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TWO-PHASE ULTRAVIOLET SPECTROPHOTOMETRY OF THE PULSATING WHITE DWARF ZZ PISCIUM

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ABSTRACT

We obtained spectra of the pulsating white dwarf ZZ Psc (=G29-38) using the *International Ultraviolet Explorer*. By using a multiple-exposure technique in conjunction with simultaneous ground-based exposure-metering photometry, we were able to obtain mean on-pulse and off-pulse spectra in the 1950–1310 Å wavelength range. The ratio of the time-averaged on-pulse to off-pulse spectra is best fitted by a temperature variation that is in phase with the optical light variation. This result is consistent with the hypothesis that the observed variation is due to a high-order nonradial pulsation.

Conventional ultraviolet spectra of ZZ Psc showed broad absorption features at 1390 and 1600 Å. These features are also found in the spectra of the cool DA-type white dwarfs G226-29 and G67-23 and appear to increase in strength with decreasing temperature. A possible explanation for the 1600 Å feature is absorption by the satellite band of resonance-broadened hydrogen Lyα. Such absorption would also help explain a discrepancy between the observed pulsation amplitude shortward of 1650 Å and the predicted amplitudes based on model atmospheres.

Subject headings: spectrophotometry — stars: individual — stars: pulsation — stars: white dwarfs — ultraviolet: spectra

I. INTRODUCTION

The ZZ Cet variables are pulsating white dwarfs with amplitudes of 0.3 mag or less and with periods ranging from 200 to 1600 s (e.g., Robinson 1979). Those stars with the largest amplitude have multiple periodicities which change on time scales of a few hours to days (e.g., McGraw and Robinson 1975). This behavior complicates observational studies of the phenomenon.

Because the observed periods are much longer than the fundamental pulsational periods for white dwarfs and because multiple periodicities are seen, models attempting to explain these usually invoke high-order, g-mode oscillations, as suggested first by Chanmugam (1972). A more refined model by Robinson, Kepler, and Nather (1982) predicts that the g-mode oscillations should appear in Strömgren system photometry as variations in the stellar effective temperature at essentially constant radius. McGraw (1979) and Robinson, Kepler, and Nather (1982) have presented Strömgren photometry of ZZ Cet–type light variations that supports this model.

The combination of ultraviolet and optical data is potentially a powerful way to study the variation of physical properties during the pulsation cycle. In the temperature range appropriate to ZZ Cet variables, the ultraviolet fluxes are much more sensitive to changes in temperature than are the visual fluxes. For example, at 11,800 K a temperature change will produce 3 times as much flux change at 1800 Å as it does in the visible. Furthermore, the ultraviolet spectrophotometry combined with visual photometry provides information on the energy budget of the star during the pulsations. Since about half the stellar luminosity is radiated in the ultraviolet, visual photometry alone may be misleading about the actual physical processes, for example, where flux redistribution plays a major role, as for the α^2 CVn variables.

This paper describes observational results obtained from ultraviolet spectra of ZZ Psc (=G29-38), one of the largest amplitude ZZ Cet variables, taken with the *International Ultraviolet Explorer* (*IUE*) during 1981 August and September. Section II describes the technique used to obtain two-phase ultraviolet spectrophotometry and the analysis techniques. Section III describes the mean effective temperatures and spectral features which are phase independent. Section IV gives the results from the phase-dependent information.

II. OBSERVATIONS AND ANALYSIS

The instrumentation of the *IUE* consists of an 0.45 m telescope, a visual-sensitive fine error sensor, a long wavelength and a short wavelength ultraviolet spectrograph, and associated cameras. Target identifications and acquisitions are performed with the aid of the fine error sensor which views reflections from an aperture plate set at a 45° angle to the optical path. The spectograph entrance apertures pass through this plate. Each spectrograph has a 10″ × 20″ oval aperture. More details of the *IUE* instrument and data reduction system are reported in Boggess *et al.* (1978*a*, *b*).

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The *IUE* spectra we obtained for this study are listed in Table 1. All the spectra of ZZ Psc in the short wavelength range (1150–2000 Å) were obtained using a technique for getting phase resolution as described below. We obtained one conventional, but underexposed spectrum of ZZ Psc in the long wavelength range (1950–3200 Å). Two conventional observations of ZZ Psc which had been made in 1978 by Dr. J. L. Greenstein were obtained from the *IUE* Observatory archives. To further investigate the spectral features seen in ZZ Psc, we took conventional ultraviolet spectra of G226-29 and G67-23, two white dwarfs with surface temperatures similar to that of ZZ Psc, and obtained a spectrum of the very hot white dwarf G191-B2B from the *IUE* Observatory archives. G226-29 is also a ZZ Cet–type variable; G67-23 is not. The spectra of G67-23 were underexposed by at least a factor of 2.

