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Parallax and Distance Estimates for Twelve Cataclysmic Variable Stars [1]

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ABSTRACT

We report parallax and distance estimates for twelve more cataclysmic binaries and related objects observed with the 2.4m Hiltner telescope at MDM Observatory. The final parallax accuracy is typically ∼ 1 mas. Notable results include distances for V396 Hya (CE 315), a helium double degenerate with a relatively long orbital period, and for MQ Dra (SDSSJ155331+551615), a magnetic system with a very low accretion rate. We find that the Z Cam star KT Persei is physically paired with a K main-sequence star lying 15 arcsec away. Several of the targets have distance estimates in the literature that are based on the white dwarf's effective temperature and flux; our measurements broadly corroborate these estimates, but tend to put the stars a bit closer, indicating that the white dwarfs may have rather larger masses than assumed. As a side note, we briefly describe radial velocity spectroscopy that refines the orbital period of V396 Hya to 65.07 ± 0.08 min.

Subject headings: stars – individual (HT Cas, KT Per, IR Gem, DW Cnc, VV Pup, SW UMa, BZ UMa, AR UMa, V396 Hya, QS Vir, MR Ser, MQ Dra); stars – binary; stars – variable.

"...Obs of Sirius must be taken as far apart as possible, mustn't they,— at least six months of what the World no doubt sees as Idleness, whilst the Planet, in its good time,

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[1] Based on observations obtained at the MDM Observatory, operated by Dartmouth College, Columbia University, Ohio State University, the University of Michigan, and Ohio University.

cranketh about, from one side of its Orbit to the other, the Base Line creeping ever longer, the longer the better...how is any of that my fault?" – Neville Maskelyne, as imagined by Thomas Pynchon in *Mason & Dixon.* (Pynchon 1997)

1. Introduction

Cataclysmic variables (CVs) are interacting binary star systems in which a white dwarf accretes matter from a close companion, which usually resembles a main-sequence star. Warner (1995) has written an excellent monograph on CVs.

This is the second in a series of papers presenting parallax and distance estimates for selected CVs and related objects. The introduction to the first paper (Thorstensen 2003; hereafter Paper I) outlines some of the indirect methods used to estimate CV distances, and the situation up until that point. Since then, more parallaxes have been measured using the Fine Guidance Sensor (FGS) on the Hubble Space Telescope (HST) (Harrison et al. 2004; Beuermann et al. 2003, 2004; Roelofs et al. 2007a). While the FGS has the best astrometric precision of any instrument currently available (save for VLBI at radio frequencies; Reid 2007), the number of parallaxes that can be measured with FGS is sharply limited. Fortunately, parallaxes accurate to ~ 1 milliarcsec (mas) can be obtained from the ground (Monet et al. 1992; Paper I).

The parallax program has been expanded to include ~ 60 stars discovered in the Lépine-Shara Proper Motion survey (Lépine & Shara 2005), headquartered at the American Museum of Natural History (AMNH). AMNH and Dartmouth both have access to the MDM telescopes, so we are coordinating our efforts and obtaining more frequent observations. Results on these objects will be published elsewhere.

In Section 2, we briefly summarize our procedures, with emphasis on refinements implemented since Paper I. Section 3 details the measurements of the individual stars and their distances. In Section 4, we present a summary and discussion.

2. Procedures and Targets

The observation and reduction protocols used for this study are nearly identical to those described in Paper I. We summarize that lengthy discussion here for the convenience of the reader.

All the images are from the 2.4 m Hiltner telescope at MDM Observatory. A 2048^2 SITe CCD detector is used, with the readout cropped to 1760^2 because of vignetting by the 50 mm filters used. The 24 μm pixels project to $0''.275$ on the sky. An I-band filter is used for all the parallax observations; this minimizes differential color refraction (DCR) effects (Monet et al. 1992). Exposure times are for the most part fairly short, typically 90 s, in order to avoid saturating the program object or the main reference stars, but this varies from field to field. We center the image on the object to within a few arcseconds in order to keep a consistent set of reference stars in the field of view. In a typical visit to an object, 6 to 10 exposures are obtained to average out the astrometric noise and to permit rejection of images that show especially large astrometric scatter. Median images of the twilight sky serve for flat field correction. When conditions are clear, we obtain one or two images of the program field in the V filter, and also observe standard star fields selected from Landolt (1992) to derive I magnitudes and $V - I$ colors for the program and reference stars.

Reduction and analysis proceed almost exactly as described in Paper I, but with greater automation of the routine steps. The reduction and analysis routines make heavy use of the scripting capabilities of the PyRAF[2] package.

Since Paper I we have measured the differential color refraction more precisely than before. In that paper we used a value of 7 mas per unit $V - I$ per unit $\tan Z$ for the DCR coefficient, but a re-measure gives a value of 5 in the same units. This also agrees better with the value we had calculated using stellar energy distributions and the atmospheric dispersion curve (see Paper I). Adopting the new value makes little difference in our results, since we take pains to observe within ±2 hr of the meridian – more usually ±1 hr – where the effect of DCR should be relatively small and consistent.

