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RAPID OSCILLATIONS IN CATACLYSMIC VARIABLES. VI. PERIODICITIES IN ERUPTING DWARF NOVAE

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ABSTRACT

We report an extensive study of the coherent oscillations observed in high-speed photometry of dwarf novae during eruption. The oscillations are in all cases singly periodic and sinusoidal to the limits of measurement. The detection of oscillations in 14 separate eruptions of AH Her and SY Cnc enables a general study of period variations. The stars trace out characteristic loops ("banana diagrams") in the period-intensity plane. New detections are also reported for SS Cyg, EM Cyg, and HT Cas.

Analysis of light curves of the eclipsing binary HT Cas in quiescence leads to a determination of the masses and radii of the component stars. The 20 s coherent oscillation observed in eruption undergoes an eclipse phase shift of $-360°$, similar to that of UX UMa. The long duration of the phase shift indicates that the entire disk participates in the oscillation, presumably by reprocessing the pulsed X-ray or ultraviolet flux from the white dwarf. The posteruption light curve suggests that that accretion disk—which expanded during the outburst—has decayed, leaving a bare white dwarf temporarily heated by the recent rain of infalling matter. New detections of "quasi-periodic" oscillations are also reported for HT Cas and three other stars.

The general characteristics of "coherent" and quasi-periodic oscillations are reviewed and compared. The former are of shorter period and usually higher coherence, and are restricted to dwarf nova eruptions. We propose that these be called *dwarf nova oscillations* (DNOs) to distinguish them from the *quasi-periodic oscillations* (QPOs) which are a more general signature of mass transfer in all cataclysmic variables. Constraints on pulsation and rotation models for the dwarf nova oscillations are discussed, but all of the present models encounter serious problems.

Subject headings: stars: accretion — stars: dwarf novae — stars: eclipsing binaries — stars: pulsation

I. INTRODUCTION

Dwarf novae are close binary stars in which matter is being transferred from a late-type star ("red star") to a white dwarf ("blue star"), forming a luminous accretion disk as it spirals in to the white dwarf. At typical intervals of ~ 1–6 months, these stars brighten by ~ 3–6 mag, returning to minimum light in 3–20 days. High-speed photometry of these stars during eruption frequently reveals rapid periodic oscillations in their light curves, with periods of 9–39 s, and typical amplitudes of $\sim 0.2\%$. These "coherent oscillations" have now been found in 12 dwarf novae in eruption; they appear to be a common if not universal feature of dwarf nova eruptions. Previous detailed accounts of the observations have been given by Nevo and Sadeh (1978), Warner and Brickhill (1978), and Hildebrand *et al.* (1980).

Three classes of models have been proposed to account for the observed oscillations: (1) white dwarf pulsations (Warner and Robinson 1972), (2) white dwarf rotation (Paczynski 1978; Petterson 1980), and (3) hot spots in the innermost parts of the accretion disk (Bath 1973). Some models combine features from the different classes (e.g., Papaloizou and Pringle 1978).

In this work we present a comprehensive account of the optical observations of coherent oscillations associated with the eruptions of dwarf novae, and a critical evaluation of the current theoretical situation. Specifically excluded are: (1) the very stable oscillations seen in one dwarf nova, WZ Sagittae, at quiescence (Robinson, Nather, and Patterson 1978; Patterson 1980); and (2) the "quasi-periodic" oscillations seen in many cataclysmic variables, including dwarf novae in eruption. In §§ II and III we present detailed studies of oscillations in AH Herculis and SY Cancri. In § IV we report the discovery of coherent oscillations and an eclipse-related phase shift in the eclipsing binary HT Cassiopeiae. We also present light curves at minimum and maximum light, and from the eclipses we derive the masses and radii of the component stars. In § V we present new observations of oscillations in SS Cygni, supplementing the study of Patterson, Robinson, and Kiplinger (1978). In § VI we confirm an earlier detection of oscillations in EM Cygni and present a list of upper limits to oscilla-

TABLE 1

AH Her Oscillations

A. Positive Detections

UT Date	Run	$\langle I \rangle$	Days after Maximum	P_{osc} (s)	$(m_v)_{max}$
1972 Feb 18	(1)	29	−1.0?	31.55	11.0?
1974 May 26 ...	Lick-5	21	+2.8	37.6→38.2	11.2
1974 May 27 ...	Lick-6	19	+3.8	38.8	11.2
1975 May 25 ...	(2)	27	0	34.3→34.8	11.3
1976 Jun 3......	1740	10	−2.1	31.3→30.7	11.5
1976 Jun 28	(3)	18	0	24.8	11.5
1976 Jul 25	1749	17	+7.7	24.2	11.1
1976 Aug 25 ...	(3)	18	−4	24.1	10.9
1978 Jun 4......	2186	15	−2	27.8	11.2
1978 Jun 5......	2189	27	−1	25.0	11.2
1978 Jun 8......	(4)	25	+2	24.0	11.2
1978 Jun 9......	(4)	24	+3	24.25	11.2
1978 Jun 10	(4)	19	+4	24.8	11.2
1978 Jun 11	(4)	18	+5	25.35	11.2
1978 Jun 12	(4)	16	+6	25.75	11.2

B. Negative Results

UT Date	Run	$\langle I \rangle$	Days after maximum	$(m_v)_{max}$
1974 May 24 ...	Lick-3	21	+0.8	11.2
1974 May 25 ...	Lick-4	20	+1.8	11.2
1974 Jun 25	Lick-12	18	−0.2	11.1
1974 Jun 26	Lick-13	19	+0.8	11.1
1976 Jun 2......	1738	5	−3.3	11.5
1976 Jul 21	1747	27	+3.6	11.1
1977 Feb 19	1829	11	−1	11.6
1977 Feb 20	1831	17	0	11.6
1977 Feb 21	1833	17	+1	11.6
1977 Mar 8	1837	17	−1	11.4
1977 Mar 9	1845	27	0	11.4
1977 Mar 11 ...	1846	25	+2	11.4
1977 Mar 12 ...	1848	22	+3	11.4
1977 Mar 13 ...	1851	21	+4	11.4
1977 Mar 14 ...	1854	19	+5	11.4
1978 Jun 6......	2194	27	0	11.2
1978 Jun 7......	2199	25	+1	11.2
1978 Jun 8......	2203	22	+2	11.2

References.—(1) Robinson 1973*b*; (2) Warner and Brickhill 1978; (3) Nevo and Sadeh 1978; (4) Stiening, Hildebrand, and Spillar.

tion amplitudes for 16 other dwarf novae. In § VII we summarize the properties of the dwarf nova oscillations and review existing models. The singly periodic nature of the oscillations tends to favor a rotational origin, but it is not clear whether the rotation is that of the white dwarf or that of the inner disk. White dwarf pulsation models are also not excluded but may have to incorporate rotation in some manner (e.g., Papaloizou and Pringle 1978).

II. AH HERCULIS

AH Herculis is a Z Cam–type dwarf nova which erupts from a magnitude of ~14.5–~11 with an average recurrence period of 20^d. Table 1 contains the results of observations of AH Her in 11 different outbursts. Data reduction and acquisition procedures have been discussed by Nather (1973) and Patterson (1979*a*). All the counting rates have been converted to the unfiltered counting rates on the McDonald Observatory 0.92 m telescope, corrected for extinction. When detected, the oscillation has an amplitude of ~0.2%–0.3%, while the 90% confidence upper limits for the nondetections are generally ~0.10%. Most of the detections indicate the presence of a constant period, but a significant period change occurred in several runs, noted in the table.

The data obtained during the eruption of 1978 June were the most extensive yet obtained for any dwarf nova. McDonald data covered the nights of June 4–8,

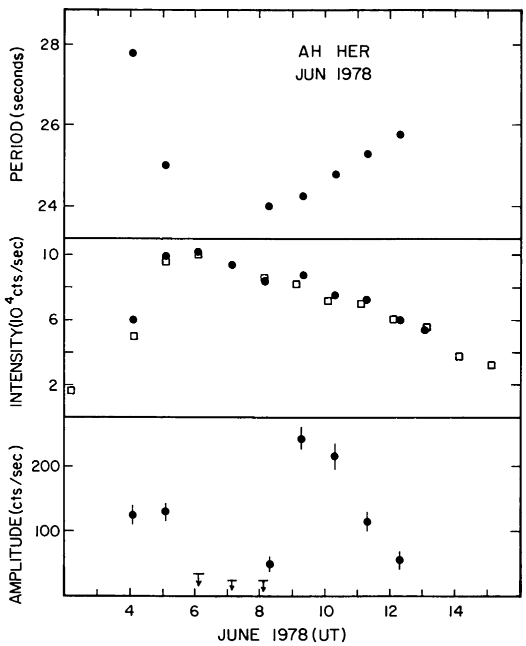

FIG. 1.—The evolution of oscillation period, total intensity, and oscillation amplitude during the outburst of 1978 Jun. In the middle frame, the filled circles are photoelectric observations, while the open squares are the visual observations of the AAVSO. McDonald observations cover the interval Jun 4–8, while those of Stiening *et al.* (1979) cover Jun 7–12.

while the observations of Stiening, Hildebrand, and Spillar (1979) on Mt. Lemmon covered June 6–12. Figure 1 shows the light curve and the evolution of the oscillation period and amplitude with time. The evolving period roughly followed the mirror image of the light curve. The behavior of the oscillation amplitude is particularly noteworthy. The oscillation became undetectable near maximum light on June 6 and 7, was weakly present on June 8, and returned in strength on June 9. This is the first case in which an oscillation has been observed to disappear and subsequently return in the course of a single eruption. A more complete account of this eruption is given by Hildebrand *et al.* (1980).

In Figure 2, all of the positive observations of AH Her have been plotted on a log-log scale of period versus intensity. When observations on more than one night in an eruption are available, the arrow shows the direction of the evolution. Clearly, there is no general correlation of period and intensity, but it is possible that evolutionary tracks like that shown in Figure 2 for the 1978 June outburst might exist for each individual outburst. We shall see below that this is probably the case for *all* dwarf novae.

III. SY CANCRI

SY Cancri is a Z Cam–type dwarf nova which rises to magnitude 11–11.5 from a quiescent magnitude of ~14, with a mean outburst period of 27^d. Because the star is fairly bright, frequently in outburst, and shows large amplitude oscillations (~0.3%), it was selected for intensive study in 1977. All of the SY Cnc observations during 1975–1978 are contained in Table 2. The durations given in parentheses indicate that the observations were obtained through clouds and reduced by the method described by Patterson (1979*a*).

a) *Coherent Oscillations*

A representative power spectrum of SY Cnc in eruption is shown in Figure 3. The single sharp spike in the power spectrum indicates the presence of a coherent periodicity of period 27.80 s. The data of Table 2 cover six outbursts of SY Cnc, and in each outburst, oscillations were found on at least one night. In Figure 4, all of the positive detections of Table 2, as well as previously published work, are plotted in the period-intensity plane. The period evolution in each eruption can be followed with the eruption code in the figure. While the solid curved lines are in some cases speculative, the figure does suggest that curves of this kind are generally followed. The mean slope in the descending branch of the light curve corresponds to $d(\log P)/d(\log I) = 0.27 \pm 0.06$. The corresponding value for AH Her in Figure 2 is 0.17 ± 0.03. Nevo and Sadeh (1976) found that the periods of both KT Per and Z Cam also moved along a linear track during the decline stage of an eruption, with $d(\log P)/d(\log I) \approx 0.2$.

b) *The Orbital Period*

i) *Photometry*

During the long observation of SY Cnc near minimum light on 1977 January 25, a long, slow hump in the light curve was observed. A similar hump was seen by Robinson (1973*b*). Because such humps have been observed to occur at the orbital period in other cataclysmic

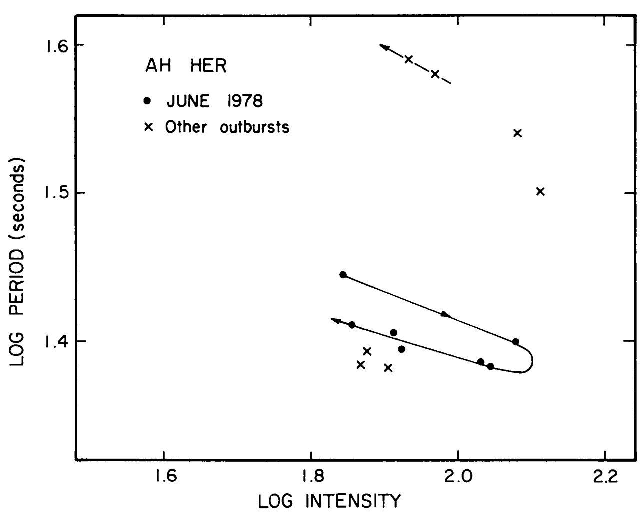

FIG. 2.—The period-intensity relation for all positive detections of oscillations in AH Her.