Although, at 13th magnitude, ZZ Psc is the brightest of the large-amplitude ZZ Cet variables, it is sufficiently faint and cool that an *IUE* exposure having adequate signal-to-noise ratio must extend through many pulsation cycles. All phase information would be lost in a conventional exposure. However, the 10″ × 20″ apertures are sufficiently large compared with the image sizes that it is possible to integrate two low-resolution spectra on the same image and to recover the individual spectra in the data reduction if sufficient care is used. Therefore, we were able to use the *IUE* to obtain some phase resolution by repeatedly moving the telescope perpendicular to the dispersion. Through appropriate timing of the back-and-forth motion, it was possible to accumulate on-pulse and off-pulse spectra on two different regions of the detector during a time period several hours in length and covering many cycles. Because we could not interrupt and resume the integration on short time scales, one of the two spectra corresponded to an integration over that fraction of the time when the star was brightest, and the second spectrum corresponded to a complementary integration over the remainder of the time. In these double-spectra images, the on-pulse spectrum always was offset in the same direction on the detector from the off-pulse spectrum.

Because we were unable to predict the light curve of ZZ Psc, it was necessary to have some method of determining its optical phase while the *IUE* spectrum was being integrated. Although the *IUE*'s fine error sensor (FES) is a visual-band detector (Holm and Rice 1981), the FES cannot see the target when its light enters the spectograph. Therefore, we used ground-based telescopes as exposure monitors. The observer on the ground would try to inform the *IUE* observer by telephone whenever the target's brightness exceeded a preselected trigger level. The *IUE* observer then would move the telescope to allow the on-pulse spectrum to integrate on the desired location of the camera tube. When the visual brightness dropped below the trigger level, the ground-based observer again would advise the *IUE* observer to move the spacecraft to allow the off-pulse spectrum to integrate in the appropriate location

During our 1981 August 30 observing run, the No. 2 0.9 m telescope at Kitt Peak National Observatory (KPNO) with R.J.P. observing provided the optical brightness information for *IUE*. It was configured with a standard *UBV* photometer and an offset guider. The time span covered by the KPNO photometry was 03:50 to 09:07 GMT. Continuous 30 s integrations through a *V* filter were obtained. For later analysis, the measurements have been corrected for atmospheric extinction with a mean extinction coefficient of 0.12 mag per air mass.

During our 1981 September 28 observing run, the 0.9 m reflector at Louisiana State University (LSU) Observatory provided the real-time exposure information. For these observations, H.E.B., A.D.G., and E.K. used the LSU two-star high-speed photometer with an unfiltered EMI 9840 photomultiplier (giving a broad-band response from the atmospheric cutoff to ~6000 Å). Continuous 4 s integrations were obtained. Figure 1 illustrates the light curve obtained at LSU during the *IUE* exposure; variations in atmospheric transparency, which never exceeded 10%, have been removed by dividing the data by simultaneous observations of a nearby comparison star made with a second photomultiplier. The LSU photometer and reduction techniques have been described by Grauer and Bond (1981). The light curve shows a dominant period of 609 s, and a maximum peak-to-peak amplitude of 0.18 mag. In addition, on this date, R.J.P. provided supplementary support from KPNO during the second half of the *IUE* observation, 03:54 to 05:00 GMT. These KPNO

TABLE 1

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Star	Date	Image Number	J.D. of Start	Duration (minutes)	Notes
ZZ Psc	1978 Dec 28	LWR 3306	2,443,870.66	50.0	
		SWP 3726	2,443,870.69	65.0	
	1981 Aug 30	SWP 14860	2,444,846.68	(60.03, 69.97)	1
		SWP 14861	2,444,846.79	(34.95, 89.05)	1
		LWR 11440	2,444,846.89	30.0	
	1981 Sep 28	SWP 15111	2,444,875.56	(96.63, 94.87)	1
G226-29	1982 Oct 21	LWR 14458	2,445,264.45	(20.0, 20.0)	2
		SWP 18357	2,445,264.48	45.0	
G67-23	1982 Oct 22	SWP 18358	2,445,264.55	90.0	
	1982 Oct 24	SWP 18385	2,445,267.47	105.0	
G191-B2B	1981 Dec 12	SWP 15719	2,444,951.29	5.15	
+33°2642	1980 Nov 1	SWP 10517	2,444,544.53	(4.0, 4.0)	2
	1981 Dec 11	SWP 15707	2,444,949.86	(4.0, 4.0)	2

NOTES.—(1) On-pulse duration, off-pulse duration. (2) Double spectrum without phase information.