The astrometric reduction yields the relative parallax $\pi_{\rm rel}$ and the relative proper motions $[\mu_X, \mu_Y]$ – all these quantities are relative to the reference stars chosen. We make no attempt to correct the proper motions to an inertial frame, but we do estimate the mean parallax of the reference stars using their magnitudes and colors (see Paper I), resulting in a correction to $\pi_{\rm rel}$; typically the estimated absolute parallax $\pi_{\rm abs}$ is larger than $\pi_{\rm rel}$ by ~ 1 mas.

In the last step of our analysis we use a Bayesian procedure that in principle generates an overall best estimate of the distance, taking into account all the available information. The procedure includes (a) a Lutz-Kelker correction, which accounts for the bias introduced by the rapidly increasing volume of space represented as the parallax becomes small; (b) a distance weighting based on the observed proper motion *and* an *assumed* velocity distribution for the CV population; (c) any prior distance estimates based on independent indicators. These include estimates based on the spectral type and apparent magnitude of the secondary, the solid angle subtended by the white dwarf as deduced from UV spectrophotometry, and other methods. When the relative precision of the parallax is good, the prior information makes little difference, but it becomes more important as the parallax precision degrades. Paper I discusses the Bayesian procedure at length.

Although we have not significantly changed our analysis procedures, we have noted some effects

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[2] PyRAF is a Python-language wrapper for the IRAF package, written at Space Telescope Science Institute. It is available at `http://www.stsci.edu/resources/software_hardware/pyraf`. IRAF, the Image Reduction and Analysis Facility, is distributed by the National Optical Astronomy Observatory, which is operated under contract to the National Science Foundation.

with more experience.

We are more aware of how strongly the photon statistics affect the centroiding accuracy. The brightest stars in the field almost always show very little scatter – less than 5 mas vector error in a single exposure in the best cases – while faint stars show very large scatter. We are now more careful to select longer exposure times for the fainter objects (which, unfortunately, overexposes some bright potential reference stars).

We have also found that the correlation between the seeing, as measured by the full-width half maximum (FWHM) of the point-spread function (PSF), correlates only approximately with the astrometric quality of the image, as judged from the scatter in the the reference star positions. Useful astrometry can come from mediocre seeing, and images taken in good seeing can sometimes show surprisingly large astrometric scatter. When the seeing is bad enough, the expected correlation does appear – images with very poor seeing (FWHM $>$ 2.5 arcsec) are essentially useless for parallax.

Finally, we have found that typically at least two seasons of data are needed in order for us to feel confident that the astrometric solution has 'settled', because the proper motion in each axis needs to be measured independently of the parallax. The statement attributed to Maskelyne in this paper's epigraph is evidently too optimistic.

We selected targets using informal criteria, which included the following: (a) We found a distance estimate in the literature, which suggested that the parallax would be detectable, or that it was astrophysically interesting to establish a lower limit on the distance. (b) The proper motion was relatively high. (c) The apparent magnitude was relatively bright for the subclass. (d) A parallax was requested by a colleague.

Table 1 lists the stars observed, ordered by constellation and variable star name, and the epochs at which we observed them. We discuss each star in turn.

3. Results

Table 2 lists positions, magnitudes, relative proper motions, and relative parallaxes for *all* the measured stars in all the fields. The proper motions are relative to the mean of all the stars in the field; they have not been reduced to a non-rotating reference frame. Table 3 lists the parallaxes and distance estimates for the program stars. The different distance estimates in Table 3 take into account different amounts of Bayesian prior information.

We now discuss the individual stars in turn, ordered as they are in the GCVS (alphabetically by full constellation name; within constellations, by variable star designation; Kholopov et al. 1999).

3.1. DW Cnc

DW Cnc is a remarkable CV, unique in that the radial velocities of its very strong emission lines are modulated on two distinct, incommensurate periods, 86.1015(3) and 69.9133(10) minutes, each of these periods having similar velocity amplitude. The light curve is modulated at the beat frequency of the two velocity periods. The three periods are most readily explained as the orbital period $P_{\rm orb}$, the rotation period of a magnetized white dwarf, and the orbital sideband (Patterson et al. 2004; Rodríguez-Gil et al. 2004).

Although the parallax is determined with good precision, the relative error σ_π/π is substantial, leading to a sizeable Lutz-Kelker correction. Because the system is unusual, we unweighted the distance prior in the Bayesian analysis by assuming a large uncertainty in luminosity. We find a proper motion $[\mu_X, \mu_Y] = [-26, +5]$ mas yr^{-1}, consistent with the USNO B value of $[-22\pm5, +0\pm2]$ (Monet et al. 2003). Our final distance estimate, $257(+79, -52)$ pc, puts DW Cnc near the peak of prior distance probability based on the proper motion alone, which in turn is based on the observation that most CVs have modest space velocities (Paper I).

Patterson et al. (2004) reported extensive photometry giving $V = 14.8$ for DW Cnc, which corresponds to $M_V = 7.8$ at 250 pc. This is within the range of values predicted by the Warner (1987) relation for an outbursting dwarf nova at $P_{\rm orb} = 86$ min; literal agreement would require an inclination $i \sim 83$ degrees. An inclination this large is ruled out by the lack of eclipses. The Warner (1987) relation was derived for dwarf novae at maximum light, and DW Cnc is not a dwarf nova; nonetheless, DW Cnc is clearly much more luminous than short-period dwarf novae at minimum light. It is evidently a rare example of a novalike variable with $P_{\rm orb} < 2$ hr.

