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THE INFRARED AND OPTICAL PULSATIONS OF G29-38

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ABSTRACT

High-speed infrared photometry at 1.25, 2.2, and 3.5 μm of the pulsating white dwarf G29-38 reveals the presence of unexpectedly large amplitude signals at 2.2 μm, with periods of 186, 243, and 268 s. Simultaneous optical coverage demonstrates the presence of signals of identical period and phase in blue light, which proves that they are ultimately seated in the white dwarf, not in the cool component known to be present in the system. But their anomalously high amplitude in the infrared suggests either a breakdown of stellar atmosphere theory or a process by which the pulsating white dwarf can very efficiently excite an oscillation in the cool component. We discuss a model in which a dusty ring reprocesses the incident radiation from the white dwarf, assumed to contain both east-west and north-south pulsations. The model has some heuristic value but requires a very special geometry to satisfy the observations.

We also use our pulse timings to study the long-term phase residuals of the dominant 615 s optical pulsation. The results do not support the idea that the phase residuals are periodic.

Subject headings: stars: binaries — stars: individual (G29-38) — stars: pulsation — stars: white dwarfs

1. INTRODUCTION

G29-38 (= ZZ Psc) is a pulsating white dwarf of the ZZ Ceti class, which normally shows a rather complex set of periods in the range of 5–15 minutes (McGraw & Robinson 1975; Shulov & Kopatskya 1973). In an infrared search for cool companions of white dwarfs, Zuckerman & Becklin (1987) found substantial excess emission from the vicinity of this star, in the 2.2 and 3.5 μm bandpasses. Assuming that this cool component could be characterized by a single temperature, they derived $T = 1200$ K, $R = 0.15\ R_{\odot}$. This suggested the possibility that the infrared light arises from an extremely low mass star or brown dwarf.

The short period and high coherence of the star's pulsations in blue light are an unmistakable sign of their origin in the white dwarf itself. If these pulsations also occur in the infrared (say at 3.5 μm, where the cool component dominates), it could provide a severe test of, and in fact eliminate, the brown dwarf hypothesis. In July of 1988, we undertook a three-night, three-telescope campaign of high-speed photometry, in order to search for infrared pulsations. Here we report the results of that campaign.

2. OBSERVATIONS AND DATA ANALYSIS

The data were acquired on 1988 July 23, 24, and 25 UT, at Mauna Kea Observatory, Hawaii. The infrared observations were made on the 3.0 m IRTF (E. B. and B. Z.) and the 3.7 m UKIRT (T. H.), in a photometric mode using a chopping secondary and a single element InSb detector. At the IRTF, a 5."5 aperture and standard K (2.2 μm) and L (3.5 μm) filters were used. A single K observation consisted of a 10 s integration on each chopped image for a total observation time of 20 s, plus a dead time of approximately 2 s. A single L measurement consisted of four such pairs for an integration time of 80 s. The UKIRT observations were made with a 12."0 aperture and standard J (1.25 μm) and K filters. A single observation consisted of a 40 s integration in K interspersed with a 20 s integration in J, again in a chopped mode. All observations were calibrated using the standard stars given by Elias et al. (1982).

The blue light observations were obtained by D. T. through a B filter on the 0.6 m telescope, using a single-channel photometer and a cooled RCA C31034a photomultiplier tube. An integration time of 10 was used (with a dead time of ∼1 s), with occasional interruptions to measure the sky background and check a comparison star.

Because the sky conditions proved to be photometric on the first two nights, we did not use the relatively infrequent measures of the comparison star to reduce the data, but only as a monitor of sky conditions. The third night was also of good quality, except for three small cumulus clouds; we therefore reduced this data in the same manner, after excluding the contaminated portions.

The entire log of observations is given in Table 1.

2.1. *Blue Light*

A total of 7.0 hr of photometry through a B filter was acquired. After removing sky background and correcting for atmospheric extinction, we obtained the light curves shown in Figure 1. They show a principal modulation with a period of about 10 minutes, along with other systematic wiggles that suggest multiperiodic structure. Essentially all of the variability seen is intrinsic to the star, with the possible exception of the

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TABLE 1

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UT Date (1988)	Telescope	Bandpass	First Point	Duration (minutes)
July 23.........	0.6 m	*B*	Jul 23.4943	151
	UKIRT	*J*, *K*	Jul 23.5006	111
	IRTF	*L*	Jul 23.4743	188
July 24.........	0.6 m	*B*	Jul 24.4994	151
	UKIRT	*J*, *K*	Jul 24.5087	78
	IRTF	*K*	Jul 24.4862	137
July 25.........	0.6 m	*B*	Jul 25.5319	110
	IRTF	*L*	Jul 25.5390	98

little dip (suspected to be due to a cloud) at 13.75 UT on July 25.

In Figure 2 we show the power spectra of the three light curves, and these confirm the presence of other periods. As earlier reported by Shulov & Kopatskaya (1973) and McGraw & Robinson (1975), there are many significant peaks—at least 15 in the frequency range of ~1–10 mHz. The dominant peak by far occurs at a period of 614.9 ± 0.2 s, consistent with the principal period found by Winget et al. (1990) throughout 1988, and with one of the principal periods found by McGraw & Robinson in 1974.

Of the many periods displayed by the star, we have chosen to study four in more detail: the 615 s period which dominates the pulsations in blue light, and the three shorter periods detected with certainty in the *K*-band observations reported below (and in blue light also). For each signal and on each night, we have folded the light curve on the pulsation period to obtain the waveforms and pulse arrival times. The results, shown in Figure 3, demonstrate that all four pulsations have roughly sinusoidal blue light curves, with amplitudes that vary somewhat from night to night. The best estimates for the periods, amplitudes, and pulse arrival times of all the labeled peaks are given in Table 2. Here, and throughout this paper, we express amplitudes as full amplitudes (i.e., peak-to-trough).