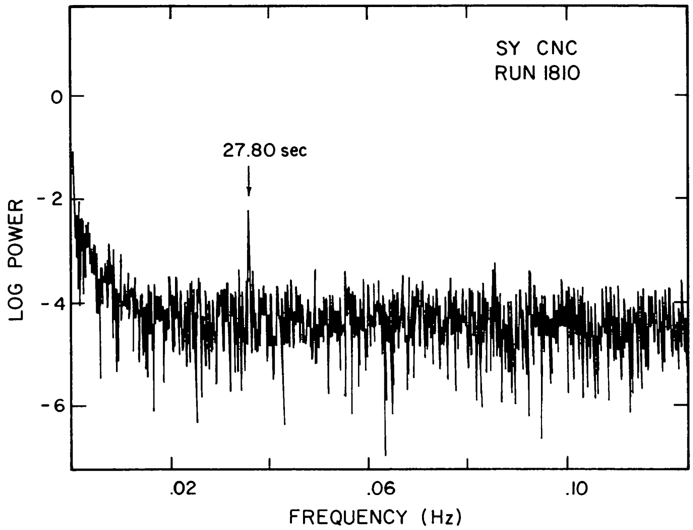

FIG. 3.—A representative power spectrum of SY Cnc in eruption. The single spike indicates the presence of a sinusoidal signal of period 27.80 s and amplitude 0.3%. The increase in power at low frequencies arises from the random flickering in the light curve.

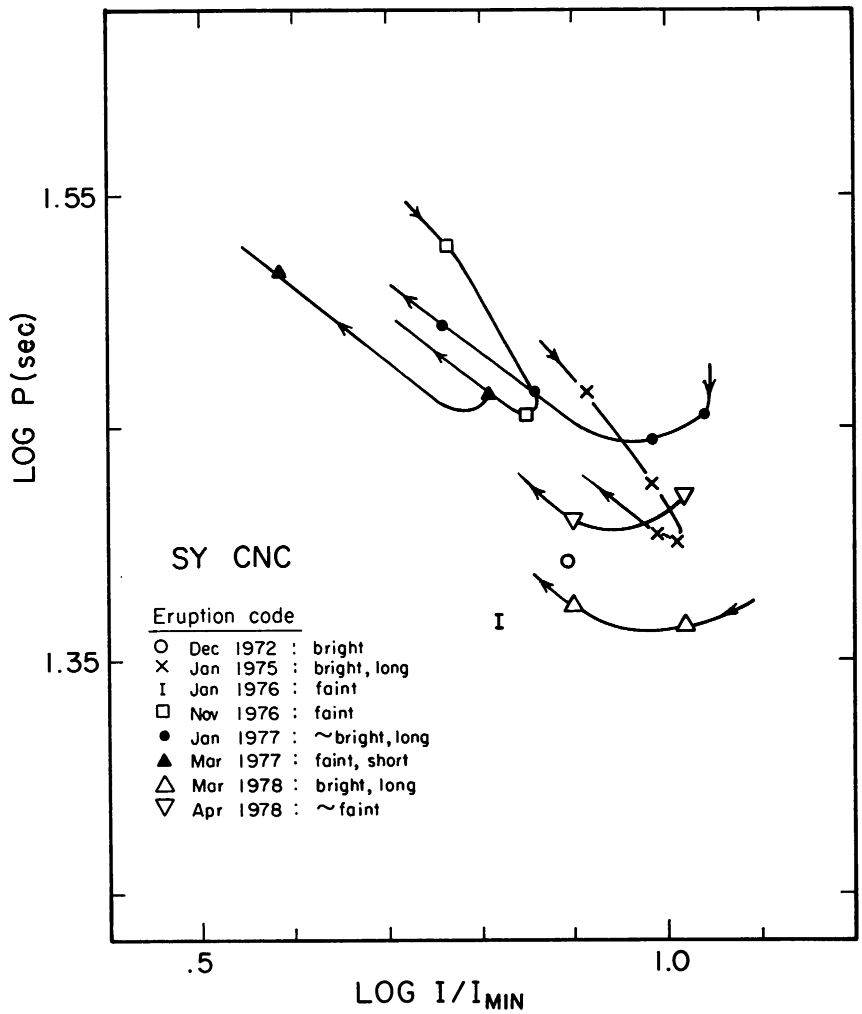

FIG. 4.—The period-intensity correlation for all positive detections of oscillations in SY Cnc. The sources of the data are: 1972 Dec, Robinson (1973*b*); 1976 Jan, Nov, Nevo and Sadeh (1978); other eruptions, this work. The solid lines with arrows indicate the evolution with time.

TABLE 2

SY CANCRI OBSERVATIONS

UT DATE	RUN	DURATION (hr)	I_{star}	OSCILLATION Period (s)	OSCILLATION Amplitude (%)	Telescope (m)
1975 Jan 13 ...	1574A	1.8	30	29.50	0.3	0.92
1975 Jan 13 ...	1574B	1.6	30	28.87	0.3	0.92
1975 Jan 14 ...	1576	2.1	36	26.71	0.3	0.92
1975 Jan 15 ...	1579	2.6	38	25.23	0.3	0.92
1975 Jan 16 ...	1583	2.6	36	25.31	0.3	0.92
1977 Jan 15 ...	1807	6.6	40	28.61	0.3	0.92
1977 Jan 16 ...	1810	4.5	38	27.80	0.3	0.92
1977 Jan 17 ...	1811	(6.5)	29	29.08	0.2	0.92
1977 Jan 18 ...	1814	(5.0)	24	31.20	0.2	0.92
1977 Jan 19 ...	1816	(6.6)	>17	...	...	0.92
1977 Jan 20 ...	1818	(4.0)	15	...	...	0.92
1977 Jan 24 ...	1821	3.1	4.5	...	<0.1	0.92
1977 Jan 25 ...	1824	(8.6)	4.3	...	...	0.92
1977 Feb 19 ...	1827	3.0	9.0	...	<0.1	0.76
1977 Feb 20 ...	1830	(8.3)	5.1	...	<0.1	0.76
1977 Feb 21 ...	1832	9.1	4.7	...	<0.1	0.76
1977 Feb 22 ...	1834	1.3	4.5	...	...	0.76
1977 Mar 8	1835	(5.7)	22	28.80	0.3	0.76
1977 Mar 9	1838	(0.8)	>24	...	...	0.76
1977 Mar 10 ...	1841	(4.1)	19	32.71	0.2	0.76
1977 Mar 12 ...	1847	6.6	8.4	...	<0.1	0.76
1977 Mar 13 ...	1849	3.4	6.1	...	<0.1	0.76
1977 Mar 14 ...	1852	2.7	4.6	...	...	0.76
1977 Mar 14 ...	1853	2.2	4.6	...	...	0.76
1978 Mar 7	2085	1.1	56	...	<0.1	0.76
1978 Mar 8	2092	1.2	55	...	<0.1	0.76
1978 Mar 9	2095	1.1	48	...	<0.1	0.76
1978 Mar 10 ...	2103	1.0	41	...	<0.1	0.76
1978 Mar 11 ...	2105	1.2	38	...	<0.1	0.76
1978 Mar 12 ...	2108	1.7	39	23.17	0.3	0.76
1978 Mar 13 ...	2111	1.2	29	23.58	0.3	0.76
1978 Apr 1	2125	1.4	39	26.26	0.3	0.76
1978 Apr 3	2129	1.0	29	25.60	0.3	0.76

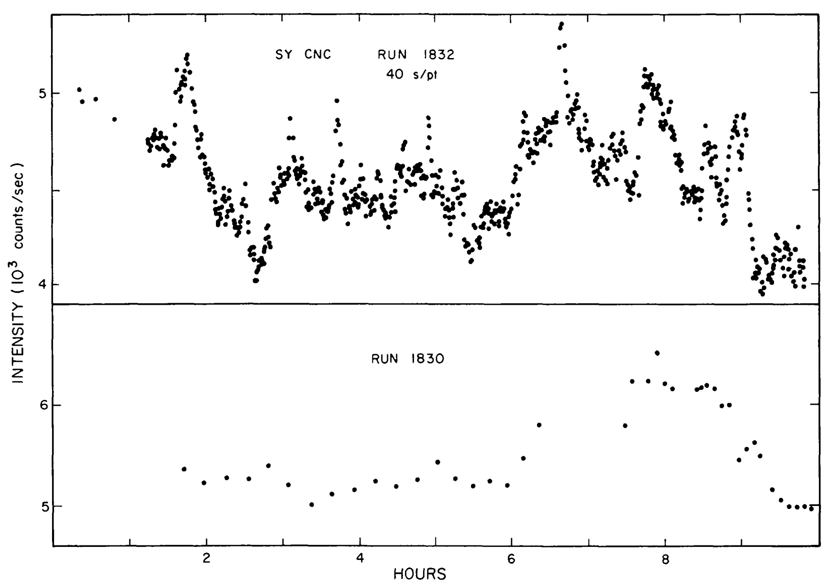

FIG. 5.—Long observations of SY Cnc near minimum light. A long, slow wave is present with a period of ~ 8 hr.

variables (e.g., U Gem), additional photometry at minimum light was obtained. The light curves obtained during runs 1830 and 1832 are shown in Figure 5. The data of run 1830 were obtained through thin clouds and were therefore reduced by using the simultaneous measurements of the monitor star in the second channel (for a discussion of this technique see Patterson 1979*a*). The long, slow waves in the light curve suggest a period of ~ 8 hr.

Six timings of hump maximum have been extracted from this data and are given in Table 3. These timings may be phased with a period of $0^d.3259$ (± 4), but an acceptable fit is also obtained with a period of $0^d.4838$ (± 4). Other nearby periods should also be considered, as there is a possibility of cycle count error. The only reliable conclusion is that the period is in the range $0^d.32-0^d.33$, or (less likely) $0^d.48-0^d.49$.

However, the photometric hump is probably not a persistent feature at minimum light. The 5 hr light curve obtained on 1977 March 14 under excellent conditions revealed no hump at the expected time. Since all of the other hump timings were obtained just following an eruption, it is possible that the hump is associated with the decline from the eruption, rather than being a feature of the system at minimum light.

ii) *The Spectrum*

The spectrum of SY Cnc at minimum light shows broad Balmer emission lines superposed on the absorption spectrum of a G star (Nather, private communication). Among cataclysmic binaries, the absorption spectrum of a late-type star is only visible for orbital periods $\gtrsim 5$ hr; thus the spectrum strengthens the case for a long orbital period. The weakness of the absorption lines tends to favor the shorter candidate period (7.8 hr), but no firm decision is possible.

IV. HT CASSIOPEIAE

HT Cassiopeiae was discovered to be an eclipsing binary by Bond (1978). Because the eclipses contain potentially valuable information on the structure of a dwarf nova system, HT Cas was a top priority object in the 1978 observing season. The complete log of observations is contained in Table 4. Figures 6 and 7 show individual light curves of HT Cas, at minimum and maximum light, respectively. Their most prominent feature is the very deep, usually asymmetrical eclipse recurring with the orbital period of 1^h46^m. All the count rates have been scaled to the corresponding count rates, corrected for extinction, on the 2.1 m telescope. The "zero" level in runs 2346 and 2360 is not trustworthy, however, because of difficulties with a nearby field star.

a) *Eclipse Data*

All of the eclipse light curves at minimum light suggest the presence of two light sources: a small, bright object which undergoes a total eclipse with ingress/egress times of 40 s; and a larger object which is partially eclipsed slightly later. This is perhaps best illustrated by Figure 8, which shows the eclipse portions

TABLE 3
TIMES OF HUMP MAXIMUM IN SY CNC NEAR MINIMUM LIGHT

UT(1977)	
Jan 25.249	Feb. 22.289
Feb 20.352	Mar 12.201
Feb 21.325	Mar 13.180

of several light curves at the original 3 s time resolution. We shall refer to these two objects as "the white dwarf" and "the ring" because these will turn out to be plausible—although not unique—identifications.

