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WY SAGITTAE (NOVA 1783): A TRANSITION OBJECT BETWEEN CLASSICAL AND DWARF NOVAE?

M. M. SHARA,[1,2,3] A. F. J. MOFFAT,[3,4,5] J. T. MCGRAW,[6] D. S. DEARBORN,[6] H. E. BOND,[7]
E. KEMPER,[2,7] AND R. LAMONTAGNE[5]

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ABSTRACT

WY Sge, the 19th magnitude remnant of Nova WY Sagittae 1783, has been found to be an eclipsing binary with a period of 3 hr 41 minutes. Radial velocity observations show a low velocity amplitude for the emission lines originating from the vicinity of the primary star, possibly suggesting that the primary is a fairly massive ($>1\ M_{\odot}$) degenerate object. The secondary, if it obeys the main-sequence mass-radius relation, is an M dwarf of 0.44 $M_{\odot}$.

On one night, we observed WY Sge to be 1.6 mag brighter than normal. This outburst, along with a spectrum in quiescence more typical of dwarf novae than of classical novae at minimum, suggests that WY Sge is an object intermediate (in mass-transfer rate from the secondary star) between classical and dwarf novae. We are unable to decide whether all novae resemble dwarf novae long after their classical-nova outbursts, or whether WY Sge is simply a nova with an atypically low mass-transfer rate.

Subject headings: stars: dwarf novae — stars: eclipsing binaries — stars: individual — stars: novae

I. INTRODUCTION

Determining how classical novae evolve during the millennia between their cataclysmic eruptions is a difficult observational task. A widely held view is that "novalike variables" (Nl's) (or UX Ursae Majoris type binaries) are classical novae, between outbursts (Warner 1976). There seem, however, to be far too *few* (by a factor of at least 10) Nl's to account for the number of classical novae observed and inferred (from M31 nova occurrence rates) to erupt annually in the Galaxy (Patterson 1983). Because of this apparent discrepancy, an observational determination of the state of classical novae between outbursts is desirable.

Ideally, a series of progressively older novae should be identified and studied. In practice, few accurate positional measurements of novae before Nova Ophiuchi 1848 exist. Recently, however, older objects have been firmly identified. CK Vulpeculae (Nova 1670) and its associated nebulosity have been recovered (Shara and Moffat 1982) and spectroscopically examined (Shara, Moffat, and Webbink 1984). An even older nova may be 0623+71, the only known UX Ursae Majoris type variable surrounded by a faint nebular shell, but the outburst was not recorded (Bond *et al.* 1984).

In this paper we discuss observations of the remnant of Nova WY Sge 1783. The remnant was identified by Weaver (1951) and was recently found to show deep eclipses (Shara and Moffat 1983).

The evolutionary time scale for posteruptive nova cooling should be of order 100 yr (Prialnik, Shara, and Shaviv 1978). *Thus CK Vul and WY Sge, as the two oldest recovered novae, are more likely to be typical of "between outburst" objects than any nineteenth- or twentieth-century novae.*

In § II we report on the photometry of five eclipses of WY Sge, leading to an accurate determination of its orbital period. This information is combined in § III with radial velocity variations gleaned from a cross-correlation analysis of a series of spectra to place limits on the masses of the constituent WY Sge stars. A unique dwarf nova-like eruption is reported in § IV. In § V we summarize our results and the implications for very old novae.

II. ECLIPSES AND PERIOD

WY Sagittae is the fifth old nova discovered to show eclipses, and, at 19th magnitude, is the faintest cataclysmic variable with a known period: 3 hr, 41 minutes, 14 s. Table 1 lists the five observed times of minimum. The ephemeris

$$\text{JD min} = \underset{\pm 9}{2{,}445{,}137.8993} + \underset{\pm 7}{0.1536342}E$$

was calculated assigning equal weights to all five times.

Our best photoelectric eclipse observation is shown in Figure 1 (cf. Fig. 2 of Shara and Moffat 1983 for a previous minimum). The Louisiana State University 0.9 m reflector and the two-star photometer and reduction techniques described by Grauer and Bond (1981) were used to monitor WY Sge and a comparison star simultaneously. The comparison star (used to remove transparency variations and atmospheric extinction) showed variations of no more than a few percent, indicating that the night was nearly photometric. The count rate outside eclipse corresponds roughly to 18.7 blue magnitude; the observations were made with no filter and a blue-sensitive EMI 9826 photomultiplier. The sky background was measured every 10 minutes; most of the considerable noise in the data is due to background variations. All five eclipses showed rapid (~5 minutes) emersions, slightly slower immersions, and similar (~30 minutes) deep (~1.5–2 mag) eclipses.

