of the reduced light curves, using a fast-Fourier transform algorithm written by R. L. White and kindly made available to us.

5. THE NONPULSATORS

Table 2 lists the objects for which we find no evidence for coherent pulsations. The final column in the table gives $A_{\max}$, the maximum Fourier (semi)-amplitude (i.e., the square root of the maximum power) in each night's power spectrum, expressed in millimagnitudes. In general, the period range searched extended from the Nyquist limit (twice

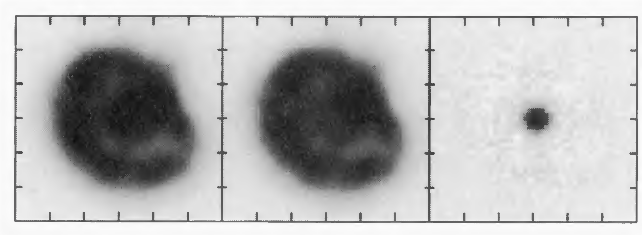

FIG. 1. On the left is an image of NGC 2867 formed by coadding five 240-s exposures with the Cerro Tololo 0.9-m telescope. The central frame is the same image, but with the central star removed via DAOPHOT's star-subtraction algorithm. To obtain this image, the magnitude of the PNN was adjusted as described in the text. The frame on the right displays the bare PNN with the nebula subtracted out.

the sum of the exposure time plus the time between exposures) up to the length of the observing run.

The statistical significance of each observed value of A_{max} was estimated by computing the distribution of A_{max} expected from randomized data possessing the same noise characteristics and time distribution as the real data. To do this, we randomly redistributed the observed PNN magnitudes among the original times of observation, computed a new power spectrum, and noted the resulting value of A_{max}. This randomization was repeated 500 times. For a peak in the power spectrum of the real data to be considered significant at the 99% confidence level, we required that its amplitude exceed 99% of the highest peaks found in the power spectra of the randomized data.

In order for us to label a PNN as a pulsator, we demanded that it either exhibit a higher power-spectrum peak than seen in any of the 500 randomizations, or that it display power at the 99% confidence level at the same (or similar) frequency on at least two different nights. Under these conservative restrictions, none of the A_{max} values listed in Table 2 represent significant pulsations.

Two caveats must be considered, however. First, experience with the known pulsating PNNs and GW Vir white dwarfs (see references cited in Sec. 1 and the discussion below) shows that their light curves occasionally exhibit intervals of very low variability (due to destructive interference between different pulsation modes), which can last up to several hours. Furthermore, as shown below, many pulsating PNNs have highly variable power spectra on longer time scales, and their variations can nearly disappear for extended intervals. Hence it is possible that some of the objects in Table 2 do pulsate, but were in temporary states of low variability during our observing runs.

A second caveat comes from the limited signal-to-noise ratio obtained on some of the fainter targets. Table 2 shows that a few of the PNNs have values of A_{max} that are not particularly restrictive, especially when one considers that the brightest object in our sample, NGC 246, pulsates with an amplitude of only $\sim$2 mmag (see below). Such a low-amplitude pulsation would have gone unnoticed in many of our other program objects. Thus, it is again possible that Table 2 does contain some true pulsators, but that the amplitudes of their pulsations are below the threshold of this survey.

Comments on some of the individual "null" objects appear below:

NGC 650-1. This PNN was too faint to observe through our y or $\lambda 5279$ filters. We therefore used a B filter for the observations and removed the nebula in software via our nebula-modeling technique.

NGC 5315. Even through the y filter, the nebula surrounding this object is bright. It was removed in software via nebula modeling.

NGC 6369. During both of our runs, the nucleus of NGC 6369 showed slow variations, with a time scale of about 2 hr and a peak-to-peak amplitude of $\sim$0.03 mag. We will show in a separate paper (foreshadowed in Bond & Ciardullo 1989) that there is a class of cooler PNNs that exhibit slow, irregular photometric variability. This object may be a hotter member of this class. In addition, the power spectrum for NGC 6369 on 1994 March 26 shows a shorter-period peak at 0.6284 mHz ($P=26.5$ min, amplitude 10.2 mmag), whose formal significance is greater than 99%. A power-spectrum peak near this frequency recurred on the next night, but only at 86% significance. Hence, under our conservative criteria, we do not claim a detection of pulsations.

NGC 7026. This faint PNN appears to have varied by a few hundredths of a magnitude between nights (e.g., from 1990 Dec 5 to Dec 7 it faded by 0.03 mag). However, NGC 7026's nucleus is embedded in a high-surface-brightness nebula, and nebula modeling had to be used to remove this background. Thus it is possible that the offset between the two nights' data arose from small differences in the nebula subtraction.

NGC 7094. During our one available 4.5-hr run, NGC 7094 varied quasi-sinusoidally with a time scale of about 2 hr and an amplitude of 0.02 mag. We suspect that it is an irregularly variable PNN. The A_{max} listed in Table 2 for NGC 7094 is for frequencies greater than 0.3 mHz.

IC 1747. Grauer *et al.* (1987b) observed this object for three nights via photoelectric photometry and found no evidence of pulsations. The PNN, however, is embedded in a high-surface-brightness nebula, so photoelectric aperture photometry is difficult. Indeed, even with the CCD, we could not monitor the central star without first modeling and subtracting the nebula. We note that to do this, two independent models had to be created: one for the 1988 observations taken with the RCA CCD, and one for the 1989 data taken with the Tek2 CCD. In neither of the two data sets did we detect any evidence for short-period variability, but the mean magnitude in the Tek2 data is $\sim$0.06 mag brighter than that recorded by the RCA CCD. Given the different pixel sizes of the two CCDs, this offset could well come from a small difference in the normalization of the two nebula models.

A 30. Grauer *et al.* (1987b) monitored this object photoelectrically for 7.3 hours (over two nights) and found no evidence of pulsational variability. Our 7.6 hours of observations (again spread over two nights) confirm this null result. A 30 apparently brightened by $\sim$0.02 mag between 1990 April 11 and April 14.

A 43. The power spectrum for our one run on Abell 43 shows a peak at 0.4043 mHz ($P=41.2$ min) with $A_{max}=3.5$ mmag; the formal significance of this detection (as defined above) exceeds 99%. Inspection of the light curve indicates that this peak comes primarily from about two cycles of the

TABLE 4. Observed pulsation modes in PNNs.