The eclipses have been analyzed as follows: (1) The times of mid-ingress and mid-egress of the white dwarf are measured; the mean of these times is, by definition, the time of mid-eclipse. In Figure 9, these times are reduced to an O-C diagram with a test period of $0^d.07364724$. The timings of mid-eclipse during quiescence are then fit with a constant period to yield the ephemeris

$$\text{Mid-eclipse} = \text{JD}_{\odot}\, 2{,}443{,}727.93722\,(\pm 2) + 0.073647217\,(\pm 8)\,E. \quad (1)$$

This ephemeris satisfies the individual timings with an rms dispersion of only 2.7 s; it is used to compute the orbital phases used in this paper. Note that the timings of minimum light during eruption appear to be systematically late by ~7 s.

2) The "white dwarf" contact times are determined by fitting straight lines to the white dwarf ingress and egress portions of the light curves. This generates columns 3, 4, 6, 7 of Table 4. This procedure is not rigorous since the eclipse of a spherical or elliptical object should produce a gently rounded light curve near the contacts. However, a rigorous least-squares fit to an eclipse geometry is not warranted, since the flat or nearly flat portions of the light curve are severely contaminated by flickering. Therefore, we will use the "pseudo-contact" times given in Table 4, and indicate below how these may be corrected to obtain the true contact times.

3) The time of minimum light is determined by inspection, and the observed interval between mid-eclipse

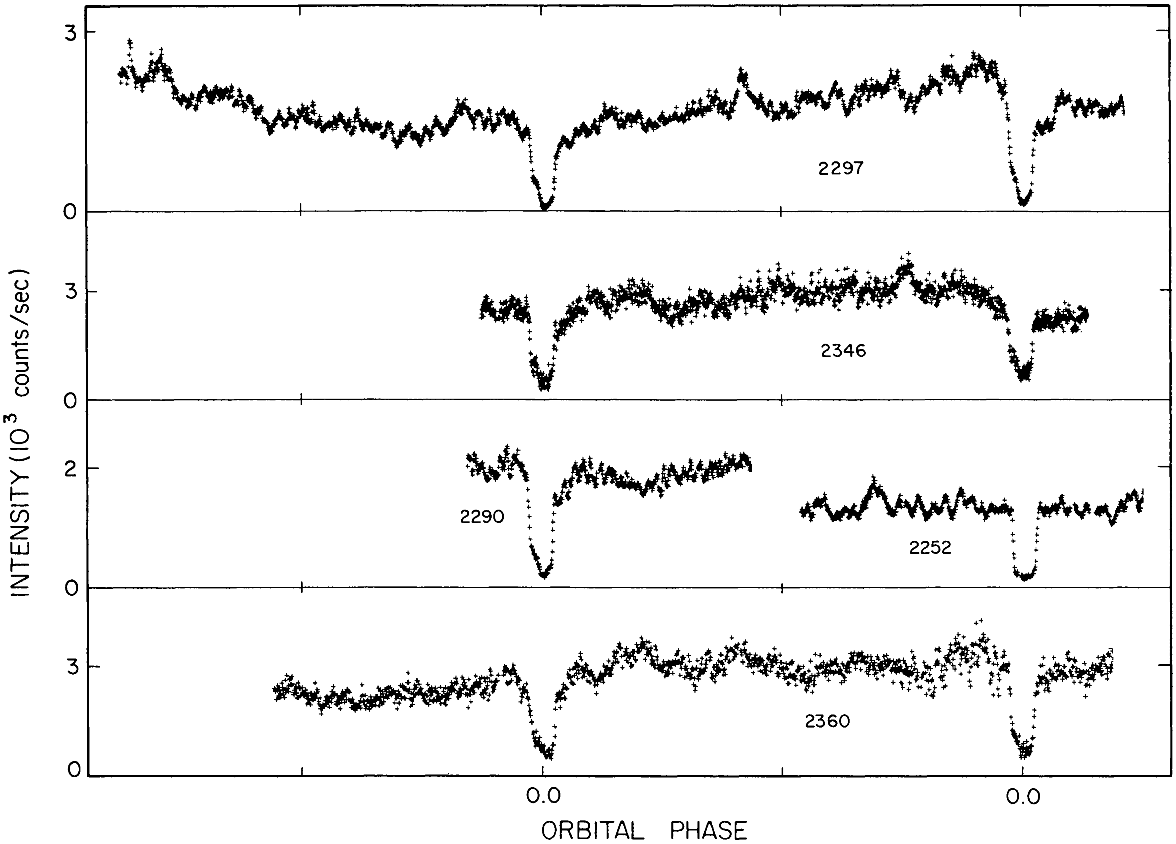

FIG. 6.—Light curves of HT Cas at minimum light, scaled to the 2.1 m count rates. These light curves are plotted with a time resolution of: 5 s, run 2346; 8 s, run 2360; 6 s, other runs.

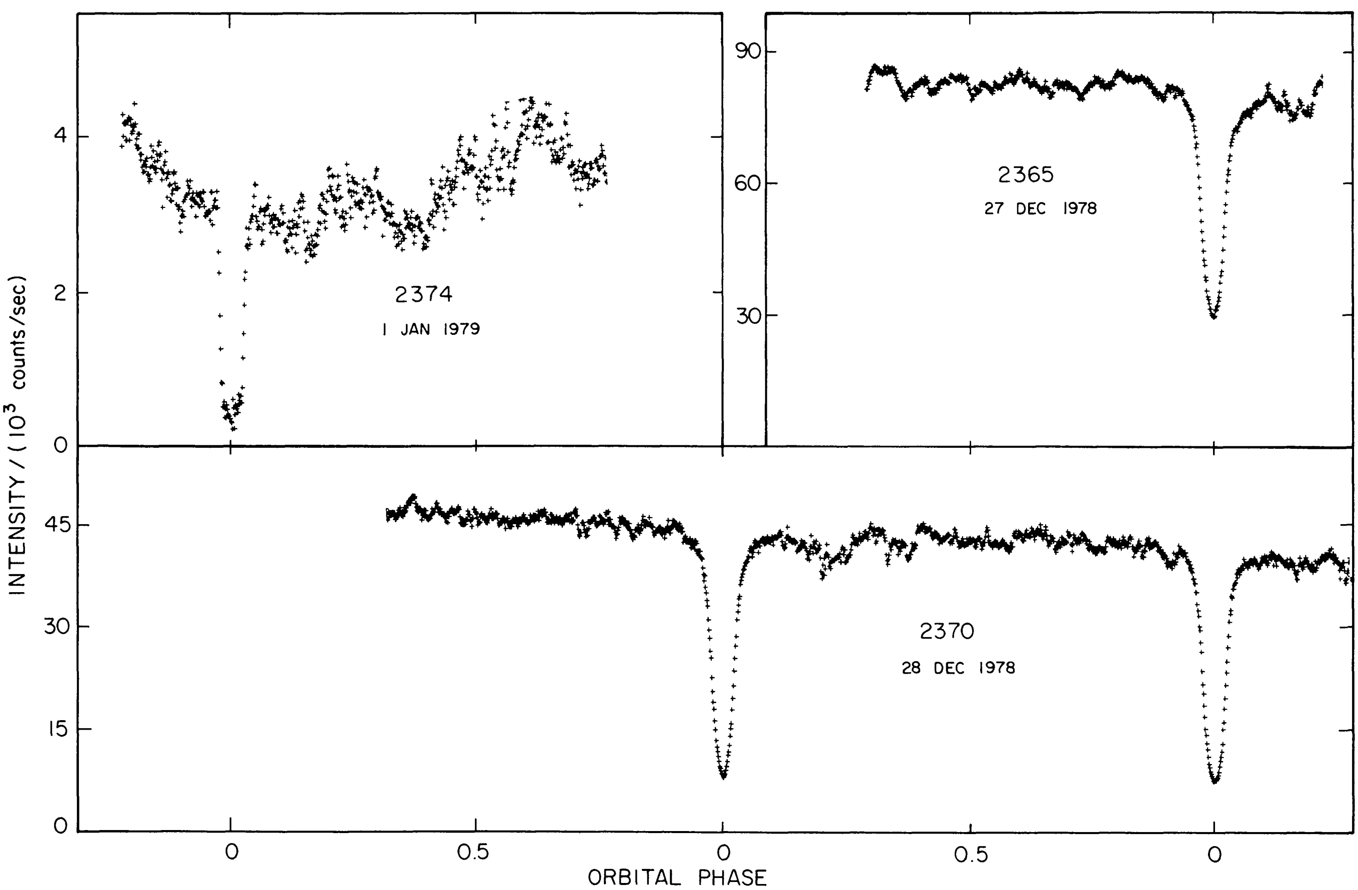

FIG. 7.—Light curves of HT Cas during the 1978 Dec eruption, scaled to the 2.1 m count rates. The time resolution is 9 s per point.

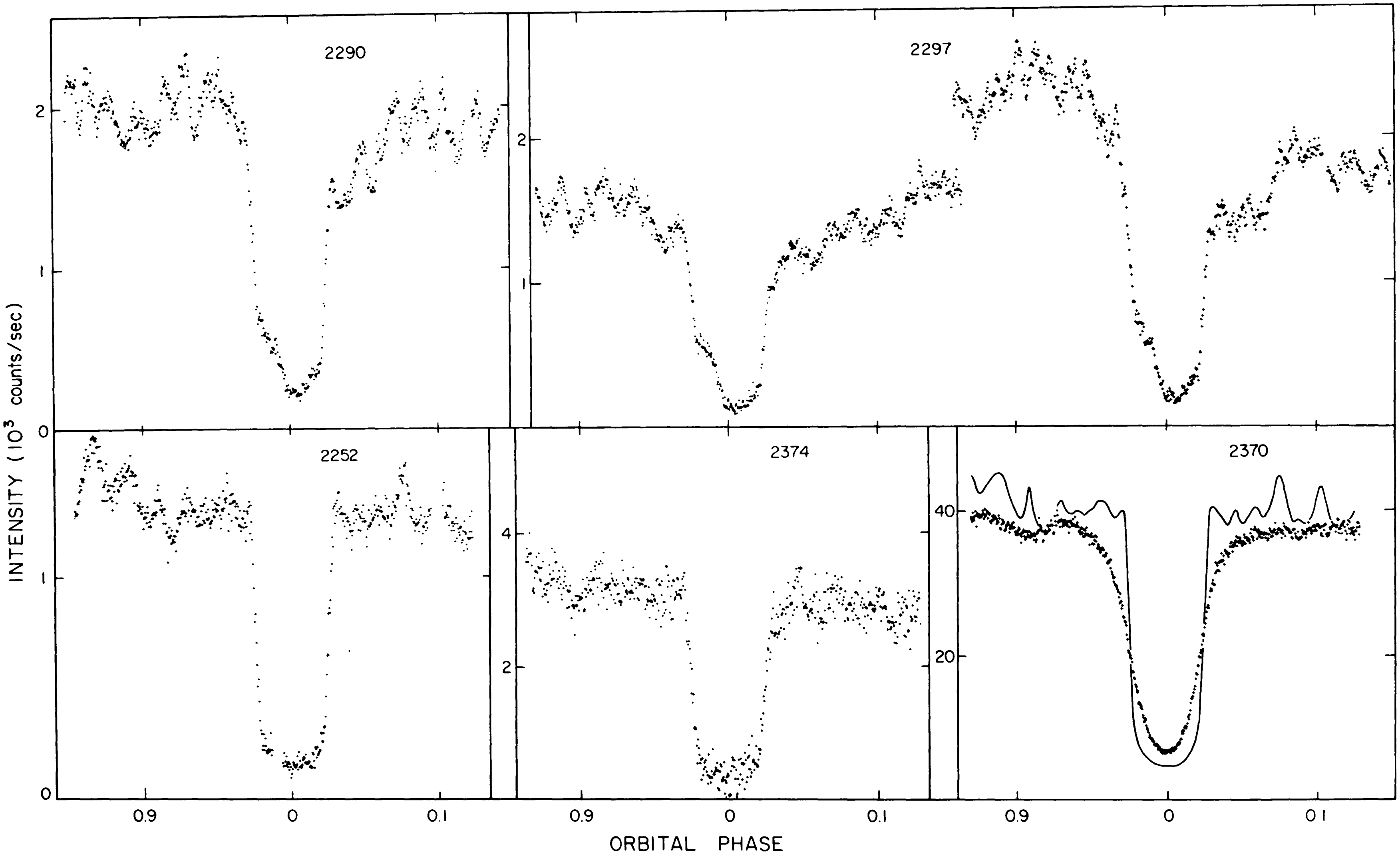

FIG. 8.—Light curves of the HT Cas eclipse, at 3 s per point. The solid line in the lower right frame is the eclipse of run 2252 superposed for comparison.

