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THE INFRARED EXCESS OF G29-38: A BROWN DWARF OR DUST?

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ABSTRACT

The white dwarf star G29-38 has an infrared excess which may be due to a cool low-mass companion, probably a brown dwarf, or to circumstellar dust. If the excess is due to dust, then changes in luminosity of the white dwarf, which is a ZZ Ceti variable, may cause the infrared excess to vary in phase with the optical pulsations. We have therefore obtained simultaneous optical and infrared light curves of G29-38 to search for variability of the excess. The known 614 s period of G29-39 is seen at B and J, with amplitudes and phases which are in excellent agreement with the predictions of adiabatic, g-mode pulsation theory. No variability with a 614 s period is found at K above that expected from the white dwarf photosphere.

We have discovered two significant periodicities in the K light curve at 181 ± 10 s and 243 ± 15 s. These periods are not found at shorter wavelengths, and we therefore conclude that they must be due to variations in the strength of the infrared excess, rather than the photospheric emission from the white dwarf. We propose a model which invokes a dust ring around the white dwarf to explain the infrared excess and variability in this system. A detection of G29-38 at 10 μm at a flux level about 3 times that expected from a brown dwarf favors the dust model.

Subject headings: infrared: sources — stars: circumstellar shells — stars: individual (G29-38) — stars: pulsations — stars: white dwarfs

I. INTRODUCTION

Brown dwarfs are hypothetical bodies with masses which lie in the range between planets and stars ($\sim 10^{-3}$–10^{-1} $M_\odot$). They are too light to ignite thermonuclear burning (i.e., less than 0.08 $M_\odot$), and therefore they do not qualify as stars. Although brown dwarfs cannot release energy through hydrogen fusion, they will glow in the infrared as they contract and cool. The discovery of a brown dwarf would be extremely significant, and the study of such objects may answer important questions such as what is the structure of substellar dwarfs below the hydrogen-burning mass limit, and how much do these objects contribute to the "missing mass" of the Galaxy?

The discovery that the white dwarf G29-38 has substantial infrared excess emission above that expected from a single star is the first result suggestive of the detection of such a brown dwarf in a survey designed to find cool companions of young white dwarfs (Zuckerman and Becklin 1987*b*). Previously Zuckerman and Becklin (1987*a*) had measured the infrared colors of 14 white dwarfs in the young Galactic clusters, the Hyades and the Pleiades, and found that none showed excess infrared emission, and so G29-38 is unusual. At optical wavelengths G29-38 appears to be a normal DA white dwarf (Greenstein 1988), but in the infrared, at $\lambda \gtrsim 2$ μm a new, cool component emerges and dominates the spectrum. The color temperature of the infrared excess is ≈ 1200 K, and the emitting area corresponds to a spherical body with a radius of ≈ 0.15 $R_\odot$ which makes G29-38 a good candidate for a white dwarf–brown dwarf binary system. The only major problem with the identification of the excess with a brown dwarf is that this radius is 50% larger than predicted by theoretical models (Zuckerman and Becklin 1987*b*). However, high-opacity brown dwarf models, by Lunine *et al.* 1989, are in better agreement with the observations.

The hypothesis that the infrared excess is due to a low-mass companion remains viable in the light of new data in the form of infrared spectroscopy and imaging (Tokunaga *et al.* 1988), and a detailed study of spectrum, carried out by Greenstein (1988). But the possibility that the emission is due to small solid particles has not yet been ruled out. The presence of dust grains in a system of age $\sim 6 \times 10^8$ yr is unexplained given that the depletion time due to the Poynting-Robertson effect of 0.5 μm grains is ~ 10 yr (Zuckerman and Becklin 1987*a*).

Giclas 29-38 belongs to the class of degenerate variables, the ZZ Ceti stars. These stars have periods in the range 200–1000 s and a variability of up to 0.3 mag. G29-38 (ZZ Psc) is one of the brightest and largest amplitude ZZ Ceti stars, a fact which suggests that searching for variability of the infrared excess in this source may be a way to test for the presence of dust. Calculations, described below, show that if the excess emission is due to dust grains heated by the white dwarf, then the dust temperature will respond to optical variations causing a detectable change in the excess at 2 μm.

In § II we describe high-speed simultaneous, and almost simultaneous, photometry at 0.45, 1.3, and 2.2 μm. The observational results are outlined in § III, including periodogram analysis of the light curves. The previously known 614 s period is recorded at 0.45 and 1.3 μm, and the variations at these wavelengths are compared with the predictions of adiabatic g-mode pulsation theory in § IV. Significant variations at 2.2 μm are found at periods of 181 ± 10 s and 243 ± 15 s, and a model where this variation is due to dust emission is described in § V.

II. OBSERVATIONS

Giclas 29-38 was observed on the night of 1988 July 4 at the f/70 Cassegrain focus of the Hale 5 m telescope. Simultaneous optical (B, 0.45 μm) and infrared photometry was obtained by using the chopping secondary to move the telescope beam 21″ E–W at a frequency of 5 Hz between a photomultiplier tube and a solid nitrogen–cooled InSb detector. The telescope was also nodded so that the infrared measurements were carried out in beam-switching mode. The seeing on this night was