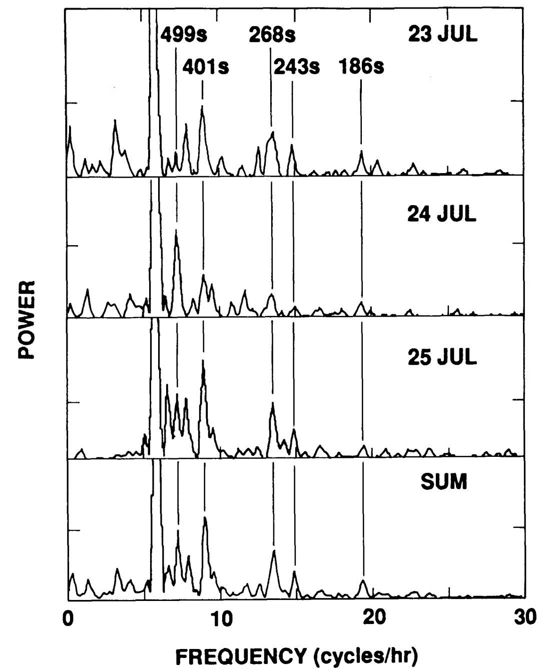

FIG. 2.—Power spectra of the *B*-band light curves, with several of the significant peaks labeled with their corresponding periods. In each case, the main peak at $f = 5.85$ cycles per hour extends through the roof by a factor of about 4. The horizontal tick marks indicate the power in a periodicity of 4% full amplitude (peak-to-trough).

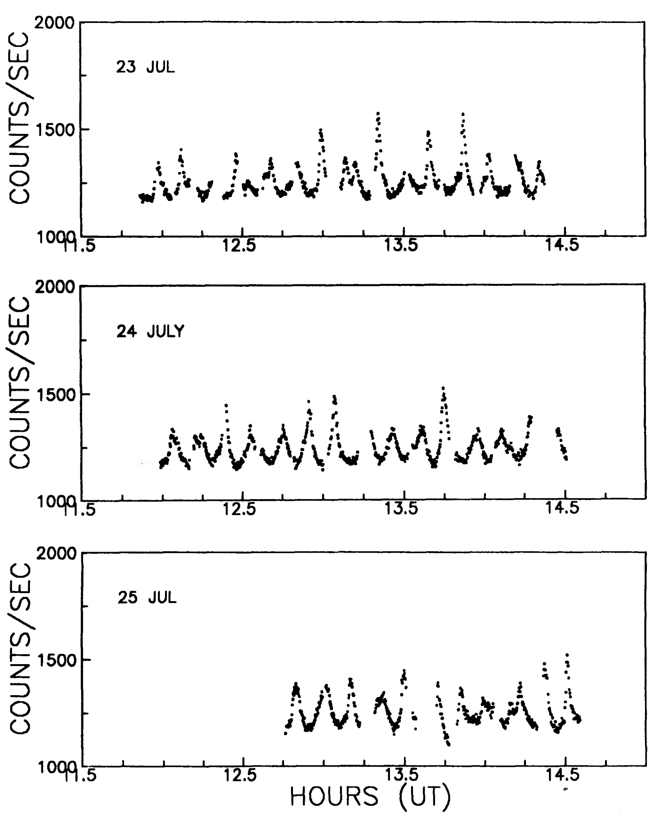

FIG. 1.—*B*-band light curves of G29-38, at a time resolution of 11 s per point. The low points at 13.75 UT on July 25 probably result from a single passing cloud.

2.2. *Infrared Light Curves*

In Figures 4 and 5 we show the reduced *J*, *K*, and *L* light curves. The *L*-band data show no clearly discernible features, and the *J*-band data show only a suggestion of the 10 minute periodicity. The *K*-band IRTF data of July 24 show small

TABLE 2

PROPERTIES OF PULSATIONS IN BLUE LIGHT

Period (s)	Pulse Amplitude (mag)	Pulse Maximum (JED$_\odot$ 2,447,000+)
614.9 ± 0.2.........	0.110 ± 0.004	7366.00333
	0.116 ± 0.005	7367.00674
	0.116 ± 0.003	7368.03885
186.1 ± 0.5.........	0.023 ± 0.003	7366.00023
	0.015 ± 0.003	7367.00374
	0.016 ± 0.003	7368.03825
242.9 ± 0.7.........	0.029 ± 0.003	7366.00075
	0.014 ± 0.003	7367.00407
	0.028 ± 0.002	7368.03889
267.9 ± 0.8.........	0.030 ± 0.002	7365.99870
	0.020 ± 0.004	7367.00567
	0.043 ± 0.004	7368.03832

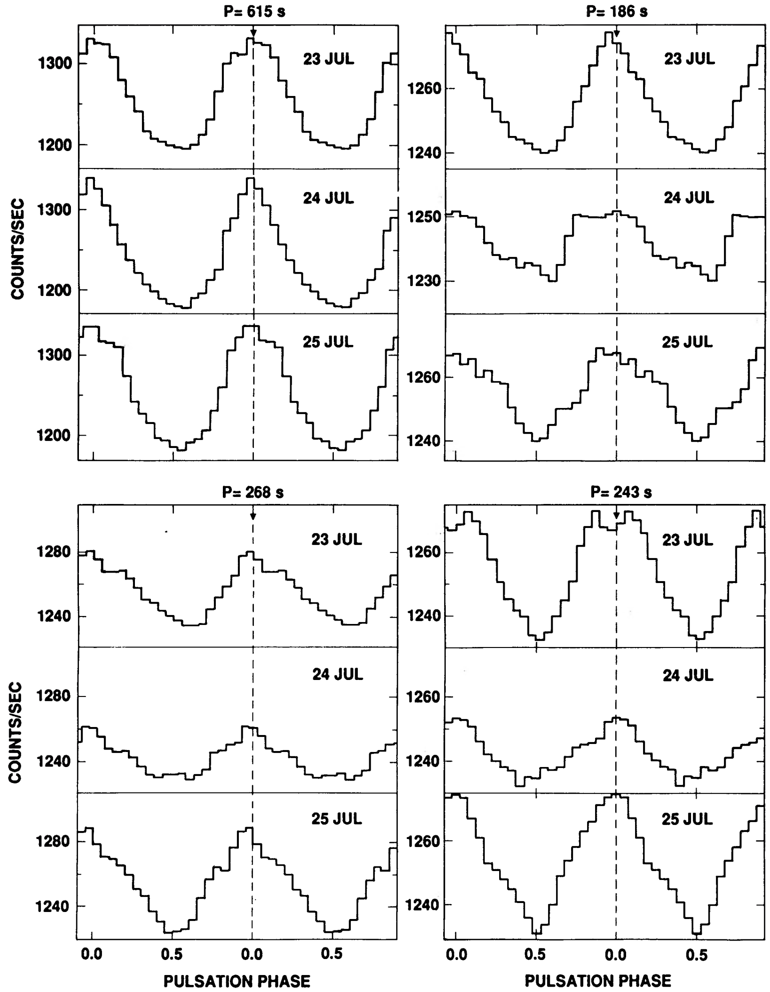

FIG. 3.—*B*-band light curves folded about the periods of the four pulsations, for each night of observation. The arrow points to the derived time of pulse maximum, given in Table 2.

wiggles on a time scale of a few minutes and a larger modulation with a period of about 40 minutes. Examination of the simultaneous *K*-band data from the UKIRT confirms that this 40 minute modulation does not arise from the telescope, and the lack of a similar modulation in the simultaneous optical or *J*-band data establishes that it does not arise from extinction variations. Thus it appears to be a real feature of the *K* light curve, with an amplitude of ~0.09 mag. On the other hand, its amplitude in the July 23 *K* light curve does not exceed 0.04 mag. More extensive photometry will be required to study the stability of this feature in the light curve.

