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HUBBLE SPACE TELESCOPE FINE GUIDANCE SENSOR ASTROMETRIC PARALLAXES FOR THREE DWARF NOVAE: SS AURIGAE, SS CYGNI, AND U GEMINORUM[1]

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ABSTRACT

We report astrometric parallaxes for three well-known dwarf novae obtained using the Fine Guidance Sensors on the *Hubble Space Telescope* (*HST*). We found a parallax for SS Aurigae of $\pi = 5.00 \pm 0.64$ mas, for SS Cygni we found $\pi = 6.02 \pm 0.46$ mas, and for U Geminorum we obtained $\pi = 10.37 \pm 0.50$ mas. These represent the first true trigonometric parallaxes of any dwarf novae. We briefly compare these results with previous distance estimates. This program demonstrates that with a very modest amount of *HST* observing time, the Fine Guidance Sensors can deliver parallaxes with sub-milliarcsecond precision.

Subject headings: astrometry — novae, cataclysmic variables —
stars: individual (SS Aurigae, U Geminorum, SS Cygni)

1. INTRODUCTION

Like many astronomical objects, the distances to cataclysmic variables are imprecisely known. Cataclysmic variables (CVs) are interacting binaries composed of a white dwarf and a main-sequence companion. The secondary star fills its Roche lobe, and matter is transferred to the white dwarf through the inner Lagrangian point. In nonmagnetic systems, the mass transfer occurs through an accretion disk. Most, but not all, CVs exhibit outbursts during which the system suddenly brightens (see Warner 1995 for a complete review of the behavior of the different subclasses of the CV family). These eruptions range from the luminous classical novae, in which the outbursts are caused by a thermonuclear runaway on the white dwarf (see Starrfield et al. 1998) and the explosion releases $E_{\mathrm{tot}} \sim 10^{45}$ ergs over the lifetime of the outburst, to the dwarf novae (DNe), in which the outburst energy is more modest ($E_{\mathrm{tot}} \sim 10^{40}$ ergs) and is generated by an accretion disk instability cycle (see Cannizzo 1998, and references therein). But our knowledge of these energies and other fundamental parameters of CV systems suffers because of the lack of accurate distance measurements.

Berriman (1987) has compiled a list of distance estimates for CVs that used a variety of techniques, including reports of astrometric parallaxes and spectroscopic parallaxes that relied on the photometric parameters of the CV secondary stars. This latter technique may be the most reliable, but its application is made uncertain by the complex spectral energy distribution of CVs at minimum light, where emission from the hot white dwarf, the accretion disk, the irradiated secondary star, and features that arise from the accretion stream and its impact with the accretion disk (the "hot spot") contaminate the systemic luminosity. To evaluate the accuracy of the various secondary distance estimators requires direct measurements of the parallaxes of a number of well-known CVs. Of the dwarf novae with astrometric parallaxes compiled by Berriman, only that for SS Cyg has a significance greater than 3 σ: 50 ± 15 pc (Kamper 1979). We show below that even this measurement is incorrect, and we conclude that until now, no dwarf nova has truly had its trigonometric parallax measured. In this Letter, we report the first high-precision parallaxes for three well-known dwarf novae: SS Aurigae, SS Cygni, and U Geminorum. These parallaxes were obtained using the Fine Guidance Sensors (FGSs) on the *Hubble Space Telescope* (*HST*).

2. FGS ASTROMETRIC OBSERVATIONS

The FGSs were designed to provide exceptional pointing and tracking stability for the science instruments on the *HST*, no matter where the telescope was pointed. As such, the FGSs were designed to have a large dynamic range and a large field of view. For normal guiding operations, only two FGSs are employed. This frees the third FGS to make astrometric measurements. There are two modes of astrometric operation: "position" and "transfer." For obtaining parallaxes and proper motions, position mode is used. For resolving close binaries, transfer mode is used. Astrometry using the FGS has been fully described elsewhere (e.g., Benedict et al. 1994, 1992; Bradley et al. 1991); however, the most comprehensive source for understanding the nuances of obtaining high-precision parallaxes with the FGS is found in the Fine Guidance Sensor Instrument Handbook (Lupie & Nelan 1998). Since our observing program followed the prescription outlined within the Handbook, only the most important details relevant for parallax measurement will be addressed here. We present a more complete discussion of the FGS astrometric data analysis for the program CVs, including their proper motions, and comparison of their astrometric and infrared spectroscopic parallaxes in Harrison et al. (1999).

