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RAPID OSCILLATIONS IN CATACLYSMIC VARIABLES. VIII. YY DRACONIS (=3A 1148 + 719)

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ABSTRACT

We have found a 16th magnitude cataclysmic variable, presumably a dwarf nova, near one of the positions permitted for the hard (2–10 keV) X-ray source 3A 1148 + 719. The location is also coincident with the reported position of the variable star YY Draconis, cataloged as an "Algol-type" variable. Since no Algol-type system can now be found in the vicinity, it is extremely likely that the published classification of YY Dra is incorrect and that the cataloged variable *is* the cataclysmic binary. A serendipitous *Einstein* observation of the star revealed a fairly strong hard X-ray source, making it nearly certain that this is the correct identification of 3A 1148 + 719.

The optical and ultraviolet spectra of YY Dra are fairly typical of cataclysmic variables, except that the TiO absorption bands of an M dwarf can be seen for $\lambda > 5000$ Å. This shows that the accretion disk is intrinsically quite faint in quiescence, suggesting a very low accretion rate. Yet the fairly blue continuum slope in the vacuum ultraviolet indicates the presence of a small hot object, presumably the white dwarf. The radial velocities at Hα indicate a 4.0 hr orbital period, and the infrared light curve appears to show the expected "double-humped" waveform from the distorted secondary.

High-speed photometry in the *U* band reveals a stable periodicity of ~1% semiamplitude at a period of 275 s, with some power also in the subharmonic at ~550 s. This identifies the star as a member of the "DQ Herculis" class of cataclysmic binary, in which accretion occurs onto a rapidly rotating, magnetized white dwarf. However, the photometric period in blue light, at a time when the star was slightly fainter, was observed to be 266 s, an orbital sideband of the 275 s period. The most likely interpretation is that the shorter period is the true sidereal rotation period, while the synodic period of 275 s appears prominently in the *U* band due to the contribution of emission lines and the Balmer continuum.

Subject headings: novae, cataclysmic variables — stars: individual (YY Dra) — stars: oscillations — white dwarfs — X-rays: stars

1. INTRODUCTION

Cataclysmic variables (CVs; see Robinson 1976 for a general review) are close binary stars in which a low-mass, late-type secondary fills its Roche lobe and transfers matter to a white dwarf primary. Because the gravitational potential well of a white dwarf is very deep (~100 keV nucleon^{-1}), it has long been realized that accretion of gas onto a white dwarf could lead to intense emission of hard (>1 keV) X-rays (Hoshi 1973; Fabian, Pringle, & Rees 1976; Pringle & Savonije 1979; Kylafis & Lamb 1982; Tylenda 1981). But optical identifications of "strong" X-ray sources (i.e., detected by the typical scanning and nonimaging telescopes of the 1970s) revealed very few CVs, nearly all with fluxes near the threshold for detection. The launch of the *Einstein Observatory* in 1978 permitted much more sensitive searches, and the results (Cordova, Mason, & Nelson 1981; Cordova & Mason 1983; Patterson & Raymond 1985) demonstrate that X-ray emission is indeed a general property of CVs, but usually at only a small fraction of the bolometric accretion luminosity.

The most efficient X-ray emitters are expected, and found, to be the radially accreting white dwarfs. Radial accretion is enforced on the infalling gas when the magnetic field is sufficiently strong to channel the flow onto the magnetic poles. If the field dominates the flow everywhere in the binary, then the white dwarf rotation is phase-locked to the orbit; these are the AM Herculis stars. But if the field is a little weaker, or the energy density in the accreting gas a little higher, then the field may only dominate near the white dwarf, in which case the star can spin up under the action of accretion torques; these are the DQ Herculis stars. About 15 members of each class are known (see Cropper 1986, Mukai 1988, and Berriman 1988 for reviews).

In 1982 we identified a 16th magnitude CV, previously cataloged as YY Draconis, as the counterpart of the hard X-ray source 3A 1148 + 719 (Patterson et al. 1982). Because this star has the highest F_X/F_V of any known CV, we suspected that it might be a DQ Her star, and have been studying it fitfully for the last decade. Here we report the results of that study. It is remarkable in showing four distinct components in the spectrum: the secondary star, an M4 dwarf; the light of a relatively cool accretion disk; a hot (>30,000 K) component probably associated with the white dwarf; and a 10^8 K component emitting X-rays. After much confusion, we believe we have found the consistent thread which describes the periodicity content of the optical light curves. In *U* light the star displays a stable 275 s period, with some power also in the subharmonic, indi-

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cating that the fundamental period is 550 s. In blue light the star shows a 266 s period, which is the high-frequency orbital sideband of the 275 s period. These data establish YY Dra as a member of the DQ Her class, although it is still not obvious which of these is the true rotation period of the white dwarf.

2. YY DRACONIS, LOST AND FOUND

2.1. *Positional Data*

In 1977 October/November and 1978 April/May, the *HEAO 1* spacecraft scanned the region of the sky near the *Ariel 5* X-ray source 3A 1148 + 719 (McHardy et al. 1981). A source was detected at the 3 σ level by the A-3 Scanning Modulation Collimator experiment (see Gursky et al. 1978 for a description of the experiment), which constrained the source to lie within one of ~ 10 diamond-shaped error regions ($30'' \times 240''$), consistent with the large *Ariel 5* error box. During a pointed observation on 1978 April 14, the source was detected again by the MC2 collimator of the A-3 experiment, at a 5.5 σ level; this constrained the source to lie within one of several lines of position, which intersected with several of the diamonds.

Inspection of a plate taken in 1982 January on the Burrell Schmidt at Kitt Peak National Observatory revealed very blue colors ($U - B < -0.6$) for a faint star in one of the lines of position, lying close to one of the diamonds. The precise position of the star is $\alpha_{1950} = 11^h40^m48\overset{s}{.}83$, $\delta_{1950} = 71° \; 57' \; 58\overset{''}{.}7$ ($\pm 1\overset{''}{.}5$). We later found that this star had also been identified in the Palomar-Green survey for UV-bright stars, and labeled PG 1140 + 72 (Green et al. 1982). The star is 19″ west and 50″ south of the cataloged position of YY Draconis (Zessewitsch 1934), which is classified as an Algol-type eclipsing binary varying from $B = 12.9$ to > 14.5 with a period of 4.21123 days (Kukarkin et al. 1969; Kholopov et al. 1987). In Figure 1 we show the various positional constraints set by the X-ray data, together with the UV-bright star (which we have labeled YY Dra, anticipating the discussion in § 2.4).