2.3. *J-Band*

The *J*-band data obtained at the UKIRT on July 23 and 24 are of high signal-to-noise ratio but are quite sparse because they were interleaved with *K*-band data and frequent background checks. The only significant feature in the power spectrum was the familiar 615 s signal. Despite the lack of other significant detections, we performed synchronous summations at all four periods of interest, in order to derive pulse arrival time information and pulse amplitude limits. These summed light curves are shown in Figure 6, averaged over the two nights and *compared in phase with the known time of pulse maximum in blue light for each frequency* (available from Table 2). Figure 6 shows that the 615 s *J*-band signal is in phase with the blue signal to within ~15° and of amplitude 0.035 mag. Upper limits to the amplitude of the other signals are: $A_{268} <$ 0.018 mag, $A_{243} < 0.019$ mag, and $A_{186} < 0.025$ mag. Averaging the three high-frequency signals together, we find an upper limit of 0.018 mag for a signal in phase with the blue light pulsations.

2.4. *K- and L-Bands*

The most extensive and interesting data were obtained through a *K* filter on the IRTF on July 24, when we monitored the star nearly continuously and acquired the light curve seen in Figure 5. The power spectrum of this light curve is shown in Figure 7. There is a very large peak at 2650 ± 130 s, corresponding to the obvious 40 minute wiggle in the light curve. There are four other obvious peaks at 1280 ± 35, 272 ± 5, 242 ± 3, and 186 ± 1 s. We interpret these respectively as the first harmonic of the 40 minute signal, and the *K*-band counterparts of the high-frequency oscillations detected in blue light. We have also labeled another peak at 597 ± 10 s, which has moderate statistical significance (2% chance of occurring by accident) and may be the counterpart of the 615 s signal which dominates in blue light. In addition, there are five other peaks of comparable significance in the period range of

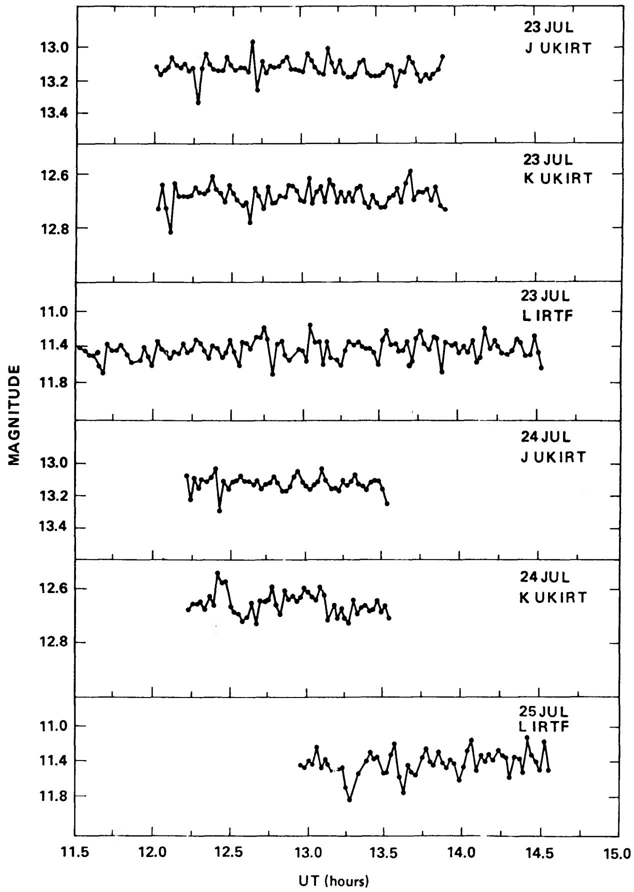

FIG. 4.—Infrared light curves obtained on the three nights. The J and K data show the original time resolution; each point of the L data represents four separate integrations.

200–600 s, just where the optical power spectrum is most rich. We consider it likely that most of these periods are real features of the star's K light curve; but because the detections are weak and not accompanied by confirming detections in blue light, we will not study these pulsations further. For future reference, we give here their periods in seconds: 477 ± 12, 374 ± 9, 351 ± 9, 297 ± 6, and 232 ± 3 s.

The average power spectrum of our two L-band observations is shown in Figure 8. No significant features are present, although the highest peak (368 ± 9 s; probability of accidental occurrence = 15%) does occur at a period consistent with one

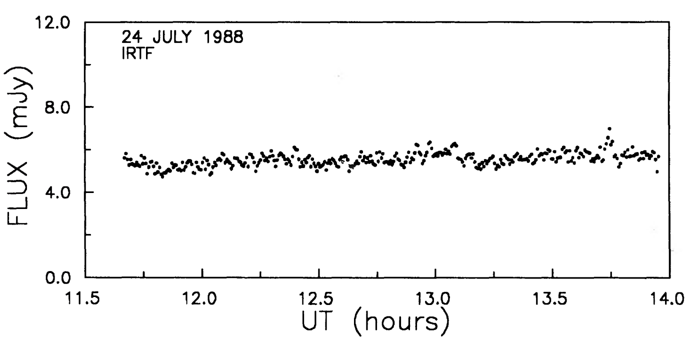

FIG. 5.—The IRTF K-band light curve obtained on July 24, at a time resolution of 22 s per point.

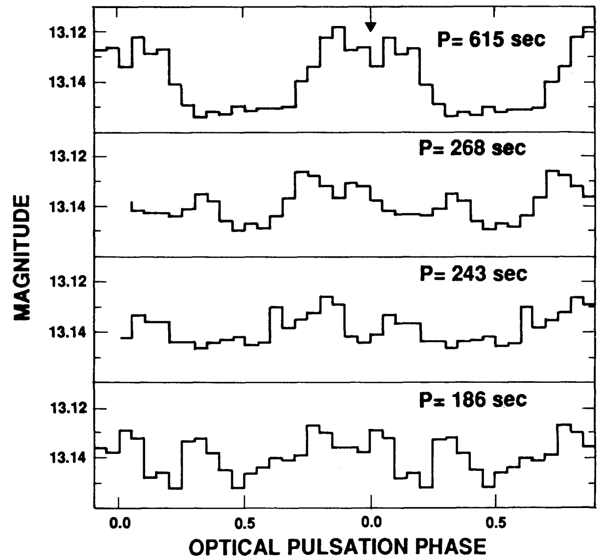

FIG. 6.—The J-band observations folded about the known pulsation periods, with zero pulsation phase defined as the pulse arrival time in blue light—empirically determined from the simultaneous optical data.