As in a classical parallax program, an FGS program consists of measuring the position of the target object with respect to a number of field stars obtained at several widely separated epochs when the parallax factors approach unity. Each FGS has a field of view (FOV) that consists of a quarter annulus of inner and outer radii of 10′ and 14′, respectively. This entire area, known as a "pickle," is accessible to the interferometer. Not all of the area of the pickle ends up being accessible in the typical astrometry project because of the different roll an-

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TABLE 1

Reference Star Parameters

Reference Star	α_{2000}	δ_{2000}	V	$V-R$	$V-I$	Spectral Type	A_V	π (mas)	Notes
SS Aur 2	06 13 29.4	+47 44 26.5	14.64	0.46	0.81	K0 V	0.0	1.77	=Misselt 5
SS Aur 9	06 13 44.4	+47 44 53.8	12.54	0.31	0.59	F8 I/II	1.0	<0.17	
SS Aur 12	06 13 09.8	+47 42 56.0	16.10	0.46	1.03	K0 V	0.0	0.90	
SS Aur 21	06 13 46.5	+47 43 22.9	14.17	0.51	0.89	K0 V	0.0	2.20	
U Gem 2	07 55 07.1	+21 59 19.2	14.77	0.40	0.77	K0 V	0.0	1.67	=Misselt 4
U Gem 4	07 55 04.6	+22 01 53.1	13.95	0.31	0.61	F4 V	0.3	0.65	=Misselt 1
U Gem 8	07 55 23.4	+21 59 57.1	12.01	0.34	0.56	G0 V	0.0	3.00	
U Gem 9	07 55 24.1	+21 58 39.8	14.20	0.33	0.61	G0 V	0.0	1.10	
SS Cyg 3	21 42 43.4	+43 34 23.6	13.36	0.27	0.39	F0 V	0.18	0.80	=Misselt 6
SS Cyg 6	21 42 33.2	+43 34 02.6	12.05	1.06	2.20	K4 III	1.31	0.98	=Misselt 1
SS Cyg 7	21 42 27.1	+43 33 44.7	10.80	0.32	0.58	F8 V	0.0	4.37	
SS Cyg 12	21 42 35.5	+43 35 44.0	15.11	0.76	1.59	G5 V	0.18	1.08	
SS Cyg 14	21 42 58.7	+43 35 18.0	12.92	0.40	0.70	G0 V	0.18	2.15	

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

gles of the *HST* found at different epochs of observation. The large FOV remains one of the greatest strengths of the FGS: it allows astrometry of objects in regions in which the density of potential reference stars is low. It is important to note, however, that the astrometric precision is a function of the location of the object within the FOV of the FGS. Objects nearer the center of the pickle are more precisely located than those near an edge. This variation arises from optical distortion across the FOV, known as the optical field angle distortion (OFAD), which is greater, and less well calibrated, near the edges of the pickle (see Jeffreys et al. 1994). A dedicated calibration program, called the long-term stability test (LSTAB; see McArthur et al. 1997), is periodically run throughout each *HST* cycle to assess the stability of the OFAD. The LSTABs detect any changes in plate scale and are vital for astrometric data reduction.

Another important aspect of the FGS is their dynamic range: positions of objects with $8.0 < V < 17.0$ can be measured without changing the instrument configuration. This is especially important for the dwarf novae in our program, since at outburst they approach $V \sim 8$, but at minimum have $V \sim 14.5$. Thus, we were able to ignore the variability of our targets in planning the observational program. The astrometric precision to which a target can be measured is a function of the brightness of the target. For objects with $V < 15.0$, the single measurement precision is ≈1 mas; for fainter objects, the precision is ≈2 mas. The entire error budget for a minimalist FGS parallax program is ≈1 mas. A carefully planned program with multiple observational epochs, like that detailed below, can achieve parallaxes with sub-milliarcsecond precision.

3. THE OBSERVATIONAL PROGRAM

An ideal FGS parallax program would consist of five or more reference stars having $V < 15.0$, all within a few arcminutes of each other and spread uniformly around the target. Such fields are not always available for objects of astrophysical interest, and therefore the choice of potential astrometry targets is limited. We based our selection of CVs on four criteria: (1) their astrophysical significance, (2) their minimum brightness ($V < 15.0$), (3) the availability of a good set of reference stars, and (4) the likelihood that their parallaxes would have a precision of ≤10%. We also confined our selection of CVs to U Gem–type DNe, objects that have similar outburst characteristics and for which the secondary star is clearly visible at minimum light. This latter criterion was imposed to allow us to evaluate the accuracy of the technique of spectroscopic parallax. Clearly, parallaxes for a large sample of CVs would be desirable, but given the scarcity of *HST* time, a modest program was proposed to confirm that high-precision parallaxes for several such objects could be obtained with a modest amount of observing time.

