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ORBITAL PERIODS OF RECURRENT NOVAE

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ABSTRACT

The class of recurrent novae (RN) with thermonuclear runaways contains only three systems (T Pyx, U Sco, and V394 CrA) for which no orbital periods were known. I report on a series of photometric observations where the orbital periods for all three systems were discovered. T Pyx is found to have a sinusoidal modulation with an amplitude of 0.08 mag and a period of 2.3783 hr (with a possible alias of 2.6403 hr). This result is startling because the orbital period is in the middle of the period gap. U Sco is found to be an eclipsing system with an eclipse amplitude of roughly 1.5 mag and an orbital period of 1.2344 days. Both the high inclination and the orbital period are also startling because of the narrow He line in the spectrum and the high inferred accretion rate. V394 CrA is found to have a sinusoidal modulation with an amplitude of 0.5 mag and a period of 0.7577 days. So two out of three RN with thermonuclear runaways (or five out of six for all RN) have evolved companions.

Subject headings: stars: individual (T Pyx, U Sco, V394 CrA) — stars: novae

I. INTRODUCTION

Recurrent novae (RN) are cataclysmic variables observed to have repeated nova eruptions on a time scale of less than a century or so. The RN can be divided into two classes with separate outburst mechanisms (Webbink *et al.* 1987, hereafter WLTO). The first class, powered by a burst of mass transfer from a red giant companion, has only three known members, T CrB, RS Oph, and V745 Sco (Duerbeck, Schwarz, and Augusteijn 1989; WLTO). The second class, powered by a thermonuclear runaway of accreted material on the surface of a white dwarf, contains only three known systems, T Pyx, U Sco, and V394 CrA (WLTO). The structure of these systems and their evolutionary status is not currently understood.

For any model of a RN, the most important parameter is the orbital period. The period sets the size scale for the entire system as well as for the companion star in particular. Then for reasonable assumptions, the nature of the secondary can be deduced as can the distance and hence, the luminosities. The period also reflects the evolutionary status and the outburst mechanism itself. For example, those RN powered by accretion instability from a red giant companion have periods of several hundred days while RN with thermonuclear runaway have periods speculated to be either under 2 hr for T Pyx or several days for U Sco (WLTO).

Unfortunately, no RN with thermonuclear runaway has a known orbital period. To provide this vital datum, I have taken time series photometry of all members of this class. This *Letter* describes the results of my photometry, where I derive orbital periods for all class members.

II. OBSERVATIONS

All observations reported in this paper were obtained by the author on the 0.9 m telescope at the Cerro Tololo Inter-American Observatory (CTIO) with the TI No. 2 CCD chip. The same filters and instrumental parameters were used on all runs. Exposure times for T Pyx varied from 1 to 4 minutes, whereas the exposures for the fainter U Sco and V394 CrA were almost all of 15 minute duration. Data were obtained over four observing runs from 1988 May 5 to May 12, 1988 June 24 to June 25, 1988 July 2 to July 5, and 1989 July 8 to July 20. Ten to 20 standard stars were measured for each color on one photometric night during each run to calibrate the brightness of comparison stars near to each target.

The CCD frames were processed with the standard CTIO reduction procedure. All magnitude measures were obtained differentially with respect to nearby calibrated comparison stars. This differential photometry removes the possibility of photometry errors arising from changing extinction, sky brightness, or seeing. All three RN had no significant background stars contributing light to the star apertures. Instrumental magnitudes for individual stars were extracted by aperture photometry either with the program CDPHOT or *MEAS, both of which use the Mountain Photometry Code. The differential magnitudes for the targets were then corrected to real magnitudes by adding the magnitude of the comparison star established from the calibrated photometric nights.

The error in an individual photometric measurement can be estimated by examining the variance of the differential magnitudes of check stars of comparable brightness to the target. For T Pyx, the check star varied with an rms scatter of 0.025 mag. For U Sco and V394 CrA, the rms scatter was 0.06 mag. Unfortunately, the nearly full moon was close to U Sco on the one clear night when an entire eclipse was visible. During this eclipse, the error was ≈ 0.20 mag.

