

HIGH-STATE/LOW-STATE PHOTOMETRIC BEHAVIOR IN THE QUIESCENT LEVEL OF THE CATAclysmic VARIABLE HT CASSIOPEIAE

JEFF W. ROBERTSON AND R. KENT HONEYCUTT

Astronomy Department, Indiana University, Bloomington, Indiana 47405

Electronic mail: bigjay@astro.indiana.edu, honey@astro.indiana.edu

Received 1996 May 7; revised 1996 July 22

ABSTRACT

We discuss the long-term quiescent light curve of the dwarf nova HT Cassiopeiae, with particular emphasis on the 1991–1995 behavior. HT Cas had no outbursts for at least eight years prior to a 1995 November 17 outburst. Its 1991–1995 light curve while in quiescence exhibits ~ 1.8 mag long-time-scale variations from about 15.9 to 17.7 mag. This is remarkable because dwarf novae while in quiescence have not previously been described as exhibiting the kind of systematic high-state/low-state variations previously associated only with magnetic and VY Scl cataclysmic variables. © 1996 American Astronomical Society.

1. INTRODUCTION

HT Cassiopeiae is a cataclysmic variable (CV) whose short orbital period of 106 minutes was first discovered by H. Bond. Its eclipses were first extensively described by Patterson (1981) and it has been well-studied both spectroscopically (Young *et al.* 1981; Marsh 1990) and photometrically (Zhang *et al.* 1986; Horne *et al.* 1991). HT Cas has a normal quiescence level of ~ 16.4 mag eclipsing down to 18th and erupting to ~ 12.5 . Horne *et al.* (1991) decomposed the eclipses into two components, a white dwarf eclipse that is always present and an accretion disk component which varies greatly from cycle to cycle and can disappear completely.

HT Cas is regarded as a member in good standing of the SU Ursa Majoris subclass of dwarf nova (DN). Reviews on SU UMa systems can be found in Warner (1985), la Dous (1994), and O'Donoghue (1992). SU UMa systems have short orbital periods, falling below the CV period gap which lies between about 2–3 hours. They exhibit occasional superoutbursts that are somewhat brighter and have substantially longer duration than their normal outbursts. During a superoutburst the SU UMa systems have photometric modulations called superhumps with periods a few percent longer than their orbital periods, which are often taken as the defining characteristic of SU UMa systems. The superhump phenomenon has been attributed to the precession of an eccentric accretion disk during a superoutburst (Vogt 1982; Osaki 1985). Mattei & Stanton (1985) and Zhang *et al.* (1986) observed superhumps in HT Cas during superoutburst, authenticating its SU UMa classification.

The evidence for normal DN outburst behavior in HT Cas comes from Glasby (1970), Wenzel (1987), and the observations of the AAVSO (Mattei 1995a). Glasby shows a series of 9 outbursts from 227 visual observations in 1967–1968 with a mean cycle length of 30–35 days lasting on average 10 days. These outbursts have an amplitude of ~ 2 mag rising from a quiescent level of 15.8 mag. Unfortunately, only an interpolated fit to the outburst data is given so it is difficult to judge how well these magnitude estimates establish

the classic DN outburst behavior, especially since later observers have not seen such short-cycle outbursts and the validity of this work has come into question (Miles 1976). Wenzel collected information on 13 outbursts from 1953 to 1985 and concluded that the most likely cycle length was 400 days. However, the eruptions tabulated are defined by only one or two data points each, so we do not know much about the duration and amplitude of these brightenings. Zhang *et al.* (1986), quoting AAVSO results, reported that HT Cas did not have any obvious outbursts from 1982 to 1984, but had a long and bright outburst lasting 20 days in 1985 January where superhumps were observed (Mattei & Stanton 1985; Zhang *et al.* 1986). The AAVSO light curve of HT Cas from 1976 to 1994 (Mattei 1995a) shows only outburst behavior because the fainter magnitudes of quiescence are only occasionally sampled. Eight normal outbursts lasting ~ 2 days and the 1985 superoutburst are apparent during this interval.