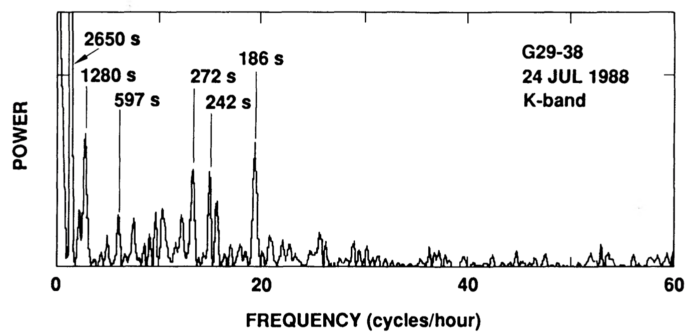

FIG. 7.—The power spectrum of G29-38 in the K band. We have labeled five highly significant peaks with their best-fit periods, plus another significant peak at 597 ± 10 s which is probably the counterpart of the dominant optical signal at 515 s. The horizontal tick marks indicate the power in a periodicity of amplitude 4%.

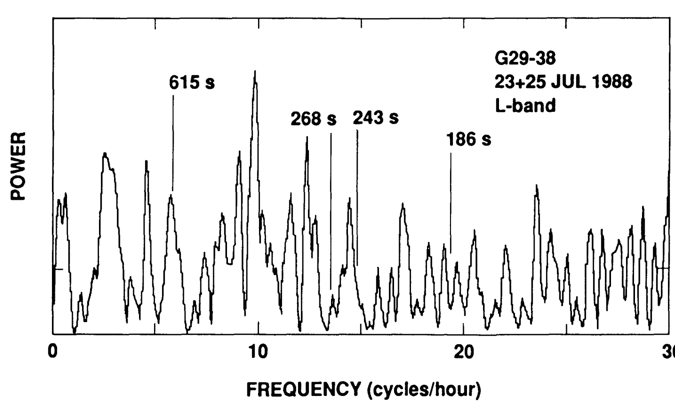

FIG. 8.—The power spectrum in the L band. The locations of the optical and K-band signals are indicated, but there are no statistically significant peaks. The horizontal tick marks show the power in a periodicity of 6% amplitude.

of the marginal K-band periods. The amplitude upper limits for the four principal periodicities studied in this paper are in the range 0.05–0.10 mag.

2.5. *Pulsation Light Curves and Amplitudes*

The three high-frequency oscillations labeled in Figure 7 have a probability of accidental occurrence which is <0.001 and are at frequencies consistent with the frequencies found and more accurately measured in the blue light power spectra (where we can obtain a cycle count accurate to within two cycles in 48 hr). Using the accurately determined values of the period, we have synchronously summed the data to obtain a mean pulsation light curve, and in Figure 9 we show these light curves for the four signals of interest, in three data sets: the K-band time series of July 24 on the IRTF, the average of the two K-band time series of July 23 and 24 on the UKIRT, and the average of the two L-band time series of July 23 and 25 on the IRTF. As in Figure 6, these synchronously summed light curves are compared with the absolute phase of the B-band pulsation at the same frequency on the same night.

In doing the summation, we folded the data on the known period into 20 phase bins, then lightly smoothed the result with a three-point smoothing filter. Consequently, a note of caution is required here. Smoothing helps to define the overall waveform, but at the cost of converting noise into structures that appear systematic (because they are in adjacent phase bins). For example, there is an appearance of a "double-humped" structure in each of the L-band light curves in Figure 9. Because this structure does not repeat well from night to night, we suspect that it arises not from the star but from the effect of smoothing random noise. The same caveat applies to all the other synchronous summations of weak signals shown in this paper.

Nevertheless, when the signal strength is adequate, these synchronously summed light curves convey a good deal more information than the power spectrum alone. In particular, they are most useful in defining the waveform and pulse arrival times, which are critical for the interpretation of these data. From Figure 9 we conclude the following:

1. *All three high-frequency oscillations show K-band light curves consistent with sinusoids in phase, or nearly in phase, with the signals in blue light.* Mean amplitudes are $A_{186} = 0.034$, $A_{243} = 0.030$, and $A_{268} = 0.023$ mag.

2. The K-band data folded at $P = 615$ s also yield a fairly smooth variation peaking at phase 0.04 ± 0.06; this strongly suggests that the weak signals seen in both the IRTF and the UKIRT data are in fact the counterpart of the dominant pulsation in blue light. The amplitude A_{615} in K light is 0.023 mag.