III. T PYXIDIS

I obtained 372 *B* band brightness measurements for T Pyx during the three 1988 observing runs. T Pyx was monitored on seven nights in the 1988 May run with observing durations from 1 to 5 hr. For the 1988 June and July runs, T Pyx was monitored for 2 hr on one night each run. The differential photometry is with respect to a star located 42″ north and 17″ west of T Pyx with a *B* magnitude of 14.86.

These data have been subjected to a discrete Fourier transform (see Fig. 1) which shows a strong peak corresponding to a period of 2.3783 hr and another nearly as strong peak corre-

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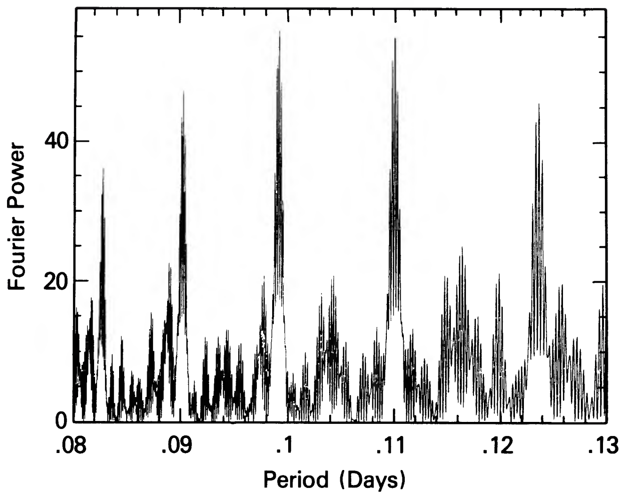

FIG. 1.—Fourier transform of 372 B mag for T Pyx. Two peaks at periods of 2.3783 and 2.6403 hr stand well above other daily aliases. Both periods are near the middle of the period gap.

sponding to 2.6403 hr. These two peaks are 1 day aliases of each other. The Fourier transform shows other strong peaks which are also 1 day aliases of 2.3783 hr. The power in the two highest peaks is more than 9.0 higher than the next highest peak. This implies that the lower peaks are to be rejected at the 99.99% probability level. The choice between the two higher peaks is difficult, but the odds are roughly 2 to 1 that the 2.3783 hr period is correct because its peak is 0.6 higher.

Szkody and Feinswog (1988) have 120 minutes of an infrared light curve which they fitted to a sinusoid with a 100 minute period. This result is not inconsistent with either alias because T Pyx has substantial cycle-to-cycle variations. My own data contain isolated 2 hr stretches where a sinusoidal fit would yield a period from 100 minutes to greater than 200 minutes.

The light curve folded around a period of 2.3783 hr is presented in Figure 2. The variations are seen to be sinusoidal with a full amplitude of 0.08 mag. The scatter around the mean light curve has an rms variation of 0.05 mag, which is considerably larger than the measurement error, so that T Pyx is undoubtedly flickering.

This observed periodicity might not correspond to the orbital periodicity for the following reasons:

1. One of the aliases of the 2.3783 day period might be the real orbital period, but the 2.6403 hr alternative is also squarely within the period gap and the other aliases have very low likelihoods.

2. The brightness modulation might be caused by ellipsoidal effects so that the orbital period is twice as long. However, this cannot be since the color of T Pyx is very blue ($B-V = -0.26$ after correction for extinction, WLTO), so that the light from the accretion disk must dominate over the light from the companion, which means that ellipsoidal effects on a red companion star could not account for the observed amplitude.

3. The 2.37 hr periodicity might arise from a physical mechanism not associated with the orbital period, say a precessional or rotational period. However, both mechanisms have difficulty explaining a period in the range of several hours.

In summary, there is no plausible alternative to the natural conclusion that the orbital period is 2.3783 hr (or 2.6403 hr) and in the middle of the period gap.

The observational result that a RN has an orbital period in the middle of the gap is exciting because of its effect on theories of the period gap. The impact arises because T Pyx has a significant mass transfer rate, as is shown by its blue color and flickering. WLTO have estimated the mass transfer rate to be $5 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ based on the deduced brightness of the accretion disk. This rate is apparently in contradiction to models that predict much lower values for systems in the gap (Robinson *et al.* 1981; Joss and Rappaport 1983; Rappaport, Verbunt, and Joss 1983; Patterson 1984).