3.2. HT Cas

HT Cas is a well-studied, deeply-eclipsing dwarf nova of the SU UMa subclass, with $P_{\rm orb} = 106$ min. Feline et al. (2005) present recent high-speed photometry and summarize some of the earlier work on this object. Because HT Cas eclipses, there is a long history of detailed time-resolved studies aimed at mapping the disk emission and constraining the white dwarf radius, which has led to several estimates of the distance. Marsh (1990) detected the secondary star, classified it as M5.4 ± 0.3, and measured the secondary's contribution to total light at eclipse. Horne et al. (1991) derived dynamical constraints using high-speed photometry of the eclipses; from these, and the secondary's contribution, they estimated a distance of 135 pc. Vrielmann et al. (2002) give a critical discussion of previous distance estimates, and using a different mapping technique, derive a distance of 207 ± 10 pc.

The parallax measurement decisively favors the shorter distance; the Vrielmann et al. (2002) distance is essentially excluded. While the ~ 130 pc distance favored by Marsh (1990) is a little longer than our astrometric distance, it lies well within the uncertainties. Our final Bayesian distance estimate includes prior distance information; for this we adopted a rough average value of previous estimates and assumed an uncertainty generous enough to includes both the longer and shorter distances, namely $m - M = 6.1 \pm 1$, or 166(+97, −61) pc. The parallax is accurate enough that this assumption increases the distance estimate by only 8 pc.

The proper motion found here, $[\mu_X, \mu_Y] = [+27, -14]$ mas yr^{-1}, agrees well with that listed in the Lick NPM2 catalog, $[+28, -10]$ mas yr^{-1} (Hanson et al. 2004). Assuming that the distance is at the far end of our 1σ error bar, the transverse velocity referred to the LSR is only ~ 6 km s^{-1}. Due to the faintness of the secondary, we were unable to find a precise systemic radial velocity γ in the literature, but emission-line studies suggest that γ is some tens of km s^{-1} or less (Marsh 1990; Young et al. 1981). The kinematics of HT Cas are clearly those of the disk.

3.3. MQ Dra

MQ Dra was discovered in the Sloan Digital Sky Survey (Szkody et al. 2003a), in which it was called SDSS J155331.12+551614.5. The spectrum shows a white dwarf with a ~ 60 MG magnetic field, and only weak emission features, indicating a very low accretion rate (Szkody et al. 2003b). It is therefore a fine example of a low accretion rate polar, or LARP (see, e.g., Schmidt et al. 2005). It has $P_{\rm orb} = 4.39$ h, and the secondary star's spectral type is ∼M4.5 (Harrison et al. 2005). The secondary's contribution to the light leads to a distance estimate of 130 to 180 pc (Schmidt et al. 2005; Szkody et al. 2008).

Although the field of MQ Dra is somewhat sparse, the parallax is measured with a formal uncertainty of only 0.7 mas; the scatter of apparent field star parallaxes suggests that this is a realistic uncertainty, but we adopt 1.0 mas to be conservative and to allow for the unmodeled uncertainty in the correction from $\pi_{\rm rel}$ to $\pi_{\rm abs}$. Our measured relative proper motion $[\mu_X, \mu_Y] = [-31, +6]$ mas yr^{-1}, agrees well the proper motion listed in the USNO B, which is $[-28 \pm 5, -8 \pm 3]$ in the same units (Monet et al. 2003). The parallax is accurate enough that the various corrections do not strongly affect the distance estimate. For the final Bayesian estimate, we include a secondary-based distance modulus corresponding to $d = 150(+60, -40)$ pc. Combining this with the parallax and proper motion yields $d = 162(+27, -21)$ pc for the final estimate.

3.4. IR Gem

IR Gem is an SU UMa-type dwarf nova with $P_{\rm orb} = 98.5$ min (Feinswog et al. 1988; Fu et al. 2004). The parallax is so small that it is barely detected, despite the large and favorable set of comparison stars available at IR Gem's Galactic latitude. The proper motion is sizeable; we measure $[\mu_X, \mu_Y] = [+53.9, -22.3]$ mas yr^{-1}, in good agreement with the UCAC2 catalog (Zacharias et al. 2004), which gives $[+51.9 \pm 3.4, -28.8 \pm 3.4]$ mas yr^{-1}. Because of the small parallax, the Lutz-Kelker correction depends critically on the uncertainty adopted, which we estimate conservatively using the scatter in the fitted parallaxes of other stars in the field (see Paper I).

