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HIGH-FREQUENCY STELLAR OSCILLATIONS. V. POWER SPECTRA FOR THE CENTRAL STARS OF PLANETARY NEBULAE

BARRY M. LASKER
Cerro Tololo Inter-American Observatory* and The University of Michigan

AND

JAMES E. HESSER
Cerro Tololo Inter-American Observatory*
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ABSTRACT

Photoelectric time-series data have been used to calculate power spectra for the central stars of sixteen planetary nebulae. No periodic activity is evident in the range from 4 to ~700 seconds. The continua of the power spectra have also been examined; no clear differences from those for white dwarfs are evident.

I. INTRODUCTION

The central stars of planetary nebulae (CSPN) have only recently begun to receive adequate attention from astronomers. One fundamental observational question concerning these objects is: What are the properties of their variability? A photographic survey of fourteen nebulae (Kohoutek 1966) indicates that a significant fraction of their central stars vary on a time scale of ~30 years. Consequently, Herbig and Boyarchuk (1968), Kostjakova *et al.* (1968), Liller and Shao (1968), Koelbloed (1968), and Kazarian (1968) have begun photoelectric studies that are already providing additional evidence for the existence of low-frequency variations in the CSPN.

Working at much higher frequencies, Lawrence, Ostriker, and Hesser (1967, hereinafter referenced as LOH) briefly reported an attempt to measure the power spectra of the central stars of NGC 1514 and NGC 2392 in the period range from 2 to ~500 seconds. LOH suspected NGC 1514 of flickering, as well as of exhibiting low-amplitude and possibly periodic activity at about 138 and 855 seconds; but they also noted that the effects of poor seeing may have introduced spurious peaks into their power spectra. Additionally, the two objects observed by LOH may not be representative of the class of CSPN: Kohoutek (1966) found an apparent secular increase in the brightness of NGC 1514 of ~0.005 mag year^{-1}, and suggested that it is a binary system (Kohoutek 1967); also, he could not exclude the possibility that the nucleus of NGC 2392 was variable. Furthermore, NGC 2392, possessing an extremely bright nebula, is not a good candidate for photometry under the conditions of mediocre seeing in which LOH worked; however, it remains an object of particular interest because of Liller's (1965) suggestion that it may have undergone continuous mass loss in the last 60 years.

It therefore seemed appropriate for us to examine a larger sample of CSPN from a location of superior seeing and transparency. In this paper we shall describe observations made at the Cerro Tololo Inter-American Observatory for sixteen such stars for which we have used the resultant power spectra to search for activity in the period range from 4 to ~700 sec. In the course of this work we had opportunity to observe a wider sample of degenerate stars than is the subject of this paper; a brief description of those results may be found elsewhere (Lasker and Hesser 1970; Hesser and Lasker 1970 hereafter called Paper IV).

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II. OBSERVATIONS AND ANALYSIS

The observational techniques and apparatus are identical with those described in Paper IV. A standard 1P21 single-channel offset-guiding photometer was used on the 36- and No. 2 16-inch telescopes at Cerro Tololo to obtain, typically, *UBV* measurements for identification, followed by about 2 hours of monitoring with a 2-sec integration time. All observations at the 36-inch telescope were guided to better than 1″ accuracy; the same applied at the 16-inch telescope, except that sporadic malfunctioning of the drive mechanism occasionally caused much larger errors.

The stars to be observed were selected from the *Catalog of Galactic Planetary Nebulae* (Perek and Kohoutek 1967), principally on the following basis: first, that the contrast between the central star and the adjacent nebulosity was high; and, second, that the nebular light was either spatially uniform or so distributed that it could pass through the diaphragm without introducing significant sensitivity to seeing or to guiding. Short-exposure Curtis-Schmidt plates were occasionally needed to assist in identifying the exciting stars. For each object observed, the diaphragm size was chosen at the telescope to give the least sensitivity to seeing and to guiding errors; objects exhibiting readily detectable sensitivity to such errors in all diaphragms were removed from the program. Since much of this observing was done under full-Moon conditions, our program stars were frequently selected for brightness.