2.2. *Optical Spectroscopy*

To identify the nature of the blue star, we obtained spectra with several instruments in 1982 and 1983. In Figure 2 we show the spectrum obtained on 1982 January 31 with the Mark II scanner (Shectman & Hiltner 1976) on the 1.3 m telescope of McGraw-Hill Observatory. It shows bright, broad H emission lines; weak, broad emission lines of He I, He II, Fe II, and Ca II; and the TiO absorption bands of an M star. The strength (equivalent width of H$\beta \sim 90$ Å) and breadth (FWHM ~ 15 Å, after correcting for instrumental resolution)

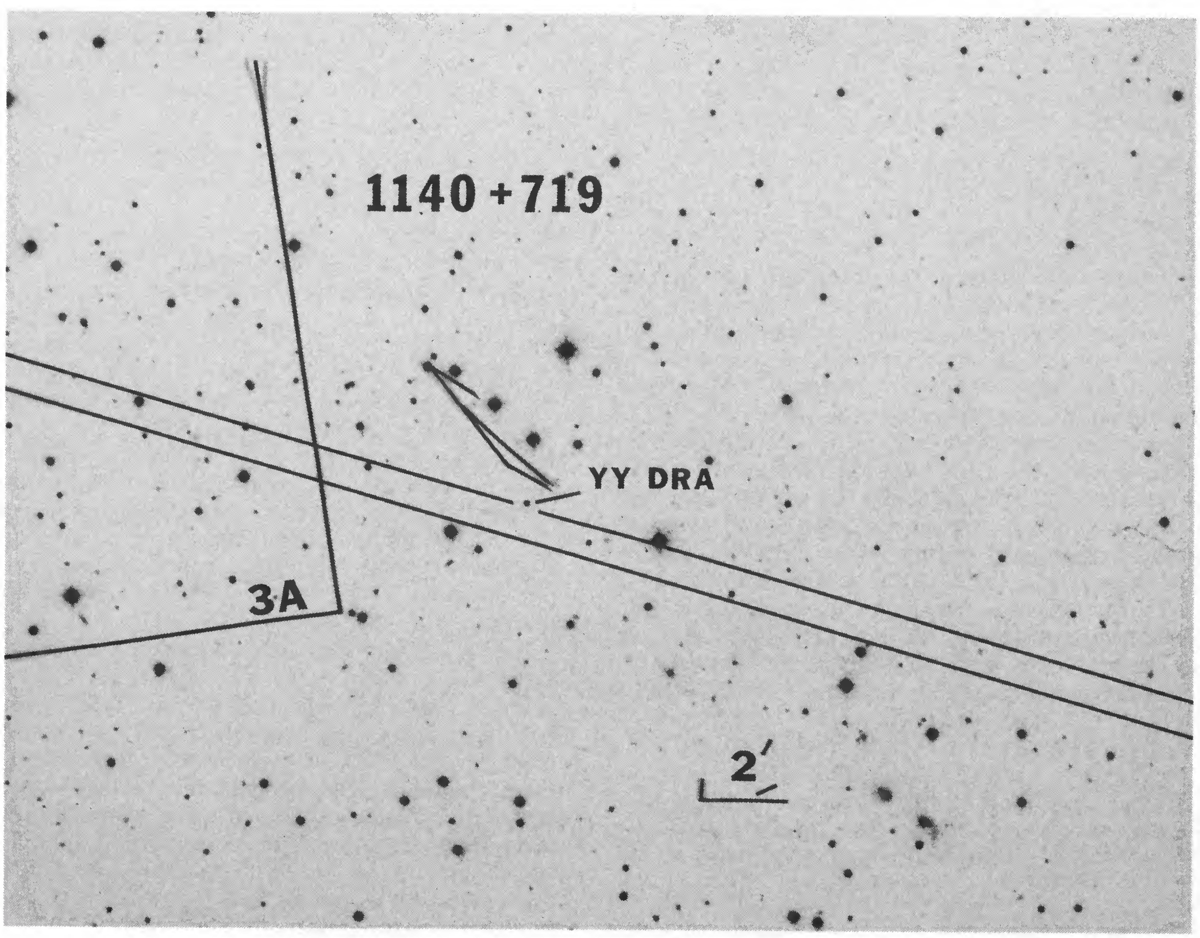

FIG. 1.—Position constraints set by the X-ray observations. North is up, and west is to the right. The "3A" box shows the *Ariel 5* detection, the diamond shows one of the positions permitted by the *HEAO* A-3 scanning observations, and the long strip shows one of the regions permitted by the pointed observation. The star indicated as YY Dra is the proposed counterpart. The bright star 5′ to the north-northwest is BD +72° 544.

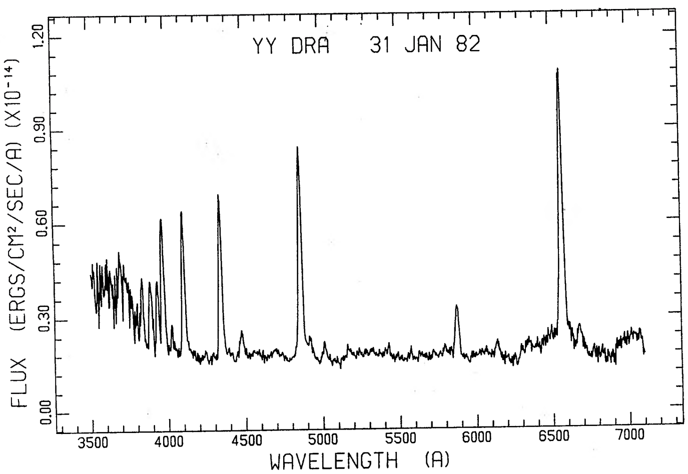

FIG. 2.—Three hr spectrum of YY Dra in quiescence. Emission lines of H, He I, Ca II, and Fe II are present. At long wavelengths, several broad TiO absorptions are also evident.

of the emission lines are fairly typical of the spectra seen in the low-$\dot{M}$ accretion disks of cataclysmic variables (Williams 1983; Patterson 1984). However, the simultaneous presence of Ca II emission, signifying gas at ~5000 K, and He II emission, suggestive of much higher temperatures, is unusual and noteworthy.

Higher resolution spectra were obtained near Hα with the Mark II scanner on 1982 February 1 to look for radial velocity variations. The spectra were reduced and analyzed by the methods discussed by Williams (1983). The radial velocity of Hα, based on this and the previous night, showed a significant variation at $P = 3.98 \pm 0.04$ hr as illustrated in Figure 3. This is consistent with the period of 3.96 ± 0.01 hr deduced by Mateo, Szkody, & Garnavich (1991) from the Na I and Ca II lines. The semiamplitude was $K = 111 \pm 10$ km s^{-1}.

2.3. *Infrared Photometry*

Because the M star dominates the spectrum beyond 6000 Å, it seemed likely that we could observe the Roche deformation of the secondary with a sufficiently long infrared light curve. On 1986 February 26 we obtained a long time series through an H filter, using the infrared photometer HERMAN on the

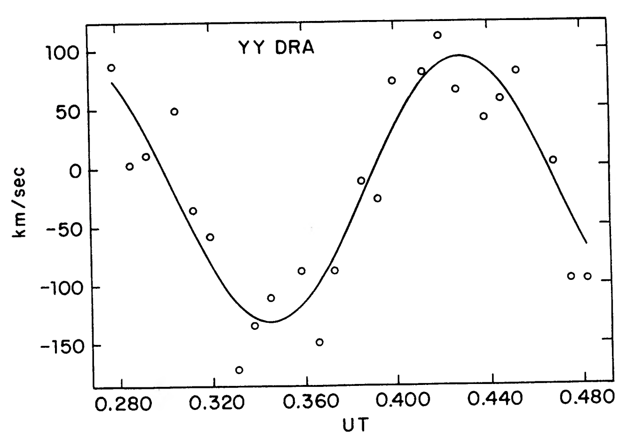

FIG. 3.—Radial velocities of the Hα emission line on 1982 February 1. The smooth curve shows a sinusoidal modulation with $K = 111$ km s^{-1}, $\gamma = -19$ km s^{-1}, and $P = 0.1658$ days.