The RoboScope light curve during 1991–1995 for HT Cas in Fig. 1 does not show any outbursts at all from 1991 August to 1995 October (JD 2448470–24485021). Instead, the photometric variations while in quiescence are characterized by 1.3 mag transitions from a high state to a low state which occur on time scales of days to months and last from days to months. While in the high state brief “dips” back to the low state, which are unassociated with its well-studied eclipses, are seen as well as systematic longer duration excursions. HT Cas had previously been seen fainter than its normal quiescence level on two occasions (Wood *et al.* 1995).

If this CV light curve of Fig. 1 were to be classified without knowledge of the orbital period or of the outburst behavior, it would likely be labeled a VY Sculptoris star (Bond 1980). These nova-like CVs have orbital periods just above the period gap and their principal light variations consist of erratic transitions between a high state and a low state (Robinson *et al.* 1981; Shafter *et al.* 1985). A modulation of mass transfer from the secondary star that leads to a highly variable accretion luminosity is thought to be responsible. High-

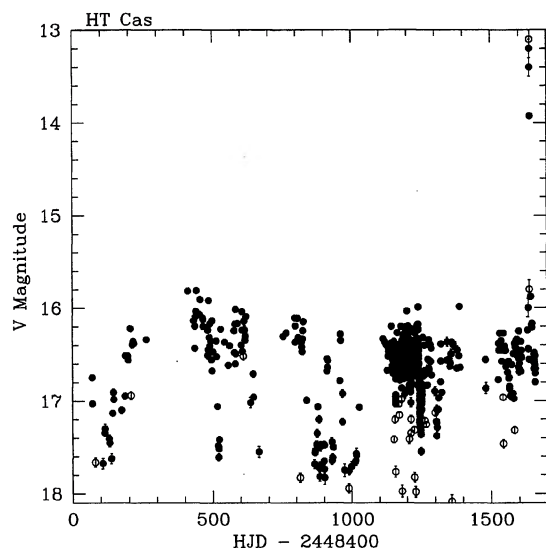


FIG. 1. RoboScope long-term light curve of HT Cas from 1991 August to 1995 December. Open circles are points during primary eclipse phases.

state/low-state changes on time scales of weeks to years are known to occur in nova-like CVs just above the period gap (VY Scl-type) and in magnetic CVs of the AM Her-type and DQ Her-type (Garnavich & Szkody 1988, and references therein). However, distinct low states while in quiescence among any of the various subclasses of dwarf nova are presumably rare. Only three other dwarf novae have been observed to have behavior resembling low states. BZ UMa was caught fainter than its quiescence level on one occasion (Kaluzny 1987), there are reports for WW Cet (Warner 1987, in a footnote; Ringwald *et al.* 1995), and Howell (1990) suggests low states in RU LMi. None of the systematics of these low states have been studied in detail. The quiescent light curve of HT Cas is clearly an anomaly worthy of further scrutiny.

2. OBSERVATIONS

HT Cas was observed from 1991 to 1995, or five observing seasons, with the CCD Automated Photometric Telescope (RoboScope) at Indiana University. RoboScope has been in routine operation since 1990, working mostly on a program of long-term photometry of cataclysmic variable stars (Honeycutt *et al.* 1990; Honeycutt & Turner 1992). This 41-cm telescope performs unattended differential stellar photometry on a program of about 140 objects, obtaining typically one observation each clear night for each program object. All necessary functions are fully automated for real-time unattended operation. The light curves are generated using the technique of inhomogeneous ensemble photometry (Honeycutt 1992). This method uses all the constant stars appearing in each exposure as a comparison, even though the number and identity of these stars varies from exposure to exposure due to clouds, sky brightness and to telescope pointing.

The telescope is most valuable for acquiring data on time scales of weeks to years, data that is otherwise quite difficult to obtain under the scheduling policies of most observatories.