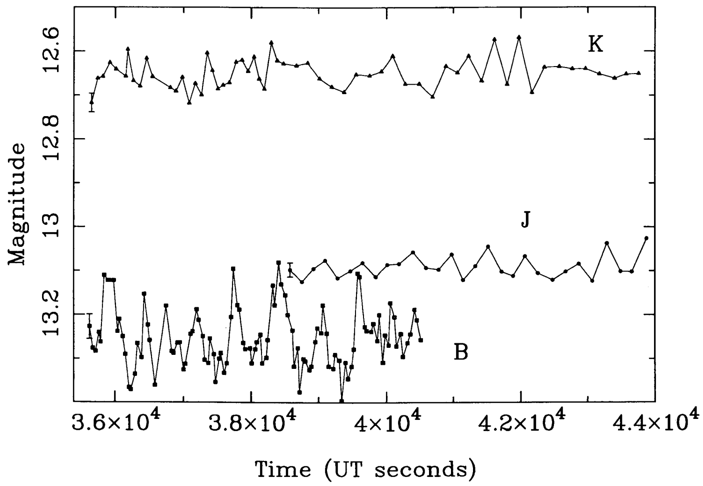

FIG. 1.—The *B*, *J*, and *K* light curves of G29-38 from 1988 July 4

1″–1″.5 diameter, and infrared and optical beams of 8″ and 6″ diameter respectively were used. An autoguider tracking a guide star 203″ E and 110″ S of G29-38 was used during all observations. Standard stars observed during the night indicate that conditions were photometric. Counts from the photomultiplier were integrated for 1 s and recorded. Each infrared data point consisted of four 10 s integrations, two on the object and two on the sky. A total of 2 hr of data were recorded. For the first 45 minutes, all the infrared data were taken using a *K* (2.2 μm, 0.4 μm FWHM) filter, and the mean sampling interval of this part of the *K* light curve was ≈90 s. Following this, alternate *K* and *J* (1.3 μm, 0.2 μm FWHM) measurements were made resulting in a mean sampling interval for *J* and *K* of ≈180 s. The statistical uncertainties in the photometry are approximately 0.006 mag at *J*, 0.014 mag at *K*, and 0.03 mag at *B*. The true uncertainty in the data is difficult to estimate because it may be dominated by systematic effects such as changes in the seeing or seeing-induced image motion which cannot be corrected for by the autoguider. Runs on a star of comparable brightness to G29-38 at *J* and *K* suggest that in these observations systematic uncertainties amount to 0.015 mag. In the following analysis we have added, in quadrature, an error of this magnitude to the statistical uncertainties. The uncertainty in the *B* photometry is large relative to the infrared data because of the high optical background due to the full Moon which was only 14° away from G29-38, because the signal was recorded in only one of the infrared beam switch positions, and because these are two reflections at the surfaces of gold-coated mirrors (including the undersized infrared secondary) in the optical path which each have low reflectivity (30%–40%) at 0.45 μm. The uncertainties in the optical data are much larger than one might expect for a telescope of 5 m aperture, and one might infer the presence of severe systematic problems. However, the signal-to-noise of the optical data is fully understood in terms of the optical losses in this system which is optimized for infrared work. Toward the end of the run, the sky brightness at optical wavelengths increased rapidly as twilight approached, rendering the last $\approx 10^3$ s of optical photometry worthless. Figure 1 shows the three light curves from 1988 July 4.

Additional infrared photometry was obtained on 1988 July 9. G29-38 was observed alternately at *J* and *K* for 2600 s. The same chopping and nodding techniques were used to subtract the sky background. The photometry consists of four 3 s integrations at *J* interleaved with 16 3 s integrations at *K*. The resultant mean sampling interval of the light curve at both wavelengths is 110 s. These light curves are shown in Figure 2. This night was also photometric, with seeing which was less than 1″ in diameter, consequently a 5″ beam was used. The noise at *K* is substantially smaller in these data than in the July 4 data set because of the smaller beam size and longer integration time used. Continuous data at *K* were also taken, without nodding, using a high-speed photometer system which records the demodulated signal from the InSb detector every 10 ms. A 2000 s long data set was recorded in this mode. The sampling interval for the high-speed photometry is known accurately but the data were not time stamped so the phase relative to the photometry is not known. The resultant *K* light curve is presented in Figure 3.

III. RESULTS

The *B* light curve of G29-38 on 1988 July 4 clearly shows variability, with a peak-to-peak range of ≈0.25 mag (Fig. 1).

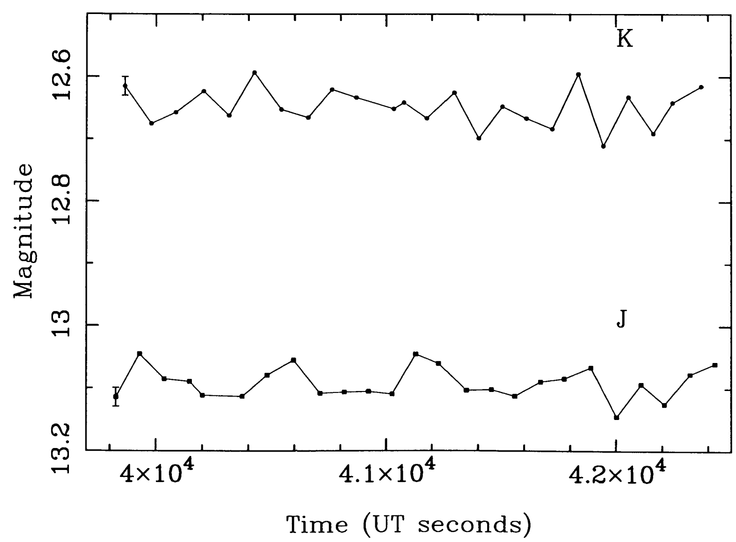

FIG. 2.—The *J* and *K* light curves of G29-38 from 1988 July 9

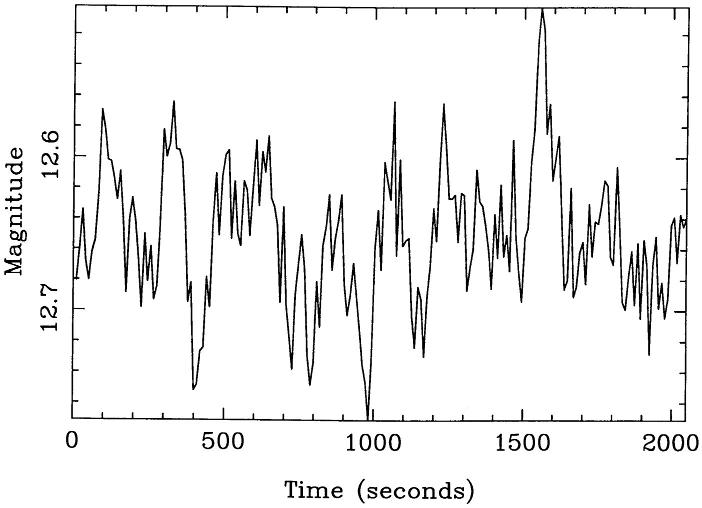

FIG. 3.—The K light curve of G29-38 on 1988 July 9 from the high-speed photometer.