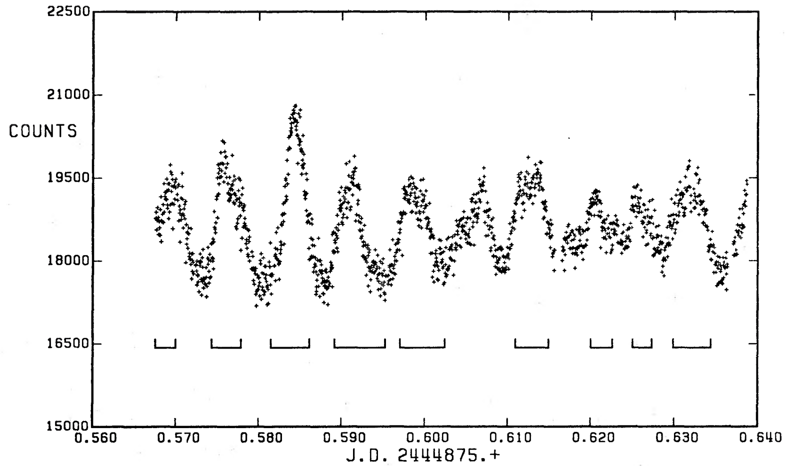

FIG. 1*a*

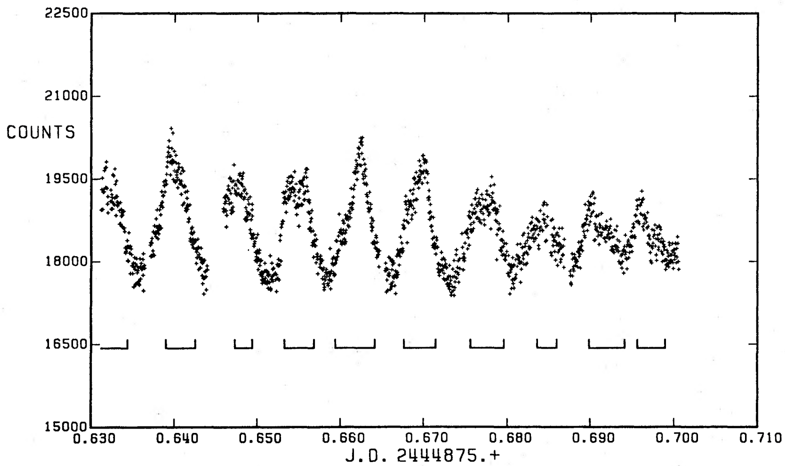

FIG. 1*b*

FIG. 1.—Optical light curve of ZZ Psc during the 1981 September 28 *IUE* spectrophotometric observation (SWP 15111), obtained by the LSU 0.9 m reflector and two-star photometer. Photon counts per 4 s integration (corrected for sky background and atmospheric transparency variations) are plotted against heliocentric Julian Date. Tick marks are at intervals of 0.01 day = 14.4 minute. Horizontal brackets show intervals during which the *IUE* spectrum was exposed at the "on-pulse" position. The *IUE* spectrum was exposed at the "off-pulse" position during the intervals between the brackets.

observations used a 10 s integration but were otherwise similar to those of the August 30 run. The reductions were handled in the same manner. Fourier analysis of this KPNO light curve shows a primary period at 605.5 s and a secondary period at 664 s. This agrees reasonably well with the LSU results.

Experience revealed that this technique tended to result in a phase lag between the visual pulse and the *IUE* integration at the on-pulse location. Furthermore, occasionally entire pulses were missed, for example, the one at JD 2,444,875.606 in Figure 1. The reasons for these errors lie both with the ground-based support and with the nature of the *IUE* operating system. The small amplitude of the variation made it difficult for the observer at the ground-based telescope to distinguish in real time between stellar pulsations, changes in the air mass as the night progressed, variations in transparency or seeing, and statistical fluctuations in the count rate. Therefore, we would often watch the star brighten for an extra 30 to 60 s to confirm that a pulse was actually occurring. Once the decision was made regarding the reality of the pulse, moving the spacecraft would take about another 30 s. This delay was caused by the controlling computer checking the safety of the requested maneuver, building the commands to accomplish the maneuver, and transmitting the commands to the spacecraft. To summarize, the *IUE* integration usually lagged by 60 to 90 s behind the pulsations. Since the average pulsation period during these observations was only 10 minutes, this lag is significant, and it increases the uncertainty in our results.

The double spectra were separated by 11″.2. The spatial resolution of the *IUE* instrument is a function of wavelength and focus, and is typically in the range of 4″.5 to 6″.8 for the full width at half-maximum (Panek 1982). Thus, at the chosen separation, there is some overlap between the two spectra. Nonetheless, this separation represented a best compromise since at wider separations some of the target's light might fall outside the end of the aperture.

The *IUE* images were processed with the 1980 November version of the *IUE* spectral image processing system (Bohlin, Lindler, and Turnrose 1981). This system does not have the capability to extract separately spectra as closely spaced as those we obtained. Therefore, the phase-resolved information was derived using our own software developed on the *IUE* Regional Data Analysis Facility at Goddard Space Flight

Center. However, for the study of spectral features and determination of effective temperatures, the standard *IUE* processing for widened spectra was used with the flux calibration of Holm *et al.* (1982).

The technique for extracting the fluxes from the on-pulse and off-pulse locations of the image used the spatially resolved or ESSR spectral files. These files provide 55 spectral orders extracted parallel to the dispersion and separated in a spatial direction by $\sqrt{2}$ pixels (Turnrose and Harvel 1980). A simple summing of the spectral orders centered on each of the spectra ignores the overlap of the spectra and the systematic residual geometrical errors of about ± 0.4 pixels (Panek, Holm, and Schiffer 1982) remaining in the images after the largest distortions are removed through a parameterized model. (Such an extraction technique was used for the preliminary results presented by Schiffer, Holm, and Panek 1982.) Therefore, we extracted the spectra by fitting the brightness distribution perpendicular to the spectral dispersion to a double Gaussian profile with one Gaussian representing each of the two spectra on the image. The instrumental point-spread function is sufficiently close to a Gaussian (e.g. de Boer, Koornneef, and Meade 1981) that the peak intensity of each Gaussian provided an accurate measurement of the intensity in the spectrum. This technique not only has the advantage that the overlap of the two spectra can be estimated and removed, but it also can easily handle the residual geometrical errors. Additional details of the technique can be found in Panek and Holm (1984).