T Pyx might be an exception to the various models because its outburst energy is high, such that the models might predict a high accretion rate even in the gap. The outburst energy is $10^{44.4}$ ergs, comparable to normal novae, yet with a recurrence time of 19 yr (WLTO). Irradiation of the companion might greatly increase the predicted accretion rate (Shara *et al.* 1986). A similar dodge was suggested by Shafter and Abbott (1989) to explain V Per. This classical nova eclipses with a period of 2.57 hr even though the accretion rate is apparently high (based on the flickering and the lack of "stepped eclipses"). However, this resolution is worrisome because then there should be many other classical novae in the period gap. Detailed calculations will be needed to reconcile any model with T Pyx.

The sizes and masses of the two components can be deduced from Kepler's Law, the Roche lobe sizes of Paczyński (1971), a main-sequence mass-radius relation (Patterson 1984), and a white dwarf mass for RN near the Chandrasekhar limit (Starrfield, Sparks, and Shaviv 1988). The mass ratio is 0.15, the secondary mass is 0.20 $M_\odot$, and the secondary radius is 0.25 $R_\odot$.

Vogt *et al.* (1990) observed radial velocity variations consistent with a K value of 30 km s^{-1}, although he did not search for periodicities below periods of 2.9 hr. This implies a mass function of 0.00028 $M_\odot$ and an inclination of 27°.

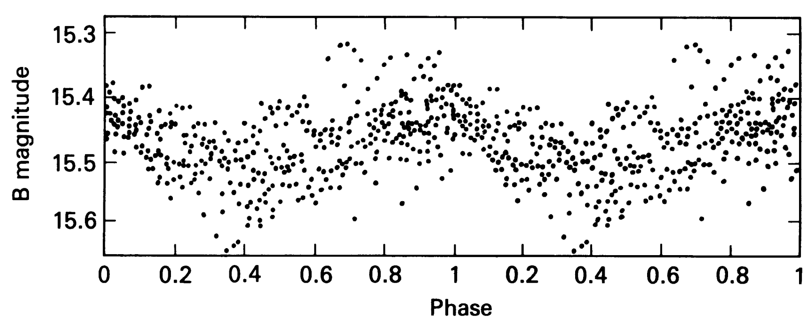

FIG. 2.—Light curve of T Pyx for a period of 2.3783 hr. The light curve is sinusoidal with an amplitude of 0.08 mag and a flickering with an rms variation of 0.05 mag. The epoch of zero phase is JD 2,440,000.

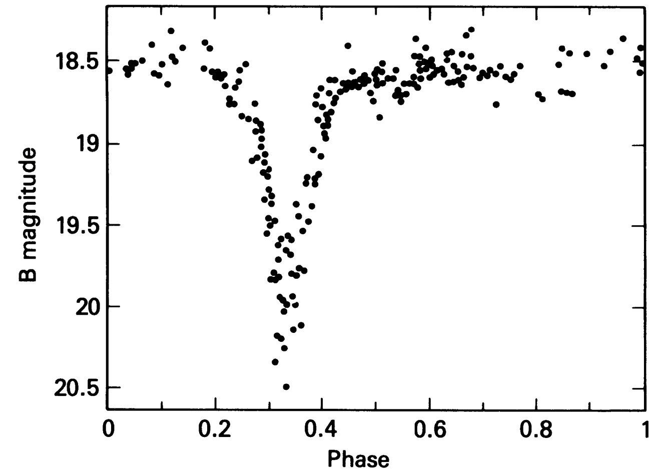

FIG. 3.—The eclipsing light curve of U Sco. U Sco is an eclipsing binary with an amplitude of roughly 1.5 mag, eclipse duration of 0.17 in phase, and flickering outside of eclipse.

IV. U SCORPII

I obtained 219 brightness measurements of U Sco. The photometry was with respect to a star 73″ west and 69″ north of U Sco with $B = 16.94$, $V = 15.83$, and $R = 15.19$. U Sco was observed to eclipse on five separate nights. A periodogram analysis was used to evaluate the period, since this function is more sensitive to an eclipsing light curve than is a Fourier transform. The best-fit period is 1.2344 ± 0.0025 days, with the epoch of middle eclipse at JD 2,447,717.606. The light curve in Figure 3 has been folded around this period. The rms scatter outside of eclipse is 0.32 mag and is much larger than the measurement errors. The total duration of the eclipse is 0.17 in phase. The amplitude of eclipse is roughly 1.5 mag, although the brightness and shape of the minimum are uncertain.