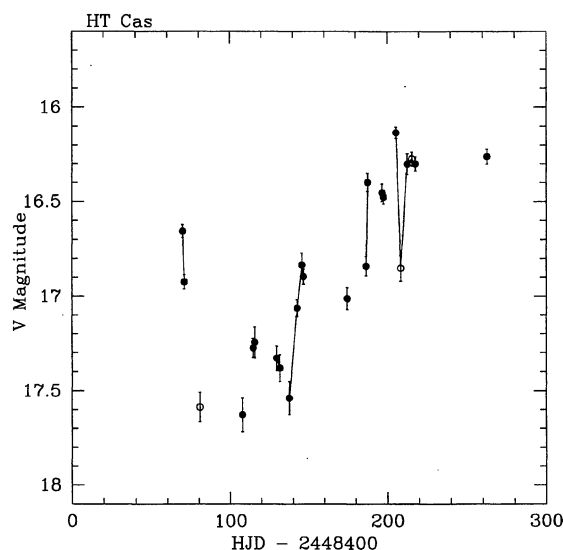


FIG. 2. RoboScope light curve of HT Cas during the 1991-1992 observing season showing a slow 1.5 mag rise over 200 days from the low state. Open circles are points during primary eclipse phases. Data points less than 5 days apart are connected.

We seldom ask the telescope to acquire closely-spaced data on a single object within a night because such scheduling degrades the long-term light curves of the other program objects. Therefore this HT Cas data has a typical spacing of 1 to 5 days, and there is seldom more than one point per night, except during the last two observing seasons where the time sampling is several points per clear night.

A total of 627 V-band exposures were obtained on 322 nights from 1991 August 01 until 1995 December 05 (JD 2448469-2450056). The ensemble solution used 96 comparison stars. The magnitude error bars on the light curves are for differential photometry and average 0.03 mag outside of eclipse. The zero point of the photometry for HT Cas was established using the secondary standards provided by Miskelt (1995) and has an error of ± 0.013 mag.

3. DISCUSSION

Figure 1 is the 5-year light curve for HT Cas and Figs. 2-6 show each of the five observing seasons on an expanded scale. The RoboScope data over a 4.5 year period shows that there were no outbursts which resemble the kind of DN behavior reported by Wentzel (1987) for 1953-1985, or for 1976-1990 by the AAVSO (Mattei 1995a). However, we note that for a 3 year interval preceding the 1985 superoutburst the AAVSO data shows an absence of outbursts. HT Cas had also ceased outburst activity for a total of 8 years before its 1995 November (JD 2450038) outburst (Mattei 1995b). The short duration (~ 3 days) and lack of superhumps indicates that this 1995 event was a normal outburst and not a superoutburst (Kato 1995).

Figure 7 shows the mean eclipse light curve of HT Cas using only data from 1994 June 11 to 1995 October 18 (JD 2449514-2450008) while HT Cas was in an extended high state. The average orbital light curve of HT Cas in the V band shows little systematic variation outside of eclipse, hav-

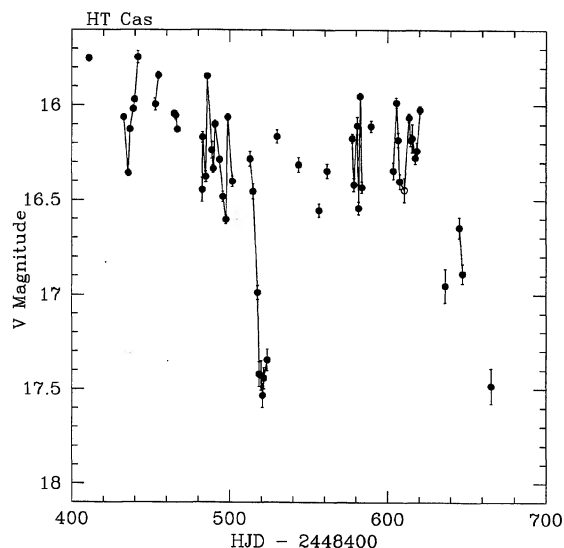


FIG. 3. RoboScope light curve of HT Cas during the 1992–1993 observing season with a well-resolved high-state/low-state transition near JD 2448920. Open circles are points during primary eclipse phases. Data points less than 5 days apart are connected.