TABLE 4

HT CAS ECLIPSE OBSERVATIONS

Run (1)	$JD_{\odot}$ Mid-Eclipse (2,443,000+) (2)	T_1 (s) (3)	T_2 (s) (4)	T_{min} (s) (5)	T_3 (s) (6)	T_4 (s) (7)	Telescope (m) (8)
2252 ...	727.93725	−176	−134	+13	+132	+178	2.1
2290 ...	760.93116	−178	−139	+29	+139	+178	2.1
2297 ...	761.88862	−176	−137	+24	+139	+174	2.1
	761.96224	−174	−141	+31	+142	+176	2.1
2320 ...	781.84697	...	−131	...	+132	+174	0.92
2324 ...	782.87803	−169	−130	...	+126	+174	0.92
2346 ...	845.69911	−175	−145	+34	+145	+175	0.76
	845.77269	−167	−139	+44	+141	+168	0.76
2360 ...	867.64594	−189	−137	+66	+143	+183	0.76
	867.71964	−173	−137	+48	+137	+182	0.76
2374 ...	874.71616	−180	−137	...	+137	+182	0.92
2365 ...	869.78183	Eruption	...	...	...	...	0.76
2370 ...	870.66567	Eruption	...	...	...	...	0.76
	870.73921	Eruption	...	...	...	...	0.76

NOTE.—Multicolor observations (Run 2252). Outside eclipse: $V=16.93$, $B-V=-0.04$, $V-B=-1.11$; mid-eclipse: $V=19.32$, $B-V=0.37$, $V-B=-1.28$.

and minimum light is entered in column 5. On the average, minimum light occurs 33 s after mid-eclipse. This suggests that the distribution of light around the ring is asymmetric, in the sense required by a classical "hot spot" on the ring.

Is the blue star the white dwarf, or the accretion disk surrounding the white dwarf? This question cannot be answered decisively, but several clues suggest that it really is the white dwarf:

1) The "white dwarf" eclipse features are always sharply defined and do not show the extensive wings that would be produced by a disk eclipse. This is especially true of run 2252, when the large and partially eclipsed object ("the ring") was very faint.

2) We shall find below that if the secondary is a main-sequence star, the blue star must have the mass and radius of a Hamada-Salpeter white dwarf.

3) Both the ingress/egress times and the duration of totality are constant to within measurement error, although the system brightness at minimum light varies by a factor of 2. For these reasons, the identification of the blue star as the white dwarf is plausible. We note, however, that the photometric appearance of an accretion disk with a low accretion rate can be very similar to that of a white dwarf (see Bath *et al.* 1974, especially their Fig. 2).

b) *Eclipse Analysis and the Structure of the Binary System*

The mean eclipse ingress and egress intervals (38.8 s) and the mean interval between mid-ingress and mid-egress (314 s) are repeating, well-defined properties of the light curve. Here we will use these two numbers for a simple analysis of the eclipse geometry and derive the masses and radii of the stars and the inclination of the binary system.

We first note that the determination of contact times by fitting straight lines to the ingress and egress portions of the light curve will be valid only if the eclipsed object is rectangular and of uniform surface brightness. Since the shape and surface brightness distribution are unknown, this limitation could be quite serious. However, since our conclusion will be that the eclipsed object is probably a white dwarf, the contact times will be corrected by using the very accurate measurements of the white dwarf eclipse in the similar system V471 Tauri

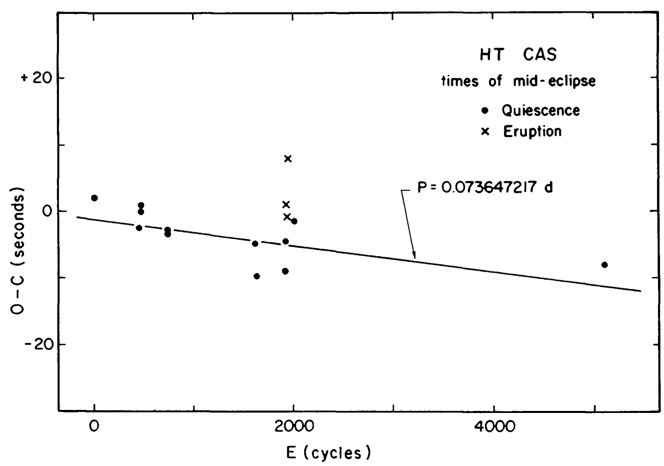

FIG. 9.—Timings of mid-eclipse for HT Cas. Filled circles refer to quiescence, while crosses refer to times of minimum light in eruption.

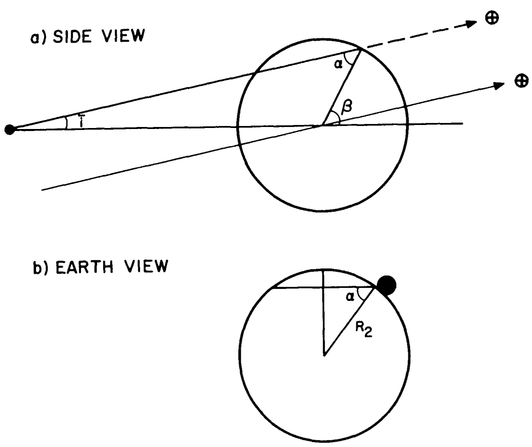

FIG. 10.—The geometry of the white dwarf eclipse in HT Cas, as seen: (*a*) by an observer in the orbital plane, and (*b*) by an earth-bound observer. The red star is represented as a spherical star of radius R_2.

(Young and Nelson 1972; Warner, Robinson, and Nather 1972). For V471 Tau, the linear fit yields contact intervals of 53 ± 3 s, while the true contact interval is 68 ± 1 s. Thus, the measured contact interval in HT Cas should be multiplied by 1.28 to obtain an interval of 49.6 ± 3 s. Essentially, this provides a correction for the sphericity and limb darkening of the white dwarf.

The geometry of the eclipse is shown in Figure 10. We may immediately use the eclipse duration to derive a relation between the mass ratio q ($\equiv m_2/m_1$) and the inclination i:

$$\Delta t = 933\left(\frac{q}{1+q}\right)^{1/3}\frac{\cos\alpha}{\sin i}, \tag{2}$$

where

$$\sin\alpha = \frac{\cos i}{0.46}\left(\frac{1+q}{q}\right)^{1/3}. \tag{3}$$

We have here used the spherical approximation (Paczynski 1971) to the radius of the lobe-filling star:

$$\frac{R_2}{a} = 0.46\left(\frac{q}{1+q}\right)^{1/3}. \tag{4}$$

Inserting $\Delta t = 314$ s into equation (2), we obtain the $q(i)$ relation shown as the dashed curve in Figure 11. The error in this curve is very small, approximately equal to the width of the dash marks.

The system may be further constrained by using the measured ingress/egress interval of 49.6 s. Now the ingress interval Δt_I is given by

$$\Delta t_I = R_1 \sec\alpha M_1^{-1/3}(1+q)^{-1/3}, \tag{5}$$

where R_1 is the radius of the white dwarf. Since we already know $\alpha(i)$ and $q(i)$ and have measured Δt_I, we can evaluate $R_1 M_1^{-1/3}$ for each value of i. We then use the Hamada-Salpeter mass-radius relation for a carbon white dwarf (Hamada and Salpeter 1961) to determine M_1 (and therefore M_2, since q is known).

The observed value of Δt_I deserves closer scrutiny. We have argued for a value of 49.6 s, but in our proverbial heart of hearts, we suspect that this value is too low. While the analogy to V471 Tau supplies the appropriate correction factor due to *geometry*, the low counting rate in the HT Cas data may necessitate an additional correction (because the gentle rollover in the light curve at the contact times is hidden in the photon-counting statistics). We have tried to estimate the importance of this in various ways (using the 25%–75% eclipse points, etc.) and conclude that *at worst* an additional correction factor of 1.33 is needed. Therefore, we perform the calculation for 49.6 and 66.0 s, the lower and upper limits on Δt_I.

The results are shown in Figure 11. The curved line segments labeled "$M_2 = 0.10 M_\odot$," etc., are bounded below by the point for $\Delta t_I = 49.6$ s and above by the point for $\Delta t_I = 66.0$ s. One can also interpret the graph as follows: for a fixed Δt_I, each point on the curve corre-

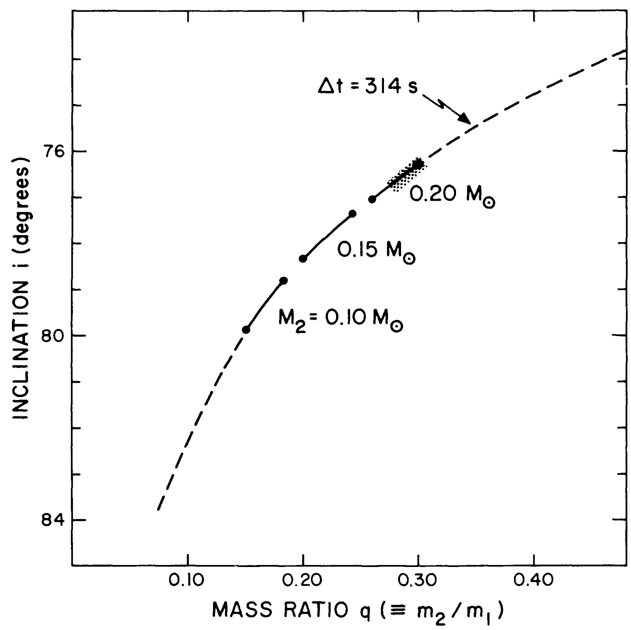

FIG. 11.—Eclipse constraints on HT Cas. The dashed curve is the eclipse *duration* constraint, while the points are the *ingress* constraints for $t_I = 49.6$ s (*lower point*) and 66.0 s (*upper point*). Only the shaded region is consistent with the radial velocity variations.

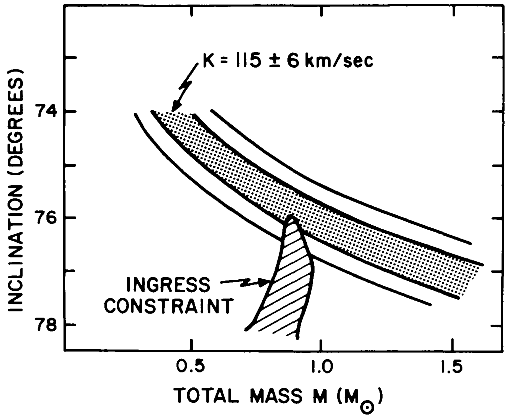

FIG. 12.—The (M, i) plane for HT Cas, as revealed by the radial velocity variations. The shaded region is the $\pm 1\sigma$ allowed region, while the flanking parallel curves indicate the $\pm 2\sigma$ bounds. The crosshatched region is provided by the eclipse constraint. The star must inhabit the intersection of these constraints, near $M = 0.9 M_\odot$, $i = 76.3°$.

sponds to a unique (M_2,M_1); but the uncertainty in Δt_I renders these solutions nonunique. The reader may interpolate or extrapolate along the curve for his/her own favorite values of M_1, M_2, i, or Δt_I. Note that for any Δt_I between 49.6 and 66.0 s, and for any M_2 between 0.1 and $0.2 M_\odot$, the white dwarf mass is well constrained, in the range $0.61 - 0.78 M_\odot$.