[1] Arizona State University.
[2] Space Telescope Science Institute.
[3] Visiting Astronomer, Multiple Mirror Telescope Observatory, a joint facility of the Smithsonian Institution and the University of Arizona.
[4] Alexander von Humboldt Research Fellow 1982–1983 at the Astronomisches Institut der Universität Bonn.
[5] Université de Montréal.
[6] Steward Observatory, University of Arizona.
[7] Louisiana State University.

TABLE 1

NOVA WY SAGITTAE 1783: TIMES OF MINIMUM

JD 2,440,000.+	E	$O-C$	Method	Source
4881.639	−1668	+0.002 ± 0.003	visual flyspanking on TV guider	MMT—Shara and Moffat 1983
4882.711	−1661	−0.002 ± 0.003	visual flyspanking on TV guider	MMT—Shara and Moffat 1983
4908.524	−1493	+0.001 ± 0.002	differential photoelectric photometry	Mégantic 1.6 m—Shara and Moffat 1983
5137.8993	0	0.000 ± 0.001	visual flyspanking on TV guider	MMT—M. M. S., A. F. J. M., J. T. M., D. S. D. (present work)
5139.7429	12	0.000 ± 0.002	differential photoelectric photometry	LSU 0.9 m—H. E. B. and E. K. (present work)

Any residual doubt as to the reality of the eclipses should be removed by inspection of Figure 2, a series of pictures of the MMT TV guider showing WY Sge going into eclipse.

III. RADIAL VELOCITIES

In a previous paper (Shara and Moffat 1983), we presented the mean quiescent spectrum of WY Sge. Now that the orbital period is well established, we can analyze each of the seven individual spectra that make up this mean and look for orbital motion. Each exposure lasted ~20 minutes, which is ~9% of the orbital period, i.e., short enough to allow sufficient time resolution. The spectra cover the range 3600–6900 Å with pixel separation ~1.7 Å; the instrumental spread function has a FWHM of ~8 Å.

In Figure 3 we show a montage of the seven spectra after applying a Gaussian filter of FWHM = 10 Å and sorted according to phase. During eclipse ($\phi \sim 0.0$), the overall flux level drops noticeably, though not as much as at the bottom of the light curve (Fig. 1). This is due to the lack of sufficient time resolution dictated by the minimum required signal-to-noise ratio for the spectra. For comparison, spectra of star A (Weaver 1951), one of which is shown in Figure 3 (the remaining spectra of star A are all similar) were obtained alternately with those of WY Sge. These are based on 2-minute exposures, since star A is ~10 times brighter than WY Sge in quiescence. The spectra of star A are very useful because they show about the same noise level and have Balmer *absorption* lines of the same strength and breadth as the Balmer *emission* in WY Sge.

Relative radial velocities were obtained for the lines Hα and Hβ in the unfiltered spectra of WY Sge and star A using a method of cross-correlation. All spectra were cross-correlated with a given spectrum of each respective star (cf. Table 2). The correlation interval of each line was chosen to include as little as possible of the continuum before evaluating the correlation function. A parabola was then fitted to this function to determine the minimum, corresponding to the difference in velocity between the two lines. Other lines were too weak (He II λ4686 + C III λ4647 and the higher Balmer lines) or contaminated by interstellar absorption (Hγ). The