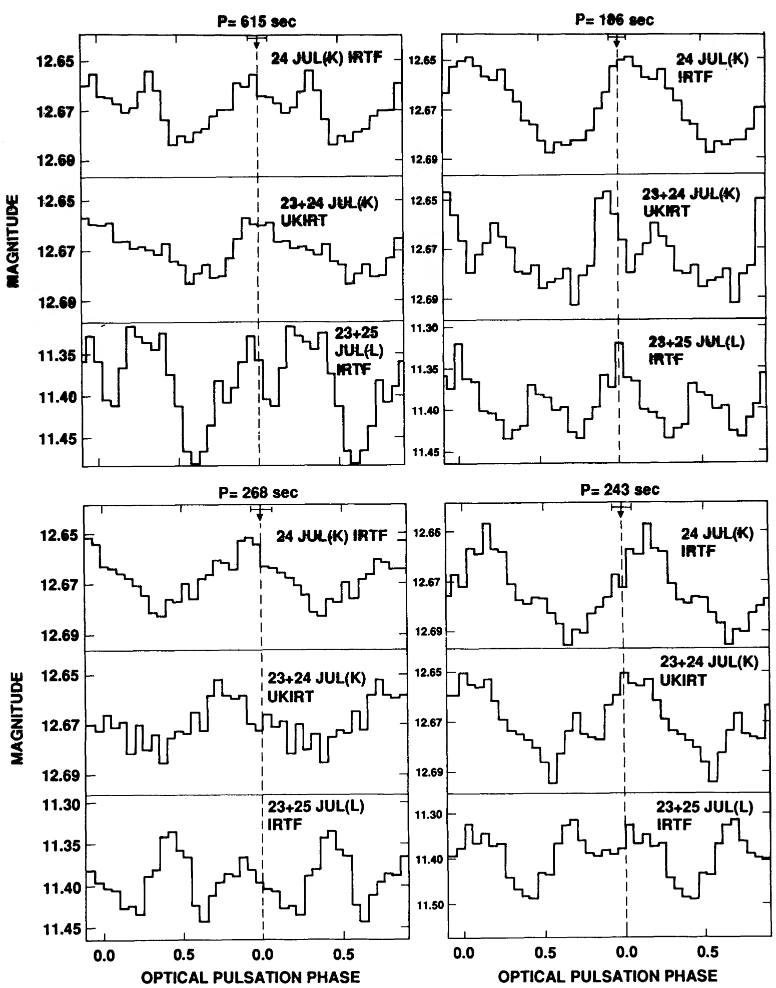

FIG. 9.—The K- and L-band observations folded about the known pulsation periods, with zero pulsation phase defined as the pulse arrival time in blue light—empirically determined from the simultaneous optical data.

3. There are no significant detections in the L-band data. Formal 2 σ upper limits are $A_{615} < 0.25$, $A_{186} < 0.11$, $A_{243} < 0.26$, and $A_{268} < 0.12$ mag.

All of the amplitude measurements and limits we have quoted have been derived by fitting sinusoids of adjustable amplitude and phase to the light curve. These are listed in the third column (A_1) of Table 3. But it appears that all of the clear detections show pulse arrival times very close to the pulse arrival times in blue light. Furthermore, since hotter regions on a star emit more copiously at all wavelengths, it is a strong prediction of white dwarf pulsation theory that pulse arrival times should be independent of wavelength (Robinson, Kepler, & Nather 1982). Therefore it seems reasonable to try to improve our amplitude limits somewhat by fixing the phase at zero (i.e., in phase with optical) and fitting our data for amplitude only. The fourth column of Table 3 contains the amplitudes determined in this manner (A_2). It is worth noting that while this procedure generally produces better limits for nondetections, it does not necessarily improve the amplitude measurements of detected signals, because the blue light phasing for the three high-frequency oscillations is only *slightly* better defined than the infrared phasing.

Since the three high-frequency oscillations appear to be very similar in phase, amplitude, and dependence of amplitude on wavelength, we have formed their composite light curves. These are presented in Figure 10, and their amplitudes are given in the last row of Table 3. This improves the statistical accuracy, but at the risk of blending features from the individual pulsations which may be significant. For example, we derive a mean amplitude that is lower than any of the separate amplitudes, principally because there is a marginal phase shift between the 186 and the 268 s oscillations. Yet the mean waveform and phasing of the K-band pulsation seen in Figure 10 is very close to that of the blue light pulsation. While this could be accidental, it does build confidence in the simple assumption we have made in merging the light curves, and in calculating A_2—that all of these oscillations are in phase with the corresponding pulse in blue light.

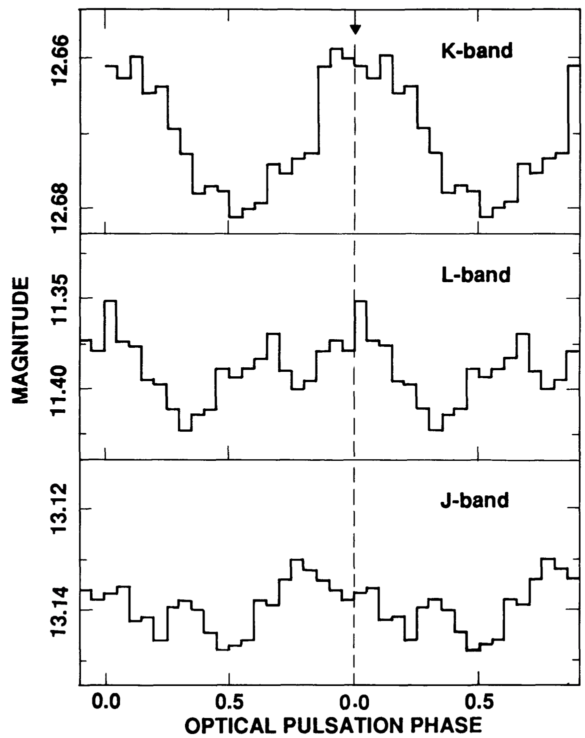

FIG. 10.—The composite pulsation (186+243+268 s) light curves of the three high-frequency pulsations, in three infrared bandpasses. We have formed these by synchronously summing the original data, aligning the synchronous light curves in phase with the simultaneously measured optical pulses, then co-adding the three signals.

TABLE 3

PULSATION AMPLITUDES

Pulsation (s)	Bandpass	Amplitude (mmag) A_1[a]	A_2[b]	A_3[c]
615	B	115 ± 4	115 ± 4	115 ± 4
	J	33 ± 3	33 ± 3	35 ± 3
	K	23 ± 4	21 ± 4	36 ± 7
	L	<250	<160	<2300
186	B	18 ± 2	18 ± 2	18 ± 2
	J	<25	<19	<20
	K	34 ± 4	30 ± 4	51 ± 7
	L	<110	<80	<500
243	B	24 ± 2	24 ± 2	24 ± 2
	J	<19	<13	<14
	K	30 ± 4	25 ± 4	43 ± 7
	L	<260	<190	NC[d]
268	B	31 ± 3	31 ± 3	31 ± 3
	J	<18	<17	<18
	K	23 ± 4	20 ± 4	34 ± 7
	L	<120	<70	<380
186+243+268	B	25 ± 2	25 ± 2	25 ± 2
	J	<18	<18	<19
	K	20 ± 2	20 ± 2	34 ± 3
	L	<80	<70	<380

[a] From amplitude and phase fit to light curve.
[b] From amplitude fit to light curve.
[c] From amplitude fit to light curve, with IR excess removed.
[d] No constraint.

Finally, in the last column of Table 3 we present the *adjusted* amplitudes (A_3), after adopting the A_2 estimates and subtracting the contribution of the infrared excess as deconvolved by Greenstein (1988). This is an appropriate correction if the pulsations arise from the white dwarf alone—one of the hypotheses we wish to test.