We press onward. Young, Schneider, and Schectman (1981) have observed the disk emission lines to move with a semiamplitude $K = 115 \pm 6$ km s^{-1}. After a little algebra, this provides a constraint between the total mass M and the inclination i. This is shown in Figure 12 for the $\pm 1\sigma$ case (shaded region) and the $\pm 2\sigma$ case (flanking parallel curves). Because Young *et al.* found to their chagrin that the phase of the variation was slightly discrepant, we prefer to adopt the safer $\pm 2\sigma$ constraint. The eclipse ingress constraint of Figure 11 is shown in Figure 12 as the crosshatched region. The star must inhabit the intersection of these constraints, near $i = 76.3°$, $M = 0.9 M_\odot$. Thus, we finally emerge with a very specific model: $M_1 = 0.70 \pm 0.07 M_\odot$, $M_2 = 0.19 \pm 0.02 M_\odot$, $i = 76.3 \pm 0.3°$. As a by-product, we also obtain the radius of the secondary: $R_2 = 0.20 \pm 0.02 R_\odot$. This demonstrates that the secondary must be a main-sequence star ($R/R_\odot \approx M/M_\odot$ on the main sequence) if the blue star is a Hamada-Salpeter white dwarf. Of course, we could turn the argument around and prove

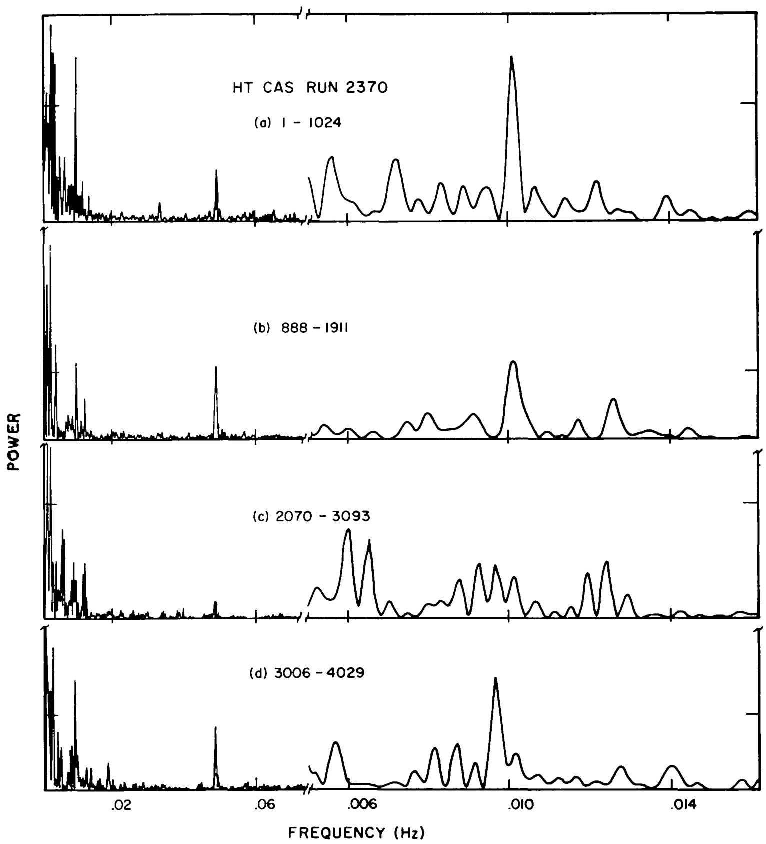

FIG. 13.—Power spectra of portions of run 2370. Each frame is labeled with the integration numbers spanned, with 3 s per integration. The low-frequency regime is magnified at right for easier inspection. The horizontal tick marks indicate the power in a periodicity of semiamplitude 0.8%.

that the blue star must be a Hamada-Salpeter white dwarf if the secondary is a main-sequence star.

It seems unlikely that this is an accident, but taking the gloomy view, one could imagine that a massive white dwarf hides within the cloak of a luminous accretion disk of slightly larger dimensions, *and* the secondary fails to be a main-sequence star. If both of these conditions occur, then our analysis is invalid, and M_1 can be larger. The white dwarf mass cannot be *less* than $\sim 0.63 M_{\odot}$, since that would require that the white dwarf be larger than the observed dimensions of the blue star.

c) *Rapid Oscillations during Outburst*

Run 2360 was obtained at minimum light on 1978 December 25. The following night, a brief visual observation showed that the star remained at minimum. At nightfall on December 27, the star was found to be at maximum light ($V=12.60$, $B-V=-0.06$, $U-B=-0.97$), and a 5.2 hr observation was acquired, although the sky was only clear during the last 1.4 hr. On December 28, the star had declined to $V=13.15$ ($B-V=-0.03$, $U-B=-1.09$) and was falling at a rate of 0.07 mag hr^{-1}. After three days of severe weather, the star was observed again on 1979 January 1 (run 2374), when it was still ~ 0.7 mag above minimum light. These outburst light curves are shown in Figure 7, and two of the eclipses are also presented in Figure 8.

Power spectra have been calculated for all of these runs. Runs 2365 and 2370 each showed weak quasi-periodic oscillations with a period near 100 s,[1] and run 2370 showed in addition a "coherent" signal whose period evolved from 20.25 to 20.45 s during the 3.8 hr observation. The mean semiamplitude of the 20 s oscillation was 0.6%. The power spectra of portions of run 2370 are shown in Figure 13, where the low-frequency regime is shown in more detail at the right. Frame (*c*) should be given little weight, as the monitor star revealed that thin clouds were present in this interval.

The phase and amplitude of the 20 s oscillation have been followed by using the sliding sine fit technique described by Nather and Robinson (1974). Figure 14 shows the results for a fit to 50 cycles (1020 s) of the light curve. The curvature in the O-C diagram indicates the steadily increasing period, and the amplitude changes show the diminished amplitude in eclipse.

In order to resolve the behavior during eclipse, a fit was also made to 10 cycles of the light curve. The results are shown in Figure 15. The oscillation appears to execute a smooth "$-360°$" phase shift through eclipse. The phase shift extends from orbital phase $\Phi=0.934$ to 0.060, and the rapid phase change near mid-eclipse occurs at $\Phi=0.995\pm0.003$. Because this phase change is so rapid ($\lesssim 1$ minute), no significant pulse timing can be obtained during this interval, and therefore the data could be equally well represented by a $\mp 90°$ phase shift.

[1]A quasi-periodic oscillation at this period is also usually present in the optical photometry of the star during quiescence, although the 20 s period is not seen (Patterson 1981).

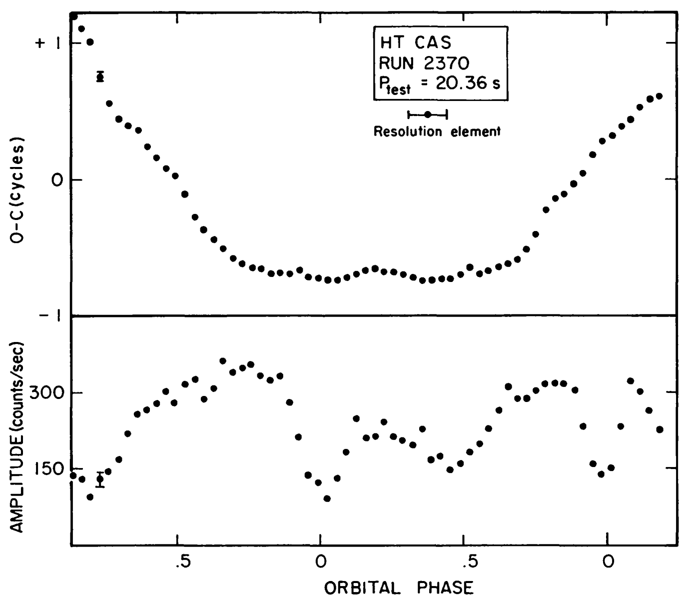

FIG. 14.—Changes in the phase and amplitude of the oscillation, averaged over 50 oscillation cycles.

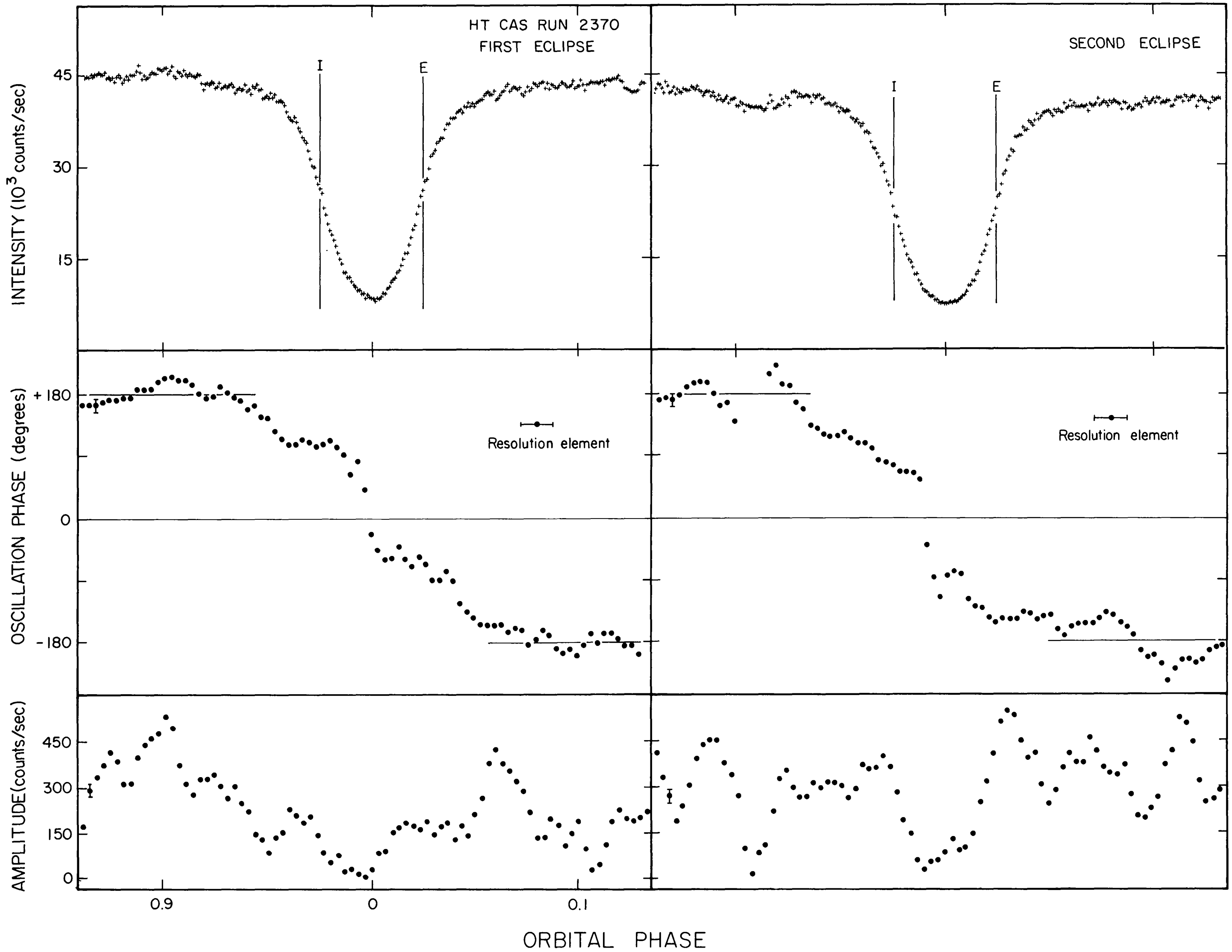

FIG. 15.—The changing phase and amplitude of the oscillation through eclipse. A period of 20.36 s has been assumed for the first eclipse, while 20.44 s was used for the second eclipse. The vertical bars labeled I and E refer to the moments of mid-ingress and mid-egress for the white dwarf, calculated from Eq. (1). The horizontal bars in the phase diagram indicate the pulse arrival time in the segments immediately before and after eclipse. The sense of the phase disturbance in eclipse is that the oscillation *loses* 1 cycle during the eclipse.

Although the data quality remained good throughout both eclipses, the pulse arrival times were found to be somewhat unstable before and after the second eclipse. Therefore, the first eclipse should probably be given higher weight in determining the mean phase shift.

d) *Conclusions from the Orbital Light Curves*

i) *Quiescence*

At quiescence, the white dwarf contributes $\gtrsim 50\%$ of the total light of the system. The ratio $I_{\rm ring}/I_{\rm white\ dwarf}$ varies from $\lesssim 0.15$ (run 2252) to ~ 1.1 (run 2297). Eclipse timings establish an asymmetric light distribution in the ring, but the usual signatures of a classical "hot spot" (viz., a periodic hump and/or a sharp-sided eclipse) are absent. The flickering appears to originate from regions very near the white dwarf. This is suggested by the large amplitude flickering in run 2252 (when the ring was very faint) and by the immediate return of flickering activity after white dwarf egress in runs 2290 and 2297.

The eclipse of the ring begins at orbital phase $\Phi = 0.948$ and ends at $\Phi = 0.074$. For the system parameters deduced above, this indicates a ring radius of 0.16 ± 0.01 $R_\odot$. This compares with a Roche radius of 0.37 $R_\odot$, and a "zero-viscosity" disk radius of 0.10 $R_\odot$ (Flannery 1975). The method of deducing the ring or disk radius is discussed in detail by Sulkanen, Brasure, and Patterson (1980).