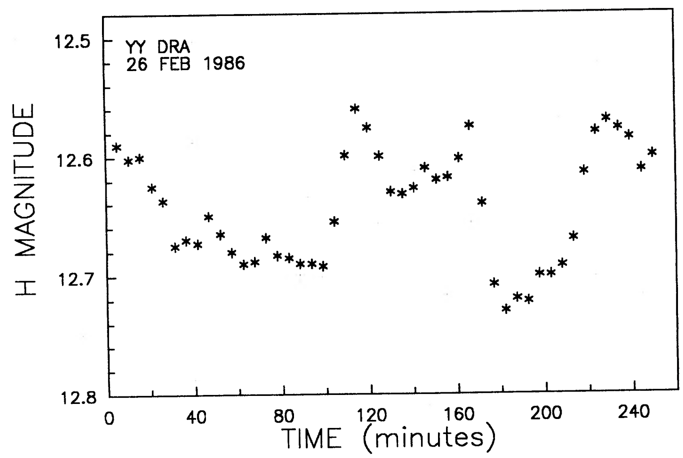

FIG. 4.—H-band light curve, showing a possible "double-humped" light variation with a full amplitude of ~0.12 mag. Each point has an uncertainty of 0.02 mag.

KPNO 1.3 m telescope. The result is shown in Figure 4. The original integration time was 45 s, but with summing of six successive integrations, plus occasional checks of a comparison star, the average time resolution of the data as displayed is ~5.2 minutes. Also, the data have been smoothed lightly with a three-point running mean filter.

The Roche geometry should produce essentially a sinusoid with $P = 0.5\ P_{orb}$, and a full peak-to-trough amplitude of 0.10–0.25 mag. While Figure 4 is inconclusive (largely because of contamination by flickering accretion light), it is at least roughly consistent with expectation. If the observed wave is due to Roche deformation, it implies an orbital period of 4.05 ± 0.04 hr.

The 8200 Å continuum light curve in Figure 2 of Mateo et al. (1991) also shows a "double-humped" variation. The discrepancy between our amplitude and theirs (0.26 mag) could be due to variable contamination by accretion light.

2.4. *Is This the Cataloged Variable Star, the X-Ray Source, Both, or Neither?*

The true position of the cataloged variable star cannot be checked, since no finding chart was published. But our examination of over 500 archival photographic plates in the Harvard collection reveals no variable star in the field (out to ~30′) other than the CV, which agrees with Wenzel's (1983a, b) survey of 700 plates in the Sonneborg collection. We can envision only two solutions to this problem: either the reported position of YY Dra is *grossly* in error, and the star is now *lost*, or the position is in error by 53″, and YY Dra is identical to the cataclysmic variable PG 1140 + 72. We strongly favor the second hypothesis, for the following reasons:

1. The positions are really in agreement; the typical accuracy of positions: in the General Catalogue of Variable Stars is only ~1′.
2. It is very unlikely that an erroneous position would *accidentally* fall within 1′ of a true variable star. At this Galactic latitude, the density of variable stars is only 0.03 deg^{-2}, implying an a priori probability of 10^{-5} for a chance superposition.
3. A 13th magnitude Algol binary at high Galactic latitude is intrinsically somewhat suspicious. The least luminous subgiants known have $M_V = +3.1$, and the alleged eclipse depth then requires the primary to have $M_V < +1.5$. This places the

star well out in the Galactic halo, at a distance greater than 1.3 kpc above the Galactic plane. Halo binaries of any kind appear to be quite rare (Batten 1973), except possibly in clusters where capture processes are likely.

4. It is not difficult to imagine how a sparse set of photographic magnitudes, for a star never observed before or since, might have produced a spurious period and classification. There are hundreds of precedents.

To our surprise, a new name was assigned to the cataclysmic variable (DO Dra; Kholopov et al. 1987). In our opinion, this was altogether misguided, based on the assumption that the original observer could not have mistaken an Algol light curve (usually at maximum) for a normal dwarf nova (usually at minimum, although many exceptions are known). But since the "discovery" consists of one line in a paper, it seems fair to guess that the observational data were sparse; and if they were obtained near a dwarf nova eruption, one would conclude that the star was usually bright. In addition, we have searched through the third GCVS to find other examples of stars at high Galactic latitude classified as "EA"; in the entire north polar cap ($b > 40°$), there are only five such stars, and *three of them are known cataclysmic variables.* We are certainly not alleging that PG 1140 + 72 used to be eclipsing but are rather citing this to support two contentions: (*a*) that stars properly classified as "EA" (essentially Algols, given the eclipse depth this star is alleged to have) are indeed very rare at high Galactic latitude, and (*b*) that the term "EA" did not in 1934 have the very specific meaning we would assign it today, when we emphatically differentiate these stars from CVs.

We conclude that it is overwhelmingly likely that PG 1140 + 72 is identical with YY Dra; and following long-established tradition, we shall use the originally assigned name. Variable stars are commonly re*classified*, but that does not warrant re*naming* them. We will eat our collective hat if the purported "lost Algol binary" ever shows up.

An independent question is: Is the star the X-ray source? Cataclysmic variables are unusual stars, and are a well-known class of hard X-ray source; but in this case the X-ray error boxes are relatively large, which weakens the evidence. However, we were fortunate to find an *Einstein Observatory* IPC field which accidentally included the position of YY Dra at its edge. A rather strong and hard source was found to coincide with YY Dra within the 60″ uncertainty of the IPC position. The observed 0.2–4.0 keV flux was 1.0×10^{-11} ergs cm^{-2} s^{-1}, and the pulse-height data could be fitted by a thermal bremsstrahlung spectrum with $kT_{\rm brems} > 5$ keV.

These properties are in reasonable agreement with those of 3A 1148 + 719, for which the *Ariel 5* catalog reports an average 2–10 keV flux of 4.5×10^{-11} ergs $cm^{-2} s^{-1}$ (McHardy et al. 1981). Unless the spectrum is heavily absorbed (say $N_{\rm H} > 10^{22}$ cm^{-2}), we would normally expect an IPC flux about a factor of 3 greater than observed. But this discrepancy is similar to that shown by cataclysmic variables as a class (see Fig. 6 of Patterson & Raymond 1985), and in any event the IPC observation is only a brief "snapshot," not a long-term average. We conclude that YY Dra is the optical counterpart of 3A 1148 + 719 (=2A 1150 + 72).

It is likely that some contribution to the *Ariel 5* flux is made by another nearby object, because the 3A catalog contains the comment "probably >1 source," and because the A-3 diamonds missed YY Dra by a significant amount. Nevertheless, the IPC and the *HEAO 1 pointed* observations establish fairly clearly that most of the *Ariel 5* flux comes from YY Dra.

3. THE HISTORICAL LIGHT CURVE

From our scattered optical coverage during 1982–1991, we see the star varying in the range $B = 15.6$–16.7. But short-lived outbursts, rising as bright as $B = 10.6$, have been reported by Wenzel (1983a), Hazen (1985), and McNaught (1986). This type of "bimodal" light curve suggests that the star is a dwarf nova, with an outburst period probably in the range 3–10 yr.