Generally, *UBV* standards were obtained twice nightly, and then representatives of these standards were monitored for about 10 min in order to determine the high-frequency photometric properties of the night. On nights of dubious quality, white dwarfs (Paper IV) or field stars were monitored for 45 min or more to provide a basis for subsequent evaluation of sky conditions. The observations, as well as certain analytical parameters to be discussed below, are given in Table 1, whose format is nearly identical with that used in Paper IV.

Standard techniques of spectral analysis, such as those described by Blackman and Tukey (1968), Bingham, Godfrey, and Tukey (1967), Hesser, Ostriker, and Lawrence (1969, hereinafter referenced as HOL), and Paper IV, were used. Generally a power spectrum containing all frequencies from the Nyquist frequency to the reciprocal of the total record length was computed. In the computations a window width was used which was nearly equal to the total record length. Our analyses have been checked in two ways: one, observations of white dwarfs (Paper IV), which are known from the work of HOL to be inactive, were used as quiescency standards; and, two, observations of nova DQ Herculis obtained at Kitt Peak in 1969 April yielded results in agreement with the findings of Walker (1954) for the 71-second variation. Examples of power spectra for representative quiescent objects may be found in HOL and in Paper IV.

III. RESULTS

a) Harmonic Activity

On the average, no low-amplitude periodic variability greater than $\sim$0.003 mag has been found in any of the stars listed in Table 1 in the period range relevant to the data (2τ to $\frac{1}{10}\tau N$, where τ is the integration time and $\tau N = T$ is the total record length).[1] Typically this range is from 4 to 680 seconds. Furthermore, the length of these observing runs would probably have been sufficient to detect the presence of longer-period activity such as that manifested by HZ 29 (Ostriker and Hesser 1968*b*) or G44−32 (Lasker and Hesser 1969), and we suggest that these stars are most probably not periodically or quasi-periodically variable on time scales extending to $\frac{1}{5}\tau N$ (typically 20–25 min) as well.

[1] Additionally, studies of NGC 40 and IC II 2149 by Ostriker and Hesser (1968*a*) also gave strong null results in the period range from 4 to $\sim$500 seconds. The former object was definitely nonvariable in Kohoutek's (1966) survey, whereas the latter was suspected of secular variations of -0.004 mag year^{-1}.

TABLE 1

SUMMARY OF OBSERVATIONS*

Designation Common	Catalog	Mag.	Sp.T.	Date	Time(UT)	Tel.	Dia.	N	A_{max}	$T(A_{max}; sec)$	Q	x
NGC 1360	220-53°1	9.9p		01/01-02/69	02:00:21	36	4	3738	0.0011	683	0.005	-0.77
				02/05-06/69	00:41:42	16	3	3597	0.0022	93.1	0.010	-0.50
NGC 1535	206-40°1	11.59*	Of*	12/27-28/68	03:08:05	36	3	3317	0.0023	482	0.005	-1.36
				01/03-04/69	02:04:24	36	3	7589*	0.0070	585	0.010	-1.17
NGC 2346	215+ 3°1	10.84p	A*	01/02-03/69	05:40:57	36	4	4147	0.0031	745	0.005	-1.28
				01/21-22/69	03:48:11	16	3	3703	0.0027	18.7	0.015*	+0.17
NGC 3132	272+12°1	8.8	A*	01/03-04/69	05:39:49	36	3	1791	0.0031	120	0.005	-0.76
				01/04-05/69	05:51:08	36	3	3899	0.0012	683	0.005	-0.51
VV 1-4	197- 2°1	11.4p		01/06-07/69	03:48:06	36	4	3569	0.0017	9.6	0.005	-0.15
				01/18-19/69	03:50:44	16	4	2659	0.0063*	410	0.020*	-1.34*
VV 1-7	235+ 1°1	8.5?p	B9?	01/01-02/69	04:31:23	36	4	3703	0.0006	119	0.004	-0.26
				01/13-14/69	03:27:27	16	3	3616	0.0011	431	0.005	-1.58
A-7	215-30°1	15.45	sdOk	01/07-08/69	02:07:26	36	4	1561	0.0065	20.5	0.015	-0.31
				01/22-23/69	01:45:41	36	3	3661	0.0040	341	0.015	-0.53
A-15	233-16°1	15.72	sdOp	01/25-26/69	01:26:55	36	3	3801	0.0044	8.3	0.013	-0.07
A-30	208+33°1	14.30*	O5fep	01/07-08/69	06:50:58	36	3	2541	0.0043	46.8	0.008	-0.31
				01/27-28/69	05:50:20	36	3	3457	0.0029	6.2	0.013	+0.26
A-34	248+29°1	16.32		01/25-26/69	06:29:21	36	3	3969	0.0051*	18.1	0.022*	+0.01*
A-36	318+41°1	11.51*	sdO7	02/05-06/69	06:17:47	16	3	1931	0.0017	83.6	0.007	-0.04
				02/06-07/69	07:04:03	16	3	3073	0.0029	178	0.008	-0.50
IC 418	215-24°1	9.57*	O7-WC7	12/29-30/68	02:44:45	36	4	3625	0.0005	431	0.004	-1.49
				01/20-21/69	02:47:18	16	4	3640	0.0006	6.6	0.005	-0.38
J-320	190-17°1	13.5p	*	01/02-03/69	01:49:01	36	4	3877	0.0058	455	0.006	-1.87
				02/06-07/69	01:08:58	16	3	4711	0.0100*	862	0.027*	-0.61*
HF-39	288- 0°1	10.5p	Beq-	01/05-06/69	06:47:25	36	4	2617	0.0006	30.2	0.003	-0.63
			P Cyg	01/14-15/69	07:54:48	16	3	1007	0.0009	56.5	0.006	*
				02/06-07/69	05:01:00	16	3	3297	0.0016	7.0	0.007	-0.34
Sh2-266	195- 0°1	11.5p		02/07-08/69	02:08:02	16	3	3633	0.0031	84.5	0.016	-0.07
				02/08-09/69	00:53:14	16	3	3647	0.0027	13.7	0.013	+0.12
AG Car*	289- 0°1	7.7-8.5var	Beq*	01/13-14/69	06:18:34	16	3	3527	0.0007	178	0.005	+0.20