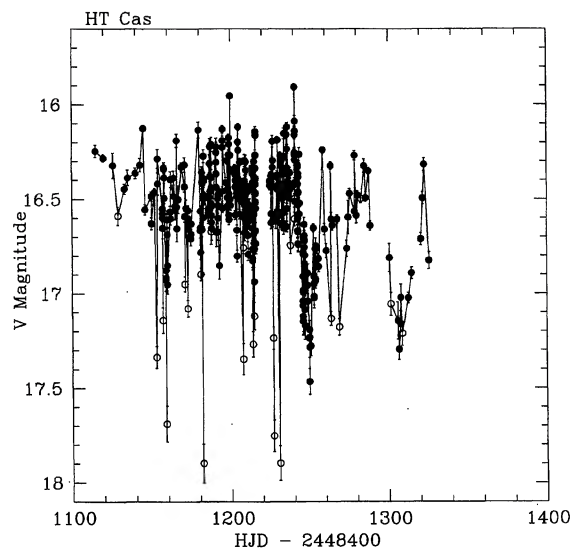


FIG. 5. RoboScope light curve of HT Cas during the 1994–1995 observing season with well resolved high-state/low-state transitions near JD 2449650 and JD 2449700. Open circles are points during primary eclipse phases. Data points less than 5 days apart are connected.

ing only random fluctuations (± 0.11 in V) about a mean brightness during any one orbit, and variations between orbits of ± 0.34 in V (based on 12 orbits, Zhang *et al.* 1986). The eclipse light curve in Fig. 7 shows random fluctuations outside of eclipses about a mean V of 16.5 ± 0.17 mag and the eclipse is similar in width and depth to the non-superoutburst eclipse parameters of Horne *et al.* (1991) and to those of Zhang *et al.* (1986) obtained during superoutburst. The eclipse is sharp and deep (~ 2.0 mag) resulting from the occultation of both the white dwarf and accretion disk by the secondary star (Horne *et al.* 1991). The eclipse covers orbital phases 0.00 ± 0.065 using the ephemeris of

$\text{HJD}2443727.93721 + 0.0736472039 \times E$ (Horne *et al.* 1991). Points lying within these eclipse phases are denoted by open circles in Figures 1–6 in order to distinguish between eclipses effects and systematic transitions.

A magnitude histogram of the HT Cas quiescent data yields a bimodal distribution with peaks near 17.65 and 16.35 mag (Fig. 8). Data during eclipses were discarded and do not contribute to the bimodality which represents two quiescent states in HT Cas. The bottom panel of Fig. 8 uses all the quiescent light curve data of Fig. 1 and the top panel uses only the first three observing seasons (Figs. 2–4). The

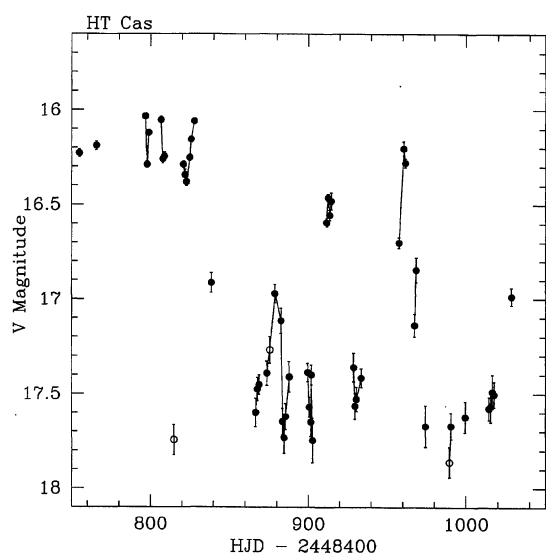


FIG. 4. RoboScope light curve of HT Cas during the 1993–1994 observing season showing several transitions between extended high-states and low-states. Open circles are points during primary eclipse phases. Data points less than 5 days apart are connected.