Object	Date	Frequency (mHz)	Period (s)	Fractional Semi-Amplitude ($\times 10^{-3}$)
NGC 246	1989 Sep 23	0.683	1464±18	1.8
	1989 Sep 24	0.648	1543±55	2.5
	1990 Jun 18	0.543	1842±58	2.0
NGC 2371-2	1989 Oct	0.9944	1005.6±0.6	3.3
		1.0593*	944.0±0.5	2.6
		1.0704*	934.2±0.5	2.8
		1.0826*	923.7±0.5	2.2
	1990 Apr	1.0175	982.8±0.2	9.7
		1.0119	988.2±0.2	4.8
		1.0020	998.0±0.2	2.5
		0.9901	1010.0±0.2	3.0
		0.5480	1825.0±0.6	5.4
NGC 2867	1991 Jan 6	...	...	...
	1994 Mar 21	1.301	769±3	19.9
	1994 Mar 22	1.301	768±3	17.4
NGC 5189	1990 Jun 9	1.448	690±3	2.7
	1991 Jan 12	...	...	...
NGC 6905	1989 May	1.1431	874.8±0.2	6.1
		1.1312	884.0±0.2	2.4
	1989 Sep-Oct	1.09606	912.36±0.04	3.1
		1.12184	891.39±0.04	2.6
		1.13664	879.79±0.04	5.2
		1.17456	851.38±0.03	3.4
		1.40772	710.37±0.02	5.2

Note for Table 4: Asterisks denote modes that may be one-day aliases of adjacent modes.

41-min period that occurred at the beginning of the 3.4-hr run. We prefer not to claim pulsational variability until more data can be obtained. If A 43 does pulsate, its period would be the longest of any PNN or GW Vir star, and it would be the only one with a "hybrid" spectrum (Napiwotzki 1992).

A 78. Grauer *et al.* (1987b) monitored this object for 9.7 hours over three nights and found no evidence for pulsations. Our two nights of observations also indicate that the object is not variable.

He 2-55. This object's mean brightness changed by 0.1 mag over the 10 days between our two runs. It may be another slow, irregular variable.

Jn 1. The highest peaks in the power spectra for our two runs occur at 0.5405 and 0.5385 mHz ($P=30.83$ and 30.95 min, respectively). However, these peaks are only significant at the 83 and 97% levels, so we do not claim pulsational variability. We do note, however, that both possible periods are typical of that seen in the longest-period PNN pulsators, and that Jn 1 does have a PG 1159-type spectrum.

M 3-30. Like NGC 650-1, this faint PNN could only be observed with a wide passband filter, which admitted a large amount of nebular light. This was subsequently removed with the nebula modeling technique.

PB 6. Another faint PNN which required nebula modeling.

VV 47. Our four nights of data do not confirm the short-period variability tentatively reported by Liebert *et al.* (1988) on the basis of photoelectric aperture photometry. However, there is some suggestion in our data that the star may vary by a few hundredths of a magnitude from night to night.

6. THE PULSATORS

Six of our targets exhibited coherent variations consistent with nonradial pulsations. To analyze their light variations, we followed procedures similar to those described by Bond & Meakes (1990). For objects observed only on two or three nights, we simply calculated power spectra separately for each night. However, when an object was observed on several nights within a short interval, we combined the nightly observations to form an extended light curve. We then calculated power spectra for these light curves, and removed the aliasing created by the inter-night gaps using the CLEAN algorithm of Roberts *et al.* (1987).

We began our assessment of the significance of each power-spectrum peak by using the randomization technique described above. However, the presence of periodicities in the real data increases the "noise" level in the light curve, and possibly hides additional real power. To reveal these peaks, we "prewhitened" (i.e., removed) all frequencies identified with $\geqslant 99\%$ confidence from the data, and then recomputed the power spectra and searched for further peaks. We repeated this process until no more significant peaks were found.

Table 4 lists all of the statistically significant modes found in the central stars of NGC 246, NGC 2371-2, NGC 2867, NGC 5189, and NGC 6905. Because of the large number of modes found in NGC 1501, we list these separately in Table 5; due to space limitations only the stronger peaks are included. (A detailed listing and analysis of the modes in NGC 1501 will be presented separately in Bond *et al.* 1996.) The errors listed in both tables correspond to the change in period

TABLE 5. Pulsation modes observed in NGC 1501.

Frequency (mHz)	Period (s)	Fractional Semi-Amplitude ($\times 10^{-3}$)	Frequency (mHz)	Period (s)	Fractional Semi-Amplitude ($\times 10^{-3}$)
	1987 Dec/1988 Jan			*1990 Jan*	
0.79525*	1257.47±0.43	6.6	0.86566	1155.18±1.10	4.7
0.78374*	1275.93±0.44	4.8	0.77537	1289.71±1.38	4.4
0.67598	1479.33±0.60	5.3	0.76668	1304.33±1.41	3.9
0.48781	2050.00±1.15	4.6	0.72863	1372.44±1.56	3.8
0.47904	2087.53±1.19	4.6	0.70787	1412.70±1.65	4.1
0.29533	3386.09±3.13	4.6	0.65604	1524.29±1.92	8.1
0.22987	4350.20±5.16	6.3	0.56892	1757.72±2.55	3.0
			0.53435	1871.45±2.90	3.0
	1988 Nov		0.52159	1917.22±3.04	3.3
			0.46625	2144.75±3.80	2.9
0.72922	1371.34±0.91	7.0	0.30407	3288.71±8.93	2.9
0.70789	1412.65±0.97	5.1	0.28178	3548.92±10.4	3.0
0.65597	1524.47±1.12	10.0	0.22335	4477.33±16.5	5.1
0.53335	1874.95±1.70	4.4	0.21346	4684.83±18.1	3.3
0.23809	4200.07±8.52	3.5	0.17993	5557.56±25.5	3.6
0.14113	7085.84±24.2	3.8	0.15732	6356.38±33.3	3.1
0.10578	9453.74±43.0	4.2	0.14491	6900.87±39.2	4.1
			0.11695	8550.43±60.1	3.2
	1989 Oct		0.07253*	13787.49±156.	4.2
			0.06138*	16291.16±217.	3.2
0.87583	1141.77±0.18	3.6			
0.73025*	1369.39±0.26	3.2		*1990 Nov/Dec*	
0.71845*	1391.88±0.27	3.9			
0.66705*	1499.13±0.31	5.4	0.86556	1155.32±0.18	4.4
0.65583*	1524.79±0.32	5.1	0.76057	1314.80±0.24	2.9
0.56820	1759.96±0.43	5.2	0.75480	1324.85±0.24	3.2
0.55840	1790.84±0.45	4.6	0.73006	1369.74±0.26	3.6
0.53406	1872.44±0.49	3.6	0.70533*	1417.78±0.28	5.8
0.46795	2136.97±0.64	4.0	0.69401*	1440.89±0.28	3.4
0.34501	2898.44±1.17	3.0	0.68948	1450.37±0.29	3.7
0.23783	4204.62±2.47	3.9	0.65627	1523.75±0.32	5.2
0.19210*	5205.63±3.78	2.8	0.51457	1943.36±0.52	3.1
0.18056*	5538.30±4.28	4.9	0.43598	2293.68±0.72	3.0
0.14456	6917.55±6.68	2.8	0.29881	3346.58±1.54	3.0
0.09215	10851.44±16.4	3.6	0.14962	6683.80±6.13	2.9
			0.06287	15904.80±34.6	2.9