The stability of the contact times for the white dwarf eclipse permits stringent limits to be placed on variations in the radii of the two stars. The approximate limits are: $\Delta R_b/R_b \lesssim 0.2$; $\Delta R_r/R_r \lesssim 0.01$.

ii) *Eruption*

During eruption, the very symmetrical eclipses indicate a large luminous region centered on the white dwarf. This must certainly be the classical, optically thick accretion disk. The +7 s residual in the eclipse timings indicates some excess light in the leading edge, but this effect is much more pronounced at quiescence, when the residual is +33 s. It is plausible that both residuals arise from the presence of a hot spot (albeit a poorly defined one) where the stream of transferred material strikes the disk.

The eclipse of the disk during outburst begins at $\Phi = 0.912 \pm 0.01$ and ends at $\Phi = 0.080 \pm 0.01$. This indicates a disk radius of 0.27 $R_\odot$. Thus, the disk has apparently expanded by $\sim 50\%$ during outburst. Since the relative radii are given directly by the contact times, this result is independent of errors in the adopted model (but is sensitive to the difficult measurement of the contact times in the presence of flickering).

Interestingly, the two currently viable models of dwarf nova eruptions predict rather different evolutions of disk radius with time. In the disk-instability theory (Osaki 1974), the sudden onset of viscosity within the disk will trigger disk expansion and accretion onto the white dwarf. In the simplest version of a mass-transfer instability (Bath *et al.* 1974), there is no need for the disk to expand since the postulated viscosity is sufficient to allow accretion at all times. More extensive high-speed photometry during outburst will be required, however, to study this point carefully.

iii) *Posteruption*

The light curve of run 2374 (Fig. 7) was obtained very late in the decline from an eruption, when the system was still ~ 0.7 mag above minimum light. The depth and contact times of the white dwarf eclipse show that virtually all of this excess light comes from the white dwarf, which is no larger than it is at quiescence. It is tempting to suggest that we are seeing the white dwarf surface temporarily heated by the recent rain of infalling matter caused by the decay of the disk. More conservatively, the increasing eclipse depth throughout the decline seen in Figure 7 indicates that the luminosity is generated at progressively smaller radii in the disk.

It would be fascinating to know if the "ringless" appearance of runs 2252 and 2374 is a consistent post-eruption phenomenon. Unfortunately, the star is not yet sufficiently well observed by amateurs to guarantee identification of all eruptions. Mattei (1980) reports that a special effort will be made by the AAVSO to identify all eruptions during the 1980–81 and 1981–82 observing seasons.

iv) *Exultation*

Finally, we do not wish to leave this amazing little star (by far the faintest of all the well-studied dwarf novae) without marveling at how readily it coughs up its secrets. The present harvest of information has been gleaned from one season of observation, primarily with a small telescope. HT Cas is truly the Rosetta stone of dwarf novae, and we suspect that we have only scratched the surface of its interpretive value.

V. SS CYGNI

Coherent oscillations in SS Cyg were detected and reported in detail by Patterson, Robinson, and Kiplinger (1978). The period was 9.735 ± 0.002 s, the mean semi-amplitude was 0.02%, and the oscillation maintained approximate phase coherence ($\pm 40°$) over the 3.5 hr observation. Additional photometry has been obtained late in the 1978 September-October outburst, and this is presented in Table 5. Early in the same eruption, Horne and Gomer (1980) found an oscillation period of 8.5 s,

TABLE 5

OSCILLATIONS IN SS CYG

Run	Date (UT)	Period (s)	I_{star}	Amplitude (%)	Notes
1774 ...	1976 Oct 25	9.74	580	0.02	also ~32 s quasi-periodic
2309 ...	1978 Sep 28	10.72	280	0.1	also ~33 s quasi-periodic
2315 ...	1978 Sep 30	10.90	135	0.1	also ~36 s quasi-periodic
2322 ...	1978 Oct 1	...	98	0.08	also ~32 s quasi-periodic
	1978 Jun 14	8.9	...	30.	0.1–1.0 Kev X-rays

with an amplitude of 0.07%. This, combined with the data of Table 5, proves decisively that the optical oscillation of SS Cyg exhibits the same kind of period changes seen in other dwarf novae.

Among the dwarf novae, SS Cyg is unique in that its oscillation has been extensively studied in both the optical and soft X-ray regimes. On 1978 June 14 a 6 hr pointed observation of SS Cyg in outburst by *HEAO 1* revealed a large amplitude (~30%) 9 s modulation in the 0.1–1.0 Kev light curve. Analysis of the X-ray data (Cordova *et al.* 1980) of this and other observations has led to the following important new results:

1) The spectrum and luminosity suggest that the oscillating object is smaller than a white dwarf.

2) The X-ray clock has very poor phase stability: the phase wanders by 90° in ~25 cycles. The average *period* is much more coherent, changing with $Q(\equiv 1/|\dot{p}| \sim 10^5$.

3) No pulsations are detected in soft or hard X-rays at minimum light.

The implications of these results for models of the coherent oscillations will be discussed in § VII.

VI. OTHER DWARF NOVAE

A large body of observations of miscellaneous dwarf novae has been accumulated over the years. Some of these observations have been previously tabulated in Patterson (1979*a*), Patterson, Robinson, and Nather (1977), and in previous tables in this work. The remainder of the observations are presented in Table 6, which gives the integration time Δt, the mean intensity $\langle I \rangle$ in units of 10^3 counts s^{-1}, and the 90% confidence upper limit to the semiamplitude of coherent oscillations. This upper limit refers to the frequency range of ~0.011 Hz to the Nyquist frequency of $(1/2\Delta t)$ Hz. A less stringent upper limit applies to frequencies below ~0.011 Hz. For the one star displaying coherent oscillations (EM Cyg), the amplitudes and periods are given in the final column. All of the count rates (which are accurate to ~±10%) have been corrected for extinction and converted to the corresponding count rates on the 0.92 m telescope. On this system, 30,000 counts s^{-1} corresponds to a blue magnitude of ~11.7.

Some of the results for individual stars, in Table 6 and in the literature, are worthy of special mention.

a) *YZ Cancri*

Over 40 hours of photometry during eruptions of YZ Cnc have been obtained (see Table 6, and Table 2 of Patterson 1979*a*). Despite this extensive coverage, coherent oscillations have never been detected, although quasi-periodic oscillations with a period of ~90 s were found during the supermaximum of 1978 December. Thus, YZ Cnc is the best-studied case of a dwarf nova that has never shown coherent oscillations. (The possible detection claimed by Moffet and Barnes (1974) is not statistically significant and should be disregarded).

b) *RX Andromedae*

Robinson (1973*b*) reported an extensive search for oscillations in RX And, with negative results. Table 6 adds two more negative observations. Szkody (1976) found a statistically significant signal at ~36 s in a power spectrum, but the width of the signal tends to favor an identification as a quasi-periodic oscillation.

c) *EM Cygni*

A likely detection of 16.6 s oscillations in EM Cyg was reported by Nevo and Sadeh (1978). Table 6 contains three positive detections, with periods ranging from 16.58 to 21.22 s. Thus, the oscillations of EM Cyg are confirmed.

d) *RU Pegasi*

An extensive study of oscillations over four nights of a 1975 outburst has already been reported (Patterson, Robinson, and Nather 1977). The evolution of the period through a minimum value was followed, and the minimum period was attained 1–2 days after maximum light. This behavior is also observed in SY Cnc and AH Her and is illustrated for all three stars in Figure 16. (The time delay between maximum light and minimum period is not quite so obvious in the case of SY Cnc, but is further supported by the 1978 April outburst, which is not plotted in Figure 16 [see Table 2].)

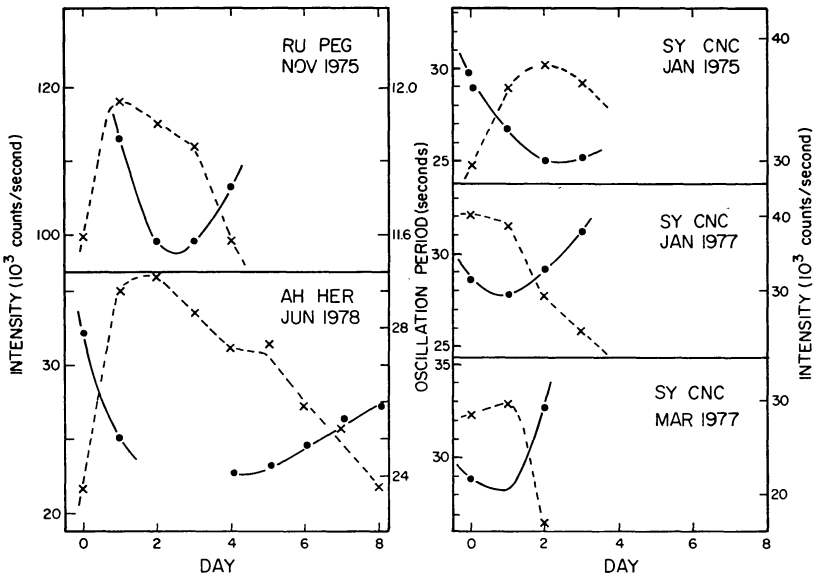

FIG. 16.—Eruption light curves and period changes in three dwarf novae. The period changes trace out an approximate mirror image of the light curve, with minimum period reached slightly after maximum light.

e) *U Geminorum*

U Gem has exhibited quasi-periodic oscillations at periods between 73 and 146 s (Robinson and Nather 1979) and has also shown 24 s quasi-periodic oscillations in its 0.1–1.0 Kev flux (Cordova, Chester, and Garmire 1980) in outburst. Table 6 contains no observations of U Gem, but Stover (private communication) reports extensive photometry during a 2 week outburst of U Gem in 1977 October, with no detection of optical coherent oscillations.

f) *VW Hydri*

A bewildering variety of periodicities is present in this star. Warner and Brickhill (1974) reported "coherent" oscillations which evolved from 28 to 32 s over a 4 hr observing run. Haefner, Schoembs, and Vogt (1979) reported a periodicity at 88 s which appeared to have the usual characteristics of the quasi-periodic oscillation. Since then many additional periods have been found: 413 s (Warner and Brickhill 1978); 266 s (Haefner, Schoembs, and Bogt 1979); and 24 s (Robinson, private communication). In general, these oscillations are of large amplitude (1%–15%) and exhibit very low coherence. There are at least three possibilities for the proper classification: (1) all of the oscillations seen are fundamentally quasi-periodic; (2) the oscillation originally found by Warner and Brickhill (1974) was "coherent", but by coincidence quasi-periodic oscillations of a similar period are also occasionally present; (3) the observed oscillation at ~30 s is always the same, but its coherence varies drastically.

The large amplitude of the oscillations in VW Hyi makes the star a convenient prototype, but presently available data are very confusing, and a new study is certainly needed.

VII. DISCUSSION

a) *Dwarf Novae Light Variations*

The light variations seen in dwarf novae have been classified into three categories: random flickering, quasi-periodic oscillations, and coherent oscillations. The power spectra of Figures 3, 13, and 17 illustrate all three categories, which we will now discuss in turn.

i) *Flickering*

In the cataclysmic variable literature, "flickering" has come to mean the nonperiodic, predominantly low-frequency variations which are seen directly in the light curve. In a power spectrum, these variations are seen as a smooth continuum of power, rising toward the low-frequency end. It is also true that scintillation and transparency variations contribute to low-frequency power, but for a dwarf nova these are of minor importance on a photometric night.

Warner and Nather (1971) have used the disappearance of the flickering during eclipse in U Gem to prove that the flickering originates in the bright spot. There is, however, evidence that in AM Her (Priedhorsky and Krzeminski 1978), AE Aqr (Patterson 1979*b*), and possibly HT Cas (§ IV), the flickering originates from the white dwarf. The origin of flickering is certainly an important unsolved problem. But it is someone else's problem; for our purposes, the smooth appearance of the flickering in a power spectrum creates no confusion with periodic signals.