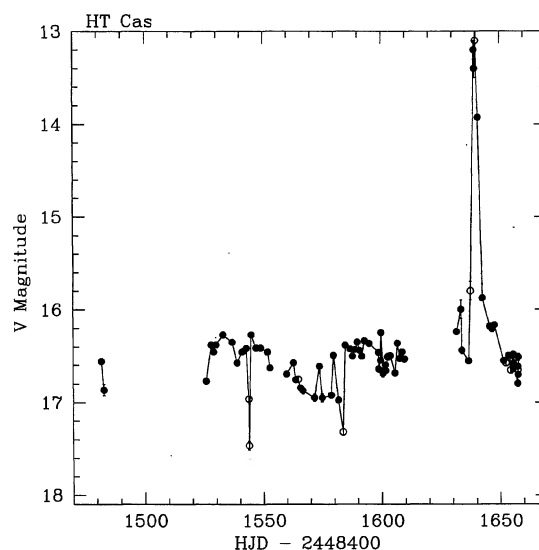


FIG. 6. RoboScope light curve of HT Cas during the 1995 observing season which contains the 1995 November outburst. Seven of the 15 data points from JD 2450030–2450055 are from AAVSO observations (Mattei 1995b). Open circles are points during primary eclipse phases. Data points less than 5 days apart are connected.

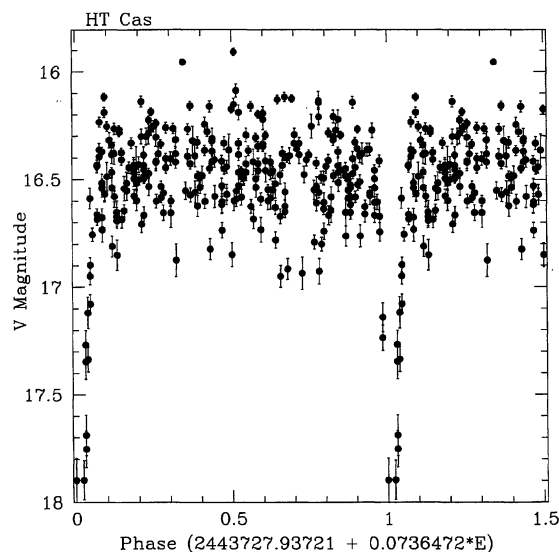


FIG. 7. RoboScope mean eclipse light curve of HT Cas during the 1994–1995 high-state. This plot uses data only in the interval JD 2449514–2449644 from Fig. 5.

bimodal nature is more pronounced during the first three observing seasons because the high-state/low-state behavior decreased in the last two seasons. The overpopulation of the high state magnitude bins from decreased activity and higher time resolution in seasons 4 and 5 combine to leave only a skewed tail for the low-state magnitude bins in the bottom panel of Fig. 8.

Occasional “dips” to the low state lasting 5–10 days in HT Cas are similar to those reported for DW Ursa Majoris (Honeycutt *et al.* 1993). There are also occasional brightenings in HT Cas with the same character as the dips (compare the dip near JD 2448920 in Fig. 3 with the rise in Fig. 4 near JD 2449360). The conspicuous low state in Fig. 3 near JD 2448920 has an ingress time of ~ 6 days, lasts for ~ 6 days and is about 1.3 mag deep. The low state in Fig. 5 near JD 2449645 starts as a gradual decline of 1.0 mag over ~ 6 days and lasts ~ 2 days before rising over ~ 8 days to its original brightness. There are also longer systematic transitions. Figure 2 shows a rise of 1.3 mag over ~ 200 days, while in Fig. 4 there is a decline of 1.4 mag occurring over ~ 40 days (JD 2449240).