Note for Table 5: Asterisks denote modes that may be one-day aliases of adjacent modes.

that would produce a relative phase shift of 0.1 cycle over the length of the observing run. This error estimate is based on simulations in which known periods were injected into the actual data and then recovered. Note that the CLEAN algorithm sometimes puts power into one-day aliases of true peaks; those frequencies where this may have occurred are marked in the tables with an asterisk.

A description of each pulsator appears below.

6.1 NGC 246

The bright ($V=11.775$) central star, BD $-12°134$, is listed as a photometric standard star by Landolt (1983), and as a non-variable by Grauer *et al.* (1987b). However, our data show it to be an extremely low-amplitude (~ 2 mmag) pulsator with periods of 24–31 min. As illustrated in Figs. 2 and 3, our claim of variability comes from the power spectra of three different nights, each of which shows the presence of one peak with greater than 99% confidence. In the two

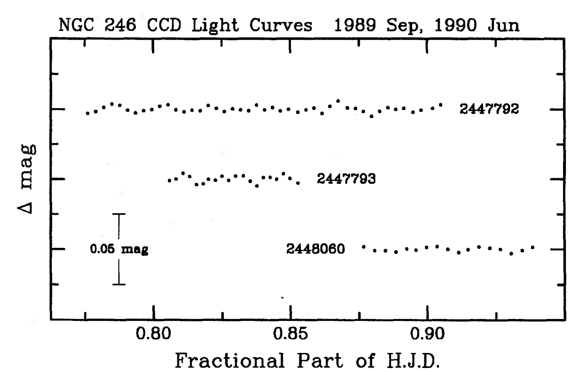

FIG. 2. CCD *B* light curves for NGC 246 for 1989 Sept 23 (top), Sept 24 (middle), and 1990 June 18 (bottom). Each point represents the mean derived magnitude from three adjacent exposures. Note the extremely low amplitude of the variations, which are never more than ~ 0.01 mag peak-to-peak. The curves are labelled with their Julian Dates.

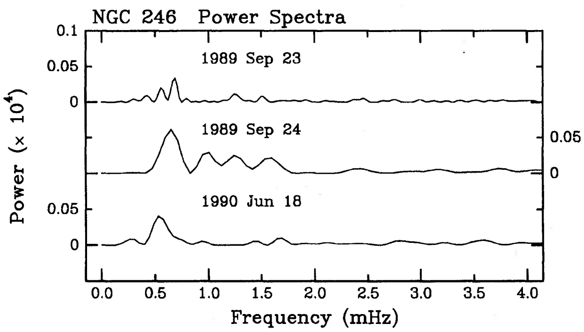

FIG. 3. Power spectra for the three nights of data on NGC 246. The data from 1989 Sept indicate a principal period of 0.67 mHz ($P \simeq 25$ min), while on 1990 Jun 18 the peak is at 0.54 mHz (31 min). The highest peak in each spectrum has greater than 99% significance.

1989 September observations, power was detected at 0.683 and 0.648 mHz; formally, these periods differ at the 1.4σ level, so that two different pulsation modes may be present. The 1990 June 18 data show a peak at a lower frequency (0.54 mHz). On all three nights, the highest peak in the power spectrum falls just at, or below, the detection limit of the Grauer *et al.* (1987b) photoelectric survey.

It should be noted that the central star of NGC 246 has a well-known K-dwarf companion star, ~ 4″ away (Minkowski 1965), which is included in large-aperture photometric measurements such as those of Landolt and Grauer *et al.* Because our PSF fitting technique only uses the core of the image profile, this companion (as well as the nebula) in no way affects our photometry.

6.2 NGC 1501

NGC 1501 is our best-observed PNN, with over ~130 hr of observations distributed over 19 nights and six observing runs. Figure 4 shows a montage of all 19 light curves. The object varies with a typical periodicity near 25 min, and a peak-to-peak amplitude of up to ~0.1 mag. However, as the light curves show, there is considerable variability in the amplitude, and at times the pulsations nearly vanish. This suggests the presence of numerous individual pulsation frequencies.

During five observatory visits we acquired data on more than one night. These observations were combined into multinight data streams, for which we calculated CLEANed power spectra. These are displayed in Fig. 5. It is immediately obvious that NGC 1501's power spectra differ dramatically from run to run. Strong modes that are present in one season can have very different amplitudes at other times, and often disappear completely. For example, the strongest amplitude seen in any of our runs was the 0.656 mHz ($P = 1524$ s) mode of 1988 November, but this frequency was not seen at all in 1987 December. Over the following two years, its amplitude decreased, and in 1990 November it was not even the strongest mode. (During a worldwide campaign on NGC 1501 in 1991 November, this mode was again undetectable.) Inspection of Fig. 5 shows numerous examples of such amplitude variability at other frequencies.

From the data it appears that, of the large number of pulsation modes available to the star, only a selection is excited at any given time. Moreover, the selection of excited modes changes over a time scale as short as three months. This behavior contrasts with that typical of the GW Vir white-dwarf pulsators, which show much greater stability in their power spectra (e.g., Winget *et al.* 1991). We do note, however, that the stronger modes in NGC 1501 are generally confined to a rather small range of frequencies between about 0.656 and 0.866 mHz ($P = 19.2$ to 25.4 min).

The rich pulsation spectrum of NGC 1501, along with its near-circumpolar location in the November sky ($4^h, +61°$), make it an ideal target for a coordinated multisite monitoring program. The first such campaign took place in 1991; the results will appear in a separate paper (Bond *et al.* 1996).