TABLE 6

OSCILLATION SEARCHES AMONG DWARF NOVAE

Star	Date (UT)	Telescope (m)	Δt (s)	⟨I⟩	Amplitude Limit (%)
AR And	1975 Nov 6	2.1	4	...	0.07
RX And	1976 Aug 20	2.1	3	42	0.04
	1976 Aug 21	2.1	2	39	0.04
UU Aql	1978 May 31	0.92	2	34	0.12
	1978 Jun 3	0.92	2	27	0.10
SS Aur	1977 Sep 9	2.1	2	12	0.10
Z Cam	1977 Feb 19	0.76	3	23	0.10
YZ Cnc	1978 Dec 24	0.76	2	67	0.07
	1978 Dec 25	0.76	3	49	0.07
	1978 Dec 26	0.76	5	44	0.07
	1978 Dec 27	0.76	3	...	0.20
	1978 Dec 28	0.76	4	...	0.12
WW Cet	1976 Aug 20	2.1	3	...	0.12
EM Cyg	1976 Jul 28	2.1	4	17	0.33 ($P=17.36$ s)
	1976 Jul 29	2.1	4	18	0.39 ($P=16.58$ s)
	1976 Aug 17	2.1	2	13	0.10
	1978 Apr 12	0.76	3	13	0.11
	1978 Sep 14	2.1	4	7	0.26 ($P=21.22$ s)
IR Gem	1976 Jan 9	2.1	4	...	0.09
EX Hya	1977 Jan 24	0.92	4	5.3	0.15
X Leo	1978 Apr 12	0.76	5	0.4	0.27
	1978 Dec 27	0.76	3	...	0.20
CN Ori	1976 Oct 25	2.1	4	...	...
	1976 Oct 26	2.1	5	5.4	0.06
	1976 Nov 16	0.92	5	12.7	0.10
	1976 Nov 20	0.92	5	8.6	0.14
	1976 Nov 21	0.92	5	6.0	0.15
CN Ori	1976 Nov 22	0.92	4	3.0	0.15
	1976 Nov 26	0.92	8	1.0	0.16
	1976 Dec 23	2.1	5	12	0.10
	1976 Dec 26	2.1	5	7.4	0.10
	1977 Jan 23	0.92	5	11.5	0.13
	1977 Jan 24	0.92	5	10.5	0.10
	1977 Jan 25	0.92	4	10.3	0.13
	1977 Nov 12	0.76	5	10.0	0.12
CZ Ori	1977 Jan 19	0.92	4	13	0.12
	1977 Jan 20	0.92	4	12	0.15
KT Per	1976 Nov 20	0.92	5	4.0	0.14
	1976 Nov 21	0.92	4	19	0.07
	1976 Nov 22	0.92	5	14	0.07
	1976 Nov 23	0.92	5	9.6	0.10
	1976 Nov 26	0.92	5	1.5	0.14
	1977 Jan 15	0.92	4	15	0.09
	1977 Jan 16	0.92	4	8.6	0.12
	1977 Dec 12	2.1	4	19	0.08
	1977 Dec 13	2.1	4	17	0.10
	1977 Dec 14	2.1	4	12	0.08
	1978 Jan 5	0.76	4	13	0.12
	1978 Jan 6	0.76	4	9.0	0.14
UZ Ser	1976 Aug 23	2.1	3	9.6	0.09
	1977 Jun 19	2.1	3	9.6	0.09
SU UMa	1977 Sep 9	2.1	2	10	0.14
	1977 Sep 10	2.1	2	10	0.07
	1977 Oct 19	0.92	5	1.2	0.10
TW Vir	1977 Mar 13	0.76	10	0.6	0.13

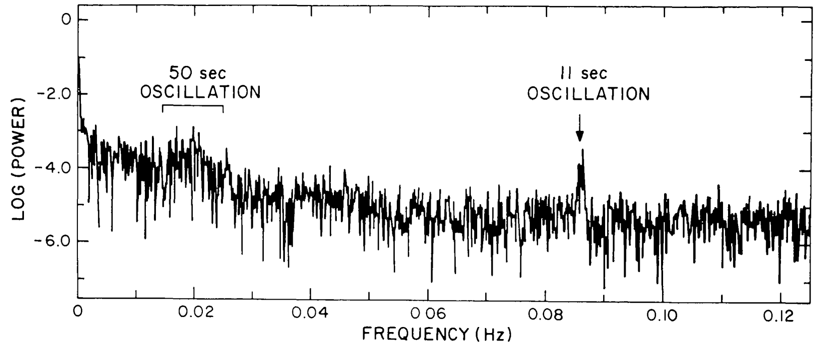

FIG. 17.—The power spectrum of RU Peg in run 1677, showing a "coherent" oscillation near 0.086 Hz and a quasi-periodic oscillation near 0.02 Hz.

ii) *Quasi-Periodic and Coherent Oscillations*

Quasi-periodic oscillations were first found in RU Peg by Patterson, Robinson and Nather (1977), and additional detections have been reported by Robinson and Nather (1979). Their usual signature is a broad hump in the power spectrum, such as that labeled "50 s oscillation" in Figure 17. Table 7 gives a list of all detections to date. As emphasized by Robinson and Nather (1979), these oscillations have coherence times of only a few cycles, and their periods are generally several times longer than those of the coherent oscillations. Based on these clues, there is usually no confusion over whether an oscillation is quasi-periodic or coherent.

However, there are a few important exceptions to this statement. VW Hyi is an extremely confused case, as discussed above; RX And and AM CVn are questionable cases; and most importantly, the detection of quasi-periodic ~24 s oscillations in the 0.1–0.5 Kev X-ray light curve of U Gem (Cordova 1979) certainly casts doubt on the dichotomy of coherent and quasi-periodic oscillations. The latter result suggests a common origin for the coherent oscillation in SS Cyg and the quasi-periodic oscillation in U Gem since the two oscillations each execute a random walk (although of different strengths) in phase.

Yet the bulk of the evidence certainly suggests that two different phenomena are involved. Chastised by the U Gem observations of Cordova (1979), we must abandon *coherence* as the distinguishing characteristic, since none of the oscillations are really coherent. We propose that the oscillations in dwarf novae are of two types: (1)

TABLE 7

QUASI-PERIODIC OSCILLATIONS

Star	Period (s)	Reference
RX And[a]	36	Szkody 1976
YZ Cnc	75-95	This work
HT Cas	~100	This work
SS Cyg	32–36	Robinson and Nather 1979; this work
AH Her	~100	This work
U Gem	73–146	Robinson and Nather 1979
VW Hyi	88–413	Warner and Brickhill 1978; Haefner *et al.* 1979
KT Per	82–147	Robinson and Nather 1979
RU Peg	~51	Patterson *et al.* 1977; Robinson and Nather 1979
AE Aqr[b]	~18, 36	Patterson 1979*b*
TT Ari[b]	~1000	Smak 1969
AM CVn[a]	26.3	Patterson 1981
GK Per[b]	~380	Patterson 1981
2A0311–227[b]	~350	Patterson, Williams, and Hiltner 1980
4U1626–67[b]	~1000	Joss, Avni, and Rappaport 1978
Sco X–1?[b]	~165?	Robinson and Nather 1979

[a] Identification as "quasi-periodic" uncertain.

[b] "Quasi-periodic" in the sense of short coherence times, but probably of a different origin.

short-period, X-ray-producing, *usually* high-Q, associated with the white dwarf and specifically with a dwarf nova eruption; and (2) long-period, not producing X-rays, low Q, associated with the accretion disk, not confined to dwarf nova eruptions. We will call these *dwarf nova oscillations* (DNOs) and *quasi-periodic oscillations* (QPOs), respectively. (It should be noted that the QPOs in cataclysmic variables *generally* are a more diverse phenomenon; the last seven entries in Table 7 are not dwarf novae, and pay little heed to our feeble efforts at classification.)

b) *Dwarf Nova Oscillations*: *Summary of Observed Properties*

With this caveat (that some of the "coherent" oscillations may have very poor coherence), we turn to summarizing the observed properties of the class. The certified members are listed in Table 8, along with their periods and estimated Qs. As emphasized by Cordova *et al.* (1980), this Q is a measure of period stability, not of phase stability. Note that the U Gem X-ray periodicity is classified as a DNO in accordance with the above criteria; we therefore predict the existence of a ~24 s optical DNO.

1) The periods are in the range 8–39 s, and each individual star shows a characteristic and smaller range of periods.

2) Period changes of a few per cent occur from night to night, leading to a characteristic Q in the range 10^4–10^6. The question of phase coherence on a short time scale is controversial. The X-ray observations of SS Cyg by Cordova *et al.* (1980) suggest a very low coherence ($Q \sim 25$), but this is not compatible with the optical observations of Patterson, Robinson and Kiplinger (1978). In addition, the eclipse-related phase shifts of UX UMa (Nather and Robinson 1974) and HT Cas (§ IV) demonstrate that phase coherence—not merely period constancy—is maintained over time scales of 20–50 minutes. On the other hand, it is certainly true of both the X-ray and optical oscillations that (in general) the pulse arrival times show significant phase residuals after removing the best-fit P and $\dot{P}$ terms. These residuals indicate that the oscillations are not simply periodic processes that slowly change their period. We conclude: (*a*) that phase coherence probably varies over at least one order of magnitude from night to night, and from star to star; and (*b*) that the existence of a random component (such as the "random walk" of Cordova *et al.* 1980) does not necessarily imply an underlying clock of low Q, since there are examples of extremely high-Q oscillators (viz., WZ Sge and AE Aqr) that also show random phase residuals on a short time scale.

3) In all cases, the oscillations are found to be pure sinusoids. The upper limit to the amplitude of harmonic components is generally ~20% of the amplitude of the principal signal.

4) In addition, the observed signals are never clearly multiperiodic. Some evidence for the simultaneous presence of different periods has been cited (Robinson 1973*b*), but because rapid amplitude changes are known to be present, this evidence is not reliable. One would like to have a second period well separated from the principal period, but this behavior has never been seen, despite the accumulation of data covering 66 nights on 12 stars.

TABLE 8
DWARF NOVA OSCILLATIONS

Star	Period (s)	Q	Reference
SS Cyg	8.5–10.9	2×10^5	Patterson *et al.* 1978; Cordova *et al.* 1979
RU Peg	11.6–11.8	4×10^5	Patterson *et al.* 1977
Z Cam	16.0–18.8	10^5	Robinson 1973*a*
EM Cyg	16.6–21.2	10^5	Nevo and Sadeh 1978; this work
V436 Cen	19.5–20.1	...	Warner and Brickhill 1978
HT Cas	20.2–20.4	3×10^4	This work
KT Per	22.0–29.2	10^5	Nevo and Sadeh 1976
SY Cnc	23.3–33.0	10^5	This work
AH Her	24.0–38.8	10^5	Stiening *et al.* 1979; this work
CN Ori	24.3–25.0	3×10^4	Warner and Robinson 1972
VW Hyi[a]	24–32	3×10^3	Warner and Brickhill 1978
Z Cha	27.7	...	Warner 1974
UX UMa[b]	28.5–30.0	2×10^5	Nather and Robinson 1974
V3885 Sgr[b] ...	29.0	...	Warner 1973
U Gem	~24 (X-ray)	...	Cordova 1979

[a] Oscillation may be quasi-periodic.
[b] Not dwarf novae, but oscillations appear to be identical to those of dwarf novae.

5) The oscillations generally conform to a period-luminosity law, but minimum period occurs slightly after maximum light. This is indicated by the schematic "banana diagram" of Figure 18. All well-studied dwarf novae execute such a loop in the diagram, *mutatis mutandis*, during each outburst; the location and shape of the banana vary from outburst to outburst. The oscillations are not detected throughout the loop, but only near maximum light.

6) The X-ray spectrum of SS Cyg indicates that the oscillating object has an effective temperature of $\sim 3 \times 10^5$ K and suggests that the radiating area is considerably smaller than a white dwarf (Cordova *et al.* 1979).

7) Despite extensive searches (especially in Z Cam, SY Cnc, and HT Cas), similar oscillations have never been seen at quiescence. If our conclusion (§ IV) that the white dwarf is the dominant luminosity source at quiescence in HT Cas is correct, then the oscillation amplitude must decrease by a factor of at least 1000.

8) The phase shifts observed through eclipse in UX UMa (Nather and Robinson 1974) and HT Cas (§ IV) demonstrate: (*a*) that the entire disk participates in the oscillation, and (*b*) that the oscillation is not radially symmetric. Since the short period requires an oscillation origin in the immediate vicinity of the white dwarf, this suggests that the X-ray or ultraviolet flux from a rotating searchlight on or near the white dwarf is absorbed and reprocessed at larger radii in the disk. Theoretical phase shifts have been calculated by Nather and Robinson (1974) for a nonradially pulsating white dwarf, and by Petterson (1980) for a rotating white dwarf. Satisfactory fits to the data may be found in either the pulsation or the rotation models. The model of Petterson fits the HT Cas data remarkably well for an inclination of 77°—which is the value independently deduced from the eclipse analysis.