In the case of IR Gem, $\pi_{\rm abs}/\sigma_\pi < 4$, so there is no local maximum in the Lutz-Kelker parallax probability function; the parallax alone does not formally give a distance. With such weak parallax evidence, the Bayesian priors steer the distance estimate. For a distance prior, we use the Warner (1987) relations. The General Catalog of Variable Stars (GCVS; Kholopov et al. 1999) lists $V = 10.7$ at maximum light. Since superoutbursts are ~ 1 magnitude brighter than the normal outbursts for which the Warner (1987) relation is calibrated, we adopt $V = 11.7$ in computing the distance prior. Applying the relation requires an inclination estimate; Feinswog et al. (1988) note that the radial velocity amplitude is low, which suggests an orbital inclination not too far from face-on. At low inclinations, the correction is fortunately nearly constant; we arbitrarily adopt $i = 30$ degrees, leading to a prediction of $M_V(\max) = 4.6$ for $P_{\rm orb} = 98$ min. The resulting distance is ~ 250 pc. We adopt an uncertainty of ± 1 mag in the distance modulus for the Bayesian prior.

The Bayesian results are as follows. The large proper motion, interpreted using the space velocity probability density assumed in Paper I, eases the Lutz-Kelker problem and results in a 50-th percentile distance near 410 pc. The prior distance estimate decreases this to 358(+104, −86) pc. At 358 pc, the transverse velocity corresponds to 98 km s^{-1} referred to the LSR; including a systemic radial velocity $\gamma = +60$ km s^{-1} (estimated from Feinswog et al. 1988) gives a space velocity of ~ 115 km s^{-1}. This puts IR Gem out on the high-velocity tail of the assumed CV velocity distribution.

3.5. V396 Hya = CE 315

V396 Hya is an AM CVn-type system, in which the secondary is evidently an evolved degenerate star with no hydrogen remaining. It was discovered as a high proper motion star in the Calan-ESO survey (Ruiz et al. 2001a), and designated CE 315 (Ruiz et al. 2001b). Its orbital period, 65 min, is the longest of all known AM CVn systems. Systems with degenerate secondaries tend to evolve toward longer orbital periods, so V396 Hya is likely to be among the most highly evolved AM CVn stars known. Bildsten et al. (2006) found that, for these relatively long-period AM CVn stars, the luminosity arises largely from the accreting white dwarf, and predicted a system luminosity. They used a preliminary version of our parallax measurement to show that the luminosity of V396 Hya agrees well with theory. At $V = 17.6$, V396 Hya is just a little too faint for the HST FGS.

In addition to our parallax determination, we have some spectra of V396 Hya taken with the Hiltner telescope and modular spectrograph; the instrumentation, procedures, and reductions were essentially as described by Thorstensen et al. (2004). We took 35 exposures, most of them 5 min, on the nights of 2001 May 14, 15, 16, and 17 UT. The average spectrum appeared very similar to that shown by Ruiz et al. (2001b). We measured radial velocities of the wings of the HeI λ5876 emission line using a double-gaussian convolution algorithm (Schneider & Young 1980a;

Shafter 1983), and searched for periods using a 'residual-gram' algorithm (Thorstensen et al. 1996). The Ruiz et al. (2001b) period was clearly detected as the strongest among several aliases (which are inevitable because the observations are clustered modulo 24 hours). By fitting the velocities from all the nights, we refine P_{orb} to 65.07 ± 0.08 min. The emission line profiles in our average spectrum are mostly triple-peaked, as described by Ruiz et al. (2001b). In an effort to constrain the systemic radial velocity γ, we fit the tops of the central peaks with Gaussians using the interactive `splot` command in IRAF. The different lines gave velocities ranging from +30 to +70 km s^{-1} (heliocentric); from a weighted average, we estimate $v = +45 \pm 20$ km s^{-1} for the line core. It is entirely possible that this does not accurately reflect the systemic velocity.

The parallax is determined to good relative accuracy and dominates the Bayesian estimate of distance. We find a proper motion of $[-277, -52]$ mas yr^{-1}, significantly smaller than the Calan-ESO value, but in reasonable agreement with the USNO B, which lists $[-264, -30]$ mas yr^{-1} (Monet et al. 2003). This large proper motion more than compensates for the Lutz-Kelker effect in the Bayesian calculation, so the 50th-percentile distance of 92 pc is essentially equal to $1/\pi_{\mathrm{abs}}$. The final estimate is slightly larger than the 77 pc preliminary estimate used by Bildsten et al. (2006), but their conclusions should be essentially unchanged. Some insight into the kinematics of this system can be had by computing the tangential velocity, referring it to the LSR, and rotating into Galactic coordinates; for a distance of 90 pc, this yields $[U, V, W] = [+79, -68, 0]$ km s^{-1} – oddly enough, nearly parallel to the plane of the Galaxy. If we adopt $\gamma = +45$ km s^{-1}, this becomes $[+57, -95, +28]$ km s^{-1}. In any case, these are not the kinematics of the thin disk (though the system apparently does not stray far from the plane). It is interesting to note that another AM CVn system, GP Com, evidently also has a high space velocity (Thorstensen 2003). It may be significant that both V396 Hya and GP Com, two of only ∼18 known AM CVn stars (Roelofs et al. 2007b), also belong in the small handful of CVs that were first discovered because of their proper motions. This suggests that AM CVn systems are fairly common, or that many are members of an old population, or both. On the other hand, Roelofs et al. (2007a) suggest that the space density is not particularly large, based on the HST parallaxes of a sample of AM CVn stars.