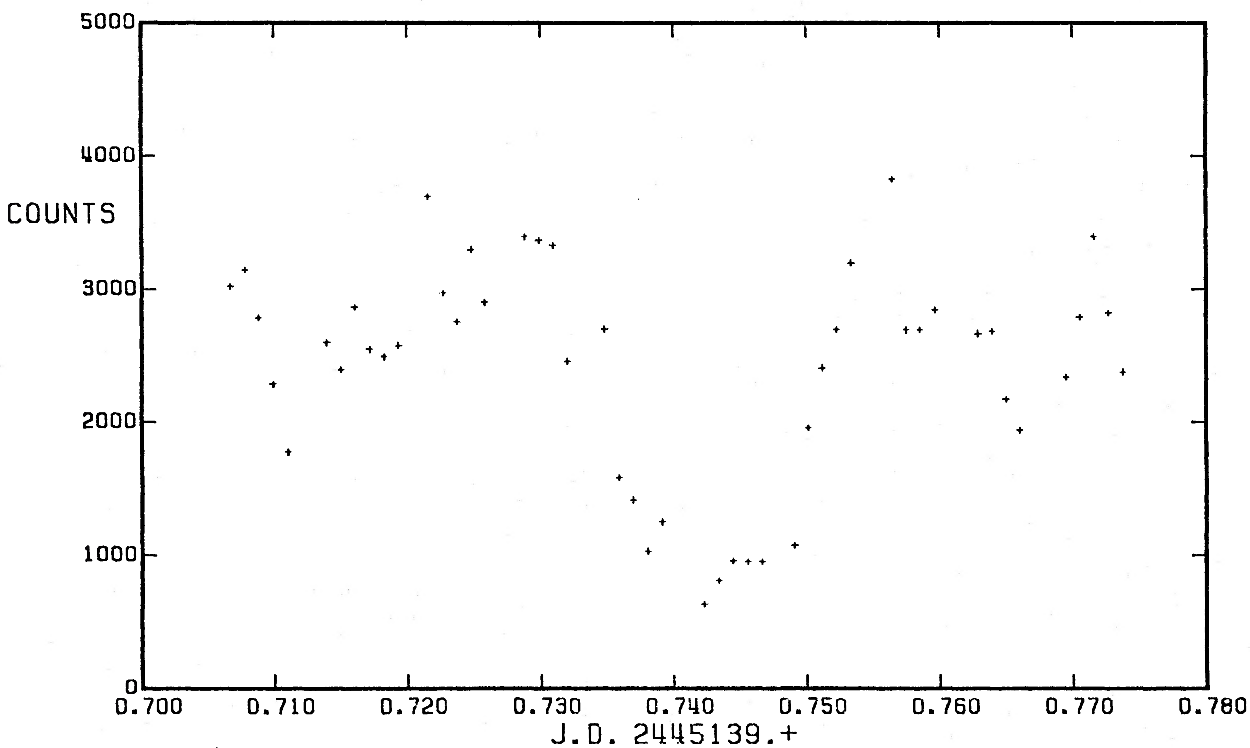

FIG. 1.—An eclipse of WY Sge observed (1982 June 19) with the LSU 0.9 m reflector and two-star photometer. Counts per 90 s integration are plotted against heliocentric Julian Date.