There is some concern that the instrumental response might not be constant along the length of the aperture and that any such variation of the response could be a function of wavelength. Such an effect would cause a false wavelength-dependent variation between the two spectra. To eliminate this possible instrumental effect, we obtained from the observatory archives two double-spectra images which had spectra of an unvarying star exposed at the same locations of the detector as used for ZZ Psc. We analyzed these images (both of BD +33°2642, a photometric standard) in the same manner as the ZZ Psc images were analyzed. We then divided the ratio of fluxes for the variable by the apparent ratio of fluxes for the standard star. This correction for instrumental effects was always less than 10% and averaged 3.3%. The largest corrections were in the wavelength interval between 1310 and 1490 Å. The BD +33°2642 spectra were obtained with a better telescope focus than the spectra of ZZ Psc. Thus, there may be some subtle differences in the shape of the point-spread function in the variable spectra and in the standard star spectra. Nonetheless, the correspondence between these ratios is as good as available.

III. THE EFFECTIVE TEMPERATURE AND SPECTRUM

In this section, the phase-resolved information is ignored to analyze the spectrum and energy distribution in terms of effective temperature and spectral features for both ZZ Psc and similar white dwarfs. The temperatures are determined by fitting the visual to far-ultraviolet energy distributions with the emergent flux distributions predicted by model atmospheres. The spectral features of interest are two strong absorption features at 1390 and 1600 Å which are not predicted by the models. This analysis is relevant to the discussion of the pulsational characteristics in § IV.

A phase-independent average spectrum for ZZ Psc between 1225 and 3200 Å was obtained by combining all available spectra, weighted according to integration time. It should be noted that neither long wavelength spectrum, Greenstein's nor ours, is of high photometric quality. Our long wavelength spectrum was underexposed; Greenstein's had a high level of camera fogging produced by particle radiation. Both circumstances might result in systematic photometric errors of up to 20% (Holm 1982). These errors are expected to be largest in the wavelength interval from ~2000 to 2500 Å.

The effective temperature given in Table 2 was estimated by fitting models to an observed energy distribution which included the time-averaged ultraviolet fluxes from 1650 to 3200 Å and Greenstein's (1976, 1982*b*) time-averaged multichannel measurement at 5525 Å. Greenstein's measurement, 13.04 mag, is in good agreement with an estimated V magnitude of 13.07 ± 0.13 from 50 measurements by the FES during our observing runs. We used Shipman's (1981) series of models of hydrogen atmospheres having $\log g = 8$ and temperatures spaced at intervals of 500 K from 10,000 to 13,500 K. Surface fluxes for atmospheres at intermediate temperatures were estimated by interpolating linearly in the logarithm of the tabulated fluxes. Tests showed that such a procedure was accurate to 2% or better for interpolations between models separated by 1000 K.

The agreement between observations and model is illustrated in Figure 2. This agreement suggests that the photometric errors between 2000 and 2500 Å are not as large as they might have been. The error estimate is based on an estimated uncertainty in the mean V magnitude of 0.035 mag, on an estimated error in the interpolation within the model sequence, and on the rms deviations of the model from the observed energy distribution. The latter was included to account for errors in the calibration and systematic measurement errors. Our value of the temperature agrees reasonably well with Greenstein's (1982*a*) value of 11,400 K derived from multi-

TABLE 2

TEMPERATURES AND ABSORPTION-LINE EQUIVALENT WIDTHS

Star	T_{IUE} (K)	$T_{\rm optical}$ (K)	W(1390 Å)	W(1600 Å)	References
G191-B2B	50,200 ± 13,700	61,900	0.5 ± 0.3	−0.0 ± 0.3	1, 2
40 Eri B	...	16,900	3.1 ± 0.2	...	1, 3
LB 3303	...	16,000	5.7	...	4
Grw +73°8031	...	15,400	5.6 ± 0.7	...	1, 2
G226-29	11,550 ± 680	11,066	17.1 ± 2.8	17.0 ± 1.1	2, 5
ZZ Psc	11,040 ± 555	11,400	15.4 ± 1.6	21.3 ± 0.7	2, 5
G67-23	10,200 ± 430	10,500	...	93.6 ± 1.4	1, 2

REFERENCES.—(1) Shipman 1979 for optical temperature. (2) This paper for *IUE* temperature and equivalent width. (3) Greenstein 1980 for equivalent width. (4) Wegner 1982 for optical temperature and equivalent width. (5) Greenstein 1982*a* for optical temperature.