3.6. KT Per

KT Per is a Z Cam-type dwarf nova with P_{orb} near 3.90 hr (Ratering et al. 1993; Thorstensen & Ringwald 1997). We chose it for parallax determination because of its substantial proper motion in the UCAC2, $[\mu_X, \mu_Y] = [+63, -5]$ mas yr^{-1} (Zacharias et al. 2004). Also, Thorstensen & Ringwald (1997) estimated a distance of 245 ± 100 pc based on the M3 secondary star, which is close enough for parallax to provide a useful check.

Our astrometry shows that the $V = 15.19$ field star located 15.4 arcsec west and 2.3 arcsec north of KT Per is evidently a physical companion, sharing with KT Per a nearly identical large proper motion and parallax. We obtained spectra of this star with the Hiltner 2.4m telescope and calibrated them using observations of flux standards. We have a library of spectra of K dwarfs classified by Keenan & McNeil (1989), taken with the same instrument. Using these for comparison, we estimate the spectral type of the companion to be K4.5 ± 1 subclass. Pickles (1998) tabulates mean colors as a function of spectral type. We measure $V - I = +1.59$ for this star, which, by his table, would indicate a K7 to M0 star, significantly later than observed. However, La Dous (1991) estimated $E(B-V) = +0.2$ for KT Per, using the strength of the 2200 Å extinction feature in archival IUE spectra. Combining this with $E(V-I)/E(B-V) = 1.35$ (He et al. 1995) yields $(V-I)_0 = 1.32$, which is nicely consistent with the spectral type. As a check, we note the reddening maps of Schlegel, Finkbeiner, & Davis (1998) give $E(B-V) = 0.32$ for the total Galactic extinction in this direction ($l = 130^\circ.2, b = -11^\circ.3$); it is not implausible that KT Per is extinguished by a substantial fraction of this total. Taking Pickles' mean value of $M_V = 7.64$ for this star, and taking $A_V = 3.2E(B-V)$, yields a spectroscopic distance modulus $(m-M)_0 = 6.9$, corresponding to 240 pc, in close agreement with the somewhat cruder estimate from the secondary star. Using cross-correlation methods described in Thorstensen et al. (2004), we find the companion's heliocentric radial velocity to be -2 ± 10 km s^{-1}.

As table 3 shows, the parallax is small, but clearly detected, and the distance derived from the parallax, while broadly consistent with the photometric estimate, is a bit shorter. The compromise Bayesian distance estimate is 180(+36, −28) pc; at 180 pc, the space velocity with respect to the LSR is 38 km s^{-1}, not too large for a disk population object.

3.7. VV Pup

VV Pup was among the first CVs to be recognized as an AM Herculis star, or polar (Tapia 1977; Bond et al. 1977). Araujo-Betancor et al. (2005) detect the white dwarf in ultraviolet spectra, and derive distances from model-atmosphere fits. They fit both one- and two-component models, giving somewhat different results; the full range of their estimate can be roughly summarized as 169 ± 35 pc, where the error bar is largely dominated by the unknown mass (hence radius) of the white dwarf. Howell et al. (2006) measured radial velocities of the secondary star in the infrared during a low state, and infer a distance of ~ 120 pc from its K-band magnitude; arbitrarily assigning this an uncertainty of ±50 pc and combining it with the white-dwarf based distance gives a weighted average of 153 ± 29 pc for the prior estimate. The astrometric distance found here is somewhat shorter than this, namely 114(+18, −14) pc; combining these leads to a final best guess distance of 124(+17, −14) pc. At this distance the relative proper motion corresponds to a tangential velocity of 43 km s^{-1}, referred to the LSR. It is therefore a little surprising that Howell et al. (2006) find a systemic velocity $\gamma = -130 \pm 18$ km s^{-1} from their observations of the secondary star, as that would imply a large space velocity directed mostly toward us. Although previous radial-velocity studies (e.g. Schneider & Young 1980b; Cowley et al. 1982; Diaz & Steiner 1994) were based on observations of emission lines in the high state, and hence may not have measured γ accurately, they do not give any indication of such a large approach velocity. Howell et al. (2006) point out that their velocities are based on an effective wavelength they assume for the blended 2.2 μm sodium doublet; an inappropriate choice for this would throw their γ velocity off. Without a reliable γ, we cannot find a full space velocity, but the transverse components suggest that VV Pup has the kinematics of the disk population.

3.8. MR Ser

Liebert et al. (1982) called attention to PG 1550+191, later named MR Ser, as the only AM Her star discovered in the Palomar-Green ultraviolet survey. Mukai & Charles (1986) detected TiO absorption bands and estimated the spectral type of the secondary as M5-M6. Using the assumptions that the secondary fills its Roche lobe and obeys a zero-age main sequence mass-radius relation, they estimated $d = 142$ pc from the secondary; Schwope et al. (1993), using similar methods, estimated $d = 139 \pm 13$ pc independently. As with VV Pup, Araujo-Betancor et al. (2005) detected the white dwarf in HST ultraviolet spectra, and again fitted one- and two-component atmospheres, yielding respectively $180(+23, -30)$ and $160(+18, -26)$ pc. Combining all these, we adopt 155 ± 25 pc as the prior distance estimate. Once again, the astrometric distance – $113(+14, -12)$ pc – is somewhat shorter than the prior estimate. This suggests that the mass of the white dwarf is fairly high, resulting in a smaller radius and hence that the solid angle inferred from the atmosphere fits corresponds to a shorter distance. The secondary star's surface brightness may also have been overestimated. In any case, the prior estimate increases the best-guess distance to $126(+14, -12)$ pc from its purely astrometric value.