Variations are seen on a time scale of about 1000 s, the pulse shape is irregular, and no clear periodicity is apparent. The B light curve presented here is similar to previous data for G29-38 (e.g., McGraw and Robinson 1975). Variability is also seen at J, with a smaller amplitude of ≈ 0.07 mag peak to peak. Inspection of Figure 1 suggests that the pulsations at J and B are correlated. Significant changes in the brightness at K are seen with a peak-to-peak amplitude of about 0.15 mag. These variations do not appear to be correlated with either B or J, and, as consecutive points of the K light curve are uncorrelated, the time scale for the variations is shorter than the sampling interval.

The J light curve obtained on 1988 July 9 shows three clear pulses with a peak-to-peak amplitude of 0.06 mag, separated by 600 s (Fig. 2). The K photometry shows significant variations on a time scale of ≈ 200 s, which are apparently uncorrelated with the variations at J. The K data from the high-speed photometry system (Fig. 3) confirm the presence of rapid variability with a peak-to-peak amplitude of ≈ 0.2 mag at this wavelength.

a) Harmonic Analysis

To search the light curves for periodic variations, periodograms were calculated according to the algorithm of Scargle (1982) and Horne and Baliunas (1986) as implemented by Press and Teukolsky (1988). Using the Scargle normalized periodogram is identical to estimating the harmonic content of a data set by least-squares fitting of sine and cosine functions. The normalization is defined so that if there is no periodic signal, and the signal is white noise, then the Scargle periodogram is an exponentially distributed random variable (Scargle 1982). Thus if the data contain no periodic signal and can be represented as white noise, the false alarm probability, P, that the amplitude of the periodogram at any of N independent frequencies exceeds an amplitude x is $P = 1 - [1 - \exp(-x)]^N$. In the current data set the light curves are sampled at roughly equal intervals. In this case we expect that the number of independent frequencies is very nearly equal to the number of data points. In general, N depends upon the number of frequencies samples, the number of data points, and their detailed spacing. Therefore, to find a more accurate estimate of N we carried out

TABLE 1

INDEPENDENT FREQUENCIES IN DATA

Data Set	Number of Data Points	Number of Independent Frequencies (N)
B Jul 4	106	131.1
J Jul 4	29	35.2
K Jul 4	59	61.5
J Jul 9	25	36.7
K Jul 9	24	32.9
K[a] Jul 9	200	232.8

[a] High-speed photometry.

Monte Carlo experiments in which the sampling times of each light curve were preserved but the order of the data was scrambled. Periodograms were calculated for many sets of scrambled data, typically 1000, and the highest peak noted. The false alarm probability function was fitted to the resultant distribution to find N for each data set. The value of N for each data set is given in Table 1. The relation between the number of data points and N found here agrees well with that of Horne and Baliunas (1986) who measured N for a variety of simulated data sets.

The periodogram for the 1988 July 4 B light curve is shown in Figure 4. The periodogram shows a very significant harmonic signal with $P < 10^{-4}$ at a frequency of 1.61 ± 0.01 mHz, which corresponds to a period of 621 ± 5 s. No other significant (>95%) periodicities are present in these data. Harmonic analysis of the light curves of ZZ Ceti stars shows that the power spectrum is variable with time, and therefore we should

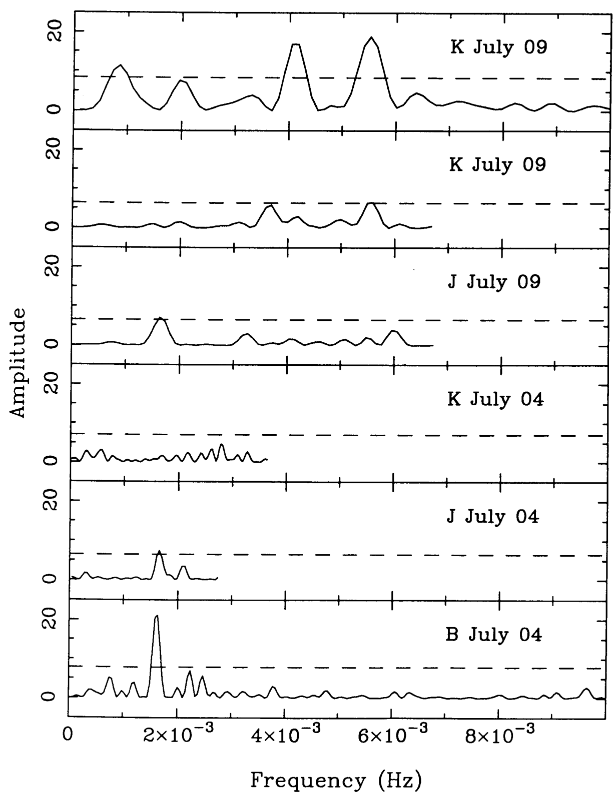

FIG. 4.—The periodograms of the light curves presented in Figs. 1–3. The dotted line shows the amplitude of a signal which would be significant at the 95% confidence level.

not expect the current data to correspond exactly with previous observations. Specifically, McGraw and Robinson (1975) find a number of peaks in the power spectrum in the range 1020–480 s, while Schulov and Kopatskaya (1973) report periods of 816 s and 612 s. The current behavior is thus quite normal. The periodogram (Fig. 4) for the 1988 July 4 J data also shows a significant signal with a frequency of 1.64 ± 0.02 mHz (611 ± 8 s) with $P = 0.02$. The B and J periods agree within the errors; we assume that they are due to a single signal with period equal to the weighted mean, 614 ± 4 s. This signal is undoubtedly related to the 612 s optical period of Schulov and Kopatskaya (1973). The periodogram for the 1988 July 4 K light curve shows no significant harmonic content below the mean Nyquist frequency of 2.5 mHz.