4. THE ULTRAVIOLET SPECTRUM

A short-wavelength *IUE* spectrum of YY Dra was obtained on 1982 July 5 (see Boggess et al. 1978 for details of the instrument). This 6 hr exposure, obtained when the star was at quiescence, is shown in Figure 5. We have assumed no interstellar reddening, and have used the 1980 May flux calibration

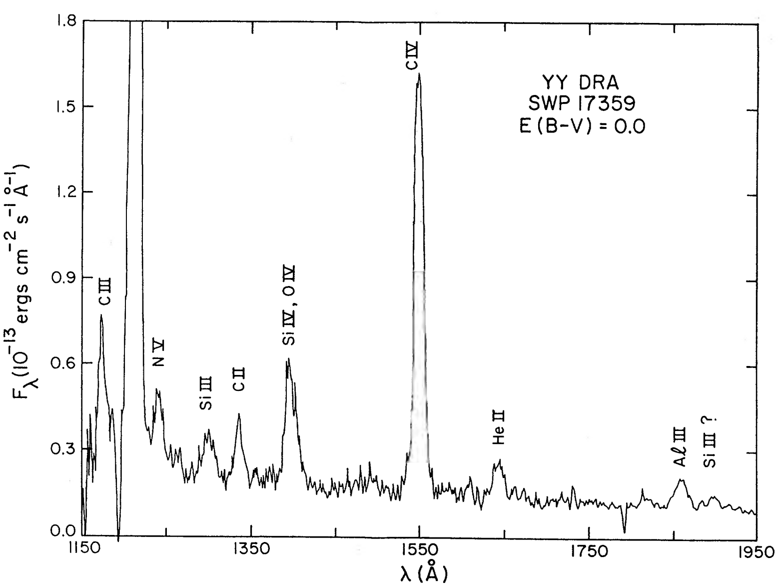

FIG. 5.—Short-wavelength ultraviolet spectrum, with no correction for interstellar reddening. The dips at 1190 and 1790 Å are due to reseau marks in the spectrum, and the C IV λ1549 line is saturated.

TABLE 1

FLUXES OF ULTRAVIOLET EMISSION LINES

Line	Flux (10^{-13} ergs cm^{-2} s^{-1})
N V λ1239	2.9
Si III λ1300	2.4
Si IV λ1400, O IV λ1400	6.6
C IV λ1549	29
He II λ1640	1.3
Al III λ1855	1.65

(Bohlin et al. 1980). The spectrum reveals bright emission lines and a fairly blue continuum flux distribution (approximately $F_\lambda \propto \lambda^{-2}$). In Table 1 we list the fluxes of the strong emission lines.

5. THE FLUX DISTRIBUTION AND ACCRETION RATE

In Figure 6 we show the composite flux distribution of YY Dra in quiescence, from 0.1 to 2.2 μm. The *JHK* magnitudes are taken from Szkody (1987), and the *UBVRI* magnitudes are taken from our 1991 January data. X-ray fluxes were reported by Patterson & Raymond (1985). The points represent the measured fluxes, and the curves represent a possible decomposition of the spectrum. We fit the infrared spectrum by assuming that 80% of the *K* light comes from the secondary, and requiring a flux distribution like that of a dM4 ± 1 star (Mateo et al. 1991; Friend et al. 1988).

It is not obvious how to fit the UV/optical flux. The slope agrees with what would be expected from an optically thick disk, but the object is much too faint, since it only barely outshines the M dwarf in *V* light. For the earliest allowable spectral type (M3, with $M_V = 11.0$ on the Boeshaar 1976 system) and our estimated largest allowable fractional contribution of the blue component to the total *V* light (0.75), we can set a bound to the visual brightness of the blue component, namely, $M_V > 9.9$. For a hot optically thick disk (sufficient to give the observed steep slope in the UV), this would require $R_{\rm disk} < 10^9$ cm. This is much too small to be the disk; could it

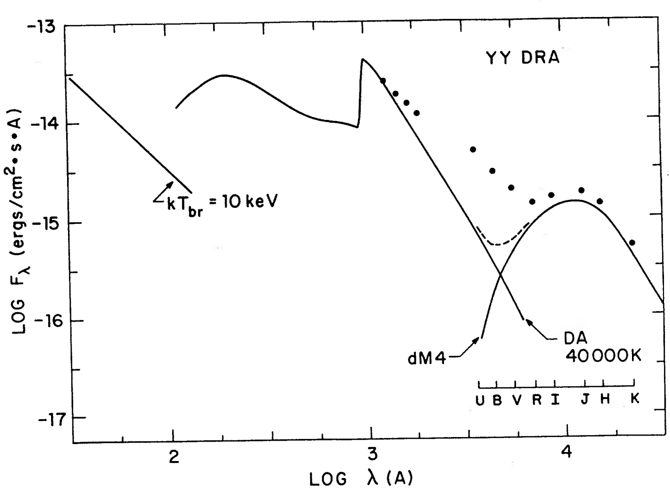

FIG. 6.—Continuum flux distribution of YY Dra. The deconvolution is determined by requiring 80% of the *K* flux to originate from the dM4 star, and all the continuum flux at 1250 Å to originate from a 40,000 K DA white dwarf. The dashed curve shows the sum of these two components in the region where they are comparable.

be a moderately hot ($T \sim 20{,}000$ K) white dwarf? It is possible, but we regard it as unlikely, for the following reasons:

1. This eliminates any need for accretion-powered continuum light in the optical. Yet the radial velocity curves of Mateo et al. (1991) show that the optical emission lines, including the broad Ca II lines which must certainly originate in cool gas, move in antiphase to the lines of the secondary. If the optical continuum light arises strictly from red dwarf + white dwarf, then the disk must radiate a pure emission-line spectrum, for which there is no precedent in CVs.
2. A 20,000 K white dwarf should show strong Lyman-α absorption, which is not seen.
3. The existence of a Balmer jump in emission indicates that the near-UV light does not come from anything like a normal white dwarf photosphere—and strongly suggests that the emitting gas is optically thin.

A much better solution, in our opinion, is to credit the UV continuum primarily to a small, hot source, with a temperature sufficient for hiding Lyman-α absorption (we estimate $T > 30{,}000$ K, given the various emission lines and reseaux which lurk in the vicinity), and to invoke a "disk" component (cooler, larger, and optically thin) to dominate the optical flux. This is the spirit behind the decomposition shown in Figure 6. For illustration we show the flux distribution of a 40,000 K DA white dwarf (Wesemael et al. 1980), forced to pass through the continuum flux point at 1250 Å. The dashed curve shows the net flux of white dwarf + red dwarf in the region where they are comparable in light.

Of course, this decomposition is far from precise. Uncertainties in the contribution to the *V* band arise from (1) nonsimultaneity among the observations; (2) the uncertain spectral type of the secondary; and (3) the uncertain slope of the "UV component." Nevertheless, we regard it as very doubtful that these uncertainties could combine to eliminate the need for a separate optical component, for the reason cited above: that it would require attributing a pure emission-line spectrum to the disk.

We can integrate under these four components to find the contributions to the total flux. In units of 10^{-11} ergs cm^{-2} s^{-1}, the fluxes are 4.5 in hard X-rays, 3.4 in the hot white dwarf, 1.4 in the optical continuum source ("disk"), and 2.2 in the M dwarf.

The "hot white dwarf" does not necessarily shine from its own reservoir of internal energy. In fact, an accretion origin for this light seems rather likely. At a distance of 155 pc (Mateo et al. 1991), the deduced luminosity from this component is 9×10^{31} ergs s^{-1}, which at 40,000 K corresponds to a radiating area of 5×10^{17} cm^2, about a factor of 10 smaller than the surface area of a 0.7 $M_\odot$ white dwarf. We obtain this result by using essentially the minimum allowed temperature, and attributing all of the observed UV flux to the white dwarf. If the temperature is higher and/or less of the flux comes from the white dwarf, then the discrepancy is even bigger. We conclude that the UV continuum light probably comes from a hot region on the white dwarf. This could be, for example, an equatorial belt or a heated polar cap.

At 155 pc, the total accretion luminosity is 3×10^{32} ergs s^{-1}, which, for steady accretion onto a 0.7 $M_\odot$ white dwarf, implies an accretion rate of $\sim 4 \times 10^{-11}$ $M_\odot$ yr^{-1}, or somewhat higher if the "white dwarf" component is significantly hotter than the 40,000 K we have assumed.