NOTES TO TABLE 1

* GENERAL NOTES.—Wherever an asterisk (*) appears in the body of the table, a note pertaining to that star will be found below. Round diaphragms were used for all observations; at the 36-inch telescope, dia. 3 = 12".5 and dia. 4 = 26".8; at the 16-inch telescope, dia. 3 = 28" and dia. 4 = 60". All data, except where noted, were taken with an integration time of 2 sec. Unless otherwise referenced, all magnitude and spectral-type information is from the catalog of Perek and Kohoutek (1967).

NGC 1535. Magnitude from Kostjakova, *et al.* (1968); Aller (1968) gives spectral type as "O, abs." $\tau = 1$ sec for night of 1969 January 3–4.

NGC 2346. Spectral type from Aller (1968); suspected variable (Kohoutek 1966). Possibly not exciting star, according to Kohoutek (1968). Some difficulty was experienced in guiding telescope on 1969 January 22–23.

NGC 3132. Spectral type from Aller (1968), who notes strong K-line. Evans (1964) doubts that it is the exciting star.

VV 1-4. Reticle light interference increased noise level; object appears to be nonvariable and values of Q, $A_{\max}$, and x not included in means.

A-30. Abell (1966) suspects it is a variable.

A-34. Critical guiding with star placed eccentrically in diaphragm was necessary to avoid faint red star under conditions of poor seeing and probably accounts for large Q-values; Q, $A_{\max}$, or x not used in means.

A-36. Noted by Abell (1966) to be a suspected variable; Liller and Shao (1968) find $V = 11.43$.

IC 418. Magnitude by Kostjakova *et al.* (1968).

J320. Large guide errors in early portion of data set. Object appears to be nonvariable, but values of Q, $A_{\max}$, and x not used in means.

HF 39. Run too short to justify analysis for x.

AG Car. Thackeray (1956) notes the P Cyg characteristics and that it is much brighter than any other planetary nebula known; consequently we did not use it in forming means. Inspection of observations on 1969 January 1–2, which have not been spectrum-analyzed, confirms nonvariability of AG Car in the higher frequency range.

The amplitude of the largest Fourier power peak in the high-resolution spectrum of each data set is listed in Table 1 under $A_{\max}$; these points are believed to represent noise peaks (see HOL).