The transverse velocity at the nominal distance is 44 km s^{-1} referred to the LSR; Schwope et al. (1993) find a mean velocity $\gamma = 7 \pm 18$ km s^{-1} for the sodium infrared doublet, which tracks the secondary's photosphere and hence should give a trustworthy reading of the systemic velocity. Including this gives an LSR space velocity of 49 km s^{-1}.

3.9. SW UMa

SW UMa is an SU UMa-type dwarf nova with $P_{\rm orb} = 81.8$ min (Shafter et al. 1986). Gänsicke et al. (2005) fit white dwarf model atmospheres to ultraviolet spectra to find $d = 159 \pm 22$ pc, after allowing for variation of the white dwarf's assumed mass in the range 0.35 - 0.9 M$_\odot$. We began taking astrometric images of this target in 1999 January, and then dropped it from the program for a time before resuming in 2004. The relative (not absolute!) proper motion is therefore determined very precisely, with formal errors near 0.2 mas yr^{-1} in each coordinate. The parallax is detected well and gives a distance in good agreement with the prior distance estimate, without substantially improving on its formal precision. The proper motion is fairly modest and implies an LSR transverse velocity of 25 km s^{-1} at the nominal distance. Combining this with $\gamma = -10$ km s^{-1} (estimated from Fig. 6a of Shafter et al. 1986) increases this only slightly to 27 km s^{-1}, comfortably consistent with disk-star kinematics.

3.10. AR UMa

This AM Her-type system has an unusually strong white-dwarf magnetic field of ~ 230 MG (Schmidt et al. 1996; Hoard et al. 2004). Remillard et al. (1994) found $P_{\rm orb} = 1.93$ h and detected features from the secondary star, which they classified as M6. Based on this, they estimated $d = 88 \pm 18$ pc. The present measurement agrees closely with this, yielding $d = 86(+10, -8)$ pc from the parallax and kinematic information alone; including the Remillard et al. (1994) estimate does not change this significantly. AR UMa is evidently one of the nearest magnetic CVs. At 86 pc the transverse velocity referred to the LSR is 16 km s^{-1}.

3.11. BZ UMa

BZ UMa is an SU UMa-type dwarf nova. Ringwald et al. (1994) found $P_{\rm orb} = 98$ min and detected an M5.5 ± 0.5 secondary, from which they estimated $d = 110(+44, -51)$ pc; however, a JHK measurement yielded an alternate constraint, $d > 140$ pc. The reference frame is rather sparse, and the parallax is only just detected; the astrometric distance (including proper motion) is $260(+93, -58)$ pc. Mixing in the secondary-based distance modulus, unweighted by a generous 1.4 magnitude estimated uncertainty, brings the distance estimate down to $228(+56, -38)$ pc. At this distance, the modest proper motion corresponds to a tangential velocity of 35 km s^{-1} referred to the LSR.

3.12. QS Vir = EC13471-1258

O'Donoghue et al. (2003) published an extensive study of this system, which is an eclipsing WD + dMe system with a period of $3^{\rm h}\ 37^{\rm m}$. While not showing clear evidence of mass transfer at present, the system appears consistent with a hibernating CV, with a secondary just filling its Roche lobe. The favorable circumstances allowed O'Donoghue et al. (2003) to determine the mass and radius of the white dwarf to be 0.78 ± 0.04 $\mathrm{M}_{\odot}$ and 0.011 ± 0.001; a white-dwarf model atmosphere yielded a distance of 48 ± 5 pc. The measurement here was undertaken as an independent check of this measurement. The astrometric distance proves to be $49(+5, -4)$ pc, in near-perfect agreement with their result, but unfortunately not significantly refining the distance estimate.

4. Conclusion

We have measured, or at least constrained, the distances to a sample of twelve CVs. As with Paper I, we do not find any striking discrepancies with previous work. Our most significant results are as follows:

1. The luminosity of DW Cnc is relatively high for its short orbital period, making it an unusual short-period novalike system.
2. The parallax of HT Cas decisively favors the shorter of two possible distance ranges in the literature.
3. V396 Hya is the first long-period AM CVn star with a known distance.
4. KT Per forms a wide physical pair with a K dwarf. This may be useful as a proxy for estimates of the system's age and metallicity.
5. Our distance for QS Vir is in essentially perfect agreement with a prior estimate by O'Donoghue et al. (2003).
6. For VV Pup and MR Ser, both of which are magnetic systems, our distances are somewhat shorter than those determined from white dwarf model atmosphere fits. The discrepancy is not too serious, but it may indicate that the white dwarfs in these systems are more massive than had been assumed.