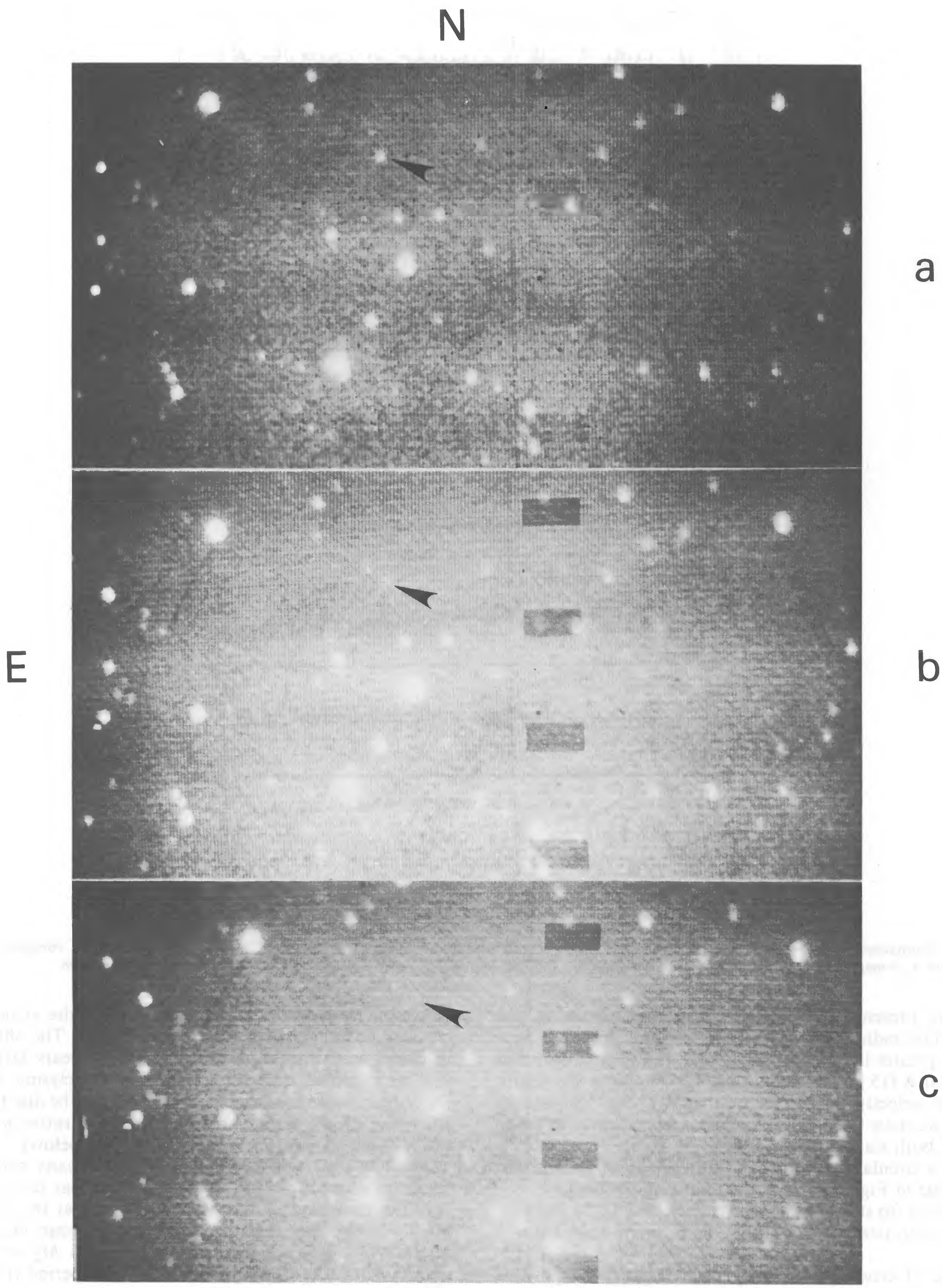

FIG. 2.—Photographs of the MMT TV guider centered on the WY Sge field: (*a*) 27 minutes before eclipse; (*b*) entering eclipse (4 minutes before full eclipse); (*c*) fully eclipsed. The three times and images refer to the same eclipse; the fully eclipsed image was taken at JD 2,445,137.899 (1982 June 17).