2.6. *Beating of High-Frequency Signals*

In addition to the smooth 40 minute wiggles and the high-frequency variations, the K-band light curve of Figure 5 also shows a few high points ("flares"?) spaced at ~40 minute intervals. Inspection of Figure 1 shows that each of these essentially coincides in time with a small flare in the B light curve. We spent some time puzzling over these events, until we noticed the beating time scales for the periodicities: the 186 s signal beats with the 243 s signal in 796 ± 16 s, and the 243 s signal beats with the 268 s signal in 2603 ± 150 s. Thus the trio beats together with a period of ~41 minutes. Furthermore, the data given in Table 2 show that the phases of the three oscillations at the peak of the most distinct flare (at 13.752 UT on July 24) are 0.10, 0.08, and 0.02 (in order of increasing period). This agreement in phase is within measurement error, and strongly suggests that the "flares" arise merely from the constructive reinforcement of the high-frequency waves.

While this appears to be true, we suspect that it understates the true significance of the 40 minute time scale in the star, for the following reasons:

1. The effect described above only explains the apparent variability in pulsation amplitude, not the slow wiggle in mean light which is also evident in Figures 5 and 7; and

2. The three most important periods in the B light curve (615, 499, and 401 s) on July 24 *also* beat together with a period of 40 minutes.

3. INTERPRETATION

3.1. $A(\lambda)$: *The Facts and The Puzzle*

At nearly the same time as our observations of G29-38, Graham et al. (1990a, hereafter GMNS) also carried out high-speed photometry of the star. The results presented above confirm their important discovery of 181 and 243 s pulsations in the K-band light. The 268 s periodicity, obvious in the data shown above, was also present in their data but was attributed to aliasing from higher frequencies; since the sampling interval in our critical July 24 K-band light curve is very short (22 s), we know that the periodicity is intrinsic to the star, *not* due to aliasing from other frequencies. We also confirm the existence of a J-band periodicity consistent in period and phase with the dominant 615 s signal in blue light.

Acquisition of simultaneous B photometry of high signal-to-noise ratio leads us to two additional significant results. First, the simultaneous detection of the high-frequency signals in both infrared and blue light (where the infrared source contributes only $\sim 10^{-5}$ of the flux) proves conclusively that they cannot come from a brown dwarf, but *must be ultimately seated in the white dwarf.* Second, we can clarify the phase relations of these various signals. For the four periodicities we study, there are a few marginal phase shifts but all of the data are reasonably consistent with a *pulse arrival time that is independent of wavelength.* This is a necessary feature of nonradial pulsations, because *temperature* variations are responsible for the signal, and a hotter surface should produce more light at all wavelengths.

The other strong prediction of nonradial pulsation theory is that the amplitudes ought to be strictly determined by the change of flux with temperature, $\partial F_\lambda/\partial T$, derived from model atmospheres (Robinson et al. 1982). Using Greenstein's (1988) estimate of $T = 11{,}500$ K and $\log g = 8$ and interpolating in Wickramasinghe's (1972) model atmospheres for DA white dwarfs, we find that the amplitudes should be in the ratio $100{:}43 \pm 3{:}32 \pm 2{:}31 \pm 2$ for the B, J, K, and L bands, respectively (the quoted errors include uncertainties in interpolation and in effective wavelength, but not in the input physics of the models). From Table 3 we find the corrected amplitudes A_3 to be in the following ratios:

(a)—$100{:}30 \pm 3{:}31 \pm 7{:}<2000$ for the 615 s signal;

(b)—$100{:}<111{:}283 \pm 50{:}<2780$ for the 186 s signal;

(c)—$100{:}<58{:}179 \pm 35{:}<\infty$ for the 243 s signal;

(d)—$100{:}<58{:}110 \pm 30{:}<1230$ for the 268 s signal; and

(e)—$100{:}<76{:}136 \pm 22{:}<1520$ for the average of the three high-frequency signals.

How do these numbers compare to those of GMNS? Although those authors used similar equipment and observing techniques, and obtained their data within a few weeks of ours, a thorough comparison is not possible because they did not detect the 615 s signal in K light, or any of the high-frequency signals in B light. A limited comparison is possible on the 615 s signal, for which they found corrected amplitudes in the ratio $100{:}48 \pm 6{:}<34$ ($3\,\sigma$ upper limit). These numbers are in mediocre agreement with ours; the K measurements are consistent, but our signal at J is decidedly weaker. However, both sets of J photometry are quite sparse: 120 data points in ours, 54 in theirs. In such data sets the formal errors often underestimate the true uncertainties, especially when the light curve may be contaminated by other frequencies. An improved estimate of the J amplitude is very desirable and will require much more extensive data. But in the meantime, we tend to agree with GMNS that the $A(\lambda)$ dependence of the 615 s signal is in at least approximate agreement with the prediction of adiabatic pulsation theory—from 0.4 through 2.2 μm.

The same can certainly not be said of the high-frequency oscillations, which are *extremely overluminous* in K light if they arise from the white dwarf. Reasoning backward from the observed corrected pulsation amplitude in the K band (34 mmag for the combined signal), adiabatic pulsation theory leads us to expect amplitudes of 101 ± 9 and 49 ± 4 mmag for the B and J bandpasses. Instead we find 25 ± 2 and <19 mmag, respectively. This is an enormous discrepancy, yet it cannot be explained by simply attributing the pulsations to the source of the infrared excess, because their presence in blue light proves that they are ultimately powered by the white dwarf.

3.2. *Atmospheric Troubles?*

Can some failure of the white dwarf model atmospheres cause this effect? It seems at best a remote possibility. Greenstein (1988) showed that the spectrum of G29-38 over the range 0.1–1.0 μm matched in detail the features of DA model atmospheres as well as those of typical DA stars. Beyond 1 μm, our ignorance of the spectra of "typical" white dwarfs allows more room to speculate. It is true that the K band lies astride the Pfund jump in the continuum, but this is unlikely to have much of an effect, for the following reasons:

1. A 3% change in temperature (see below) is inadequate to change appreciably the continuum jumps.

2. The model atmospheres (Wickramasinghe 1972; Wesemael 1980) show that all of the higher order continuum jumps (Paschen, Brackett, Pfund) should be small; this is confirmed by plentiful observations of DA white dwarfs at the Paschen jump, including G29-38 (Greenstein 1988).

3. It would be necessary for the required gremlins to enhance the K amplitudes for some pulsations (186, 243, 268 s), but not for others (615, 499, 401 s).

3.3. *Reprocessing in a Dusty Disk*

Another possibility is to invoke the presence of a second object, which we independently suspect from the broad-band flux distribution to be present in the system. This cannot be a pulsating brown dwarf, but rather cool material ($T \sim 800$–1200 K, if it is identical to the source of the infrared excess) which responds to at least *some* of the white dwarf pulsations. GMNS proposed such a model, in which a dusty ring surrounds a white dwarf and is heated in a periodic manner as the little ripples in temperature run around the star's facing hemisphere. Let us examine this model to see if it can satisfy the available data.

