High-Frequency Stellar Oscillations. The Cerro Tololo Search for Luminosity-Variable White Dwarfs

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(Read by W. KUNKEL, Cerro Tololo)

Abstract

The techniques and procedures of time-series monitoring and Fourier analysis which are used at Cerro Tololo to search for luminosity variations in white dwarfs are summarized. Further null results from this program, which are applicable to the problem of defining the region of white-dwarf variability in the HR-diagram, are considered; and the properties of the four known variables are reviewed as possible archetypes of a group.

„Some stars are big, and some stars are little" — LUCY

I. *Introduction*

The same theoretical arguments that explain the conspicuous (and often periodic) luminosity fluctuations in non-degenerate stars are relevant to the degenerate ones. The calculations of pulsation periods for white dwarfs have been summarized by OSTRIKER (1971); periods of the order of 2 to about 50 sec. are expected for radial pulsations in zero-temperature white dwarfs. Rapid rotation shortens the periods to as little as 1/4 sec. (OSTRIKER and TASSOUL 1968), while certain non-radial modes (HARPER and ROSE 1970) give somewhat longer periods. Binary and/or rotational phenomena could also result in quite short periods.

Yet the situation as of five years ago was that no variable white dwarfs had been discovered outside of binary systems, where their presence is inferred from studies of nova-like variables [see e. g., WALKER (1954, 1957), MUMFORD (1967)]. It appeared that white dwarf variables are either very few in number or moderately difficult to detect. The climate for a systematic search for luminosity variable white dwarfs (LVWD) became more favorable after the spectroscopic and photometric investigation by EGGEN and GREENSTEIN (1965a, b, 1967; hereinafter referenced as EG).

That the anticipated periods are so short and that no variables are known from any previous routine photometry implied that new techniques were required to make an effective survey. The necessary new techniques were, *first*, automatic data-registering equipment for acquiring long data sets at high time resolution on the candidate objects, and *second*, the so-called fast Fourier transform (FFT) algorithm (COOLEY and TUKEY 1965) for taking Fourier transforms in N ln (N) operations rather than the N^2 naively required.

These techniques clearly define the procedures to be used. The Fourier transform is used to search for periodic „signals" in a long data set, and its easy use implies that the elements of the data set are to be equally spaced in time. A periodic signal in the time domain appears as a peak in the frequency domain (power spectrum), while random noise in the data appears as a flat noise component in the frequency domain. Similar operations are routinely employed by communications engineers (see e. g., BLACKMAN and TUKEY 1958) for analysis of signals buried in noise.

Initial observations following this outline were begun at the Princeton University Observatory in 1966; no evidence for luminosity variations of white dwarfs in the period range, 2 to $\sim$ 360 sec, was found [LAWRENCE, OSTRIKER and HESSER 1967 (LOH); HESSER, OSTRIKER and LAWRENCE 1969 (HOL)]. Observations of nova DQ Herculis 1934 (WALKER 1954, 1957), however, demonstrated that the techniques were sufficiently sensitive to study much smaller variations with the same instrumental configuration (single channel photometer with no filter and a 36-inch telescope). It was also learned that limits on variability

https://doi.org/10.1017/S0252921100032887 Published online by Cambridge University Press