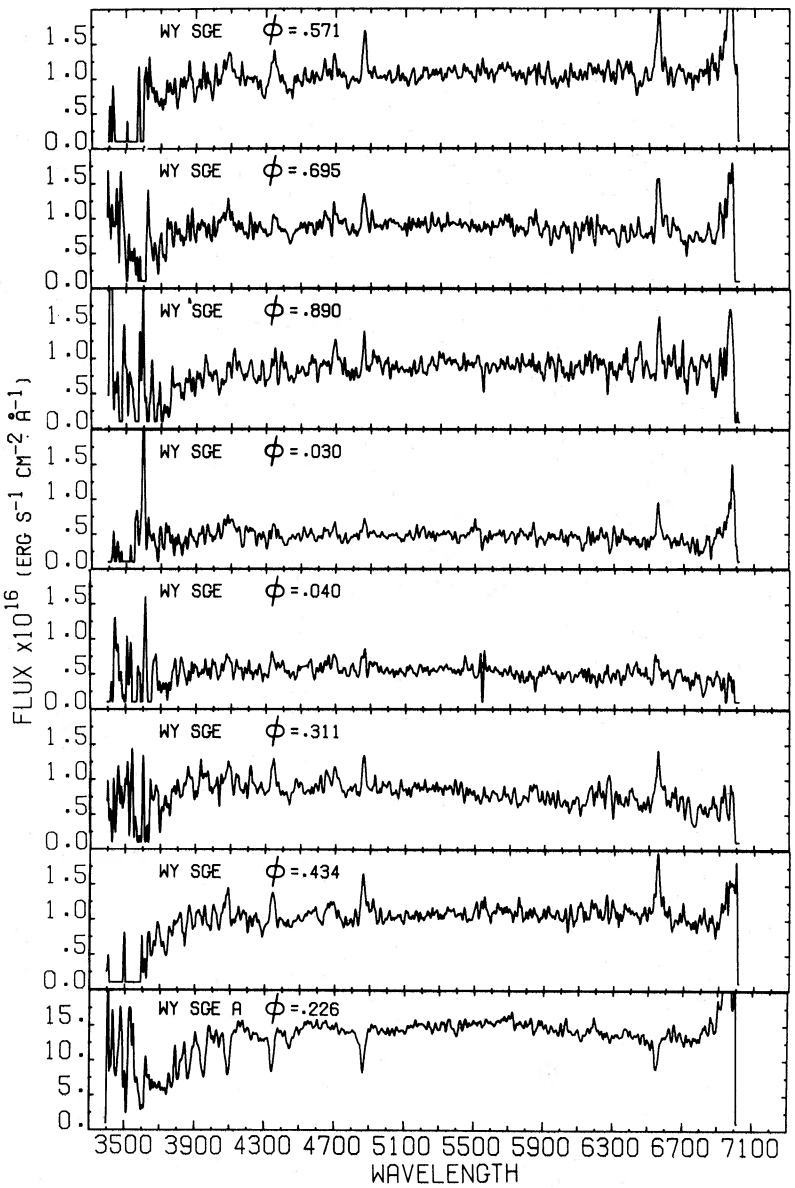

FIG. 3.—Normalized, filtered MMT spectra of WY Sge on the nights of 1981 October 4 and 5, sorted in phase. A spectrum of comparison star A (spectral class A, *B*-magnitude = 16.56) taken during the same run and reduced the same way is shown in the bottom panel for comparison.

results are presented in Table 2. The rms scatter of the emission-line radial velocities of WY Sge (52 km s^{-1}) is a factor 3.5 greater than the rms scatter of the same absorption lines in star A (15 km s^{-1}). This strongly supports the reality of orbital velocity variations in the WY Sge system. In Figure 4, we show the radial velocities as a function of WY Sge phase for both stars.

Fitting a circular orbit to the mean velocity of Hα and Hβ for WY Sge in Figure 4 yields the following parameters:

1. Relative (to star A) systemic velocity $\gamma = 28 \pm 11$ km s^{-1};
2. Emission-line velocity amplitude $K_1 = 57 \pm 15$ km s^{-1} (1 σ);
3. Time of crossing γ velocity from negative to positive E_0 = JD 2,444,882.761 $\pm$ 0.007 ($\phi = 0.33 \pm 0.05$);
4. Scatter about the fitted orbit $\sigma(O-C) = 24$ km s^{-1}.

The $(O-C)$ scatter with the orbit is similar to that obtained directly from star A and again lends support to its reality. However, we note the large phase shift of the velocity zero crossing compared with the eclipse minima. The shift, $\sim$0.3 in phase, is in the same direction but appears larger than that seen typically ($\Delta\phi \lesssim 0.15$) in other cataclysmic variables (N. Vogt, private communication). This may be due to strong streaming effects, particularly for a system of rather high mass ratio, which we suspect WY Sge to be (see below).

The low observed K_1 (compared with many cataclysmic variables where $K_1 \sim 150$ km s^{-1}) implies that the secondary is of low mass and luminosity. Assuming that the secondary fills its Roche lobe and that it obeys the mean mass-radius relation of the lower main sequence yields $M_2 = 0.44\ M_\odot$ and $R_2 = 0.42\ R_\odot$ directly from the orbital period (Paczyński 1981).

The length and shape (sharp ingress, sharp egress, and flat bottom) of the eclipses preclude inclination angles, *i*, much different from $i = 90°$. If we assume that the emission lines

TABLE 2

RADIAL VELOCITIES OF WY SAGITTAE AND COMPARISON STAR A

JD 2,444,000.+	WY Sge[a] Phase	Mean RV (km s^{-1}) Hα, Hβ
	WY Sagittae	
881.642........	0.030	+104
882.607........	0.311	0[b]
882.626........	0.434	−2
882.647........	0.571	+4
882.666........	0.695	−38
882.696........	0.890	+42
882.719........	0.040	+90
Mean		+29
σ		52
	Star A	
882.594........	0.226	0[b]
882.615........	0.363	+6
882.635........	0.493	+22
882.655........	0.623	−11
882.674........	0.747	−17
882.701........	0.923	−7
882.729........	0.105	−21
Mean		−4
σ		15

[a] Zero phase defined by JD 2,445,137.8993 + 0.1536342E.