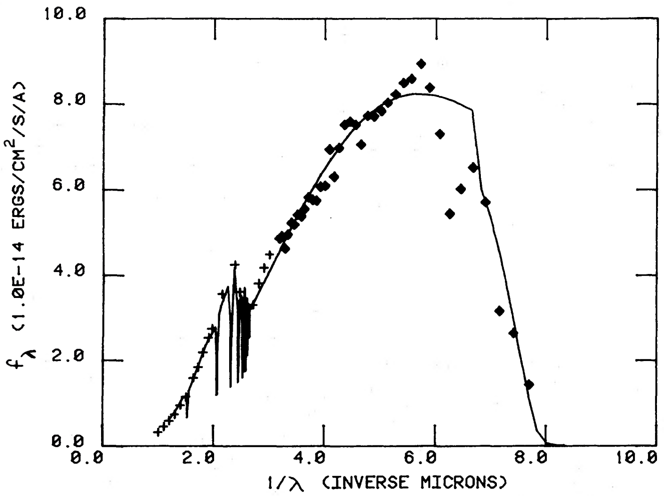

FIG. 2.—Observed energy distribution of ZZ Psc (= G29-38) and that for a $T_{\rm eff}$ = 11,040 K, log g = 8 model atmosphere (Shipman 1981). The ultraviolet fluxes from *IUE* spectra (*diamonds*) are averaged in 25 Å bins. Visual spectrophotometry (*crosses*) is from Greenstein (1982*b*). The *IUE* fluxes between 4 and 5 μm^{-1} may be somewhat inaccurate because of systematic errors in the image processing. The absolute calibration between 5 and 8 μm^{-1} may have errors of as much as 10%. The agreement between the model and the observations is good except at 6.25 and 7.2 μm^{-1}, where strong absorption features are seen in the stars that are not reproduced in the model.

channel spectrophotometry. Greenstein also used Shipman's models.

This technique for estimating effective temperatures by fitting an energy distribution is subject to systematic errors when applied to ZZ Cet variables, which have a range of temperatures present simultaneously on their surfaces. Such stars tend to have flatter overall energy distributions than a star with a unique surface temperature. Therefore, the fitting technique tends to overestimate the temperature of the star.

To explore the error in fitting composite energy distributions with single-temperature atmosphere models, we conducted simulations with various arbitrary temperature distributions. These simulations involved surface temperature ranges of 1000–2000 K. The results show that the model atmosphere which best fits the composite energy distribution may have a temperature that is tens to hundreds of degrees higher than the mean temperature weighted by surface area, which we will call the geometrical mean temperature. Furthermore, the predicted surface flux at any wavelength is greater than the simulated flux by 1%–5%. Thus, this fitting technique would tend to overestimate the geometrical mean temperature and to underestimate the radiating area. Despite these errors, however, the single-temperature energy distribution can fit the slope of the composite energy distribution with deviations which typically are only a few percent.

For G226-29 and G67-23, the effective temperatures in Table 2 were estimated in a similar manner as for ZZ Psc, but using the published V magnitudes instead of multichannel spectrophotometry in the optical. The temperature estimate for G191-B2B was based on the Wesemael *et al.* (1980) model grid, on Greenstein's (1976) 5405 Å spectrophotometry, and on *IUE* fluxes between 1300 and 1970 Å. For these three stars the error estimate assumes an uncertainty of 0.10 mag in the visual.

The energy distribution fitting for G226-29, G67-23, and ZZ Psc was limited to the wavelength range longward of 1650 Å because all have an unexpected broad absorption feature at 1600 Å.

The mean spectrum of ZZ Psc shows strong absorption features at 1600 and 1389 Å (Fig. 3). The 1600 Å feature is strongest in this spectrum. This feature also appears in the spectrum of G67-23 (shown in Fig. 3) and of G226-29 (not illustrated, but similar to ZZ Psc). The DC-type star G33-49 has a stronger and wider feature at approximately the same wavelength which Vauclair *et al.* (1981) tentatively identified with a blending of the C I multiplies at 1561 and 1657 Å. Wegner (1981) also identified C I absorption features in the spectrum of a DC-type white dwarf, G218-8. However, the 1600 Å feature in ZZ Psc cannot be identified with a blending of the neutral carbon lines because it is not broad enough to include the 1657 Å multiplet. Furthermore, ZZ Psc does not have the C I multiplet 33 absorption that both Vauclair *et al.* and Wegner found.

A possible identification of this 1600 Å absorption feature is with the satellite band of resonance-broadened Lyα (also referred to as quasi-molecular hydrogen absorption). Figure 3 shows for comparison the opacity due to resonance-broadened Lyα in a 5000 K gas as calculated quantum mechanically by Sando and Wormhoudt (1973). Since a large fraction of hydrogen atoms in this star's outer atmosphere would be neutral, resonance-broadened Lyα could be a significant opacity source shortward of 1650 Å. In fact, Praderie and Stecher (1973) suggested that this opacity source was important even for main-sequence A-type stars.