The colors of U Sco at maximum light were measured to be $U-B = -0.34$, $B-V = 0.56$, $V-R = 0.36$, and $R-I = 0.47$. At one time of mid-eclipse, I measured $B-V = 1.0$ and $V-R = 0.6$, while for another eclipse I obtained $B-V = 1.0$. The colors at minimum light are consistent with a G3–6 star and an $E(B-V) \approx 0.2$ (see WLTO), suggesting that the eclipse is total so that no light from the accretion disk is visible at mid-eclipse.

WLTO conclude that U Sco is viewed within 7° of pole-on to account for the 2560 km s^{-1} FWZI of He II emission lines at quiescence (Hanes 1985). But since U Sco is edge-on, a different explanation of the line width is needed. Perhaps the inner accretion disk is disrupted by magnetic fields (Williams 1989), or perhaps the inner region is hidden from view by regions farther out, or perhaps the hot spot is the source of the helium emission lines.

From Kepler's Law, the Roche lobe–filling requirement, Patterson's mass-radius relation, and a white dwarf near the Chandrasekhar mass, the companion star will have a radius $1.86q^{-0.55}$ times that of a main-sequence star, with q the mass of the companion star divided by 1.4 $M_\odot$. For $q < 1$ so that runaway accretion does not occur, the companion star must be larger than a main-sequence star of the same mass.

For this evolved companion star, the surface temperature is roughly that of a G3–6 star and its radius is at least 1.86 times that of a main-sequence star, implying an absolute V magnitude of brighter than 3.8 mag. The apparent visual magnitude of the companion star is greater than roughly 18.6 mag, since it must be fainter than the brightest magnitude at mid-eclipse with a color correction. For A_V of 0.8 mag (WLTO), the distance to U Sco must be greater than 6.8 kpc. This limit can be improved when a better V light curve is available. If the eclipse is total and the amplitude is 1.5 mag, then the distance varies from 29 kpc to 8 kpc as q varies from 0.1 to 1.0. The analysis will be more complicated if any light from the accretion disk is still visible at mid-eclipse.

V. V394 CORONAE AUSTRALIS

I observed V394 CrA on 13 consecutive nights from 1989 July 8 to 20. Two observations were made with a U and V filter, while 119 measurements were through a B filter. The photometry was with respect to a star 4″ west and 35″ south of V394 CrA, which has $U = 18.33$, $B = 17.75$, and $V = 16.73$. The colors of the RN were $U-B = -0.09$ and $B-V = 0.94$ when $B = 19.20$.

V394 CrA showed large and significant variability. A Fourier transform of the data (Fig. 4) shows a significant peak at a frequency that corresponds to 0.7577 days. A transform of the window function shows no features which could account for the peak. The other peaks near the highest peak are aliases of the highest peak. The average power at high frequencies is roughly unity, as expected since the normalization of Belserene (1988) was used. Therefore, the highest peak is greatly above the average power level (also greatly above any alias peaks), so that a photometric period of 0.7577 days is highly significant.

The light curve folded around this period is presented in Figure 5. The light curve has a scatter which is much larger than the measurement error and so which is likely to be flickering as is normal for cataclysmic variables. The average magnitude for the phases of maximum and minimum light are 19.0 and 19.5 for an amplitude of 0.5 mag. The variations are roughly sinusoidal in shape with no evidence for eclipses.

As with U Sco, the companion star will be $1.33q^{-0.55}$ times the size of a main-sequence star. For $q < 1$ so that runaway accretion does not occur, the companion star must be larger than a main-sequence star of the same mass.