Warner & Robinson (1972) and Chanmugam (1972) first suggested that the periodicities in variable white dwarfs arise from nonradial pulsations, and this hypothesis has survived well over the years. Osaki & Hansen (1973) showed in particular that nonradial g-mode pulsations in white dwarfs should have periods of a few hundred seconds, as required by the observations. Robinson et al. (1982) showed that the color variations of ZZ Cet are in good agreement with nonradial pulsation theory, and several studies have shown that the κ-mechanism in the hydrogen ionization zone can excite the nonradial g-modes of DA white dwarfs (Dziembowski & Koester 1981; Dolez & Vauclair 1981; Winget et al. 1982; Cox et al. 1987).

For the normal modes of a slowly rotating white dwarf in nonradial pulsation, the perturbations of the physical variables (temperature, in our case) have the form

$$Y_l^m(\theta, \phi) \cos \omega t ,$$

where $Y_l^m(\theta, \phi)$ denotes the spherical harmonics, θ the colatitude and ϕ the azimuth angle in spherical polar coordinates, and ω the angular frequency. The number of nodal lines on the star is given by the harmonic degree l, regardless of the m value, while the azimuthal order m specifies the number of nodal lines in longitude. (A lucid discussion of the geometry of the pulsation modes is given by Unno 1979).

Theory does not yet specify which pulsation modes should be excited, but when the observations integrate over an entire hemisphere of the star, the many adjacent bright and dark regions produced by high-order modes will tend to cancel each other out, and hence escape detection. Thus we restrict our attention to the low-order modes.

Since a nonradially pulsating white dwarf maintains a constant luminosity when averaged over 4π sr, a surrounding spherical dust cloud heated by the white dwarf will not be seen to vary by a distant observer—and therefore can be ruled out. The other natural geometry to consider is a flattened disk or ring. If the disk is particularly small or nearly edge-on as seen from Earth, such a structure can produce occultation effects either from itself or from the body of the white dwarf, but since they arise from special geometries, we will not consider them further. Let us consider a disk which is seen sufficiently face-on to be free from any occultation effects.

A good candidate for the 615 s period is the $l = 1$, $m = 1$ mode, which is a pattern that features a single bright spot propagating around the star's equator. Observers close to the star's equator will see a discernible modulation, with an amplitude matching the observed amplitude if $\Delta T/T = 0.034$ (where ΔT is the full amplitude of the temperature variation). For higher order pulsation modes and/or for observers farther from the star's equator, there is partial cancellation of bright and dark regions, and hence a larger ΔT is required to give the same observable effect. The heating of the dusty disk depends on the exact choice of pulsation mode. But for all modes with $m = l$ (the "sectoral modes," i.e., those propagating strictly east-west), there is no periodic heating of the disk, since the disk, unlike the distant observer, is illuminated simultaneously by cool as well as bright regions on the white dwarf. This is in accord with our observations of the phase and amplitude of the 615 s signal in K light, which suggest no role for the disk.

To explain the infrared pulsations, GMNS suggested that the higher frequency modes correspond to the $m = 0$ modes, in which the light-dark pattern is a north-south standing wave oscillation, with nodes on circles of fixed latitude. Since the disk will be predominantly heated by the equatorial regions, all of which brighten simultaneously, this can be a fairly efficient way to vary the heating of the disk and will produce infrared signals for essentially any viewing angle.

The more extensive data presented above allow us to test this possibility in more detail. First, let us restrict our attention to blue light, where the white dwarf dominates. If we assume that the ratio $(A_{186}/A_{615})_{\rm wd}$ arises strictly from the viewing angle, then the observed low value of 0.16 indicates that we are located near one of the nodes of the 186 s wave. Specifically, Y_{20} has its only node on the star's facing hemisphere at $\theta = 55°$, and the observed amplitude ratio indicates $\theta = 59 \pm 2°$ or $52 \pm 2°$. The more "equatorial" choice (59°) must be the correct one, since our observations of the phase agreement between the optical and IR indicate that the hemisphere facing us brightens at the same time as the hemisphere facing the disk.

But it is much more likely that the observable ratio $(A_{186}/A_{615})_{\rm wd}$ derives partly from viewing angle and partly from the intrinsic size of the temperature perturbation. These are impossible to decouple uniquely, but we could estimate the $\Delta T/T$ of the 186 s signal by asking what would be required to give the observed 0.08 mag pulsation amplitude of the disk light at K. Since the dust must extend quite far from the white dwarf (10–100 $R_{\rm wd}$, in order to obtain a reradiated component with the observed low temperature of 800–1200 K), there is substantial cancellation of bright and dark regions even for the most favorable case, the (2, 0) mode. In order to obtain 0.08 mag, the incident flux must vary by at least 8%, which corresponds to at least a 21% variation in the surface flux between bright and dark regions on the white dwarf. This requires $\Delta T/T > 0.051$, a greater temperature perturbation than is likely for the 615 s signal. Yet the observed amplitude of the white dwarf's 615 s signal vastly exceeds that of the 186 s signal.

This is a troubling turn of events. Within the model discussed, it can only be understood if the white dwarf is viewed almost exactly above the node at $\theta = 55°$ (as supposed by GMNS, who did not detect the 186 s signal in blue light). We are thus driven back into the arms of an exceedingly special geometry, despite all efforts to avoid it. This does not inspire much confidence, even though the temperatures and viewing angles can be formally juggled to fit the data.

3.4. *Other Hypotheses from Hell*

All of the above discussion has assumed that the disk is axisymmetric and in the star's equator. If the disk is significantly asymmetric (e.g., elliptical), the extra free parameter wreaks havoc with the model. There is then no chance of identifying the pulsation modes, the viewing geometry, or ΔT. Qualitatively, the IR pulsations might then even arise preferentially from east-west waves, since, for an elliptical ring, the bright and dark regions travelling around the white dwarf's equator would *not* illuminate the disk equally, and therefore would not cancel each other's effects.

The origin and stability of an elliptical ring are related to the unknown origin of the ring particles and the uncertain gravitational quadrupole moments of the white dwarf and the orbiting disk. Tokunaga, Becklin, & Zuckerman (1990) discuss a similar uncertainty in regard to the origin and maintenance of a "warp" in the disk, invoked to reconcile the optical/infrared energy budgets in a reprocessing model.