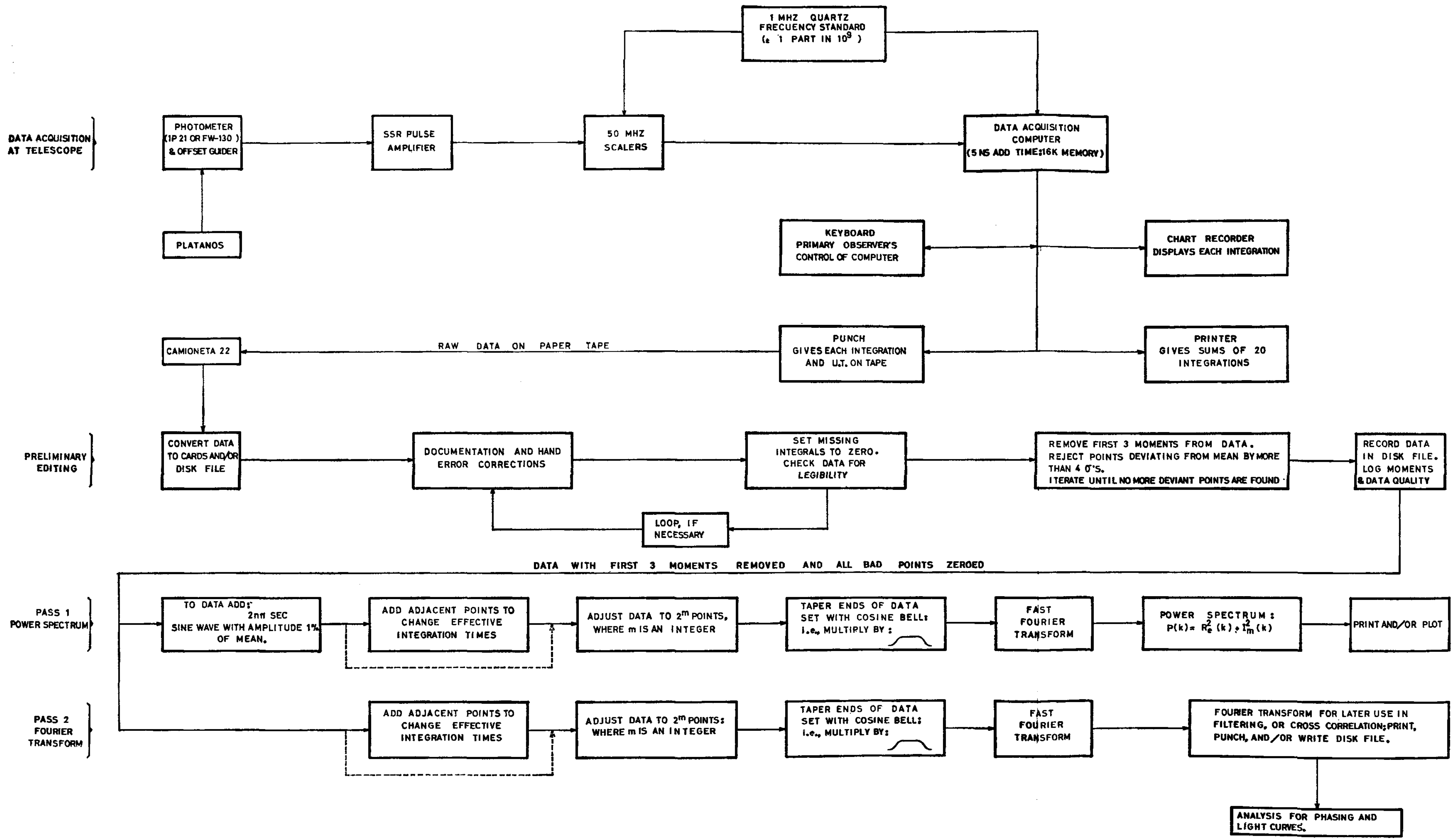

Fig. 1: A block diagram representing the acquisition, editing, and two-pass analysis schemes employed in the Cerro Tololo search for luminosity variations in degenerate stars.

https://doi.org/10.1017/S0252921100082887 Published online by Cambridge University Press

obtainable through routine photometry generally only under good conditions at superior sites were routinely achievable under less favorable conditions with the new approach. Usually two data sets were taken on each star so that comparison between independent power spectra could be used either to confirm or deny a possible high-frequency variation or to increase the detection probability for objects not always varying.