Wegner (1984) has suggested an alternative identification of this feature with the Mg I $3s^2\ ^1S$ absorption edge. However, if his identification is correct, a second feature should be seen at 2513 Å which is due to the Mg I $3p^3\ P^o$ absorption edge. According to Peach (1970), the opacity at the 2513 Å edge should be 5 times that at the 1621 Å edge for a 10,000 K gas. The ratio of opacities will increase with increasing gas temperature. Even allowing for an order of magnitude error in the

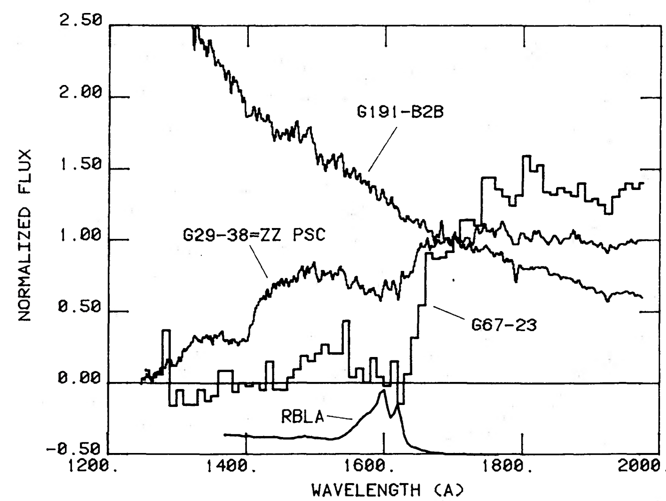

FIG. 3.—Comparison between the short wavelength spectrum of ZZ Psc, G191-B2B, and G67-23 and the predicted opacity of resonance-broadened Lyα (labeled by RBLA). The stellar spectra are normalized at 1700 Å. The opacity of resonance-broadened Lyα is scaled and offset below the zero of the figure for visibility. The cooler white dwarfs have absorption features at 1389 and 1600 Å. The spectrum of G191-B2B shows neither feature and, therefore, provides evidence that the features are real, not calibration errors. The agreement between the 1600 Å feature and the resonance-broadened Lyα opacity suggests that they are related. (The spectrum of G226-29 is not shown but is very similar to that of ZZ Psc.)

relative cross sections, the observed absence of a 2513 Å feature in the ZZ Psc spectrum (Fig. 2) argues against Wegner's hypothesis.

The second strong feature in the spectrum of these white dwarfs occurs at 1389 Å. It has an equivalent width of 15 Å in ZZ Psc and 17 Å in G226-29. Greenstein (1980) and Wegner (1982) have called attention to this feature in the spectrum of 40 Eri B and of LB 3303, respectively. It is also present in the spectrum of Grw +73°8031 (Greenstein and Oke 1979). Table 2 gives the measured equivalent width of this feature for the stars in which it is seen. Greenstein suggested it be identified with the (0,5) Lyman band of molecular hydrogen. However, the (0,4) Lyman band at 1334 Å, which is also expected (Greenstein 1980), definitely is not seen in the cooler stars. Thus, the molecular hydrogen hypothesis continues to have difficulties. An alternative identification with the Si IV λ1400 resonance lines, however, is ruled out by our discovery that the feature increases in strength with decreasing effective temperature.

There may be some concern that such broad features are the result of errors in the instrumental calibration. Bohlin *et al.* (1980) state that the basis for the absolute calibration might have errors of ~10% in this wavelength range. To test this possibility, we have measured the strength of these features in the spectrum of the very hot white dwarf G191-B2B. The equivalent widths are 0.5 ± 0.3 Å and -0.0 ± 0.3 Å for the 1389 Å feature and the 1600 Å feature, respectively. From a high-resolution spectrum of this star, Bruhweiler and Kondo (1981) report absorption by Si IV at 1394 and 1403 Å having a combined equivalent width of 0.15 Å. This probably accounts for some of the nonzero equivalent width of 1389 Å measured from the low-dispersion spectrum. The measurements for G191-B2B clearly show that the features seen in the cooler stars are real.

IV. PULSATIONAL CHARACTERISTICS

In this section we analyze the ratio of fluxes measured in the time-averaged on-pulse spectrum to those measured in the spectrum corresponding to the remaining portion of the pulsational cycle (here called off-pulse for simplicity). From this analysis we attempt to show that the observed changes are consistent with a nonradial temperature pulsation. As a by-product of this work we find that there appears to be an opacity source below 1600 Å which is not well approximated in available model atmospheres.

Figure 4 shows the mean ratio of the on-pulse spectrum to the off-pulse spectrum derived from *IUE* observations. The Gaussian fitting technique was used for extracting these spectra from the spatially resolved spectral files as discussed in § II. Only the two best-exposed images, SWP 14860 and SWP 15111, were used here. The ratio of on-pulse to off-pulse were nearly identical for both images after the fluxes were adjusted for the relative exposure lengths. Therefore, an unweighted mean of the two was used for all further analysis. The shape of this ratio differs from that discussed by Schiffer, Holm, and Panek (1981), who found an apparent increasing amplitude from 1700 to 1950 Å. We now interpret that increase as being caused by the systematic residual geometrical errors left in the processed camera images and by the simplistic extraction procedure used at the time. The increase in the ratio shortward of 1700 Å is similar to that reported previously.