Among known CVs, YY Dra shows the highest ratio of

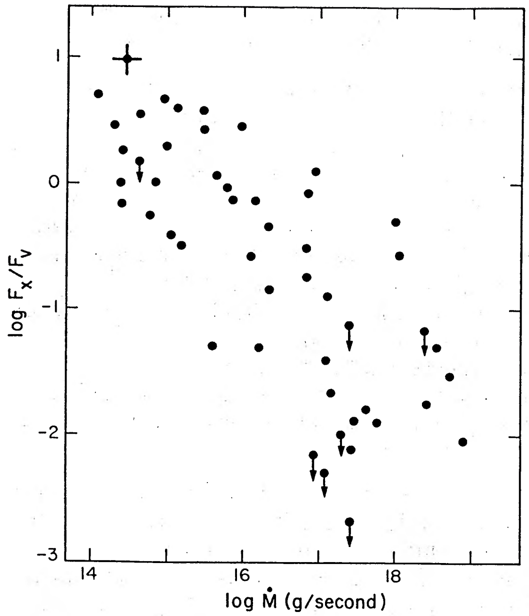

FIG. 7.—Correlation of F_X(0.2–4.0 keV)/F_V(5000–6000 Å) with $\dot{M}$, for all the cataclysmic variables observed by the *Einstein* IPC (from Patterson & Raymond 1985). The plus sign denotes the location of YY Dra.

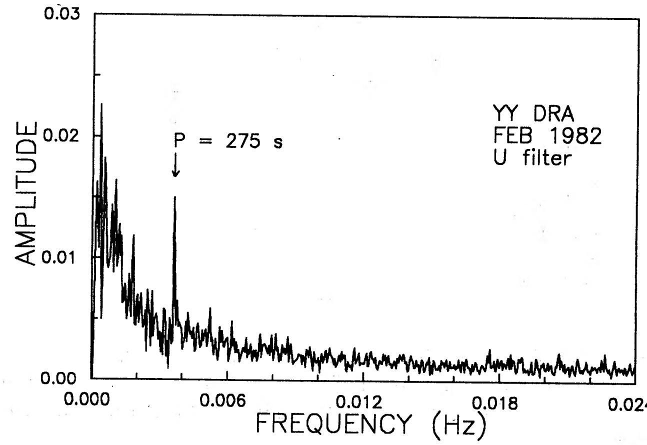

FIG. 8.—Average amplitude spectrum in the *U* light curves of 1982 February. An obvious spike occurs at $P = 275 \pm 1$ s, and a very likely signal at the "subharmonic" period of 549 ± 3 s.

X-ray to optical luminosity. Adopting the "bolometric" estimates given above, we have $F_{hx}/F_{disk} = 3$; or, if we use the well-observed 5000–6000 Å and 0.2–4.0 keV bandpasses, we find $F_X/F_V = 10$. Figure 7 shows that among all CVs observed with the *Einstein* IPC, YY Dra is the champ in the F_X/F_V competition.

The strong hard X-ray emission suggested the possibility of radial accretion onto the white dwarf. We therefore began a photometric search for short-period oscillations, which would be indicative of the rotation period of a magnetic white dwarf.

6. HIGH-SPEED PHOTOMETRY IN 1982–1983

6.1. *Light Curves*

Time-resolved photometric observations were made on four nights in 1982–1983, using an RCA C31034a photomultiplier tube in the automated filter photometer with the 0.9 m telescopes of Kitt Peak National Observatory. A focal-plane aperture of 14″ diameter was used. Good-quality light curves were obtained on 1982 February 20 and 1983 March 16. The observations of 1982 February 18 and 19 were somewhat contaminated by light clouds.

The light curves are fairly typical of CVs in showing irregular flickering on time scales of ~5–30 minutes. There is no sign of an orbital variation exceeding ~0.2 mag.

6.2. *Spectral Analysis*

Amplitude spectra were calculated for each light curve, using a fast Fourier transform algorithm. On each of the 1982 observations, a spike occurs at $\nu = 0.00364$ Hz, consistent with a signal that maintains constant phase through each night. The semiamplitude was ~0.02 mag on February 18 and 20, and appeared to decline to 0.008 mag on February 19. In Figure 8 we show the average amplitude spectrum during these three nights.

This spectrum reveals an additional bump of ~3 σ significance at a period of 550 ± 3 s. Such weak features in erratic variable stars are normally of no consequence (even though "statistically significant"), but this appears at a period consistent with exactly twice that of the primary signal. It is hard to state the formal likelihood of such an accident, since it requires adopting a specific fit to the rising continuum in the low-frequency part of the amplitude spectrum, but we estimate it is probably in the range 0.3%–1.0%. Thus we have moderately high confidence (but not certainty) that the true period of the oscillation is 550 s, with most of the power at the first harmonic.

Using primarily the first harmonic, we attempted to refine our knowledge of the period as follows. The weighted average of the three individual nights yields $P = 274.6 \pm 1.0$ s. A discrete Fourier transform of all the data yielded three candidate periods: 275.8, 274.9, and 274.0 (± 0.1) s. The same procedure was carried out for the fundamental period, with the results 552.56, 549.00, and 547.25 (± 0.24) s. *If we require that the periods be in exactly a 2:1 ratio*, then *all* of the candidate periods are disqualified.

A slightly different constraint on the period can be obtained by examining the synchronously summed light curve on each night. Figure 9 shows the synchronous summation, relative to an assumed period of 549.72 s. The waveform is not very stable. In particular, the strong detections on February 18 and 20 yield timings of "primary minima" which are ~180° out of phase with each other. If the timings of primary minima are taken as fiducial marks, then the fundamental period is found to be 548.75, 550.56, or 552.39 s. Again, none of these periods is found to be exactly twice that of the higher frequency signal.

Since the 275 s period is the stronger signal, and since the three nights of data are consistent with a stable phase in this period, we conclude that a stable period is probably present. The "subharmonic" at $P = 550$ s (which we have called the "fundamental" in preview of the interpretation we shall give it in § 7) *is not stable in phase over the three nights of observation.*

The amplitude spectrum of the 1983 March light curve, obtained in blue light, shows only the random noise associated with a flickering source. The amplitude upper limit to a 275 s signal is 0.004 mag. A weak bump is present at $P = 266$ s, but would certainly have been too weak to believe, were it not for the 1990 January observations reported below.

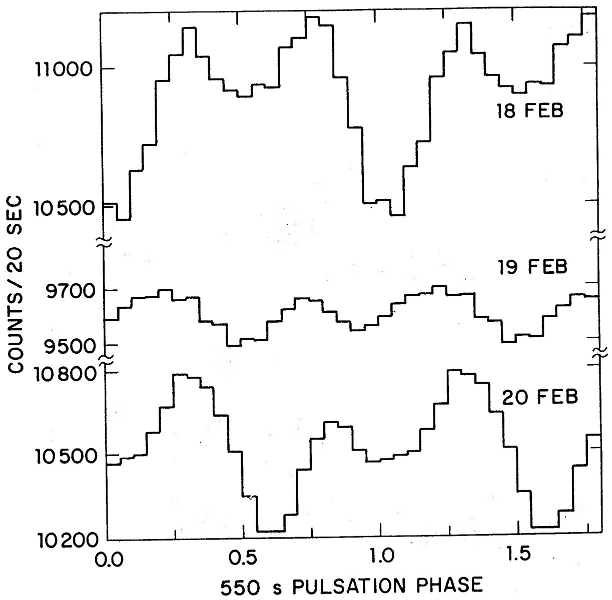

FIG. 9.—The 1982 light curves synchronously summed with $P = 549.72$ s. The lack of stability in the waveform indicates either that the "primary minimum" is a drifting feature or that the folding period is incorrect.