Although the initial Princeton search failed to discover any variables, the announcements of variability in two stars spectroscopically certified to be white dwarfs, HZ 29 (SMAK 1967) and HL Tau 76 (LANDOLT 1968), proved that LVWD do exist outside of binary systems. As the detailed study of HZ 29 [OSTRIKER and HESSER 1968 (OH)], of DQ Her (HERBST, OSTRIKER and HESSER 1970), and of numerous quiescent objects had demonstrated the efficacy of the power-spectral technique, we decided in 1969 to continue the search from the darker and more stable skies of Cerro Tololo. Our subsequent experiences are summarized in the remainder of this paper.

II. Techniques

We have used single channel, off-setting photometers of conventional design with 1P21 or FW 130 photomultipliers for all observations. Pulse counting and accurately controlled timing intervals are used throughout, both being readily available with the Cerro Tololo data acquisition computer system (LASKER 1971a, b). Our observing procedure is, typically, to monitor a candidate for $\sim$ 120 minutes in integrated light with 2.0 second integration times. Sky measurements are usually made only at the beginning and end of a data set; and, as the Fourier transform used in the analysis does not respond well to numerous breaks in the data set, no comparison star measurements are taken during the monitoring. We thus rely heavily on the sky stability; however, for the period and amplitude ranges of current interest, 4 seconds to $\lesssim$ 25 minutes and $\lesssim$ 0.015 mag., respectively, extinction, changes in background, guiding errors, etc., do not degrade the data in an unrecoverable manner.

The consecutive, equally-spaced integrations are outputted from buffers within the computer onto paper tape for off-line analysis. The U.T. is derived from a crystal clock (with stability of $\sim$ 1 part in 10^9) and is punched after every seventh integration. Numerical output is available to the observer from a teletype on the observing platform, as is a conventional analog display on a chart recorder.

The starting point in an analysis is to remove the first three moments (in time) from the data set and then to reject all points departing from the quadratic fit to the data by more than 4σ. The process is repeated, using newly-calculated sets of moments, until no more points are rejected. Since each unnecessary discontinuity in the time domain produces what amounts to noise in the frequency domain (i. e., irrelevant sine waves), the editing process greatly reduces the spurious noise level in the final power spectrum.

Following the editing process a statistic defined in HOL as

$$Q = (\sigma^2 - m)^{1/2}/m,$$

where m is the mean count rate and σ is the standard deviation, is generated to characterize the intrinsic variability of the data set. This statistic has proven useful in a number of specific cases; and we plan to introduce on-line calculation of it and related parameters (see MURDIN et al. 1971) as soon as possible. The general values for Q in quiescent objects are given in HESSER and LASKER [1971a (Paper IV)] and LASKER and HESSER [1971a (Paper V)]. We specifically note that the value of Q depends on the atmosphere, as well as on fluctuations intrinsic to the star, and thus is useful in describing the photometric quality of the sky.

We sometimes add to the edited data a sine wave whose amplitude is 1 percent of the mean count rate; the appearance of the consequent delta-like tracer in the power spectrum is a check on the frequency scale, the presence of unwanted side-lobes, resolution, etc., as well as a measure of the amplitude of any suspected variation. Obviously, for an accurate relative amplitude calibration, good sky measurements are required. The ends of the data set are generally smoothed with a split cosine bell (see BINGHAM et al. 1967).

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The spectral analysis itself follows the precepts recommended in BLACKMAN and TUKEY (1958), BINGHAM et al. (1967) and SINGLETON (1967) and is performed on an IBM 1130 computer. A block diagram summarizing the entire procedure is given in Figure 1.

Among the improvements that could be made to the program described above, we mention only two, one instrumental and one scientific. Instrumentally, significant improvements in the reliability of the low-frequency portion of the power spectrum can be achieved with a (star)/(sky) or (star)/(reference star) chopping photometer. Scientifically, although the limited survey of HOROWITZ et al. (1971) suggests that twe have not overlooked high-frequency activity, more work should be done with increased time resolution.