The overall long-term system brightness is controlled by the accretion disk and ultimately the mass transfer rate. It is of interest to know whether large amplitude systematic variations while in quiescent are common in other DN systems because this would influence theories about mass transfer modulations. The quiescent light curves of 12 other DN systems of the SU UMa type on our RoboScope program (8 of which have densely sampled quiescent light curves) show ≤ 0.5 mag variations around a mean quiescent brightness. These DN quiescent variations are consistent as being orbital in nature and/or associated with small stochastic brightness changes in the accretion disk, and not systematic, large amplitude excursions. The magnitude histograms for the eight well-sampled SU UMa systems are shown in Fig. 9 with their associated means and standard deviations. Any skew

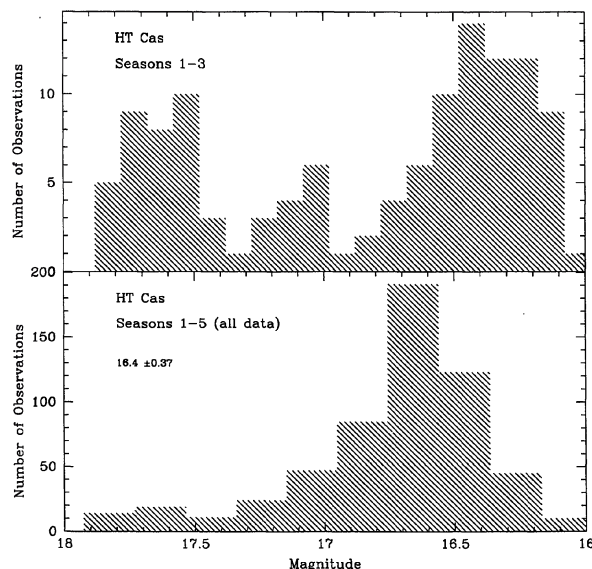


FIG. 8. Quiescent magnitude histogram of HT Cas observations made by RoboScope. Normal outbursts, superoutbursts and eclipses have been removed. The bimodal nature indicates two quiescent states (17.65 and 16.35) separated by 1.3 mag.

towards brighter magnitudes in Fig. 9 is due to inclusion of the very onset and end of outbursts from quiescence. None of the SU UMa histograms show bimodality or are skewed toward fainter magnitudes as in HT Cas, except for SU UMa. The skew in SU UMa however, is caused by the overall decrease of 0.5 mag in quiescent level during one observing season.

The only other dwarf nova with large quiescent variations we find on our program is WW Cet. As previously mentioned Warner (1987) noted that WW Cet has been seen ~ 1.5 magnitudes fainter than quiescence on occasion. WW Cet is a DN of uncertain subclass which has an orbital period of 4.22 hours. The RoboScope quiescent light curve of WW Cet over 3.5 years (Ringwald *et al.* 1995), shows erratic excursions of ± 1.0 mag about 14.0 mag lasting 5–10 days somewhat similar to HT Cas. In addition there are outbursts of up to 2.0 mag rising from 14.0 mag lasting up to 10 days.

4. CONCLUSION

Mass-transfer modulations are likely responsible for the high-state/low-state behavior seen in the VY Scl class of nova-like CVs and AM Her stars. The time scales for VY Scl behavior (low states lasting from days to years) are similar to that seen in HT Cas. Also, the fraction of nova-like CVs showing VY Scl behavior at any one time is 10%–20%, similar to the fraction of SU UMa stars inferred here. However, the amplitude of the excursions in HT Cas (1.3 mag) and in WW Cet (1.0 mag) are smaller than in nova-likes (2–6 mag). It is reasonable to consider that the quiescent variations in HT Cas might be due to the same mechanism responsible for the VY Scl behavior.

Suggestions for the origin of mass transfer modulations in CVs include evolution of the secondary star as it becomes fully convective (Spruit & Ritter 1983; Shafter 1992, refer-