7. SUBSEQUENT PHOTOMETRY

7.1. *Confirmation of a Stable Period*

The disappearance of the oscillation in 1983 led us to doubt our original detection, and when a sensitive 1988 observation again failed to reveal the signal, we suspected the possibility of a telescope drive error (since all the detections occurred on the KPNO No. 1 0.9 m telescope, and all the nondetections occurred on the No. 2 0.9 m). In 1990 and 1991 we searched again for the signal on the No. 2 0.9 m. The complete observing log is given in Tables 2 and 3.

The decisive confirming observations were made in 1990 May and 1991 January, when we again observed through a *U* filter, for 28 hr spanning seven nights. The light curves in 1991 January are shown in Figure 10, and the mean amplitude spectra of both data sets are shown in Figure 11. An obvious spike occurs at 275.5 ± 1.2 s, consistent with the period seen in 1982.

It seems likely that the period is stable. In Figure 12 we show the relevant region of the discrete Fourier transform for each of the three data sets in *U* light. The high peaks are aligned to within the measurement error of ~ 0.06 s; the period is probably 274.87 s, with 275.76 s not excluded. But the *waveform* is not very stable. Night-to-night variations are seen in Figure 9, and month-to-month variations are seen in Figure 13, which

TABLE 2

AVERAGE MAGNITUDES[a]

Date	*U*	*B*	*V*	*R*	*I*
1982 Feb	15.1	16.3	16.1	...	...
1983 Mar	...	16.9	...	...	...
1988 May	...	16.3	...	...	...
1990 Jan	...	17.4	...	...	...
1990 Feb	...	16.4	...	...	...
1990 May	15.0	...	...	...	...
1991 Jan	14.9	16.0	15.8	15.3	14.3

[a] Uncertainties are 0.2 mag.

TABLE 3

HIGH-SPEED PHOTOMETRY OF YY DRA

UT Data	Start	Telescope, Filter	*t* (s)	Points
1982 Feb 18	9:03:43	No. 1 0.9 m, *U*	20.180	678
1982 Feb 19	5:44:37	No. 1 0.9 m, *U*	20.180	698
1982 Feb 20	7:19:20	No. 1 0.9 m, *U*	20.180	876
1983 Mar 16	7:48:22	No. 2 0.9 m, $CuSO_4$	20.24	737
1988 May 19	5:19:09	No. 2 0.9 m, $CuSO_4$	5.005	2496
1990 Jan 26	10:46:05	No. 2 0.9 m, $CuSO_4$	10.00	839
1990 Jan 27	7:49:06	No. 2 0.9 m, $CuSO_4$	10.00	1903
1990 Jan 30	11:39:46	No. 2 0.9 m, $CuSO_4$	10.00	524
1990 Feb 24	11:14:26	No. 2 0.9 m, $CuSO_4$	10.01	543
1990 Feb 25	5:30:15	No. 2 0.9 m, $CuSO_4$	10.01	450
1990 Feb 25	7:34:17	No. 2 0.9 m, $CuSO_4$	10.01	623
1990 Mar 2	5:29:16	No. 2 0.9 m, $CuSO_4$	10.01	937
1990 May 23	3:43:09	No. 2 0.9 m, *U*	5.005	2957
1990 May 25	4:03:08	No. 2 0.9 m, *U*	5.005	3009
1990 May 26	4:21:06	No. 2 0.9 m, *U*	5.005	2662
1991 Jan 11	8:29:05	0.9 m, *U*	10.005	1653
1991 Jan 13	10:26:03	0.9 m, *U*	10.005	905
1991 Jan 14	7:48:04	0.9 m, *U*	10.005	1912
1991 Jan 15	8:18:35	0.9 m, *U*	10.005	1741

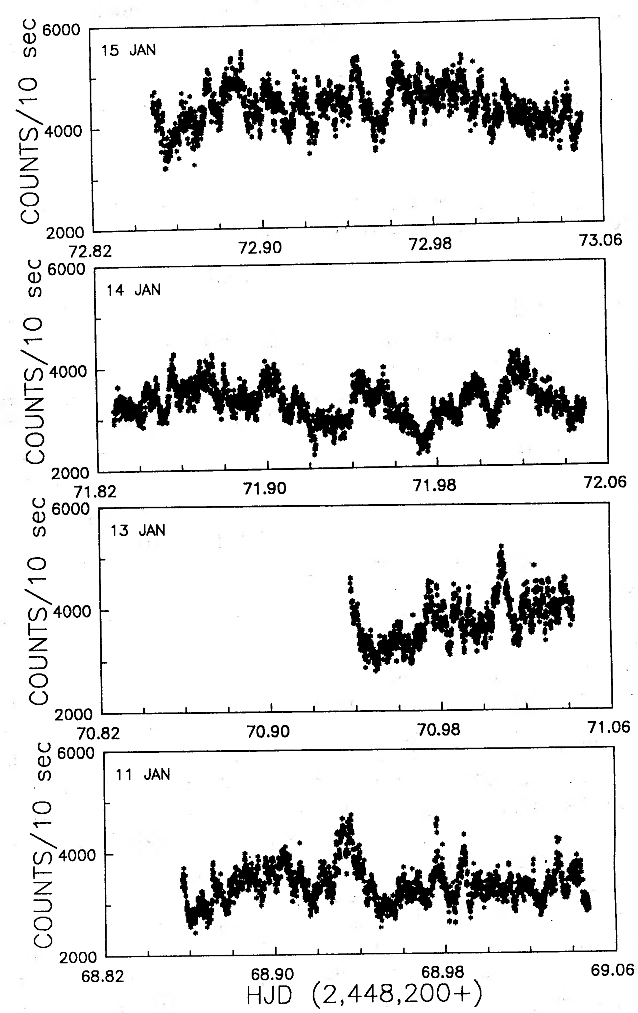

FIG. 10.—Ultraviolet light curves in 1991 January, at 10 s point^{-1}

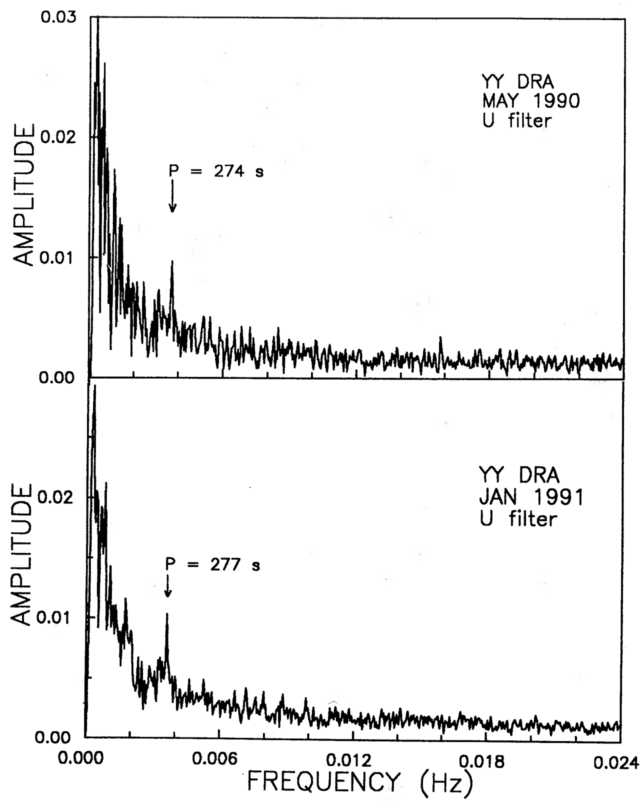

FIG. 11.—Average amplitude spectra in the U light curves of 1990 May and 1991 January, showing a sharp spike at 275.5 ± 1.2 s.