III. *Pre-white-dwarf stages*

The evolutionary precursors of at least some white dwarfs are generally presumed (O'DELL, 1971) to be the central stars of planetary nebulae (CSPN). Calculations (ROSE 1967) indicate that the fundamental pulsational modes of helium-shell burning stars of 0.75 $M_{\odot}$ are about 300 seconds. Associating such models with the CSPN suggests that one look for high-frequency variations, as well as the low-frequency ones already known or suspected (KOHOUTEK, 1966; HERBIG and BOYARCHUK, 1968; KOSTJAKOVA et al. 1968; LILLER and SHAO, 1968; KOELBLOED, 1968; KAZARIAN, 1968).

Three such surveys have been reported. Our observations at Cerro Tololo (Paper V) failed to produce any variable CSPN in the period range of 4 to $\sim$ 700 sec with amplitudes greater than, typically, 0.003 mag. HOROWITZ et al. (1971) extended the high-frequency limit to 100 Hz for a smaller list of stars, with only slightly less stringent amplitude limits for their null result. LOH, however, suspected the nucleus of NGC 1514 of flickering on a rapid time scale; their observations clearly need to be repeated under optimum conditions. Tentatively, we conclude that high-frequency oscillations in CSPN are either non-existent or highly transitory phenomena; but it would be of value to extend the survey to a wider range of objects and frequencies.

IV. *The quiescent white dwarfs*

The results given in HOL and in Paper IV for white dwarfs demonstrate their general quiescency in the frequency range from 2 to about 700 sec. Typical values for the noise parameter, Q, (see section II), and for A_{max}, the maximum Fourier amplitude in the relevant frequency range, are 0.011 and 0.004 mag., respectively. Moreover, for four objects, the work of HOROWITZ et al. (1971) suggests that this result is valid up to 0.006 sec.

Since the preparation of Paper IV, we have observed 21 white dwarfs, all but one of which have proven to be quiescent; their properties are summarized in Table I, which is in the same format as Table I in Paper IV. In these recent observations we have made greater efforts to obtain second data sets for each object in order to compare two independent power spectra for coincidences *and also* in order to increase the probability of detecting variations not always present. [The later point is relevant to R 548 (see section V) and to HL Tau 76, WARNER and NATHER (1970)]. Special attention has been paid to the region of the two-colour plane at $B{-}V \approx +0.25$ and $U{-}B \approx -0.55$, which contains three of the four known LVWD [LASKER and HESSER, 1971b (Paper VI)]. These new null results sufficiently augment the set of quiescent degenerate stars to be of value in attempting a delineation of the group properties of the variable ones. We shall proceed with this after a brief consideration of the individual known variables.

V. *The luminosity-variable white dwarf stars*

Excluding binary systems such as DQ Her, four LVWD stars have been discovered; their properties are given in Table II. From the two-color plot, Figure 2, one notes the congregation of LVWD near the junction of the blackbody line and EG's empirical boundary for DA spectral types at $B{-}V \sim +0.25$, $U{-}B \sim -0.55$. Some specific characteristics of the individual LVWD stars are noteworthy.

https://doi.org/10.1017/S0252921100032887 Published online by Cambridge University Press