4. LONG-TERM TIMING CONSIDERATIONS

Yet another observing campaign on G29-38 was carried out in 1988, nearly contemporaneous with ours. Winget et al. (1990) report a very extensive set of photometric observations, obtained in blue light over a 79 day baseline. They found, as we did, that the optical power spectrum was dominated by a single strong peak at $P = 615$ s. They also found that the 615 s pulse timings showed small phase residuals on a time scale of a few months and reported that the residuals faithfully mimicked light-travel time variations across a binary orbit with $P \sim 115$ days.

Although our data are much less extensive, they are favorably placed ~ 90 days before those of Winget et al. and therefore can test the predictive power of their ephemeris. In Figure 11 we reproduce their $O-C$ diagram, adding five points: three timings of ours, plus two (at the upper left) that we have extracted from the light curves of GMNS. We determined the latter pulse maxima to occur at $\text{JED}_{\odot}$ 2,447,346.9398 (± 3) and 2,447,351.9798 (± 5). Our timings are in very poor agreement with the prediction, with the maxima occurring an average of 151 ± 13 sec too early. One of the two points of GMNS is in satisfactory agreement with the curve, while the other occurs $\sim 170 \pm 30$ s too late. Thus the ephemeris does not fare well in this test.

We have tried to fine-tune the "orbital" parameters to eliminate the discrepancy, but it is difficult. A slightly longer period and larger amplitude helps somewhat, as does adoption of a slightly shorter mean pulsation period (Winget et al. used 615.15 s). But the improvements are small; we cannot find any period that can represent these residuals to within the accuracy suggested by the small scatter in the night-to-night pulse timings. In addition, the radial velocity observations also appear to rule out binary motion with the predicted amplitude and period (Liebert, Saffer, & Pilachowski 1989; Graham et al. 1990b). Despite the very impressive clustering of points about the curve in Figure 6 of Winget et al., suggestive of great phase stability, there seems to be no true periodicity in the residuals.

5. SUMMARY AND THE VIEW AHEAD

Our K-band photometry confirms the discovery of infrared pulsations in G29-38, and our B-band photometry establishes that pulsations of the same period and phase are simultaneously present in blue light. Because the white dwarf totally dominates in blue light, this proves conclusively that the pulsations are ultimately seated in the white dwarf, not in a putative brown dwarf (as conjectured, e.g., by Marley, Lunine, & Hubbard 1989).

The amplitude of the infrared pulsations is anomalously high. This is particularly difficult to understand, since all other tests of the dependence of amplitude on wavelength in ZZ Ceti stars (including that of the optically dominant 615 s period in G29-38) have yielded results in substantial agreement with theory. Following Ockham's Razor (Pluralitas non est ponenda sine necessitate; Ockham 1490), it seems wise to try to account for this with a mechanism that also accounts for the other major anomaly in the system: the existence of a cool component which appears in the infrared light.

In principle, we can understand both of these observations with a model in which a ring or disk of dust surrounds the white dwarf and reprocesses incident optical/UV light from the photosphere. To account for the low temperature of the infrared component [~ 800–1200 K, as recently determined by Tokunaga et al. (1990)], the ring must be large, at least 1 $R_{\odot}$. For a circular ring or disk, the pulsation modes giving rise to the observed IR periods must be low-order "zonal" modes (in which the pulsation travels north-south), in order to account for the large amplitude. If the ring is very asymmetric in azimuth (elliptical, for example), then the opposite could be true: i.e., the IR periods could originate from east-west travelling waves.

But with such a large disk, the observed efficiency for producing a pulsed signal from the disk is low. Our attempt to understand the relative amplitudes basically fails, unless a very special geometry is invoked, in which we are hovering precisely over a nodal line on the star. This certainly undermines the credibility of the model.

There remain at least four major points in need of further exploration:

1. The white dwarf and cool component contribute about equally to the K band, so we cannot say with certainty which component produces the oscillating light at K (although we know it is *driven* by the white dwarf). We have instead relied on a theoretical argument for this. Detection of periodicities in the L band, where the white dwarf contributes only $\sim 3\%$ of the light, would be conclusive.

2. The observations give tantalizing clues that 40 minutes is a significant period in the system, and is (perhaps) very strongly seen in the infrared light curve. We have not offered any explanation for this feature (which needs to be confirmed by more extensive observation).

3. Ockham's Razor is not infallible. Zuckerman & Becklin (1991) have surveyed most of the known ZZ Ceti stars without finding any other anomalous cool components, but extensive high-speed infrared photometry has been obtained *only* for G29-38. If any other systems display IR pulsations of unexpected amplitude, this would suggest that the origin is in a breakdown of a white dwarf atmosphere theory, not a secondary dust component.

4. Finally, and perhaps most important, the origin and maintenance of a dusty disk around a white dwarf, where the orbital lifetimes due to Poynting-Robertson drag are quite short (Zuckerman & Becklin 1987), still must be reckoned a total mystery.

We are very grateful to H. Epps for originally calling our

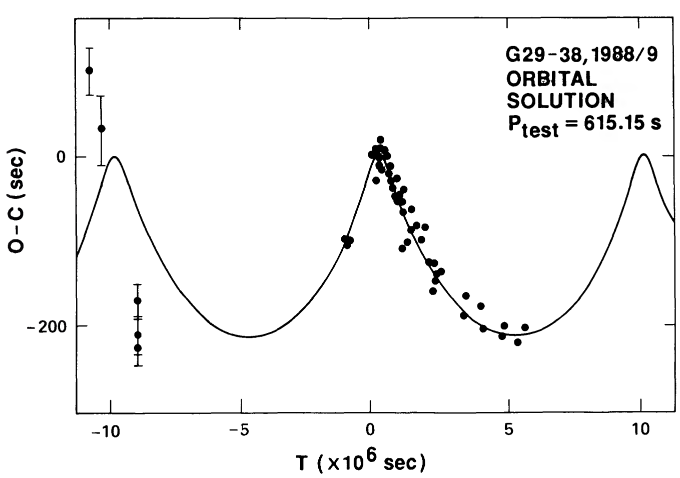

FIG. 11.—$O-C$ diagram of the 615 s optical pulse timings in the 1988–1989 season, relative to a test period of 615.15 s. The large cluster of points in the middle of the figure is from Winget et al. (1990), and the curve represents their "orbital" solution to the phase residuals. The failure of the curve to reproduce the five timings early in the season casts doubt on the idea that there is a periodicity in the residuals.

attention to the possibility that time variations might be a useful diagnostic of the G29-38 system, and to C. Shelton for assistance with data reduction. We thank M. Jura and J. Graham for helpful conversations. We acknowledge partial support from NSF grants AST 87-17871 to UCLA and AST 89-16995 to Columbia University.

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