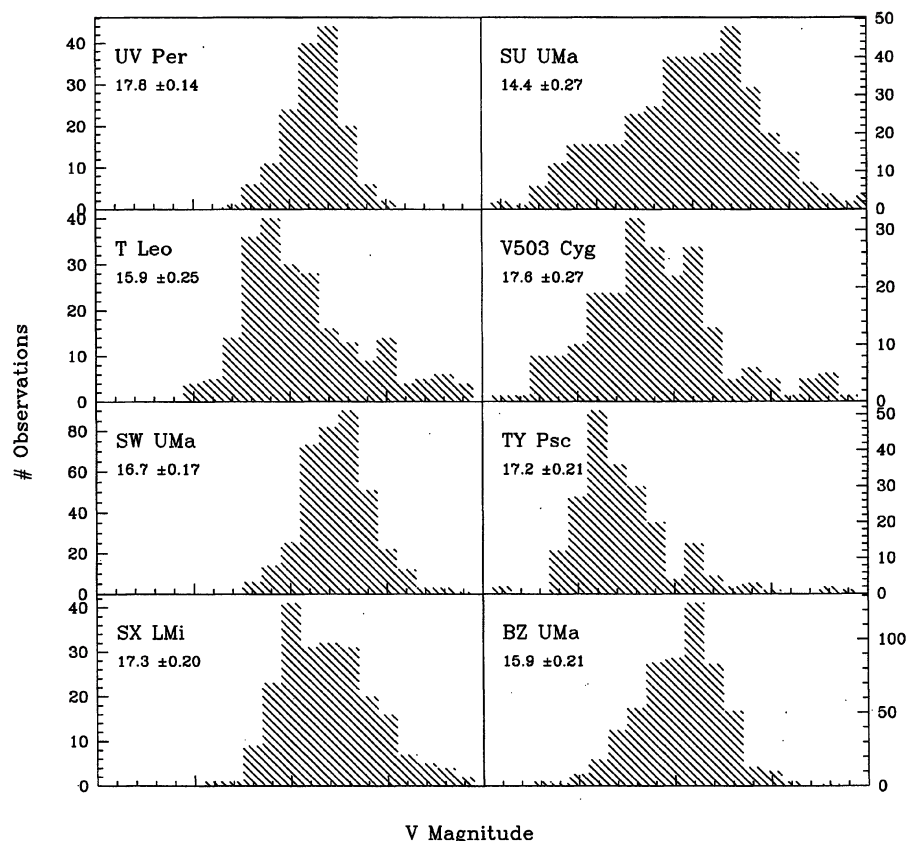


FIG. 9. Magnitude histograms of eight other SU UMa systems observed by RoboScope that have well-sampled quiescent light curves. All abscissas span 2.0 mag.

ences therein), solar-type magnetic cycles of the secondary (Warner 1988; Bianchini 1990), and perhaps dynamical instabilities in the secondary star of the type originally proposed by Bath *et al.* (1974) to explain DN outbursts. Livio & Pringle (1993) argue, by appealing to the work of Ritter (1988), that the high-state/low-state behavior in VY Scl stars cannot be caused by the same effect that turns off mass transfer at the upper end of the period gap because the time scales are too disparate. They propose instead that starspots occasionally cover the L_1 point causing the mass transfer rate to drop, resulting in the low state of VY Scl stars. The radiative-convective interface is central to the dynamo models of stellar activity. The fully convective secondaries in SU UMa CVs might therefore be expected to have rather different starspot properties from those CVs above the period gap which have more massive secondaries. These HT Cas observations suggest that whatever mechanism produces VY Scl variations above the period gap also operates below the pe-

riod gap. We also note that single stars also appear to remain active in the totally convective regime (M dwarfs), at least as judged by the strengths of coronal x-ray emission (Fleming *et al.* 1993; Pye *et al.* 1994). The starspot mechanism for mass transfer modulations in CVs has not yet been explored in detail, particularly for the regime of low mass transfer rates, low mass secondaries, and rapidly rotating secondaries as found in SU UMa systems. Pending such work we can only emphasize that large amplitude variations on time scales of weeks to years are apparently present in nearly all CV classes, an observational property successful models need to address.

We are grateful for discussions with J. Mattei about the AAVSO light curve observations of HT Cas. This research is supported by the National Science Foundation. We have also made use of the SIMBAD database, operated at CDS, Strasbourg, France.