Table 1: Summary of additional observations of white dwarfs⁺

Designation Discover	EG	V	Sp. T.	Date	Time (U.T.)	N	A_{max} (mag)	T (A_{max}; sec)	Q
W1	2	15.31	(DA)	10/29—30/70⁺	02:33:35	3696	.008	256.0	.005
				10/31—01/70*⁺	00:41:44	3738	.004	303.4	.009
L796—10	6*	15.26	(DA)	10/28—29/70⁺	04:23:34	3626	.006	53.5	.006
				10/29—30/70⁺	00:12:34	3724	.009	482	.017
R548	10*	14.1	DA						
HZ 10	30	14.14	DA	01/27—28/71	00:49:37	3073	.003	12.8	.026
HZ 2	31*	13.86	DA	10/27—28/70⁺	05:26:08	4800	.003	13.6	.0009
				10/28—29/70⁺	06:55:18	2856	.002	120.0	.005
HZ 9	38*	13.95	DAe	10/29—30/70⁺	05:01:19	2940	.002	117.0	.006
				11/22—23/70	05:46:47	4269	.003	138.8	.007
L879—14	41*	14.10	4670	11/01—02/70	07:48:43	1862	.002	6.704	.006
HZ 14	42	13.83	DAn	01/29—30/71	00:54:54	3759	.003	40.16	.011
G102—39	44*	15.86	DC	01/25—26/71	02:22:38	3647	.005	482.0	.011
L745—46 A	54*	12.98	DF	01/25—26/71	04:44:52	2048	.001	151.7	.009
NGC 2477—116	55*	13.66		01/03—04/71	04:47:49	1848	.001	24.82	.005
				01/04—05/71	04:08:10	3633	.003	683.0	.009
				02/22—23/71	00:27:29	3808	.003	70.62	.014
L97—12	56*	14.5	DC	01/08—09/71	05:01:51	1813	.005	91.0	.011
				01/29—30/71	03:19:02	3661	.003	12.10	.008
L817—13	57	13.56	DA	02/24—25/71	02:17:42	3773	.002	303.4	.006
G 49—33	69*	15.09	DA	01/29—30/71	05:35:03	3619	.006	12.98	.012
L825—14	70*	12.97	DAn	01/03—04/71	07:06:34	1407	.001	390.0	.007
L898—25	74*	14.28	DA	01/28—29/71	05:34:36	3629	.005	390.0	.010
				02/24—25/71	04:48:37	3472	.003	41.17	.009
R627	79	14.24	DF	01/28—29/71⁺	07:38:12	2065	.003	68.27	.012
L94	163*	14.6		08/08—09/71⁺	06:45:58	6300	.002	68.2	.0015
				08/09—10/71⁺	05:29:43	8869	.004	108.5	.0025
L362—81	165*	13.05	(DAs)	10/27—28/70⁺	01:36:54	5467	$\geq$.003	546.1	.005
				10/28—29/70⁺	01:41:04	3668	$\geq$.001	61.60	.003
				11/01—02/70⁺	00:26:21	1938	$\geq$.001	2.727	.005
G 163—27*		14.35		01/26—27/71	04:51:40	6574	.002	273.1	.009
				01/27—28/71	05:59:59	4361	.005	221.4	.010
				01/29—30/71	07:42:25	2100	.003	74.47	.010
BD +16°516*		9.6		01/26—27/71	00:53:18	1638	.003	157.5	.011
				01/26—27/71	01:20:36	3633	$\geq$.001	8.063	.012

Notes:

Where an asterisk (*) appears in the body of the table, a note pertaining to that star follows. Except as noted, the data were acquired using a 1P21 photomultiplier with no filter; and the integration time was 1.99 sec with integral spacings of 2.00 ± 10^{-9} sec. A cross (⁺) indicates the use of an FW-130 photomultiplier (S-20 response).

EG 2. Observed as a control on the night in which activity in R 548 (Paper VI) was discovered.

EG 6. Seeing deteriorated badly during observations on 10/29—30/70.

EG 10. R 548. A variable with 213 and 273 sec. periods; see Paper VI.

EG 31. Periodic guide errors associated with telescope drive are possibly responsible for 120 sec. activity on 10/28—29/70.

EG 38. EG comment, „Probably an unresolved double of DA and dMe types.“ See also HUMASON and ZWICKY (1947).

EG 41. One sec. spacings; earlier observations given in Paper IV.

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EG 44. Observations made with two stars in the diaphragm.
EG 54. Eccentric guiding used to isolate star.
EG 55. Four sec. spacings on 01/03—04/71.
EG 56. Clouds formed during observing on 01/08—09/71. Earlier data in Paper IV.
EG 69. Data taken at large airmass.
EG 70. Four sec. spacings. Earlier data in Paper IV.
EG 74. Guiding difficulties encountered on 01/28—29/71.
EG 163. Both stars included in the diaphragm; U filter used on 08/09—19/71.
EG 165. Both stars included in diaphragm.
BD $+16^{\circ}516$. One sec. spacings. First data set taken during entry to primary eclipse, second, during exit (see NELSON and YOUNG 1970).
G 163—27. Guiding difficulties on 01/26—27/71.