The amplitude calibration was made by mathematically adding a sine wave of 1 percent amplitude to the original data set before analysis (see HOL for details). The resultant $A_{\max}$ values are somewhat approximate in that it was difficult, especially with the 16-inch telescope, to determine the contribution of nebular light to the total intensity monitored. In cases where the majority of the nebulosity was inside the observing diaphragm, significant errors in $A_{\max}$ are possible; however, this should not weaken our principal conclusion, as in no case does $A_{\max}$ exceed HOL's criterion of $\langle P \rangle$, the mean spectral-power level, by more than a small factor.

The noise statistic, Q, which is independent of the intensity and which varies proportionally to the noise amplitude, of an object (see HOL for a complete definition and discussion) has a mean of 0.008 ± 0.001 for twenty-six selected CSPN observations of Table 1; and the mean of $A_{\max}$ for the same sample is 0.0026 ± 0.0004. These parameters are compared with those for other observations in Table 2. The CSPN do appear quieter than the white dwarfs; however, as explained in Paper IV, our strongest efforts and best observing conditions were used on CSPN; therefore, the somewhat greater noisiness of the white dwarfs may be an effect of observational selection.

b) The Continuous Power Spectra

In the manner described in Paper IV, we characterize the rapidly decaying, low-frequency parts of the power spectra by a function of the form $P(f) \propto f^x$ for each spectrum for the period range from $\frac{1}{10}T$ to $\frac{1}{83}T$; it is in this range that lower-frequency or aperiodic ("flickering") behavior would manifest itself. The results are given under x in Table 1 and are compared with those for other data in Table 3. The values of x do vary greatly, with σ_x being comparable to x. This is at least partly attributable to our treating the sky background and extinction according to HOL; clearly a continuous subtraction by using either a two-cell or a chopping photometer would be superior.

TABLE 2

COMPARATIVE NOISE STATISTICS

	N	$\langle Q \rangle$	σ_i*	σ_m†	$\langle A_{max} \rangle$	$\sigma_{A_{max}}$
White dwarfs:						
Cerro Tololo..	12	0.011	0.008	0.002	0.004	0.004
Princeton‡....	42	0.019	0.016	0.002	0.012	0.009
CSPN:						
Cerro Tololo..	26	0.008	0.004	0.0008	0.0026	0.0018

* Standard deviation for $\langle Q \rangle$.
† $\sigma_m = \sigma_i/\sqrt{N}$ (Poisson statistics assumed).
‡ See HOL.

TABLE 3

LOW-FREQUENCY SLOPE FOR SELECTED CERRO TOLOLO DATA

Object	Conditions	No. of Observations	x	σ_x
White dwarfs........	All data combined	9	−0.31	0.29
	36-inch	5	−0.32	0.33
	16-inch	4	−0.29	0.28
Planetaries..........	All data combined	17	−0.59	0.57
	36-inch: all data	11	−0.81	0.59
	36-inch: diaphragm 3	6	−0.68	0.57
	36-inch: diaphragm 4	5	−0.96	0.63
	16-inch: all data	6	−0.16	0.28
Field stars...........	All data combined	5	−0.23	0.60

However, the preliminary results presented here are of interest, if only as a guide to future experiment. In Table 3, from which data possibly rendered less reliable by a moonrise, moonset, or some obvious difficulty have been removed, we find $\langle x \rangle = -0.59 \pm 0.57$, which is to be compared with the white dwarf value of -0.31 ± 0.29. The initially steeper falloff for the CSPN is at least partly attributable to the residual effects of seeing on the nebulosity. As we were aware of more serious guiding errors at the 16-inch telescope and as the optical and mechanical integrity of the 36-inch telescope is much superior, it is perhaps noteworthy that the 36-inch data taken alone indicate a somewhat steeper decay to the low-frequency continuum for the CSPN than for white dwarfs, i.e., $x = -0.81 \pm 0.59$ and -0.32 ± 0.33, respectively. It may also be seen from Table 3 that the diaphragm diameter at the 36-inch telescope only marginally affected the mean value of x.

IV. DISCUSSION

Clearly it is important to decide if the initial results of LOH were seriously influenced by seeing effects, for the present study indicates that a wider sample of CSPN are quite inactive in a similar frequency range. The NGC 1514 results, for example, are of considerable theoretical importance (see, e.g., Rose 1967) if confirmed. At this time we must tentatively conclude that the excitation of high-frequency oscillations in the CSPN is either insignificant or highly transitory, occurring in short evolutionary stages.

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