A significant period of 614 s is seen once again in the 1988 July 9 J light curve (Fig. 4), but the periodogram for the improved K photometry still shows no significant period near 614 s. A 614 s period is not seen in the high-speed K data either. Surprisingly, the K photometry shows evidence for power at frequencies of 3.67 mHz ($P = 0.08$), and 5.54 mHz ($P = 0.04$) as shown in Figure 4. By itself the slowly sampled K photometry is not very convincing evidence for the presence of these rapid periodic variations, especially because the most significant period at 5.5 mHz is close to the average Nyquist frequency. But the high-speed K photometry confirms that there are two very significant ($P < 10^{-4}$) high-frequency periodic signals at this wavelength. The periodogram of the high-speed K photometry in Figure 4 shows peaks at both 4.11 ± 0.24 mHz (243 ± 15 s) and 5.52 ± 0.33 mHz (181 ± 10 s). Thus both data sets contain a signal at 5.5 mHz. There is another peak in the K high-speed photometry periodogram at 0.86 mHz. The peak at 0.86 mHz is significant under the assumption of white noise ($P = 0.003$), corresponds to a period of 1160 s which is more than half the length of the observation, and therefore could easily be due to slow changes in atmospheric transparency or seeing. As the 0.86 mHz signal was not detected in either the 1988 July 4 or July 9 K data it must be due to one of these effects, and therefore the probability calculated on the assumption of white noise is an overestimate of its significance. We can make a strong argument that the 243 s and 181 s signals in the K high-speed photometry are not due to 1/f noise or effects such as periodic drive errors or telescope vibrations which may modulate the signal, but are intrinsic to the source, because of the absence of comparable power at these frequencies in the J light curve. Furthermore, before G29-38 was observed on 1988 July 9, some 1000 s of data were collected with the high-speed photometer at K on a star of similar brightness ($K = 12.6$ mag). Identical analysis of these data shows no harmonic content up to the Nyquist frequency with $P < 0.2$.

The 3.7 mHz peak in the slowly sampled K photometry periodogram is due to aliasing of power at 5.5 mHz, because 5.5 mHz is close to the average Nyquist frequency. This conclusion is verified by Monte Carlo simulations using the photometry sampling times which show that if a 5.5 mHz signal is present, power is aliased to 3.7 mHz. The average Nyquist frequency for the K photometry obtained on 1988 July 4 is 2.5 mHz, and therefore, it is not surprising that this fast period was not noted in the earlier data.

IV. THE 614 S PERIOD

The simultaneous optical and infrared photometry from 1988 July 4 can be used to compare the behavior of the 614 s mode at different wavelengths. We have fitted a sinusoidal variation with frequency 1.63 mHz of arbitrary amplitude and phase to the B and J light curves. Figures 5 and 6 show the data folded at twice this period along with the best-fitting sinusoid. This exercise yields the amplitudes and phase of the variations. We find amplitudes $\Delta B = 0.056 \pm 0.004$ mag, and $\Delta J = 0.024 \pm 0.004$ mag. The relative phase of the B and J variations is $\Delta\phi = 18° \pm 10°$ (i.e., *B lags behind J.*) The periodogram analysis of the 1988 July 4 K light curve shows that there is no significant 614 s period of arbitrary phase, and the data are consistent with the presence of a 614 s periodicity in phase with the optical variation with an amplitude $\Delta K < 0.02$ mag 3 σ.

The alternate J and K photometry obtained on 1988 July 9 has been analyzed in the same way to give $\Delta J = 0.027 \pm 0.004$ mag, and $\Delta K < 0.01$ mag 3 σ. We have combined the amplitude measurements from the photometry on these two nights to give the amplitude ratios shown on the first line of Table 2.

The luminosity variations of ZZ Ceti stars such as G29-38

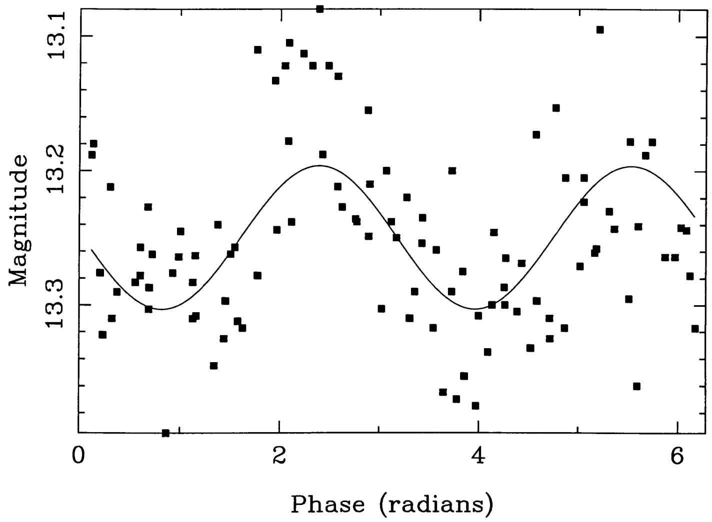

FIG. 5.—The B light curve from 1988 July 4 folded at period of 2×614 s into the phase interval 0–2π. The solid line is the best-fit sinusoid.