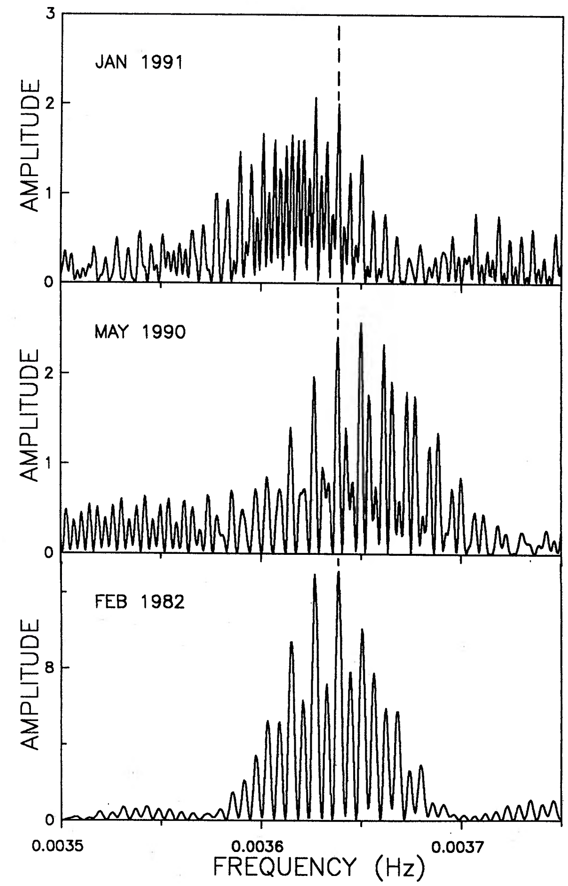

FIG. 12.—Amplitude spectra of each month's data. The dashed line indicates the most probable value of the period, 274.86 s.

shows the light curves folded with $P = 549.74$ s, and zero phase fixed at the start of each month's observation.

7.2. *The* 266 s *Period*

The other light curves were obtained through a $CuSO_4$ filter, giving a broad bandpass centered around 4700 Å. Most were of poor quality due to clouds, but with extensive editing we rescued 21 hr of data suitable for spectral analysis. Combining this with the earlier data obtained through a $CuSO_4$ filter, we calculated an average amplitude spectrum, which is shown in Figure 14. A high-frequency signal is seen, but with a period of 265.8 ± 1.3 s, quite distinct from the period present in U light. It should be emphasized, however, that the only unambiguous detections of this signal occur in 1990 January, when the star was ~1.2 mag fainter than normal (see Table 2). In other words, it is not clear whether the shorter period oscillation is due to the different bandpass or is due to the slightly different luminosity state of the star.

On one occasion, while observing with a $CuSO_4$ filter, we obtained long observations on consecutive nights. We used these to measure more precisely the 266 s period, by calculating the discrete Fourier transform of the combined light curve. The result is shown in Figure 15, which demonstrates that the period is 265.49 s, or possibly the one-day aliases of 264.61 and 266.39 (±0.12) s.

These numbers contain a very suggestive hint about the relationship between the two short-period oscillations. The beat period between 264.61 and 274.87 s is 1.97 ± 0.02 hr, and the beat period between 275.76 and 265.49 s is 1.98 ± 0.02 hr. Within the uncertainty, these "beat periods" are equal to just half the spectroscopically determined orbital period of

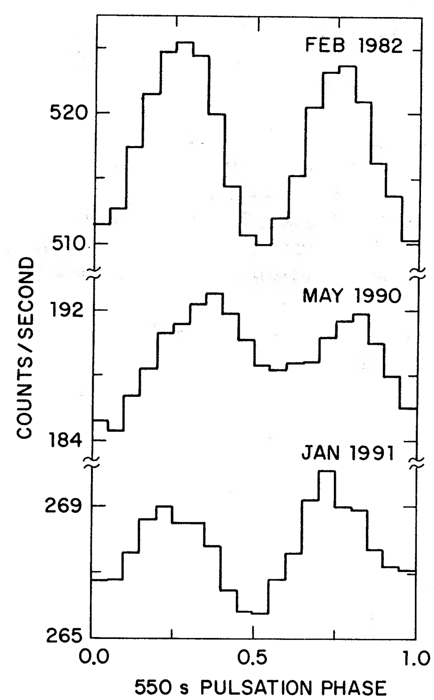

FIG. 13.—Ultraviolet light curves folded with $P = 549.74$ s, and with phase zero fixed at the beginning of each observation.

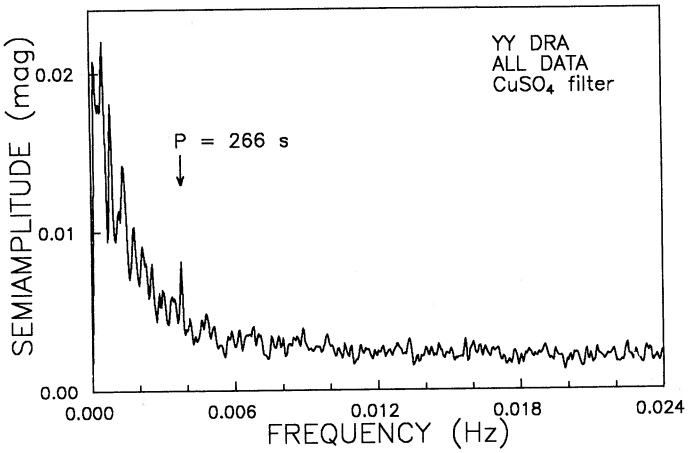

FIG. 14.—Average amplitude spectrum of the 1990 January light curves, showing a sharp spike at 266 ± 2 s. A three bin smoothing filter has been applied.

3.96 ± 0.01 hr. Or, if the fundamental short periods are taken to be 550 and 529 s, then one can describe this result by saying that the two short-period clocks go out of phase by one cycle per orbital period.

8. INTERPRETATION

The existence of a stable short-period oscillation in the light curve is the essential defining criterion of the DQ Herculis class of CVs. Most, and perhaps all, of these systems contain white dwarfs sufficiently magnetic to channel the flow of accreting gas onto their magnetic poles, where a strong shock develops and heats the gas to $T \sim 10^8$ K. As the star rotates, the X-ray–emitting region wheels about and, in a periodic manner, can illuminate the observer directly, the white dwarf photosphere below the shock, the inner edge of the accretion disk, the disk proper, the secondary star, and the bright spot at the edge of the disk. All of these are possible sites for the production of an optical periodicity, either directly or by reprocessing of the X-rays.

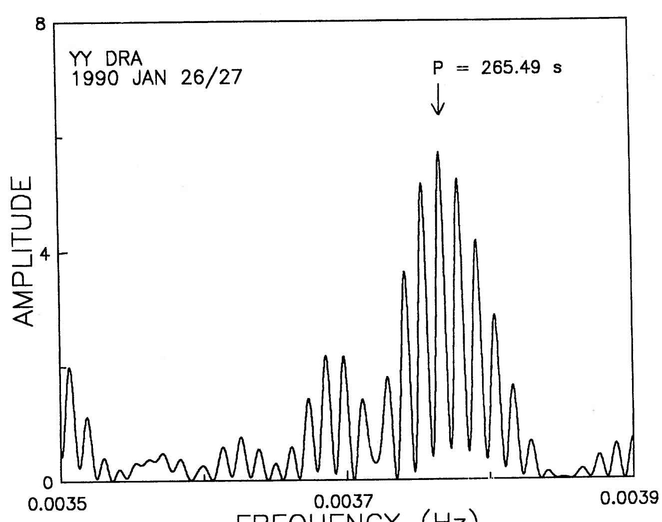

FIG. 15.—Amplitude spectrum of the 1990 January 26/27 light curves. The central peak occurs at a period of 265.49 s, but the flanking peaks (at 264.61 and 266.39 s) are also satisfactory fits to the data.