6.3 NGC 2371-2

When we first observed NGC 2371-2 during three nights in 1989 October, the star varied with a peak-to-peak amplitude of only ~0.03 mag. When we revisited the object six months later, the amplitude had increased dramatically, as the light curves in Fig. 6 show. Moreover, as Fig. 7 demonstrates, the power spectra were completely different during the two seasons. In 1989 October, only two significant frequencies were present in the power spectrum (the strong mode at ~15.6 min has been aliased in the CLEANed spectrum into a triplet); in 1990, five new modes are present.

6.4 NGC 2867

NGC 2867 illustrates the vagaries one encounters in monitoring PNNs for variability. We first observed the object for 5.7 hr on 1991 Jan 6 with the CTIO 1.5-m telescope. Although we usually monitor our light curves in near real time, using "quick-look" photometric reductions, this was not possible for this object: its bright, asymmetrical nebula (shown in Fig. 1) makes quick-look photometry impossible. Thus the data reduction had to be postponed until a model of the surrounding nebula could be made. When this was done, the object showed a behavior typical of an irregular or even a binary PNN (cf. Bond 1994), with only a slow, low-amplitude (~0.03 mag peak-to-peak) modulation occurring over a timescale of ~2.5 hr. At higher frequencies (>0.2 mHz), there was no significant variability down to a limit of A_{max}= 7.4 mmag.

In order to pursue the possibility that the star was a very short-period binary, we obtained two additional nights of photometry in 1994 March with the 0.9-m telescope at CTIO. Only then did we detect the star's nonradial pulsations (but the 2.5-hr period was gone!). As Fig. 8 shows, the light curves have a "noisy" appearance, which is due partly to random noise from the bright nebula, and partly to a high-amplitude coherent pulsation. The power spectra in Fig. 9 reveal a single high-amplitude (~18 mmag) pulsation mode, present on both nights in 1994 March at the same frequency of 1.301 mHz (768±3 s). NGC 2867 is thus another example of a pulsating PNN with a highly variable power spectrum. However, it is difficult to attribute the original 2.5-hr

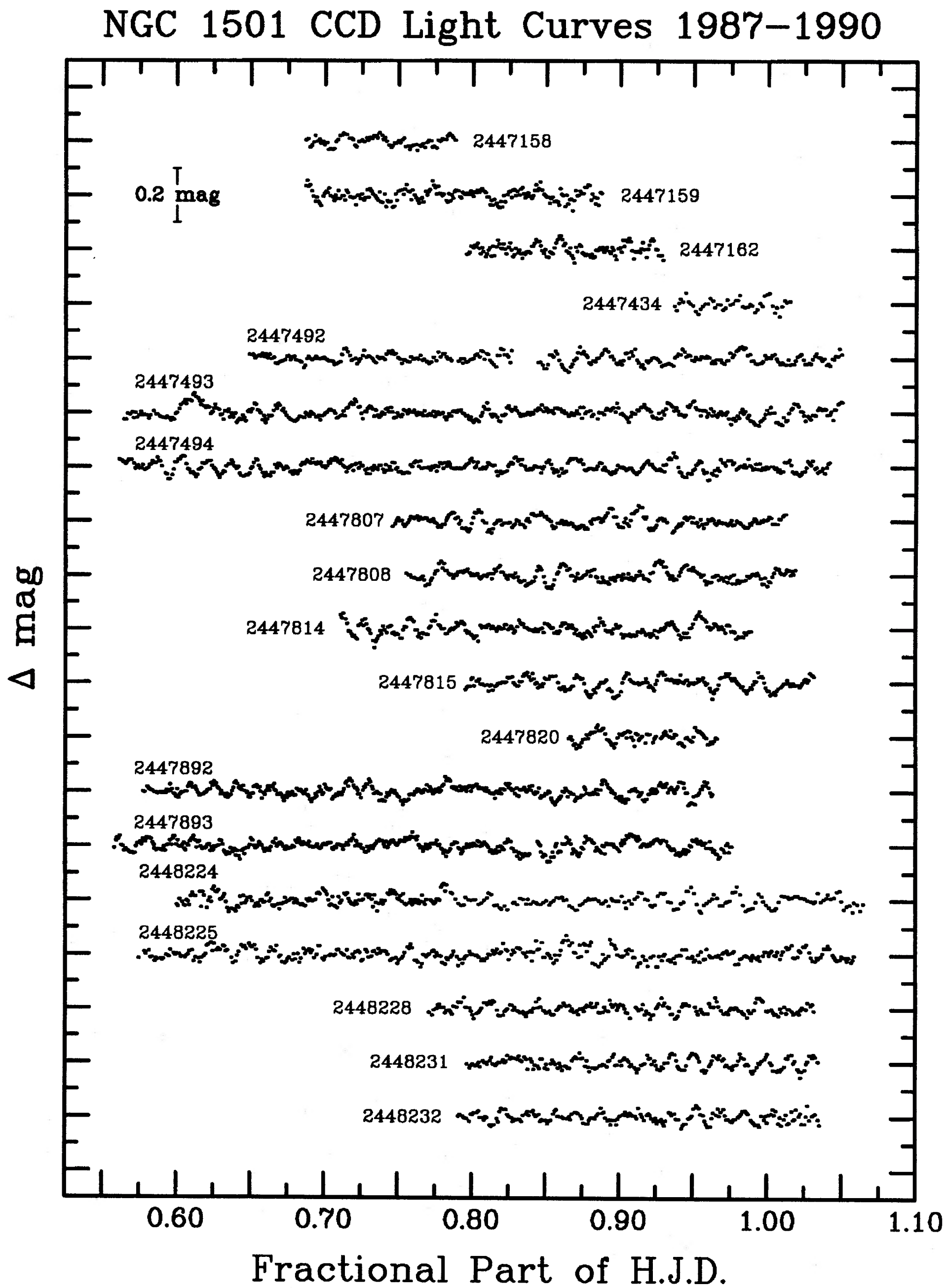

FIG. 4. CCD light curves at 5279 Å for NGC 1501 on 19 nights between 1987 December and 1990 December. Pulsations with a typical period near 25 min are usually present, but are sometimes weak for several cycles. Each curve is labelled with its integer Julian Date, and the x-axis shows the fractional part of the Julian Date. Labelled ticks have a spacing of 0.1 day= 2.4 hours.

variation to pulsations since its period is five times longer than any seen in other hot PNNs; it remains unexplained.

6.5 NGC 5189

Figure 10 shows the light curves of the central star of NGC 5189 on one night each in 1990 and 1991. Our claim of pulsations is based on the data from the longer of our two runs, a 5-hr observation on 1990 June 8–9. During this run, the power spectrum showed one significant peak with an amplitude of 2.7 mmag at a frequency of 1.448 mHz (11.50 ± 0.05 min). Seven months later a 2-hr observation revealed no statistically significant variability; however, since the limiting $A_{\max}$ for this run was only 2.7 mmag, the pulsation seen previously would be at our detection limit. Note that the second light curve does suggest that two or three cycles of the same pulsation period may have occurred at the end of the observation. The power spectrum for the 1990 June 8–9 data is shown in Fig. 11.