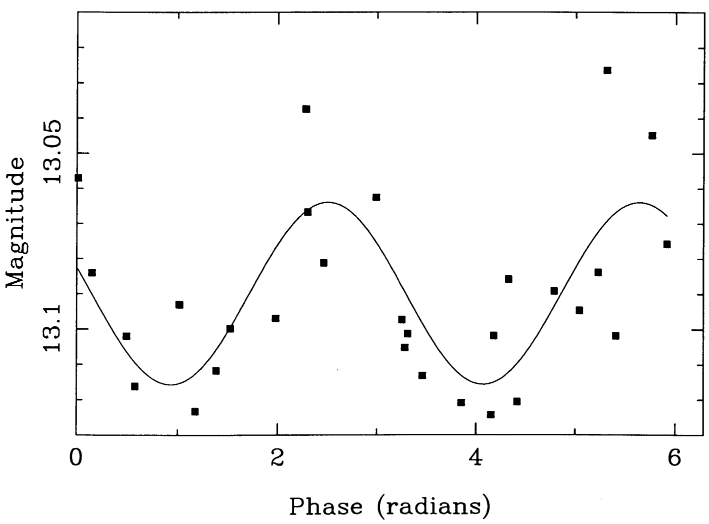

FIG. 6.—The J light curve from 1988 July 4 folded at period of 2×614 s into the phase interval 0–2π. The solid line is the best-fit sinusoid.

TABLE 2

AMPLITUDE RATIOS AND PHASE OF THE 614 s PERIOD

	$\Delta J/\Delta B$	$\Delta K/\Delta B$	$\Delta K/\Delta J$	$\phi_J - \phi_B$
Observed	0.46 ± 0.06	$<0.2(3\ \sigma)$	$<0.4(3\ \sigma)$	$18° \pm 10°$
Predicted[a]	0.47 ± 0.03	0.21 ± 0.01	0.45 ± 0.04	0°

[a] The predicted amplitude ratios are corrected for the contribution of the IR excess.

are thought to be due to nonradial g-mode pulsations. These pulsations do not change the radius or shape of the white dwarf significantly but cause oscillating hot and cold patches on the surface. It is these temperature fluctuations which lead to variability. Adiabatic g-mode pulsation theory predicts that the relative amplitude of a given mode at different wavelengths can be found simply from the change in flux, F_ν, with temperature, T, $\partial F_\nu/\partial T$ derived from model atmospheres (Robinson, Kepler and Nather 1982). Appropriate parameters for a model atmosphere of G29-38 are $T = 11{,}500$ K and log $g = 8$ (Greenstein 1988). Wickramasinghe's (1972) model atmospheres for DA white dwarfs can be used to predict amplitude ratios of $\Delta B{:}\Delta J{:}\Delta K$ of 1:0.50:0.34. Before these amplitude ratios can be compared with the observations, a correction must be made for the infrared excess, which is assumed to be constant in time. The predicted amplitudes, adjusted using Greenstein's (1988) decomposition of the observed flux into white dwarf and cool excess components, are compared with the observed amplitudes in Table 2. Adiabatic pulsation theory also predicts that the light curve must have the same phase at all wavelengths (Robinson, Kepler, and Nather 1982). Inspection of Table 2 shows that the current optical and infrared observations of the 614 s mode are in excellent agreement with the prediction of adiabatic pulsation theory. Robinson, Kepler, and Nather (1982) showed that the optical color variations of the ZZ Ceti star R548 found using the Stromgren b, u, and y filters agreed with pulsation theory from 0.35 μm to 0.55 μm. The current results for the 614 s period of G29-38 demonstrate that adiabatic g-mode pulsation theory accounts for the behavior over an even larger wavelength interval, reinforcing confidence that this theory correctly describes the nature of ZZ Ceti variability.

V. EMISSION FROM DUST

A major motivation for obtaining the data described here was to place constraints on dust as the origin of the infrared excess. If the white dwarf and dust grains are blackbody emitters, then energy balance requires that a single dust grain will undergo temperature fluctuations $\delta T_g/T_g = \delta T_{\rm wd}/T_{\rm wd}$. The measured amplitude of the 614 s period light variations at B and J together with model atmospheres require that $\delta T_{\rm wd}/T_{\rm wd} = 1.7 \times 10^{-2}$, so with $T_g = 1200$ K, blackbody emission from a single dust grain will have an amplitude of 9% at 2.2 μm. An equilibrium temperature of 1200 K for the excess suggests that the dust is at a radius of 3×10^{10} cm, or 1 light second, so the variation of the white dwarf and dust emission should be in phase (except for large dust grains, >10 cm), and the amplitude due to the variation of the excess plus the variation of the white dwarf should be 0.11 mag at 2.2 μm. Variability with this amplitude, in phase with the optical pulsations, would have been detected with a high signal-to-noise ratio in the current data. Remember, however, that the pulsations of ZZ Ceti stars are thought to be nonradial and that there are no g-modes with $l = 0$ (l and m are the meridional and azimuthal orders of the mode, respectively). Therefore, the integrated response of dust depends upon the distribution of the dust and which modes are excited. For example, the mode with $l = 1$, $m = 0$ has one hemisphere of the white dwarf hot and the other cold. The emission from a spherically symmetric dust shell around a white dwarf in this mode will show no variation because the effect of the change in emission from the hot and cold halves will cancel. This is true in general for small amplitude oscillations when dust is distributed with spherical symmetry. As a result, it is not possible to use the limits on the amplitude of the 614 s period at K to constrain the presence of dust in the system without a detailed model which describes both the geometry of the dust distribution and the modes responsible for the 614 s period.