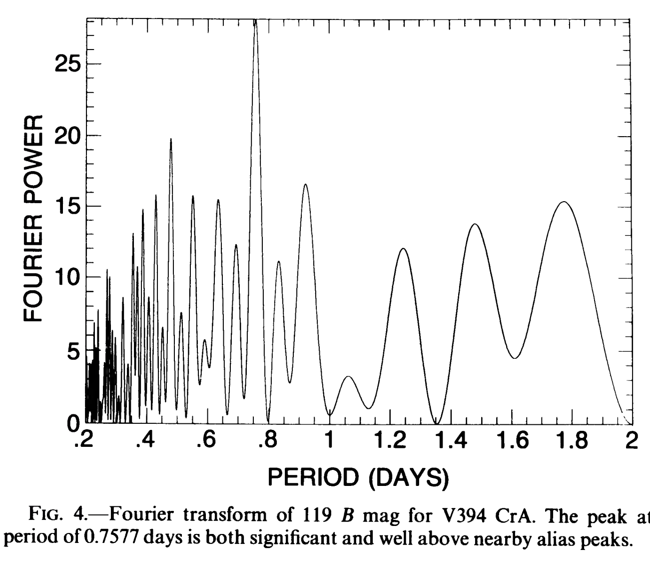

FIG. 4.—Fourier transform of 119 B mag for V394 CrA. The peak at a period of 0.7577 days is both significant and well above nearby alias peaks.

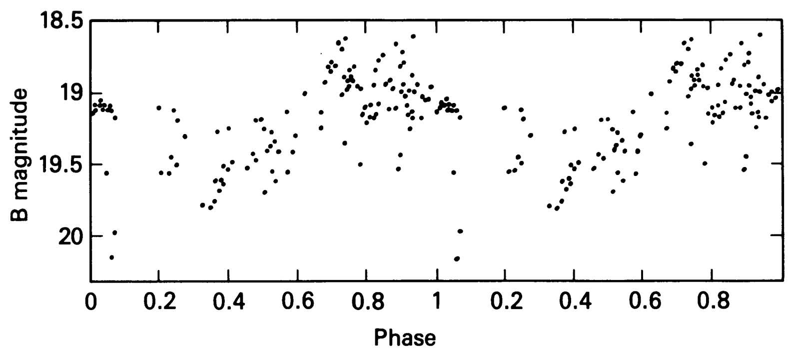

FIG. 5.—Light curve of V394 CrA for a period of 0.7577 days. V394 CrA varies sinusoidally with an amplitude of roughly 0.5 mag. There is no obvious evidence for an eclipse, as the two faint points near phase 0.06 (both taken at the end of the same night as clouds came over) have several other points of normal brightness at the same phase. The epoch of zero phase is JD 2,447,000.

VI. DISCUSSION

RN have several unique properties when compared to normal novae:

1. RN recur on a time scale of decades.
2. RN tend to have a smaller amplitude than normal novae.
3. RN tend to have bright He II emission lines (Williams 1989).
4. RN should have a mass accretion rate higher than most normal novae so as to provide the critical mass for eruption in a short time (WLTO).
5. RN tend to have evolved companion stars. This is true for two out of three RN with thermonuclear runaways and for three out of three RN with accretion instabilities, whereas only one normal nova (GK Per) out of many has an evolved companion. The statistics for RN may be poor, but they cannot have the same probability for an evolved companion star as does a normal nova.
6. RN should have white dwarfs with masses near the Chandrasekhar limit so that a smaller envelope mass is required for ignition (WLTO).

Properties (5) and (6) are the two fundamental requirements for a RN. Property (2) is a result of property (5), since the presence of an evolved companion will increase the quiescent brightness and decrease the amplitude. Property (4) is a result of property (5) since long-period systems will have high accretion rates (Patterson 1984). Both properties (6) and (4) will result in property (1) (Starrfield, Sparks, and Shaviv 1988). R. Wade (1989, private communication) notes that property (3) could be caused by property (6), since a higher mass white dwarf will have a higher shock temperature in the boundary layer. There is no obvious causal connection for why a system with a high mass white dwarf should tend to have an evolved secondary star.

M. Shara (1986, private communication) first suggested that RN orbital periods be measured before their next eruption so that the difference with the posteruption orbital period will yield a dynamical measure of the mass ejected (as for BT Mon, see Schaefer and Paterson 1983). So it is important that the ephemerides for the three RN be improved up until the time of the next eruption, and then measured again after eruption. It is also important that a radial velocity curve be acquired for T Pyx to test whether the photometric period is also the orbital period. R. Wade (1989, private communication) notes that a radial velocity curve for the *eclipsing* U Sco can test the strong theoretical prediction that the white dwarf mass is near the Chandrasekhar limit.

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