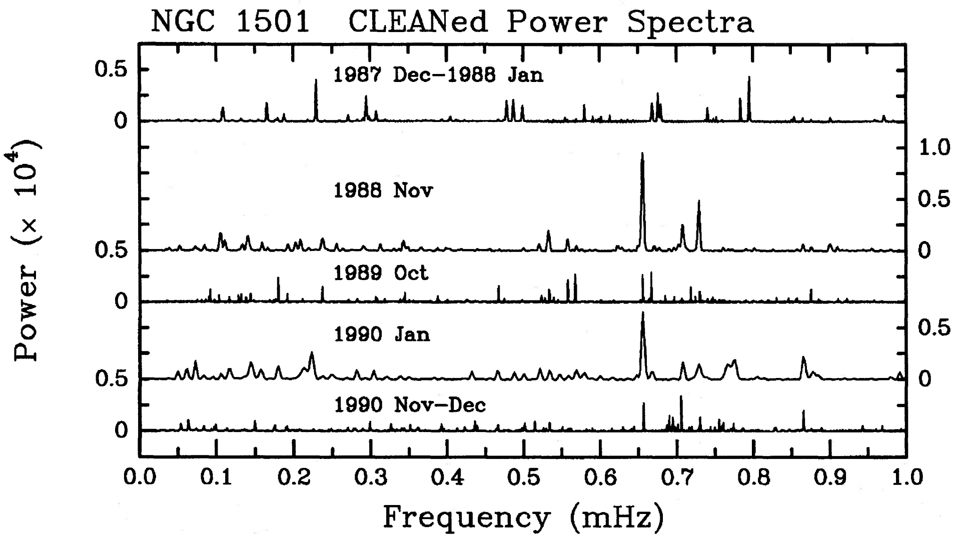

FIG. 5. The CLEANed power spectra of NGC 1501 for five observing runs. No significant power was seen at frequencies greater than 1 mHz. Note the large number of pulsation modes, and their large amplitude variations from one run to the next. The vertical scale is the same for all five spectra.

The mean light level of the central star appeared to brighten by about 0.04 mag between these two runs.

6.6 NGC 6905

Like most of the above pulsating PNNs, this object shows striking variations in its light curves and power spectra. Figure 12 displays all of our light curves, obtained during two multinight runs in 1989 May–June and September–October, plus a lone night in 1990 December. The data on Heliocentric Julian Date (HJD) 2447679 provide a good example of how the photometric variations of a pulsating PNN can virtually disappear for more than two hours. In contrast, the star was very active on all five nights in 1989 September–October, with peak-to-peak amplitudes reaching 0.1 mag on HJD 2447806.

The third run plotted in Fig. 12 (HJD 2447672) began at CTIO and was continued at KPNO, with a small amount of overlap. The agreement between the two data sets in the overlap region is excellent (as indicated by the superposed plotting points appearing to be darker).

Figure 13 shows CLEANed power spectra for NGC 6905 for the first six nights of data on 1989 May and the five nights of data in 1989 September–October. The May spectrum shows only two significant peaks, near ~1.14 mHz (~14.6 min). However, four months later, five significant new modes had appeared, and the original two had disappeared. Like NGC 1501 and NGC 2371-2, the principal pulsation modes of NGC 6905 lie within a fairly restricted range of frequencies (1.09 to 1.41 mHz), but the individual modes that are actually excited change completely on a time scale of a few months (or less).

7. DISCUSSION

There are now 14 known hot hydrogen-deficient pulsating (pre-)degenerate stars: four GW Vir-type DO white dwarfs (GW Vir itself [PG 1159−035], PG 0122+200,

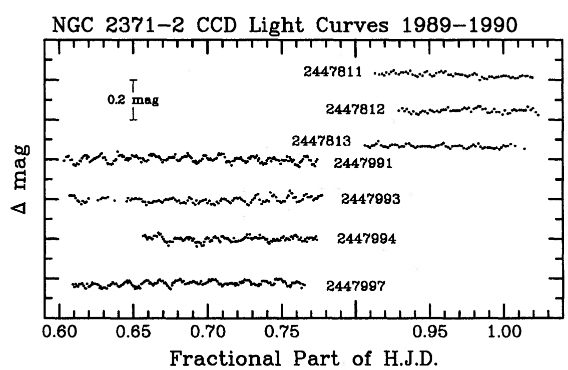

FIG. 6. CCD *B* light curves for NGC 2371-2 during 1989 October (top) and 1990 April (bottom). During 1989, the PNN's variability was barely detectable; by 1990, the amplitudes of the pulsations had strengthened dramatically. The Julian Dates of the runs are indicated.

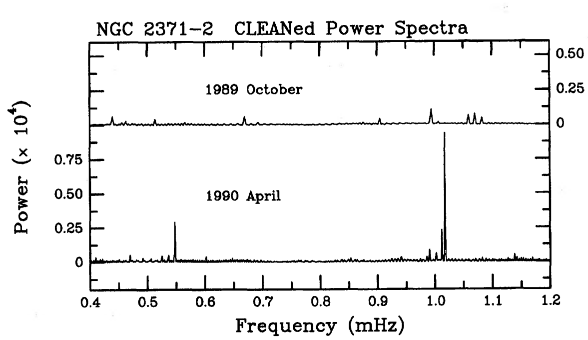

FIG. 7. The CLEANed power spectra for NGC 2371−2. None of the modes present in 1990 April appear in the 1989 October power spectra. The triplet of peaks at ~1.07 mHz in the top spectrum is most likely three one-day aliases of a single peak.

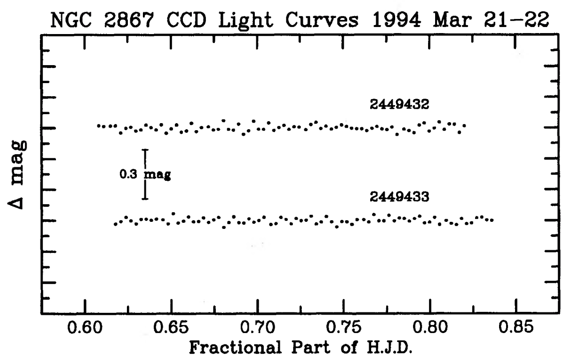

FIG. 8. CCD *y* light curves of NGC 2867 on 1994 Mar 21 (top) and 22 (bottom).