[b] Zero velocity since this was the reference spectrum for cross-correlation analysis.

arise homogeneously from the entire disk (rather than from a hot spot in the disk), then we can associate the emission-line radial velocities with the compact object's radial velocity. Adopting $K_1 = 57 \pm 15$ km s^{-1} then yields very high primary masses ($5.0^{-1.6}_{+3.2}$ $M_\odot$), i.e., greater than the Chandrasekhar mass. The primary masses calculated above are very sensitive to the adopted K_1; a value of $K_1 \geq 115$ km s^{-1} yields $M_1 \leq 1.4\ M_\odot$. The 14 mag outburst amplitude of WY Sge (Gould 1866) is typical of white dwarf–dominated novae (Warner 1976). We conclude that (*a*) the observed K_1 is probably contaminated with Keplerian disk motion involving a hot spot, i.e., inhomogeneity, and (*b*) the modest value of K_1 might be, but is not unquestionably, indicative of a fairly massive ($\gtrsim 1\ M_\odot$) degenerate primary. We also reemphasize that our data are noisy and that the parameters given are preliminary and should be treated with caution.

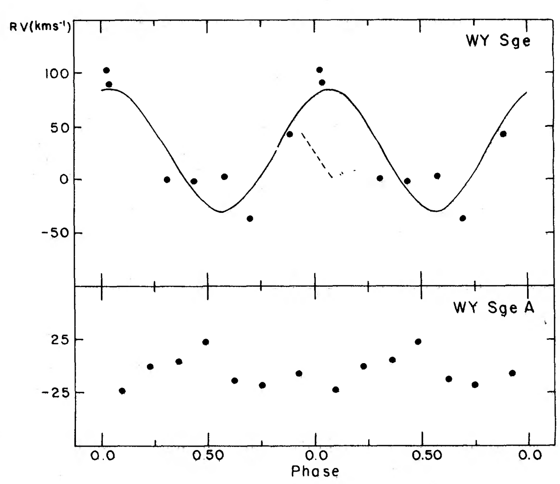

FIG. 4.—Radial velocities of (mean of the best lines, Hα and Hβ) WY Sge and comparison star A as a function of WY Sge phase using the eclipse ephemeris. The continuous curve represents the calculated circular orbit; the broken segment shows how the orbit might look with no phase shift.

IV. PHOTOMETRY

In an attempt to determine accurately the shape of the eclipse light curve of WY Sge, high-speed photometry was carried out with a single-channel photometer on the MMT during the night of 1982 June 17. The light curve shown in Figure 5 is expressed in counts s^{-1} averaged to 30 s integrations reduced to outside the atmosphere.

The maximum amplitude of variation was $\sim 50\%$, with most fluctuations at the $\sim 10\%$ level. Comparison with star A (assumed to be nonvariable) hints why this happened, and how extraordinary was the behavior of WY Sge that night. *WY Sge was ~1.6 mag brighter than its usual quiescent level.* The measured intensity ratio of WY Sge to star A was 0.222. On the next night (which was not photometric) this old nova was observed back at its previous $m_B \approx 19.3$, and an eclipse centered at JD 2,445,137.8993 was observed. The LSU observation two nights later also showed WY Sge to be at its quiescent brightness.

We are unaware of any other old nova ever showing such a rapid change in brightness. The old nova GK Per (1901) has exhibited outbursts lasting ~2 months, but taking ~1 week to brighten and several weeks to fade. V603 Her also shows oscillations at minimum (J. Mattei, private communication), but none comparable with WY Sge.

Dwarf novae brighten by 2–6 mag in 1 or 2 days, and then fade back to their former brightnesses in several days. We speculate that we may have observed WY Sge on the decline part of a dwarf-nova outburst.

Warner (1971) reported ~0.2–0.3 mag oscillations in WY Sge when the star was in quiescence at $m_B \sim 19.3$. The somewhat smaller fluctuations we observed on June 16–17 are characteristic of dwarf novae in outburst—as are the magnitude range and speed of fading from 1982 June 16–17 to June 17–18. The lack of a deep eclipse during the outburst of WY Sge is also typical of dwarf novae. An expected eclipse (centered 3720 s after the start of observations in Fig. 5) is not seen, though the star dimmed by $\sim 50\%$ a few minutes before the expected start of eclipse. WY Sge is within photometric range of 1 m telescopes, and as a potential link between classical and dwarf novae richly deserves to be monitored for further outbursts.