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Table 1. Journal of Observations

Star	$N_{\rm ref}$	$N_{\rm meas}$	$N_{\rm pix}$	Epochs
DW Cnc	37	80	106	2004.03(17) , 2004.16(17) , 2004.87(7) , 2005.21(2) , 2005.30(9) , 2005.88(12) , 2006.04(15) , 2006.19(8) , 2006.84(7) , 2007.07(4) , 2008.05(8)
HT Cas	85	158	130	2004.03(15) , 2004.86(11) , 2005.71(15) , 2005.88(11) , 2006.04(12) , 2006.64(18) , 2006.84(14) , 2007.07(6) , 2007.65(5) , 2007.73(7) , 2007.91(7) , 2008.05(9)
MQ Dra	29	62	124	2003.46(17) , 2004.16(15) , 2004.47(27) , 2005.21(12) , 2005.30(4) , 2005.48(14) , 2005.70(5) , 2006.20(2) , 2006.38(6) , 2006.44(7) , 2007.23(9) , 2007.48(6)
IR Gem	48	75	174	2003.08(10) , 2004.03(22) , 2004.16(23) , 2004.87(9) , 2005.08(9) , 2005.20(8) , 2005.88(11) , 2006.04(25) , 2006.20(15) , 2006.83(10) , 2007.07(8) , 2007.24(7) , 2008.04(9) , 2008.15(8)
V396 Hya	43	82	199	2003.08(17) , 2003.46(20) , 2004.03(9) , 2004.16(24) , 2004.47(34) , 2005.21(13) , 2005.30(2) , 2005.49(8) , 2006.03(12) , 2006.20(4) , 2006.38(8) , 2006.44(10) , 2007.07(9) , 2007.23(11) , 2007.47(3) , 2008.05(9) , 2008.37(1) , 2008.47(5)
KT Per	49	82	104	2003.77(1) , 2004.03(19) , 2004.87(14) , 2005.08(5) , 2005.70(24) , 2005.87(12) , 2006.03(14) , 2006.66(5) , 2007.65(2) , 2007.73(8)
VV Pup	78	131	153	2003.08(12) , 2004.03(18) , 2004.16(16) , 2004.87(9) , 2005.08(6) , 2005.20(10) , 2005.30(8) , 2005.88(12) , 2006.03(14) , 2006.20(16) , 2006.83(12) , 2007.07(8) , 2007.23(1) , 2008.05(5) , 2008.15(6)
MR Ser	47	73	107	2003.46(1) , 2004.47(16) , 2005.21(10) , 2005.30(9) , 2005.48(10) , 2005.71(6) , 2006.20(10) , 2006.37(8) , 2006.44(10) , 2007.23(10) , 2007.34(4) , 2007.47(8) , 2008.37(5)
SW UMa	19	76	120	1999.05(27) , 2000.03(18) , 2000.26(9) , 2004.03(9) , 2004.16(6) , 2004.87(5) , 2005.20(9) , 2005.88(8) , 2006.04(8) , 2006.20(6) , 2006.84(8) , 2007.23(7)
AR UMa	19	44	106	2003.08(2) , 2005.08(22) , 2005.21(7) , 2005.30(7) , 2005.89(9) , 2006.03(11) , 2006.20(10) , 2006.37(8) , 2007.07(4) , 2007.23(10) , 2008.04(5) , 2008.14(7) , 2008.37(4)
BZ UMa	19	50	87	2000.26(1) , 2002.81(2) , 2004.03(15) , 2005.88(12) , 2006.03(18) , 2006.20(10) , 2006.83(3) , 2007.07(8) , 2007.23(10) , 2008.04(8)
QS Vir	32	72	131	2003.08(9) , 2003.46(6) , 2004.03(2) , 2004.16(18) , 2004.47(26) , 2005.21(14) , 2005.30(10) , 2005.48(6) , 2006.05(1) , 2006.20(14) , 2006.37(5) , 2006.44(10) , 2007.23(5) , 2007.35(5)

Note. — Overview of the data included in the parallax solutions. $N_{\rm ref}$ is the number of reference stars used to define the plate solution, $N_{\rm meas}$ is the total number of stars measured, and $N_{\rm pix}$ is the number of images used. The epochs represent different observing runs, and the numbers in parentheses are the number of images included from each run.

Table 2. Positions, Magnitudes, Parallaxes, and Proper Motions

α [h:m:s]	δ [°:′:″]	Weight	σ [mas]	V	$V-I$	$\pi_{\rm rel}$ [mas]	μ_X [mas yr^{-1}]	μ_Y [mas yr^{-1}]	σ_μ [mas yr^{-1}]
DW Cnc:									
7:58:51.44	+16:13:20.6	0	12	18.34	0.77	-2.3 ± 1.8	−3.2	3.0	1.0
7:58:51.42	+16:19:32.2	1	9	19.05	1.65	-0.2 ± 1.3	11.7	−2.2	0.7
7:58:52.07	+16:17:23.0	1	12	18.78	0.61	0.2 ± 1.8	1.7	1.5	1.0
∗7:58:53.04	+16:16:45.2	0	5	15.00	0.52	4.0 ± 0.8	−25.7	4.8	0.4
7:58:53.47	+16:15:18.6	1	6	17.60	0.82	-0.2 ± 1.0	−1.4	−2.1	0.5
7:58:54.04	+16:16:40.4	1	12	18.18	0.25	0.2 ± 1.8	−0.2	1.7	1.0