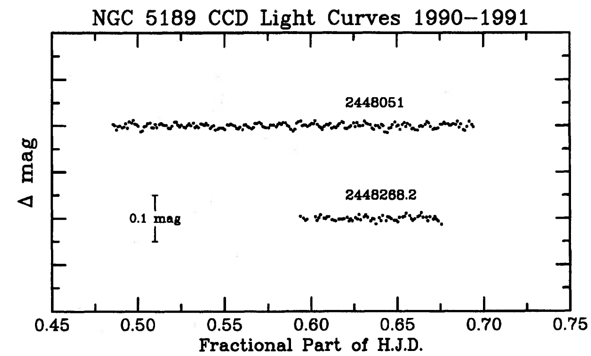

FIG. 10. CCD BG38 light curves of NGC 5189 on 1990 Jun 8–9 (top) and 1991 Jan 12 (bottom). For display purposes we have subtracted 0.2 day from the 1991 times. Low-amplitude pulsations with a period near 11.5 min are seen in the top light curve. A few cycles of the same period may have occurred at the end of the bottom curve.

PG 1707+427, and PG 2131+066), nine planetary-nebula nuclei (the six announced in this paper, plus K 1-16, Lo 4, and RX J2117.1+3412), and the WO-type field star Sanduleak 3 (Bond *et al.* 1991). From the data presented above, it is clear that most (if not all) PNN pulsators have power spectra that vary considerably on time scales of months or less. This is in contrast to the GW Vir pulsators, whose power spectra are much more stable (Koupelis & Winget 1987; Winget *et al.* 1991; Kawaler *et al.* 1995), generally varying only on time scales of years. Why the selection of excited modes in PNNs should change so much more quickly is a mystery. Although these PNNs are in a phase of rapid evolutionary contraction, this time scale is much too slow to account for the observed power-spectrum variations. A more promising hypothesis is suggested by the recent observation of an episode of enhanced mass loss from the pulsating PNN Lo 4 (Werner *et al.* 1992). The detection of this event was made in spite of the object's very brief observational history, implying that such occurrences must be frequent. Since the driving zone for pulsations is close to the stellar surface (e.g., Starrfield *et al.* 1984), such changes in surface conditions may conceivably alter the mode amplitudes. Regular spectroscopic monitoring of hot PNNs (preferably in conjunction with photometric monitoring of the pulsations) will be required in order to see to what extent the stellar winds of these objects vary, and how such changes affect the pulsations.

Whether or not a PNN pulsates seems to have no correlation with its spectral type. Pulsators have been found among all types of O VI central stars, from WC 4 through O(C)/PG 1159. Neither of the "transition" objects A 30 and A 78 pulsate, but as this class contains only two objects, this is not particularly significant. Similarly, none of the three "hybrid" objects in our sample (NGC 7094, A 43, and Sh 2-68) appear to pulsate. Although again based on small-number statistics, this finding was expected in light of the fact that even a small amount of hydrogen will quench pulsations if partial ionization of carbon and oxygen is the driving mechanism (Cox 1986; Starrfield 1987).

Overall, out of the 29 hydrogen-deficient PNNs monitored in our survey, six (20%) were identified as nonradial pulsators, and two others, Jn 1 and NGC 6369, came close to satisfying our criteria. In view of the degree of variability displayed by the power spectra of these objects, and the fact that some of the PNNs may be pulsating at extremely low amplitudes (such as NGC 246), it is possible that the true fraction of pulsators in our sample is much higher.

Figure 14 shows a semi-schematic representation of the mode spectra of the nine known pulsating PNNs and all four known GW Vir white dwarfs. To improve the visibility of the weaker modes, we have plotted amplitudes rather than power, and we have normalized the amplitudes to that of the strongest peak in each spectrum. All detected modes, regard-

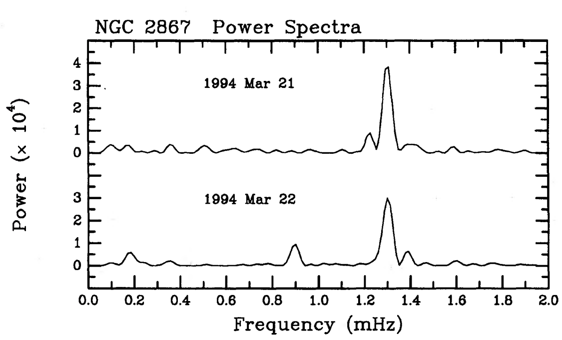

FIG. 9. Power spectra for NGC 2867 on the two nights in 1994 March. A strong pulsation mode was present on both nights at 1.301 mHz (P=12.8 min).

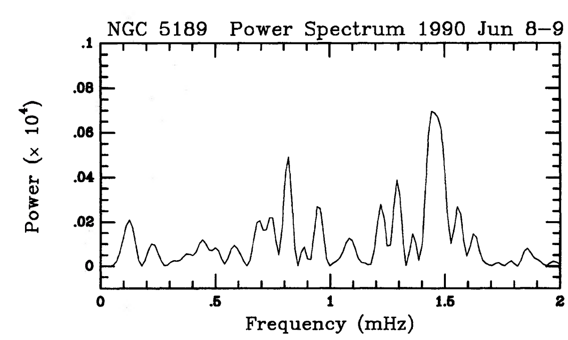

FIG. 11. The power spectrum of NGC 5189 on the night of 1990 Jun 8–9. There is one statistically significant peak at 1.448 mHz (P=11.51±0.05 min).