V. SUMMARY

Our findings may be summarized as follows. WY Sge, the remnant of one of the oldest known classical novae, has been found to be an eclipsing binary with a period of 3 hr 41 minutes 14 s. The low radial velocity amplitude observed for emission lines originating near the primary star possibly indicates that the primary is a rather massive ($>1\ M_\odot$) degenerate object. On one night we observed WY Sge to be 1.6 mag brighter than normal, indicating that it may have undergone a dwarf nova–like outburst. One and three nights later, WY Sge was observed to be back at its quiescent brightness.

Our spectra of WY Sge show that it has fairly strong emission lines, in contrast to the majority of classical novae at minimum light, which have weak emission lines (H. E. B.,

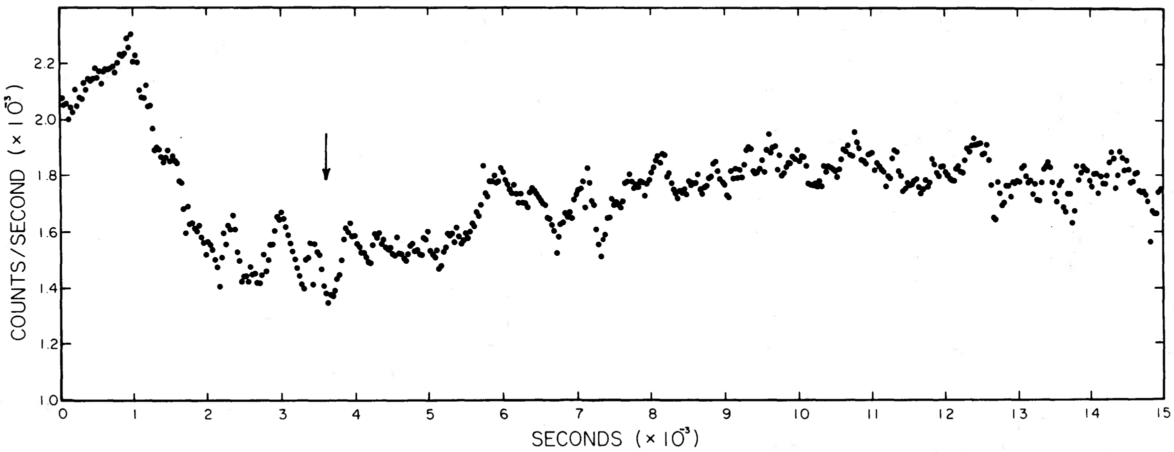

FIG. 5.—High-speed photometry of WY Sge carried out with the MMT on 1982 June 16–17. The old nova is about 4 times brighter than normal and flickering with roughly half its usual amplitude. An expected eclipse centered 3720 s after the start of observations (see arrow in figure) is not seen.

unpublished observations). Thus WY Sge spectroscopically resembles dwarf novae more than typical classical novae, in agreement with our observation of a possible dwarf-nova outburst.

Two interpretations of our observations seem to be possible in regard to the question of the appearance of classical novae long after their outbursts. If WY Sge is typical of most novae, it suggests that the mass-transfer rate gradually subsides a few hundred years after outburst, so that very old novae will resemble dwarf novae in their spectroscopic appearance and light-curve behavior. Alternatively, WY Sge may simply be an object intermediate in behavior between classical and dwarf novae (i.e., intermediate in mass-transfer rate from the secondary star), and not typical of most classical novae; according to this view, all cataclysmic variables undergo classical-nova outbursts, but the interval between outbursts is inversely proportional to the mass-transfer rate so that the discovery probability for novae like WY Sge is relatively low.

Only additional discoveries and studies of very old novae can tell us which of these possibilities is more likely.

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H. E. BOND: Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803

D. S. DEARBORN and J. T. MCGRAW: Steward Observatory, University of Arizona, Tucson, AZ 85721

E. KEMPER and M. M. SHARA: Space Telescope Science Institute, Homewood Campus, Baltimore, MD 21218

R. LAMONTAGNE and A. F. J. MOFFAT: Dept. de Physique, Université de Montréal, CP 6128, Succ. A, Montreal, P.Q. H3C 3J7, Canada