Note. — Parameters for all measured stars in all the fields. The program star in each field is marked with an asterisk. The celestial coordinates are from mean CCD images and are referred to the USNO A2.0 or UCAC2, which are aligned with the ICRS; the epochs of the images used are typically around 2005. Coordinates should be accurate to $\sim 0''.3$ external and somewhat better than this internally. A 1 or 0 in the next column indicates whether a star was used as a reference star. The next column gives the scatter around the best astrometric fit (see text); very large scatter indicates some kind of problem with the centering of that particular star (caused, for example, by saturation on some images). The V and $V-I$ colors come next, with typical external uncertainties of 0.05 mag. Next come the fitted parallaxes, proper motions in X and Y, and the uncertainty in the proper motion (per coordinate). The full table available in the electronic version of this paper; a small sample is shown here as a guide to its form and content.

Table 3. Parallaxes, Proper Motions, and Distances

Star	π_{rel}	π_{abs}	$[\mu_\alpha, \mu_\delta]_{\mathrm{rel}}$	$1/\pi_{\mathrm{abs}}$
	d_{LK}	$d(\pi, \mu)$	$(m - M)$ prior	$d(\pi, \mu, m - M)$
DW Cnc	4.0 ± 0.8[1.0]	4.8(1.0)	−25.7, +4.8(0.4)	208(+55, −36)
	268	257(+79, −52)	···	257(+79, −52)
HT Cas	7.9 ± 0.8[1.0]	9.0(1.1)	+27.3, −13.9(0.6)	111(+16, −12)
	118	123(+20, −15)	6.1; 1.0	131(+22, −17)
MQ Dra	5.7 ± 0.7[1.0]	6.7(1.0)	−30.8, 6.2(0.6)	149(+26, −19)
	165	167(+35, −25)	5.9; 0.7	162(+27, −21)
IR Gem	2.1 ± 0.6[1.1]	3.0(1.1)	+53.9, −22.3(0.3)	333(+193, −89)
	···	413(+138, −112)	11.7; 4.6; 1.0	358(+104, −86)
V396 Hya	10.3 ± 1.2[1.2]	11.1(1.2)	−276.7, −52.4(0.7)	90(+11, −9)
	94	92(+13, −10)	17.6; 13.5; 1.	90(+12, −10)
KT Per	5.8 ± 0.9[1.2]	6.9(1.2)	58.1, +0.2(0.8)	145(+30, −22)
	172	162(+36, −26)	6.9; 0.7[a]	180(+36, −28)
VV Pup	8.8 ± 1.4[1.2]	9.3; 1.2	+19.0, −70.4(0.8)	108(+16, −12)
	115	114(+18, −14)	5.9; 0.6	124(+17, −14)
MR Ser	8.4 ± 0.8[1.0]	9.2(1.0)	−35.7, +65.6(0.6)	109(+13, −11)
	114	113(+14, −12)	6.0; 0.5	126(+14, −12)
SW UMa	5.6 ± 0.8[1.2]	6.6(1.2)	−31.6, +8.9(0.2)	152(+34, −23)
	193	180(+49, −33)	6.0; 0.4	164(+22, −19)
AR UMa	11.2 ± 1.2[1.2]	12.2(1.2)	−68.5, +3.4(0.8)	82(+9, −7)
	85	86(+10, −8)	4.7; 0.6	86(+9, −8)
BZ UMa	3.8 ± 0.9	4.9(1.1)	21.9, −5.8(0.5)	204(+59, −37)
	···	260(+93, −58)	5.2; 1.4	228(+63, −43)
QS Vir	20.6 ± 1.7[1.7]	21.2(1.7)	50.1, 19.9(1.1)	47(+4, −4)
	48	49(+5, −4)	3.26; 1.0	49(+4, −4)

Note. — Summary of the parallaxes, proper motions, prior information, and distance estimates. Two lines are given for each star, as follows. *Line 1.* Column 1: Name of star. Column 2: relative parallax and its uncertainty; the first uncertainty given is from the formal error of the fit, and the estimated external error is given in square brackets. Column 3: Adopted absolute parallax and its error (in parentheses). Column 4: Relative proper motion in X (i.e., eastward) and Y (northward), and the formal error per coordinate in parentheses. Column 5: Distance implied by the absolute parallax, and its uncertainty, with no further corrections applied. *Line 2.* Column 1: Left blank. Column 2: 50th percentile of the distance probability distribution after the Lutz-Kelker correction is applied. Column 3: 50th percentile distance estimate using the parallax and proper motion information, and a model for the intrinsic CV velocity distribution. The uncertainties given are the 16th and 84th percentile points, equivalent to $\pm 1\sigma$. Column 4: Prior distance estimate. Where two numbers are given, they are the distance modulus $m - M$ and its assumed uncertainty; where there are three numbers, they are an apparent magnitude m, an absolute magnitude M, and an uncertainty in $m - M$. Column 5: The 50th percentile Bayesian distance estimate, including all the prior information. Uncertainties are again 16th and 84th percentile points.

[a] The photometric distance constraint for KT Per is from the spectroscopic parallax of the common-proper-motion companion; see text for details.