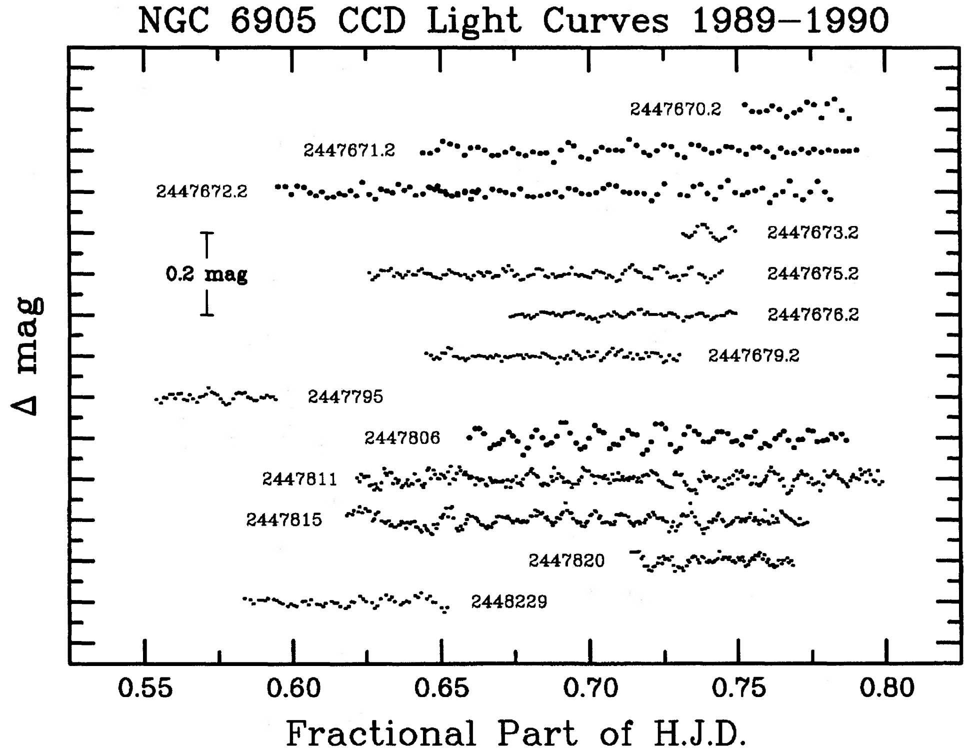

FIG. 12. CCD light curves for NGC 6905 on nights in 1989 May and October and 1990 December. The run on HJD 2447672 began at CTIO and was continued at KPNO, with a small amount of overlap. Note the excellent agreement between the two data sets in the overlap region. For display purposes 0.2 day is subtracted from the 1989 May Julian Day fractions.

less of the epoch of observation, have been plotted; modes with varying amplitudes are displayed with their highest amplitude. For the six pulsators discovered here, the frequencies plotted are as given in Tables 4 and 5; the modes and amplitudes for the other objects are taken from Grauer *et al.* (1987a), Bond & Meakes (1990), Winget *et al.* (1991), Fontaine *et al.* (1991), Vauclair *et al.* (1993), Kawaler *et al.* (1995), and Vauclair *et al.* (1995).

The objects in Fig. 14 are displayed in a spectroscopic sequence, with the WC-type PNNs at the top, O(C) PNNs (in the scheme of Méndez *et al.* 1986) in the middle, and the GW Vir white-dwarf pulsators at the bottom. It is generally

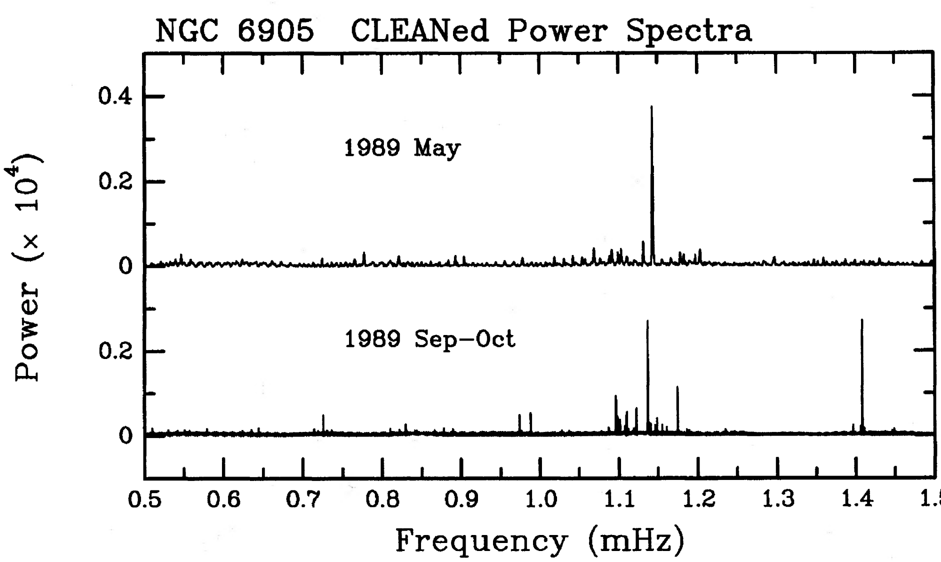

FIG. 13. The CLEANed power spectra of NGC 6905 for 1989 May and 1989 October. Although the power spectra appear qualitatively similar, there is no pulsation frequency that is common to both observing runs.