8.1. *Family Resemblances*

Among the DQ Her stars, there are two which show periodic behavior reminiscent of YY Dra. The optical power spectrum of AE Aquarii shows sharp spikes with comparable power at 33.08 and 16.54 s (Patterson 1979); the fundamental rotation period is known to be 33.08 s from the X-ray pulsations (Patterson et al. 1980; Eracleous, Patterson, & Halpern 1991). Almost certainly, the white dwarf has two accreting poles, with some variability in the pattern of accretion flows onto the two poles. The observed properties of the periodicity in YY Dra also seem to be consistent with this description.

AO Piscium (=H2252 − 035) shows the rotation period of 805 s in X-rays (White & Marshall 1981) and two optical periods (805 and 859 s), the longer of which arises from reprocessing in structures fixed in the orbital frame (Patterson & Price 1981; Warner, O'Donoghue, & Fairall 1981; Hassall et al. 1981). Comparison with YY Dra suggests that the sidereal and synodic rotation periods should be identified respectively as 529 and 550 s. However, in AO Psc it is well known that the *shorter* period tends to dominate in ultraviolet light (van der Woerd, de Kool, & van Paradijs 1984), which is entirely reasonable since at short wavelengths the white dwarf is a more important contributor to the light. But in YY Dra the *longer* period is dominant at shorter wavelengths.

8.2. *Interpreting the Period Structure*

How are we to understand this? If the observed signal in the U band arises from the continuum (as is true for all other sufficiently studied DQ Her stars), then it seems very likely that it represents the true sidereal rotation period of the white dwarf—in which case we would be forced to conclude that the white dwarf is rotating *retrograde* with respect to the orbit. This would certainly be difficult to understand, since accretion torques from the disk should enforce prograde rotation.

However, YY Dra has quite strong emission lines and a large Balmer jump in emission (see Fig. 2). We estimate that these bound-bound and free-bound transitions, probably arising from recombination, are responsible for at least 15% of the flux through the U filter; thus they would have to be pulsed at only 7%, or less, to give the observed 1% pulse fraction. This requirement is easily met. High-speed spectroscopy of DQ Her stars shows that pulsed fractions of 10%–30% in the lines are quite common (Penning 1985; Hellier & Mason 1990; Buckley & Tuohy 1990). The blue light ($CuSO_4$ filter) would be much less affected by the behavior in the lines, since it includes ~2000 Å of continuum.

The latter possibility, which seems to us more likely, identifies 529 s as the sidereal rotation period, and 550 s as the synodic period. The U-band pulsations must arise in a structure fixed in the orbital frame. This is likely to be the bright spot at the edge of the disk, which is periodically ionized by the X-ray or extreme ultraviolet (EUV) flux. The longer period pulsations are then produced by recombinations.

Although it is plausible that the difference in period arises entirely from a bandpass effect, it is also possible that the period of the pulsed reprocessed flux is highlighted when the star is bright because of physical changes in the binary, e.g., a bloating of the disk in the vicinity of the bright spot. High-speed multicolor photometry can resolve this important point.

8.3. *System Energetics Revisited*

In the standard model for DQ Her stars, the optical flux arises primarily from the gravitational energy released in the disk, and the X-ray flux from the accretion shock which overlies the magnetic pole. The F_{hx}/F_{disk} ratio is then expected to be $\sim(R_{disk})_{inner}/R_{wd}$, or slightly less, since some of the hard X-rays should be absorbed by the white dwarf surface. This ratio should certainly exceed unity, and it is a continuing embarrassment to the theory of DQ Her stars that no known system complies with this elementary requirement! (See White & Marshall 1981 and Berriman 1988 for a discussion of this.)

For YY Dra, the observed ratio is ~ 3, or as high as 6 if the "hot white dwarf" is reckoned as a component of the radial accretion luminosity. It is heartwarming that, at least in this case, there is no conflict with theory.

9. SUMMARY

1. We report the identification of 3A 1148 + 719 with a faint blue star, evidently a dwarf nova, coincident in position with the cataloged coordinates of YY Draconis. Since no other variable star can now be found in the vicinity, we conclude that the dwarf nova *is* the star originally designated as YY Dra.

2. The radial velocities of the Hα emission line move with a period $P = 3.98 \pm 0.04$ hr and a semiamplitude $K = 111 \pm 10$ km s^{-1}. These are reasonably consistent with the values obtained for the Ca II emission by Mateo et al. (1991): $P = 3.96 \pm 0.01$ hr and $K = 87 \pm 13$ km s^{-1}.

3. The *H*-band light curve appears to show the expected "double-humped" variation due to the Roche deformation of the secondary.

4. The 1100–2000 Å spectrum shows evidence for a rather hot star; the continuum slope requires $T > 20{,}000$ K, but the absence of Lyman-α absorption suggests a stronger limit of $T > 30{,}000$ K. In order for such an object to be drowned out by the light of the cool secondary at long wavelengths, it must be quite small; we estimate an emitting area smaller than that of a white dwarf surface by a factor of ~ 10 or greater. The heated polar cap of the white dwarf is a possible origin.

5. High-speed photometry reveals the existence of two periodicities: a 275 s period in ultraviolet light and a 265 s period in blue light. Both appear to be accompanied by "subharmonics," indicating that the fundamental periods are really 550 and 529 s, which are orbital sidebands of each other. The existence of these periods establishes the membership of YY Dra among the DQ Herculis stars.

6. It is surprising that the *longer* period is present in ultraviolet light, where the "white dwarf" component is stronger. The simplest geometrical interpretation of this is that the white dwarf is rotating *retrograde* to the orbit. However, retrograde rotation is difficult to understand, and we suggest instead that the true rotation period is 529 s, with the 550 s period arising from the reprocessing of high-energy radiation in structures fixed in the orbital frame (secondary star, and the bright spot at the edge of the disk). We speculate that the longer period is manifest in the *U* filter because of the large contribution of emission lines and Balmer continuum radiation in this star.

7. We note with delight and irony that, essentially alone among DQ Herculis stars, YY Dra actually shows an energy budget in compliance with the simple models of asynchronous rotators. It took a long time to find a star that agrees with the models!

8. A harvest of predictions follows. Extensive X-ray observation should reveal pulsations with $P = 529$ or 265 s. High-speed spectroscopy should show large pulsations in emission lines arising from photoionization. If the lines originate in the disk proper, their profiles should vary with $P = 529$ or 265 s. The same is true if the lines originate in the accretion column. If the lines arise in the bright spot, both profiles and intensities should vary with $P = 550$ or 275 s.

A 10 year study always leaves behind a paper trail of data that contributed to the science but does not quite make it into the svelte paper that finally appears. For such contributions I thank Rob Fesen, Greg Bothun, Paula Szkody, Wendy Roberts, and Robin Ciardullo. And to the same people, I promise faster movement, and an all-around better deal, next time around. This research was supported in part by NSF grant AST 89-16995 and NASA grant NAG 5-1598.

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