There are two characteristics of the on-pulse to off-pulse flux ratio which should be noted. First, because the ratio is greater

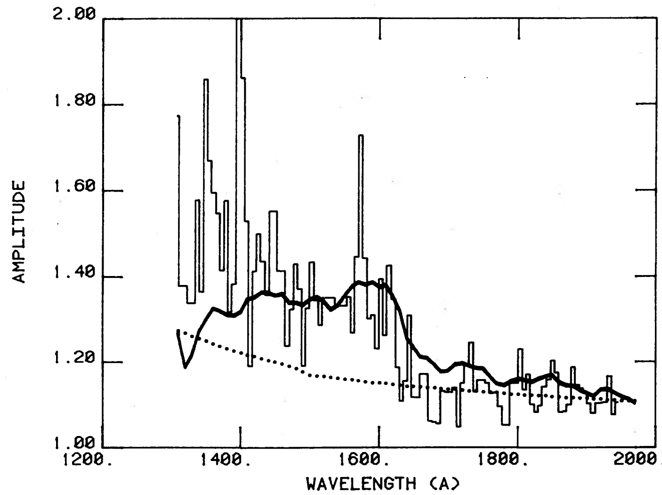

FIG. 4.—On-pulse/off-pulse ultraviolet flux ratio of ZZ Psc (=G29-38) compared with a semiempirical model that fits both the ultraviolet and the visual. The observed amplitude (histogram plot) represents an unweighted average of the 1981 August 30 (SWP 14860) and the 1981 September 28 (SWP 15111) ratios of "on-pulse" spectrum to "off-pulse" spectrum as described in the text. The semiempirical model (*dark line*) is based on a heavily smoothed ratio of the observed mean energy distributions of ZZ Psc and G226-29. For comparison, the ratio of two model atmospheres differing by 200 K in effective temperature is shown (*dotted line*).

than 1.0, the ultraviolet pulsation is in phase with the optical. Second, there is a discontinuity near 1600 Å. This feature will be discussed later.

We attempted to model the wavelength dependence of the ultraviolet flux ratio by assuming that the on-pulse and off-pulse spectra can each be represented by an energy distribution characterized by a single effective temperature. Scaling of the ratio of these two energy distributions was permitted and could be interpreted as a variation in the effective radiating area. These simplistic assumptions were made in the absence of a good model to describe the pulsational characteristics of ZZ Psc. We recognize that our actual spectra are integrations over time of energy distributions which are themselves composite. However, as we discussed in § III, the individual composite energy distributions can be fitted reasonably accurately. Furthermore, we will show below that this approximation does, in fact, give a solution.

We used the emergent flux predictions of Shipman's model atmospheres (1981) in the first attempt to apply our model. Figure 4 illustrates the result of a fit to the 1650–1946 Å range of the observed ratio. We were not able to fit the ratio across the 1600 Å discontinuity with any assumed temperature difference. This failure could be the result of the simplistic assumption of single-temperature energy distributions, or it could be an artifact of the atmosphere models. Keeping in mind that the atmosphere models do not reproduce the absorption features seen at 1600 and 1389 Å, we suspected that they contributed some portion to the failure and sought an alternative way of determining the change in energy distribution with temperature.

Accordingly, we used observed white dwarf spectra to define empirically the change in energy distributions as a function of temperature. The spectra used for this purpose were those of ZZ Psc itself and of G226-29. The appropriateness of this choice of standard stars is discussed here. Because both stars are ZZ Cet–type variables, we do not have good determinations of their geometrical mean temperature. However, that their energy distributions are composite may be beneficial in that we are trying to fit the ratio of composite energy distributions. Furthermore, we expect these two stars to be similar in terms of gravity, composition, and other physical characteristics. The analysis described in § III showed that their temperatures differ by ~500 K. We find below that this is about the same as the difference in the temperatures which characterize our mean on-pulse and off-pulse spectra. Therefore, the opacity differences between the two stars will be appropriate to the opacity changes which occur during the pulsation of ZZ Psc. Moreover, the distances to both stars are small (Shipman 1979), so their intrinsic energy distributions will not be significantly modified by interstellar extinction.

A second refinement in how we modeled the ratio of the on-pulse to off-pulse energy distributions was to force the solutions to fit the corresponding optical flux ratio. Time-averaged optical count rates were calculated for the intervals when the *IUE* spectra were being integrated in the on-pulse and off-pulse locations. The optical flux ratio was defined to be the ratio of the mean on-pulse count rate to the mean off-pulse count rate. This ratio was 0.025 mag for the 1981 August 30 measurements from KPNO and 0.047 mag for the 1981 September 28 measurements from LSU. While we have identified several possible causes of this difference, none of them was completely satisfactory. Therefore, we simply averaged the August 30 and September 28 ratios to get a mean optical flux ratio of 0.035 ± 0.014 mag. The temperature difference reported in the next paragraph would change by only 20 K if either of the individual optical flux ratios were used in place of the mean.