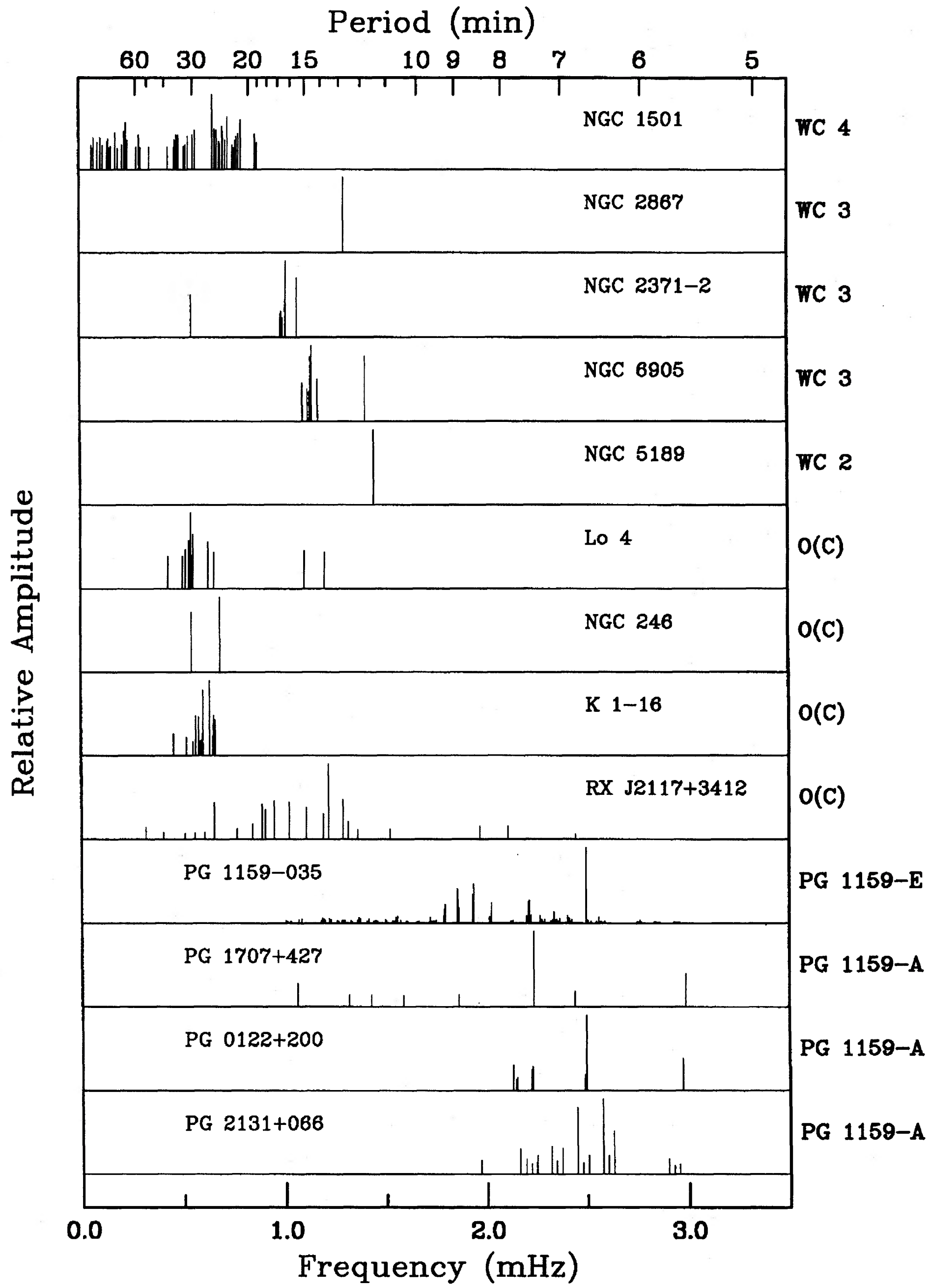

FIG. 14. Semi-schematic amplitude spectra for the nine known pulsating PNNs and four known GW Vir pulsating white dwarfs. Spectral classes for each object are given on the right-hand side. The five WC stars, which lack atmospheric analyses, are presented in order of WC spectral type; the four O(C) PNNs and the four GW Vir white dwarfs are shown in order of increasing surface gravity (as tabulated by Werner 1995). Although the ordering is presumed to correspond to an evolutionary sequence, there is no obvious relation among the PNNs between evolutionary stage and pulsation frequencies. However, the GW Vir pulsators do have systematically shorter periods.

considered (e.g., Werner 1992, 1995, and references therein) that this spectroscopic sequence corresponds to an evolutionary sequence, in which a post-AGB remnant that has been stripped down to layers containing products of hydrogen and helium burning contracts to white-dwarf dimensions. As the star contracts, the initially powerful stellar wind seen in the WC objects dies away, while the surrounding planetary nebula dissipates. Note that the nebular properties are in general agreement with this putative stellar evolutionary sequence: the high-surface-brightness NGC nebulae are at the top of the figure, mostly low-surface-brightness nebulae are in the middle, and the isolated GW Vir stars are at the bottom.

Under this scenario, one would expect that objects with WC and O(C) spectral types would be less evolved and have longer pulsational periods than their PG 1159-type counter-

parts. Indeed, the most obvious feature of Fig. 14 is that the four GW Vir white dwarfs do have systematically higher-frequency modes than do any of the PNNs.[3] However, within the PNNs there is surprisingly little evidence for any evolutionary progression. In fact, the earlier-type WC nuclei have generally *shorter* periods than the presumably less-evolved WC 4 nucleus of NGC 1501, while three of the more-evolved O(C) nuclei have similar periods to those of NGC 1501. One might expect RX J2117.1+3412, which lies within a very large, low-surface-brightness PN (Appleton *et al.* 1993), to be a "transition" object with pulsation frequencies between those of the PNNs and the white dwarfs. Indeed it does have a few high-frequency modes similar to those of the GW Vir pulsators, but overall most of its frequencies are at the lower values typical of the other PNNs. Note that Werner *et al.* (1991) describe NGC 246 and K 1−16 as spectroscopic "twins," and in fact their pulsation modes are at similar frequencies (though the amplitudes in NGC 246 are much lower).

We conclude by mentioning two avenues of future research on pulsating PNNs that are likely to prove fruitful. At present relatively few detailed atmospheric analyses have been performed on our targets, particularly for the WC-type objects with strong stellar winds. While Zanstra temperatures are available for most of the planetaries, these are generally only lower limits. Moreover, placement of these PNNs in the HR diagram requires accurate distances. It would be extremely useful to have detailed atmospheric analyses for hydrogen-deficient PNNs of all spectral types. This would allow a much more detailed comparison of their evolutionary stages with their pulsation characteristics than is currently possible.

The second avenue of research will be multi-site asteroseismological campaigns on individual pulsators found in our survey. The detailed mode spectrum of a pulsating PNN can provide information on its mass, rotation rate, and internal stratification (e.g., Winget *et al.* 1991; Kawaler *et al.* 1995). Moreover, because PNNs are in a phase of rapid evolution, their pulsation periods should be changing at a rate short enough to be detected in a few years or less; such a measurement would provide a direct test of theoretical evolutionary timescales. However, our survey demonstrates that the power spectra of pulsating PNNs change over intervals as short as a few months. This variability will complicate the search for evolutionary period changes, since it may not be possible to follow a single mode for the required period of time. On the other hand, the constantly changing power spectra may facilitate mode identification, since, eventually, a wider variety of the pulsation frequencies available to the star will be sampled. We have begun to exploit the power of asteroseismology with a multisite campaign on the new pulsator NGC 1501. The results will be presented in a forthcoming paper.

[3]The reality of the very low-frequency modes seen only in NGC 1501 (below about 0.25 mHz) is somewhat dubious since, as mentioned above, low-amplitude variations on timescales of a few hours may arise from subtle instrumental effects, and/or phenomena related to stellar winds. In any case, only the circumpolar NGC 1501 had light curves on individual nights that were long enough to show periods of this length, so their absence from the other PNNs is of no significance.

We acknowledge generous allocations of observing time and staff support from Kitt Peak National and Cerro Tololo Inter-American Observatories. We thank B. Goodrich for early assistance with the observing program and the "cdphot" postage-stamp extraction routine. Skillful support at the CTIO telescopes during these tedious observations was provided by E. Cosgrove, M. Fernandez, A. Gomez, L. Gonzalez, M. Hernandez, D. Maturana, O. Saa, N. Saavedra, H. Tirado, and R. Venegas.

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