REFERENCES

- Bath, G. T., Evans, W. D., Papaloizou, J., & Pringle, J. E. 1974, *MNRAS*, 169, 447
 Bianchini, A. 1990, *AJ*, 99, 1941
 Bond, H. E. 1980, paper presented at the 5th Annual Workshop on Cataclysmic Variables and Related Objects, University of Texas, Austin
 Fleming, T. A., Giampapa, M. S., Schmitt, J. H. M. M., & Bookbinder, J. A. 1993, *ApJ*, 410, 387
 Garnavich, P., & Szkody, P. 1988, *PASP*, 100, 1522

- Glasby, J. S. 1970, *The Dwarf Novae* (Constable, London), p. 177
- Honeycutt, R. K. 1992, *PASP*, 104, 435
- Honeycutt, R. K., Livio, M., & Robertson, J. W. 1993, *PASP*, 105, 922
- Honeycutt, R. K., & Turner, G. W. 1992, in *Robotic Telescopes in the 1990's*, edited by A. Filippenko (ASP, San Francisco), p. 77
- Honeycutt, R. K., Vesper, D., White, J., Turner, G.W., & Adams, B. R. 1990, in *CCDs in Astronomy II: New Methods and Applications of CCD Technology*, edited by A. G. D. Philip, D. J. Hayes, and S. J. Adelman (Davis, Schenectady), p. 177
- Horne, K., Wood, J. H., & Stiening, R. F. 1991, *ApJ*, 378, 271
- Howell, S. B., Szkody, P., Kreidl, T. J., Mason, K. O., & Puchnarewicz, M. 1990, *PASP*, 102, 758
- Kaluzny, J. 1987, *IAU Circ.*, 4287
- Kato, T. 1995, private communication and the Variable Star Network (VSNet)
- la Dous, C. 1994, *SSR*, 67, 1
- Livio, M., & Pringle, J. E. 1993, *ApJ*, 427, 956
- Marsh, T. R. 1990, *ApJ*, 357, 621
- Mattei, J. A. 1995a, private communication
- Mattei, J. A. 1995b, *IAUC*, 6264
- Mattei, J. A., & Stanton, R. H. 1985, *Proceedings of the 9th North American Workshop on CV's*, University of Washington
- Miles, H. G. 1976, *J. Brit. Astron. Soc.*, 86, 335
- Misselt, K. A. 1995, *PASP*, 108, 146
- O'Donoghue, D. 1992, in *Vina Del Mar Workshop on Cataclysmic Variable Stars*, edited by N. Vogt (ASP, San Francisco), p. 136
- Osaki, Y. 1985, *A&A*, 144, 369
- Patterson, J. 1981, *ApJS*, 45, 517
- Pye, J. P., Hodgkin, S. T., Stern, R. A., & Stauffer, J. R. 1994, *MNRAS*, 266, 798
- Ringwald, F. A., Thorstensen, J. R., Honeycutt, R. K., Robertson, J. W., & Smith R. C. 1995, *BAAS*, 187, 7908
- Ritter, H. 1988, *A&A*, 202, 93
- Robinson, E. L., Barker, E. S., Cochran, A. L., Cochran, W. D., & Nather, R. E. 1981, *ApJ*, 251, 611
- Shafter, A. W., Szkody, P., Liebert, J., Penning, W. R., Bond, H. E., & Grauer, A. D. 1985, *ApJ*, 290, 707
- Shafter, A. W. 1992, *ApJ*, 394, 268
- Spruit, H. C., & Ritter, H. 1983, *A&A*, 124, 267
- Vogt, N. 1982, *ApJ*, 252, 653
- Warner, B. 1987, *MNRAS*, 227, 23
- Warner, B. 1988, *Nature*, 336, 129
- Warner, B. 1995, in *Cataclysmic Variable Stars*, edited by A. King, D. Lin, S. Maran, J. Pringle, and M. Ward (Cambridge University Press, Cambridge), p. 187
- Wenzel, W. 1987, *Astron. Nachr.*, 1, 75
- Wood, J. H., Naylor, T., Hassall, B. J. M., & Ramseyer, T. F. 1995, *MNRAS*, 273, 772
- Young, P., Schneider, D. P., & Shectman, S. A. 1981, *ApJ*, 245, 1035
- Zhang, E. H., Robinson, E. L., & Nather, R. E. 1986, *ApJ*, 305, 740