Table 2: Parameters for the known luminosity-variable white dwarfs‡

Name	EG	V	B—V	U—B	Spectrum	Period (sec.)	Amplitude (mag)	Coherent?	References*
HZ 29	91	14.2	−0.23	−1.01	DBp	1051.118 ± 0.015	0.01	yes	Period: OSTRIKER and HESSER (1968); SMAK (1967)
HL Tau 76	265	15.2	+0.20	−0.50	DA†	750	0.3	no	Period: LANDOLT (1968); Spectrum: LANDOLT (1968); Coherence: WARNER and NATHER (1970)
G44—32	72	16.6	+0.29	−0.58	DC	1638 822 600	0.02	?[1]	Period: LASKER and HESSER (1969); Spectrum: GREENSTEIN (1970)
R548	10	14.1	+0.20	−0.54	DA	212.864 ± 0.031 273.0 ± 0.6	0.01	yes?[2]	Period: LASKER and HESSER (1971)

‡ None of the stars in this table have known polarization variations.
* Spectral classification and UBV photometry from EGGEN and GREENSTEIN (1965) except as noted.
† LANDOLT's spectrum variation not confirmed by GREENSTEIN (1969, 1970).
[1] Data insufficient for a phase analysis.
[2] Analysis of phase properties of R548 in progress.

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HZ 29 (SMAK 1967) has regular periodic variations with a 17.52 minute cycle (OH). The light curve is a double sine wave with amplitude ∼ 0.01 mag. (OH). Standing quite apart from the other three, HZ 29 is the bluest of the four variables in Figure 2. Spectroscopically, HZ 29 has been found to be a DBp star possessing shallow, possibly double He I lines (GREENSTEIN and MATTHEWS 1957). The peculiar spectrum has aroused much speculation BURBIDGE et al. 1967), which has been summarized in OH. That it may be an evolved descendant of a magnetic variable, presently having a surface magnetic field near 10^7 gauss (OH), has been challenged but not refuted by the circular polarization measurements of ANGEL and LANDSTREET (1970).

HL Taurus 76 (LANDOLT 1968) has a quasi-periodicity of about 12.5 min. with an amplitude of ∼ 0.3 mag. This amplitude is distinguished by being a factor of 10 larger than those for the other three variables. WARNER and NATHER (1970) have shown that under certain conditions the variations disappear and that, upon reappearance, they have clearly lost phase coherence with their previous oscillations. LANDOLT's (1968) spectral-type assignment of DA has been confirmed by GREENSTEIN (1969, 1970), but possible spectral variations remain unconfirmed. VILA (1970, 1971) has proposed pulsational models for this object.