This brings us to address the origin of the 181 and 243 s oscillations discovered at K. The amplitude of the 181 and 243 s signals are 0.028 ± 0.001 mag and 0.027 ± 0.001 mag, respectively (Figs. 7 and 8), yet there is only a very weak signal at J in phase with K at 181 s ($\Delta J < 0.02$ mag 3 σ). If the variations at K were directly due to brightness changes of the white dwarf, then we would expect an amplitude at J of 0.07 ± 0.01 mag, a 6 σ discrepancy. If the white dwarf model atmospheres and pulsation theory are correct, then the K variation cannot be due to changes in the 2 μm flux of the white dwarf, but must be attributed to the 1200 K component. Section IV shows that the predicted relative amplitudes and phases of the pulsations are in fine agreement with observations which span almost a factor of 3 in wavelength, so there is no reason to expect that the predictions for K are in error. Photometry of other ZZ Ceti stars by Zuckerman and Becklin (1989*a*) also suggests that our theoretical understanding is correct because they find no other ZZ Ceti stars with infrared excesses. Consequently, we contend that the infrared excesses of G29-38 is not associated with the ZZ Ceti phenomenon, and that the unexpected appearance of the 181 s and 243 s periods at K is not due to some breakdown in the theory of pulsating white dwarf atmospheres.

The oscillations at K must be due either to pulsations in the putative brown dwarf companion of G29–38, or to the

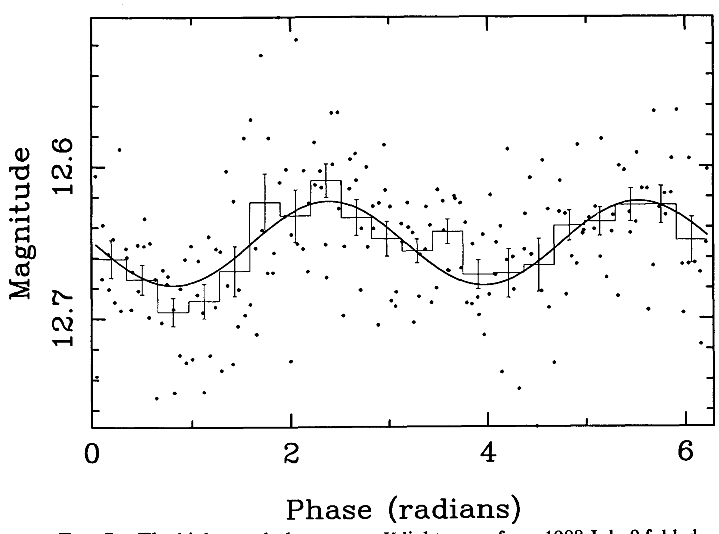

FIG. 7.—The high-speed photometry K light curve from 1988 July 9 folded at period of 2×181 s into the phase interval 0–2π. The binned data together with standard errors are also shown. The smooth curve is the best-fit sinusoid.

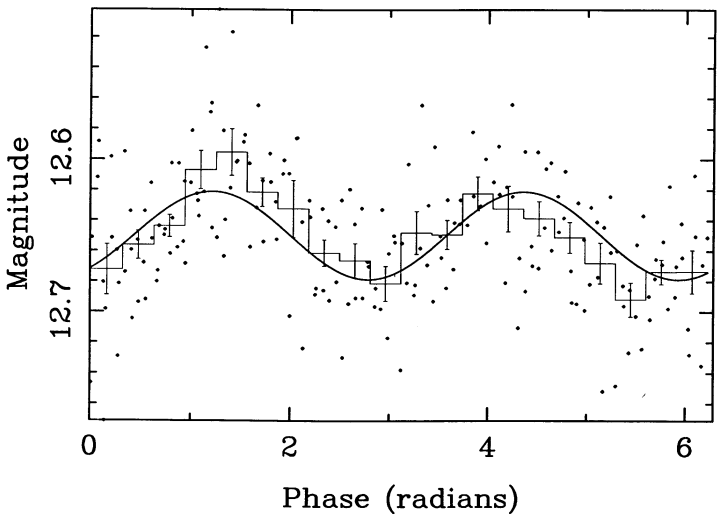

FIG. 8.—The high-speed photometry K light curve from 1988 July 9 folded at period of 2×243 s into the phase interval 0–2π. The binned data together with standard errors are also shown. The smooth curve is the best-fit sinusoid.

response of dust to temperature variations on the surface of the white dwarf which are somehow not directly observable. The second proposal is an appealing possibility because periods close to 181 s and 243 s are often seen in ZZ Ceti stars. But the amplitude of the white dwarf required to drive the observed variation in the dust emission at K is 0.016 mag and 0.008 mag at B and J, respectively—above current detection thresholds. Ostensibly this solution is eliminated by our failure to detect these periods at B or J. However, we can describe a dusty model of G29-38 which accounts for the observed periodic signals at different wavelengths.

The pulsation amplitude of the surface of the white dwarf is described by spherical harmonics, $Y_{lm}(\Theta, \Phi)$, of degree l and order m, where the origin of the usual spherical polar (r, Θ, Φ) coordinate system is located at the center of the star and the pulsation axis, $\Theta = 0$, is assumed to be aligned with the spin axis of the star. This is probably a legitimate assumption for G29-38, which is not a magnetic white dwarf. If Θ_0 is the angle to the line of sight, then the amplitude of the flux variation of a given mode recorded by a distant observer $\propto Y_{lm}(\Theta_0, 0)$ (Robinson, Kepler, and Nather 1982). A spherical distribution of dust is improbable on dynamical grounds; if G29-38 rotates, then its gravitational field will have a nonzero quadrupole moment and a thin disk or ring perpendicular to the spin axis of the star is more likely. Furthermore, to account for the luminosity and single temperature of the infrared excess, the dust distribution is also likely to be optically thick, and so collisions will play an important role in the dynamics of the ring, favoring a flattened geometry. The distance of the dust from the white dwarf must be about 3×10^{10} cm, given the temperature of the excess. This is much greater than the white dwarf radius, and the dust, to a good approximation, qualifies as a distant observer viewing the star at $\Theta_0 = 90°$.