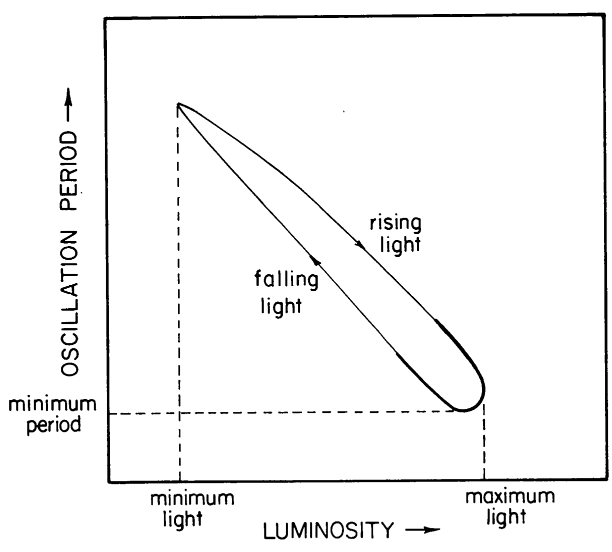

FIG. 18.—Schematic evolution of a dwarf nova in the period-intensity plane through an outburst. The oscillations are detected only near maximum light (*heavy line at lower right*).

c) *Models*

i) *Orbiting Blobs in the Disk*

Bath (1973) suggested that the observed oscillations could be produced by the eclipses of transient hot spots at the inner edge of the accretion disk. These "blobs" are quickly destroyed as a result of cooling and differential rotation in the disk; both time scales are $\sim 10^3$ s. This is consistent with the observed coherence times. Since the oscillation period is that of a Keplerian orbit, the period changes are attributed to a change in the radius of blob production. More specifically, Bath proposed that the radius of blob production is the radius of the white dwarf magnetosphere. Then the period changes result from the varying ram pressure of infalling matter, in the sense that minimum period occurs when the accretion rate is highest. As we have seen, this also agrees with observation (the observed time delay between maximum light and minimum period may be simply due to the changing bolometric correction). However, since the accretion rate is probably varying by a factor of ~ 5, the relatively small variations in the observed period ($\sim 25\%$) are not easy to understand.

This model makes one inescapable prediction: the observed oscillation period must always *exceed* the Keplerian period at the surface of the white dwarf. Among the oscillating dwarf novae, there are six for which estimates of the white dwarf mass are available. In Figure 19, these masses are plotted versus the minimum observed oscillation period, and the solid line is the Keplerian period at the surface of a Hamada-Salpeter carbon white dwarf (Hamada and Salpeter 1961). All points lie above the line, as the model requires. The orbital radii corresponding to the observed oscillations range between 1.1 and 2.4 white dwarf radii. As more data on oscillations and white dwarf masses are obtained, this test may become particularly useful.

ii) *White Dwarf Rotation*

The white dwarfs in dwarf novae are expected to be rapidly rotating as a result of the accretion of high angular momentum material from the disk. Rotation is a straightforward way to obtain rapid coherent oscillations, provided a mechanism can be found to create spots, or an asymmetric radiation field, on the white dwarf. The problem has always been to account for the observed period changes. The kinetic energy of a rapidly rotating white dwarf is so enormous ($\sim 10^{49}$ ergs) that

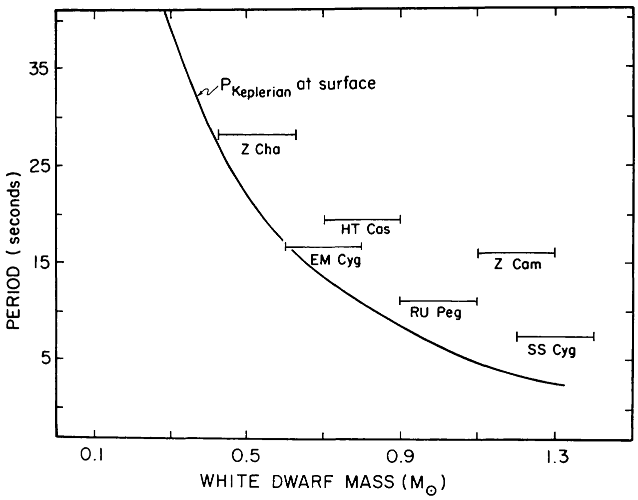

FIG. 19.—The minimum oscillation period vs. white dwarf mass, for the six stars with available mass estimates. An arbitrary error of $\pm 0.1 M_\odot$ has been assigned. The curved line is the Keplerian period of a zero-temperature carbon white dwarf. References for masses: SS Cyg (Stover, private communication); HT Cas (this work); Z Cha (Smak 1979); others (Robinson 1976).

no significant period change should occur during an eruption which involves only $\sim 10^{40}$ ergs. Yet period changes of up to 25% are observed. Paczynski (1978) has suggested that this problem may be overcome by attributing the period changes to a thin surface layer ($\sim 10^{-9}\ M_\odot$) which is decoupled from the more slowly rotating core and spun up by the torques exerted by accreting matter. A magnetic field is invoked to account both for the spots on the white dwarf and the core-envelope coupling. A similar model has been suggested by Lamb, Pines, and Shaham (1978) to account for anomalous period changes in X-ray pulsars.

This version of a rotator hypothesis is simple and plausible, but recent work has produced three new difficulties, each of which might by itself have sufficient force to exclude the model.

1) In SS Cyg, hard X-rays at minimum light are not pulsed (to $\lesssim 5\%$, Swank 1979). Since in a magnetic rotator the hard X-rays should come from the poles, why aren't they pulsed?

2) In SS Cyg, the 9 s pulsed soft X-ray flux shows not only deviations from a strict periodicity, but also from one that is smoothly changing. The time scale for this jitter can be as short as $\lesssim 3$ cycles. This suggests that the angular momentum associated with the oscillation is tiny—and in fact casts doubt on *all* schemes that attribute the oscillation to the white dwarf.

3) In HT Cas, it is likely that the white dwarf is dominating the optical luminosity at quiescence, and that most of this is *accretion* luminosity (note the active flickering in run 2252 [Fig. 6]). If a 20 s magnetic rotator is present, why do we see no power at a period of 20 s?

Because of these difficulties, the magnetic rotator model is not presently viable. Nevertheless, rotation is a natural way to produce oscillations which are singly periodic and near a characteristic period, and further theoretical work along these lines is highly desirable.

iii) *Nonradial White Dwarf Pulsations: g-Modes*

Many authors have suggested that the dwarf nova oscillations could arise from nonradial pulsations of the white dwarf (Warner and Robinson 1972; Osaki and Hansen 1974). Because the radial pulsation periods of $\sim 1 M_\odot$ white dwarfs are in the range 1–10 s, the pulsations must be nonradial. The nonradial requirement is reinforced by the observed phase shifts in HT Cas and UX UMa. Since the nonradial *p*-modes have periods comparable to those of the radial modes, only the gravity modes, or *g*-modes, will produce periods in the range of 10–40 s. This has been verified by calculations of Brickhill (1975) and Osaki and Hansen (1974).

Bath *et al.* (1974) have raised the very severe objection that these calculations are irrelevant to dwarf novae, since the observed phase and amplitude changes occur on a time scale at least 10^5 times *too short* to be identified with true white dwarf pulsations. The pulsation hypothesis can only be rescued if the pulsations are confined to a thin surface layer, where only small amounts of mass and energy are required to produce observable effects. Models of Papaloizou and Pringle (1978) appear to confirm that a self-consistent model of a *g*-mode pulsation can be constructed which confines the pulsation to the outer layers, and displays transient effects similar to those observed.

iv) *Nonradial White Dwarf Pulsations: Effects of Rapid Rotation*

Papaloizou and Pringle (1978) have studied the nonradial oscillations of *rotating* white dwarfs and have identified another class of low-frequency modes which they call "*r*-modes". The periods of *r*-modes are on the order of P_{rot}/m, where P_{rot} is the white dwarf rotation period and *m* is the azimuthal quantum number (which gives the number of bright spots around the circumference of the star). The modes of high radial wave number have amplitudes strongly concentrated in the outer layers of the star, which allows the transience of the observed oscillations to be understood. The period-intensity relation can be understood as the result of accretion torques exerted on the surface by infalling matter (as in § VII*c* iv above).

Papaloizou and Pringle also found that the characteristics of *g*-mode pulsations depend on the rotation. In particular, for fast rotation (i.e., when the rotation period is much less than the oscillation period of a nonrotating star), the *g*-modes can be trapped near the equator of the star and will have periods $P \sim P_{rot}/m$. Thus, the case of a trapped *g*-mode closely resembles that of *r*-modes.

These pulsation models remain viable as possible explanations for the origin of dwarf nova oscillations. However, there are several observations which may pose stumbling blocks for these models and should certainly be addressed in the future development of the models:

1). *The continuing absence of a single star displaying a clearly multiperiodic oscillation.*—Although nonradial pulsations are expected to be multiperiodic in general, it may be that the specific excitation mechanism favors the creation of a single periodicity.

2). *The size of the pulsating object*—Since pulsation amplitude should vary smoothly over the surface of the star, one expects that the luminosity should come from a region with the approximate dimensions of a white dwarf. Cordova *et al.* (1980) obtained a size of $\lesssim 100$ km from fitting the X-ray temperature and luminosity of SS Cyg. If more extensive data confirm this small size, it will be a powerful constraint on pulsation models, and may eliminate them.

3). *The random character of the pulse arrival times.*—Cordova *et al.* (1980) found that the phase of the 9 s X-ray oscillations in SS Cyg executed a random walk with excursions of 90° in 25 cycles, i.e., 4 minutes. If further X-ray observation confirms that this very low phase coherence is typical of dwarf novae, it may prove difficult to understand in models of pulsating white dwarfs.

4). *The pulsation amplitude.*—The X-ray oscillations in SS Cyg showed a very large amplitude, averaging ~30% and occasionally reaching 100%. This suggests that there is just *one* bright spot (or at most a few) on the white dwarf, and casts doubt on the idea that the random walk in phase is due to a multitude of independent pulsations.

VIII. SUMMARY AND CONCLUSIONS

1) Extensive study of the oscillations of AH Her and SY Cnc demonstrates the general pattern of period variations during the outburst. Loops such as that of Figure 18 are traced out in the period-intensity plane. The time delay between maximum light and minimum period is a significant and repeating feature. However, it is quite possible that bolometric luminosity may be maximum at the time of minimum period, and this is consistent with the changing broad-band colors through the outburst (Smak 1971).

2) A modulation of the brightness of Sy Cnc near minimum light is reported with a period of $0^{d}_{.}32$–$0^{d}_{.}33$ (or possibly $0^{d}_{.}48$–$0^{d}_{.}49$). This is probably the binary orbital period.

3) Light curves of HT Cas during quiescence and eruption are presented. A quiescence, a total eclipse of a small, bright object at the center of the disk, is superposed on a partial eclipse of a larger object of lower surface brightness. Arguments are given for identifying the small and large objects as the white dwarf and the accretion ring, respectively. A model of the eclipse geometry yields the system parameters: $M_r = 0.19\ M_\odot$, $R_r = 0.20\ R_\odot$, $M_b = 0.70\ M_\odot$, $R_b = 0.011\ R_\odot$, $i = 76.3°$.

During eruption, the eclipses become partial, shallower, wider, and more symmetrical. Evidently the entire accretion disk has brightened and become larger. Dwarf nova oscillations at a period of 20.4 s were detected one day past maximum light. A phase shift through eclipse was found, indicating the nonradial nature of the oscillation and the role of reprocessing in the system.

4) Additional detections of oscillations in SS Cyg and EM Cyg are reported. A list of null results for 16 other dwarf novae is given.

5) The relationship between DNOs and QPOs is discussed. A firm dichotomy between the two types on the basis of coherence alone is probably not possible, and a less rigid classification scheme is proposed. A summary of the observed properties of the DNOs is given.

6) The present status of available models is discussed. All encounter very serious problems. The singly periodic nature of the oscillation favors rotation of the white dwarf or inner disk. However, the observations are not yet sufficiently sharp to firmly exclude any of the models discussed.

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