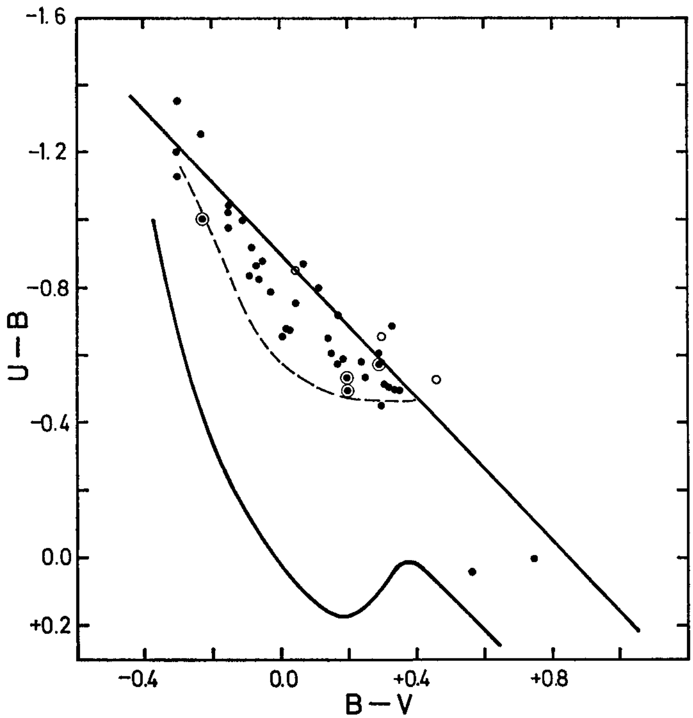

Fig. 2: The two-color diagram for white dwarfs according to GREENSTEIN (1969), in which we plot white dwarfs that have been observed to be quiescent in the Princeton-Tololo searches for LVWD as dots, the four known LVWD as circled dots, and the three white dwarfs for which measurable circular polarization has been reported as open circles. The dashed curve represents EG's empirical boundary for white dwarfs of DA spectral type.

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G44—32 (LASKER and HESSER 1969) is the faintest of the known LVWD and is the only one of DC type (GREENSTEIN 1970). The variability appears complex from our limited data: periods at 10.0, 13.7 and 27.3 min. are found in our power spectra with relative strengths (clustered about 0.02 mag.) varying from night to night. No light curve is available at this time. WARNER et al. (1970) recorded a momentary brightening, apparently due to an optical flare pertaining to the star, during an observation in early 1970. EGGEN (1970) found no infrared excess in this object, implying that it is not accompanied by a bright dMe companion. G44—32 is in need of extensive further observation. It would seem particularly valuable to confirm that the star is DC and not DA, for it is the one luminosity-variable object that implies — from MATSUSHIMA and TERASHITA's (1969) discussion of EG's parallel sequences in the M_V, U—V plane — that the range of M_V may be large for the LVWD.

R 548 (Paper VI) appears to possess two nearly sinusoidal variations of 213- and 273-sec. periods and with amplitudes of ~0.01 mag. Although we originally believed that the 213 sec. period was clearly dominant in amplitude, analysis of extensive observations shows that the role of maximum amplitude on a given night is shared about equally between the two periodicities. Furthermore, on some nights the activity level is extremely low and, from these nights alone, discovery would have been unlikely. The most fundamental questions to be answered concern the nature of the variations: Are they coherent? Are they filtered stochastic processes? What is the nature of the amplitude modulation? Is phase modulation present? From extensive data acquired during the 1970—1971 season, we are attempting to resolve these issues using the methods described above and in OH. The result is uncertain at this time, primarily because we have only one data set sufficiently long that we may extrapolate phase to the next night. However, preliminary results indicate that the 213-sec. period remains constant to better than 0.25 % over 24 hours and a light curve has been constructed (Paper VI). From a single trail image-tube spectrogram obtained with the 60-inch telescope on Cerro Tololo[1]), we confirm the DA spectral type and note no dramatic spectral changes with phase. Additionally, simultaneous two-color observations (HESSER and LASKER 1971b) suggest that the star is reddest at maximum light.

VI. *Summary*

From the data in hand, some of the characteristics that have begun to emerge for the class of LVWD may be listed.

I) Only *about 10 % of all white dwarfs observed to date are luminosity variables with* amplitudes in excess of, typically, 0.004 mag. in the period range of our survey.

II) The observed periods of the LVWD are at least 10 times longer than expected from simple, zero-temperature, pulsation theory.

III) Three of the four variables (R 548, G44—32, and HL Tau 76), appear to exhibit complex variability, which, at times, almost disappears. Clean sinusoidal variations are observed in at least one of the objects (HZ 29).

IV) Amplitudes in the unfiltered spectral region covered by most photometric observations made to date range from a few thousandths of a magnitude to a few tenths.

V) Only one star, HZ 29, the hottest variable, has shown phase stability over a long (3 months) time interval; R 548, for which the analysis is incomplete, may also be stable.

VI) There exists an apparent grouping of LVWD near B—V ~ + 0.25, and U—B ~ —0.55.