The 614 s period is probably a high-order radial mode, $n \approx 11$, with $l = 2$ (Winget, Van Horn, and Hansen 1981), while the faster 181 s and 243 s periods are due to lower order n modes. The ratio of the 181 s and 243 s periods is 1.3, which is consistent with the theoretical periods of $l = 2$, $n = 1$ and $l = 2$, $n = 2$ modes, respectively (Brickhill 1975). There are $2l + 1$ m modes associated with each l mode, but not all will necessarily be excited. Let us assume that most of the power of the 181 s and 243 s periods is in $m = 0$ modes, and that the 614 s period is $m = 1$ or higher order. This assumption has the following observational consequences: (1) the 614 s $m = 1$ modes does not cause any variation in the brightness of the dust emission because adjacent sections of the dust ring are alternately hot and cold and yield no net change; (2) the $m = 0$, 181 s and 243 s periods, *do* cause the excess to vary because the dust temperature changes in phase all around the equatorial ring; (3) the relative amplitude, A_{lm}, of the white dwarf modes, $l = 2$, $m = 0$ and $l = 2$, $m = 1$, at optical wavelengths is

$$\frac{A_{20}}{A_{21}} \propto \frac{3\cos^2\Theta_0 - 1}{\cos\Theta_0 \sin\Theta_0}, \tag{1}$$

and therefore if $\Theta_0 \approx 54.7°$ the $l = 2$, $m = 0$ mode will appear weak relative to the $l = 2$, $m = 1$ mode. Thus variations of the white dwarf with periods of 181 s and 243 s will be hard to detect optically, yet will be revealed by changes in the dust emission. A sketch of this model is shown in Figure 9.

The upper limit on the amplitude of the 181 s period at J requires that $45° < \Theta_0 < 65°$. The uncertainty in Θ_0 is such that there is a 30% chance that the inclination of the axis of G29-38 to the line of sight will be appropriate for the geometric factor in equation (1) to suppress the amplitude of the $l = 2$,

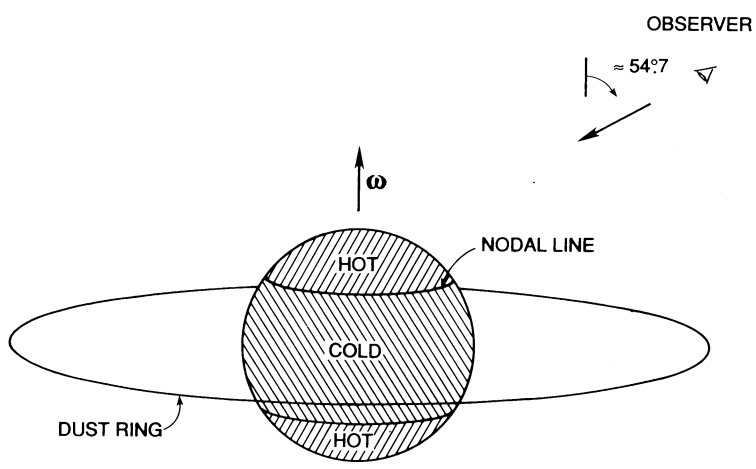

FIG. 9.—A sketch of the G29-38 system showing the $l = 2$, $m = 0$ mode on the white dwarf.

$m = 0$ mode enough so that it will be undetectable, except through its effect on circumstellar dust.

Any model for G29-38 which involves dust must explain the origin and presence of this material in a system which is $\sim 5 \times 10^8$ yr old. First, let us discuss the origin of the dust. The progenitor of G29-28 was probably an intermediate mass star ($1\ M_\odot < M < 8\ M_\odot$). While on the asymptotic giant branch, this star would have lost its envelope, forming a planetary nebula. Dust particles are common in the outer atmospheres of asymptotic giant branch stars, and in planetary nebulae. The lifetime (10^4 yr) of these dusty phases is brief compared to the age of G29-38, and we expect that any dust from this period of evolution would have dispersed a long time ago, and all that is left of the planetary nebula is the central star which is now a white dwarf. Solid particles could not have survived the asymptotic giant branch evolution of the progenitor star on their current orbits. Thus the putative dust cloud must be the debris of some relatively recent catastrophic event, such as near collision between an asteroid or comet and the white dwarf.

Even if a dust cloud is formed by the disintegration of an asteroid there are further issues which must be addressed because the depletion time of dust particles due to Poynting-Robertson drag is only $2 \times 10^5 a$ yr, where a is the grain radius in cm. If we account for the excess by a cloud of solid particles which have been present since the formation of G29-38, $\sim 6 \times 10^8$ yr ago, then the particles must have dimensions of a few tens of meters. The observed emitting surface area needed to explain the infrared excess requires a mass of $1.1 \times 10^{21} a$ g. Thus the mass required is comparable to that of a large asteroid (e.g., Ceres, $M = 1.2 \times 10^{24}$ g). It is unlikely that the capture efficiency of a disrupted asteroid into a circumstellar ring will be 100%. This may indicate that the dust cloud is composed of smaller particles and is shortlived compared to G29-38. Smaller particles are required for another reason. We cannot use boulder-sized ring particles to explain the 181 s and 243 s variability, because as we show below the cooling time of a meter-sized object is long compared to these periods, and temperature variations are smoothed out.