Based on the empirical determination of spectrum change as a function of temperature, the combined optical and ultraviolet ratio of on-pulse to off-pulse fluxes was fitted by a temperature difference of 290 ± 150 K with an apparent effective area change of $-3.3\% \pm 3.3\%$. Much of the quoted uncertainty comes from the rms of the high-frequency scatter between the observed flux ratio and the model ratio. This is an overestimate to the actual uncertainty in the determination of the temperature difference.

One feature in Figure 4 that should be noted is that both the observed and the model ratios show the discontinuity at 1600 Å. A conclusion that may be drawn from the presence of this discontinuity in both ratios is that there appears to be an opacity source in the stars which is not accounted for in the atmosphere models. The simplest interpretation is that this is the same opacity source which causes the absorption feature seen at 1600 Å in individual spectra. This suggests that, while the absorption peaks at 1600 Å, it also includes a component in the wavelength range between 1400 and 1600 Å that increases rapidly with decreasing temperature. This behavior is consistent with that expected for resonance-broadened Lyα (Sando and Wormhoudt 1973). We regard the presence of the discontinuity in both the ratio of the mean ZZ Psc and G226-29 spectra and in the ratio of the on-pulse to off-pulse spectra of ZZ Psc as confirmation that the pulsation is associated with an overall temperature rise. This statement is based on our observed increase of strength of the 1600 Å feature with decreasing stellar temperature (Table 2) and on the proposed identification of that feature with resonance-broadened Lyα. If hydrogen is the source of the feature, then the changing strength between the on-pulse and off-pulse spectrum and between the spectra of ZZ Psc and G226-29 must be due to a change in physical conditions in the gas. However, if neutral magnesium is the source of the feature (Wegner 1984), then the differences between ZZ Psc and G226-29 may be due to chance variations in the abundances.

Overinterpretation of our results should be avoided. We have shown that the ratio of two time-averaged composite energy distributions can be approximated by the ratio of two stellar flux distributions whose characteristic temperatures differ by a few hundred degrees. However, this ratio corresponds to a visual flux ratio of only 0.035 mag, while the peak-to-peak amplitude of the visual fluxes may be as large as 0.2–0.3 mag (but it might be noted that the average peak-to-peak amplitude is considerably smaller than the maximum). Thus, one can expect that the peak-to-peak variations of the geometrical mean surface temperature are correspondingly larger than the results we have found. Furthermore, one can expect there to be a range of surface temperatures present about the geometrical mean temperature. Therefore, the actual range of surface temperatures on this star during the course of the pulsation will far exceed the 290 K difference we found for the specific spectra available to us.

We interpret our results as being consistent with the hypothesis of high-order g-mode pulsations. The coincidence of optical maximum with a hotter energy distribution certainly is consistent with this hypothesis. The question that remains is whether the 1 σ decrease in apparent radiating area causes problems. The uncertainty in the measurement of radius change is such that zero radius change predicted by Robinson, Kepler, and Nather (1982) remains a possibility. However, even if the change in apparent area is real, it may be interpreted as an effect of the composite nature of the spectrum rather than as a significant radial pulsation of the white dwarf. As stated in § III, the surface fluxes of a composite generally fall below those of the single-temperature model which best mimics the energy distribution. Therefore, the surface area estimate based on the single-temperature model would be smaller than the actual area. Furthermore, the extent to which this occurs depends on the details of the functional dependence of fractional surface area with temperature. Thus, if the range of the temperature distribution or the number of vibrational modes on the visible hemisphere varies during the pulsation, the effect could appear as a change in effective area.

V. SUMMARY

We obtained *IUE* spectra of the pulsating white dwarf ZZ Psc = G29-38. By using a multiple-exposure technique guided by real-time ground-based observations, we were able to obtain some phase resolution during the pulsation of this variable. Ultraviolet spectra of three other white dwarfs, G226-29, G67-23, and G191-B2B, were either observed or obtained from the *IUE* data archive.

1. Temperatures for the four stars were derived by comparing the visual-to-ultraviolet energy distributions with the predictions of model atmospheres (see Table 2). The only significant change from temperatures derived from ground-based photometry was that the the ultraviolet flux distribution showed G226-29 to be ~500 K hotter than ZZ Psc, while Greenstein (1982*a*) had them in the opposite order.

2. The spectra of the cooler DA-type white dwarfs have absorption features at 1600 and 1389 Å which increase in strength with decreasing effective temperature (Holm *et al.* 1983). The source of the 1389 Å feature remains uncertain. Its

increasing strength with decreasing effective temperature rules out an Si IV explanation, but the absence of a feature at 1334 Å due to the (0,4) Lyman band also causes difficulties for a molecular hydrogen interpretation. A potential source of the 1600 Å feature is the satellite band of resonance-broadened Lyα (Sando and Wormhoudt 1973).

3. The phase-resolved data shows that the pulsation amplitude is considerably larger in the ultraviolet than in the visible. The observed ratio of time-averaged on-pulse to time-averaged off-pulse fluxes were fitted with a model having a positive temperature variation and a small negative apparent area change. Given the approximations inherent in fitting composite energy distributions by a single-temperature model, we interpret this result as being consistent with the high-order *g*-mode pulsation hypothesis.

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