VII) Quiescent white dwarfs are found in the same region of the two-color plane as the LVWD, thus indicating the existence of parameters other than position in that diagram which influence the variability.

VIII) A variety of spectral types are represented by the LVWD, as well as by the quiescent stars.

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[1]) We are particularly grateful to Dr. W. E. KUNKEL for his help with the Carnegie image-tube spectrograph.

https://doi.org/10.1017/S0252921100032887 Published online by Cambridge University Press

IX) No connection between luminosity variability and measurable circular polarization has, to our knowledge, been reported.

X) The polarization stars (EG 129, 248 and 250) do not seem to share the same region of the two-color plane as the LVWD (see Figure 2).

XI) No accurate absolute magnitudes are available for any of the LVWD.

This outline of the currently known properties of the LVWD is certainly a provisional one and it will be surprising if a number of items do not undergo at least modest revision in the coming months. However, it clarifies, for the present moment, the five areas in which active efforts should be particularly useful: I) delineation of variables from non-variables; II) comparative analysis of the properties of the variables; III) further investigation of the oscillatory properties of the known LVWD's; IV) determination of fundamental parameters, especially absolute magnitudes, for the variables; and V) seeking properties in common between the LVWD and those WD for which circular polarization has been found.

Acknowledgement

We wish to explicitly acknowedge the continued advice, aid and encouragement of our colleagues at Cerro Tololo and elsewhere, and the excellent, cheerful help provided at the telescope by the Cerro Tololo night assistants. We are also grateful to the National Science Foundation for its continued support of the Cerro Tololo Inter-American Observatory.

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https://doi.org/10.1017/S0252921100032887 Published online by Cambridge University Press

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Variable X-Ray Sources

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Introduction

There are at least five types of variable galactic X-ray sources (i. e. „stars") known:

Pulsar, as NP0532
Transient Sources as Cen XR-2
Quasi-periodic rapid variables, as Cyg X-1
Periodic rapid variables, as Cen X-3
Aperiodic variables, as Sco X-1

In this paper, I will not discuss the pulsar or the transient sources, as we at AS & E have not made any new observations of these sources yet with the UHURU satellite. The paper by RAPPAPORT (1970) reviews the observations of NP0532 to that date. Since then, HILLIER, JACKSON, MURRAY, REDFERN and SALE (1971) have observed it above 0.6 MeV. The transient sources Cen XR-2 which appeared in 1967 and Cen XR-4 which appeared in 1969 have not reappeared in the UHURU data, although the previous position measurement accuracy for these sources was not sufficient to allow us to rule out a possible weak remaining source.

The main emphasis in the following will be to describe the behavior of the quasiperiodic rapid variable Cyg X-1, the periodic variable Cen X-3, and the aperiodic variable Sco X-1. These objects are not well understood. The bulk of the X-ray data on them were accumulated in the past six months, so models of them have not had much time to be formulated. However, I will try to summarize briefly the current trends of thought on the nature of these sources.

1. *Cyg X-1: A Quasi-Periodic Rapid Variable*

Intensive studies have been done on Cyg X-1 at AS & E, since we recently discovered that it has rapid fluctuations in intensity (see ODA et al., 1971). The UHURU satellite was pointed to a position where Cyg X-1 was in the band visible to the X-ray detectors, and the spin rate was slowed down to one revolution per hour to allow continuous observations of the source up to 100 sec. One such sample of data is shown in Figure 1. The count rate from the source is estimated by onboard accumulation of counts for 0.096 sec. Figure 1 (a) shows a plot of these sequential data samples with the same 0.096 sec. time resolution as received from the satellite. Parts (b), (c) and (d) are plots with coarser time resolution obtained by summing over several data points at a time, so that the accumulation time is 0.48, 4.8 and 14.4 sec. respectively. Significant fluctuations in the intensity of the source are present in each case. A large fraction of the total X-ray power emitted by Cyg X-1 is fluctuating in this way.

https://doi.org/10.1017/S0252921100032887 Published online by Cambridge University Press