To estimate what size particles can respond to the rapidly varying flux from the white dwarf and give observable amplitude variations we have solved the heat conduction equation for a uniformly illuminated solid sphere cooling by radiation. The problem is described mathematically by the equation

$$\nabla^2 T = \frac{1}{\kappa} \frac{\partial T}{\partial t}, \quad (2)$$

where T is the temperature, t is time, and κ is the thermal diffusivity. We have used a value of $\kappa = 0.013\ \mathrm{cm^2\ s^{-1}}$ which is appropriate for refractory material such as silicates at $T \approx 1200$ K. The results of these calculations are summarized in Table 3. For the sake of definiteness we have assumed that the white dwarf exhibits a 180 s oscillation with an amplitude, $\delta T_{wd}/T_{wd} = 1.7 \times 10^{-2}$, which is the same as that inferred for the 614 s period. The smallest particle considered, with radius $a = 0.1$ cm, has a negligible heat diffusion time and rapidly reaches its equilibrium temperature, so that it tracks the temperature fluctuations of the white dwarf closely. The amplitude of the temperature fluctuations of the sphere decreases with increasing size until at 100 cm the amplitude is only 17% of that of a 0.1 cm particle. Therefore, if we insisted on 100 cm bodies the amplitude of the 181 s and 243 s periods would have to be ~ 5 times that of the 614 s period. However, particles with dimensions ≤ 10 cm can respond suitably to a periodic driving flux of reasonable amplitude. Ten cm particles have a Poynting-Robertson lifetime of 2×10^6 yr and need 1.1×10^{22} g of material, only $\sim 1\%$ of the mass of a large asteroid.

TABLE 3

Amplitude of 2 μm Flux Variations as a Function of Grain Size[a]

Grain Radius (cm)	$(\delta F/F)_{2.2\ \mu m}$
0.1	0.035
1.0	0.030
10.0	0.023
100.0	0.006

[a] See § V for details.

If a steady state is achieved where the rate of depletion of dust, due to the Poynting-Robertson effect, is matched by the supply of new grains, then there will be an accretion rate onto the surface of the white dwarf of $5.4 \times 10^{15}\ \mathrm{g\ yr^{-1}}$, independent of grain size. When expressed in solar units this mass accretion rate seems almost negligible ($2.7 \times 10^{-18}\ M_\odot\ \mathrm{yr^{-1}}$) and is therefore unlikely to make a significant difference to the surface abundances of the white dwarf and cause spectral peculiarities. The mass supply rate is also not extreme. Once the ring is formed, collisions between the larger ring particles will provide a continuing source of small grains. Ten percent of the mass of one large asteroid could supply the necessary dust for $\sim 10^7$ yr.

Thus we imagine a ring composed of large rocks ~ 100 cm, which account for most of the mass in the ring ($\sim 10^{23}$ g), yet present negligible surface area. Collisions between these boulders generate the ≤ 10 cm particles which we need to yield the surface area required to account for the infrared excess, and to respond to the rapid temperature variations of the white dwarf.

VI. CONCLUSIONS

We have presented the first multicolor photometry of a ZZ Ceti variable which extends into the infrared. The amplitudes and phases of the 614 s period measured at B, J, and K for G29-38 are, within the observational errors, in agreement with adiabatic g-mode pulsation theory. These results increase the wavelength range over which this model has been tested photometrically by more than a factor of 3. There is still the potential for making a much more accurate test of pulsation theory because the current data were obtained from relatively short runs.

Despite the good agreement with pulsation theory, it is difficult to use the results for the 614 s period to constrain dust models of the infrared excess. This is because the response of dust to luminosity changes of the white dwarf depends on which modes are excited on the surface of the white dwarf and the geometry of the dust distribution. For example, we expect to see no variation at all for a spherically symmetric dust shell.

Nonetheless, this photometry has provided an important new clue to help determine the nature of the infrared excess. In addition to detecting the pulsating photospheric emission in the infrared, we have found new periodicities in the K light at 181 s and 243 s. The B and J data show no evidence for signals with these periods. Thus we conclude that the variability at K must be due to changes in the amplitude of the infrared excess. We reject the possibility that the signal is due to pulsations of the brown dwarf because we have no reason to expect such behavior, although we would encourage calculations to test the pulsational stability of brown dwarf models. The absence of infrared excesses in other ZZ Ceti stars (Zuckerman and Becklin 1989) excludes the possibility that the unexpected appearance of the 181 s and 243 s periods at K is due to failure of the model atmospheres or pulsation theory and the excess is not associated with the ZZ Ceti phenomenon. Consequently, we suggest a model where dust in a ring is responding to low l, low m oscillation modes in the white dwarf that are suppressed optically emission because of the viewing geometry of the white dwarf. A critical test of this model would be the detection of the optical counterparts of the 181 s and 243 s infrared pulsations.

Note added in manuscript.—Two recent developments strengthen greatly the dust interpretation of the infrared excess of G29-38 presented here. The bolometer system at the Palomar 5 m telescope was used to measure G29-38 on 1989 October 19 for 3 hr, during conditions of excellent transparency and fair seeing (2″). The observations were made using a 4″.8 aperture and an N filter with effective wavelength of 10.6 μm. The flux, measured relative to HR 337 (β And), was found to be 14 ± 2 mJy. The error includes the statistical errors and systematic uncertainties in the flux calibration. This flux is discrepant at the 2.6 σ level with the measurement of Tokunaga *et al.* (1989), who reported 3.9 ± 3.3 mJy. However, it is in agreement with more recent observations (Tokunaga, Becklin, and Zuckerman 1990; Telesco, Joy, and Sisk 1990). The measured flux at 10 μm is approximately 3 times that expected from a brown dwarf at this wavelength. The spectrum of G29-38 can no longer be described by a single temperature, and a dust model, which naturally accounts for a range of temperatures, must be invoked.

D. Winget and E. Nather (private communication 1990) have kindly made available the power spectrum of extensive optical photometry of G29-38 from 1988. The power spectrum shows a peak at 242.3 s and a doublet at 186.67 s and 186.74 s, all with amplitudes of $\approx$0.005 mag. These optical pulsations are undoubtedly the optical counterparts of the 243 s and 181 s infrared period which the dust model predicts. The discovery of these optical counterparts rules out the possibility that the infrared oscillations are due to a pulsating brown dwarf.

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