Three target DNe that met the above criteria were SS Aur, U Gem, and SS Cyg. U Gem and SS Cyg are very well known, having been observed continuously for more than 100 yr. SS Aur is probably less well known outside of the CV community, but it is a regularly studied DN (see Shafter & Harkness 1986; Tovmassian 1987; Cook 1987).[7] Using the *HST* Guide Star Catalog (Lasker et al. 1990), potential reference stars were identified that fell within the pickle centered on the target DNe. We then selected the brightest and best positioned to serve as reference stars. As stated above, ideally five or more reference stars are desired for an FGS astrometry program. But the actual number of reference stars used must be balanced versus the time within a single *HST* orbit available for reference star measurement. The fainter the object, the longer the time required for a position measurement. For U Gem and SS Aur, only four reference stars were used because of the overall faintness of the reference stars and the targets. For SS Cyg, a brighter target in a well-populated reference field, five reference stars were used. The positions, *VRI* photometry, spectral types, visual extinction, and spectroscopic parallaxes of all 13 reference stars employed in our program are listed in Table 1.

An observational sequence consists of slewing to the target field, acquisition of the target DN, and then repeated measurement of the position of the target and each of the reference stars. As described in the Handbook, the pointing of the *HST* exhibits a small drift throughout an orbit. To account for this drift, one (or more) of the reference stars is chosen as a “drift check star.” This star is measured more frequently than the other reference stars, allowing this drift to be modeled and removed during data reduction. A typical observing sequence for SS Aur was SS Aur, Reference 2 (drift check star), Reference 12, Reference 21, Reference 9, SS Aur, Reference 2, Reference 12, Reference 21, Reference 9, SS Aur, Reference 2, Reference 12, Reference 21, Reference 9, Reference 2. In the case of SS Aur, each star was observed for 60 s. The acquisition of each object has an associated overhead, and the combined exposure times and overheads for the observational

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[7] For further information on these and other DN systems, as well as outstanding problems in CV research, the reader is directed to Warner (1995).

TABLE 2

OBJECT AND REFERENCE FRAME PARALLAXES AND THE DISTANCES TO THE PROGRAM DWARF NOVAE

Dwarf Nova	Relative Parallax (mas)	Observed Reference Parallax (mas)	Model Reference Parallax (mas)	Parallax (mas)	Distance (pc)
SS Aur	3.74 ± 0.63	1.26 ± 0.13	1.2	5.00 ± 0.64	200.0 ± 25.7
U Gem	8.77 ± 0.47	1.60 ± 0.16	1.4	10.37 ± 0.50	96.4 ± 4.6
SS Cyg	4.14 ± 0.42	1.88 ± 0.19	1.7	6.02 ± 0.46	166.2 ± 12.7

sequence described above consumed an entire 54 minute *HST* "orbit." Using the Handbook guidelines, we estimated that two such sequences were necessary at each epoch to achieve the program goal of parallaxes with a precision of $\leq$1 mas.

During a single exposure time, a large number of independent samples of the target's position are collected. For objects with $V = 14$, the number of samples obtained in a 60 s exposure is $\approx$600. These samples are averaged to determine a single position in FGS coordinates. At the end of a observational sequence, the x and y positions in FGS coordinates for all of the targets are obtained. These positions then go thorough an extensive calibration process that accounts for the OFAD, the pointing drift during the observation, and the differential velocity aberration caused by the motion of the *HST* through space. The result is a set of positions for one epoch of observation. To measure a parallax, observations at a minimum of two epochs are necessary. To account for the proper motions of the target and reference stars, observations over as long a time line as possible are desired. To secure a set of observations approaching those needed for a classical parallax measurement, we obtained data on three epochs. Each observational epoch occurred at the season of the maximum parallax factor for the target DN. Originally, these three epochs were separated by 6 months, but because of the difficulties with NICMOS and the subsequent changes in *HST* proposal priorities, our third-epoch observations were delayed by an additional 6 months. Thus, from start to finish, the observational program spanned 2 yr.

4. PARALLAXES OF THE DWARF NOVAE

After the observations were obtained and processed, astrometric solutions were sought for each of the targets. As stated earlier, two observational sequences were obtained at each of the three epochs. Thus, six independent sets of measurements were used in the astrometric solution, performed by the Space Telescope Astrometry Team (STAT) at the University of Texas (see Benedict et al. 1994). A master plate was constructed using a six-parameter plate solution that is simultaneously solved for translation, rotation, scale, and terms for independent scales on the x and y axes. The solutions were robust for SS Cyg and U Gem, but less so for SS Aur. During the first observational epoch for SS Aur, the FGS could not lock on to one of the reference stars (Reference 8), apparently because it was much fainter than estimated in the Guide Star Catalog. Subsequently, for epochs 2 and 3, we replaced this reference star with another (Reference 21). Therefore, the solution for SS Aur was not as well constrained, and the resulting precision was slightly poorer than found for the other two DNe (see Harrison et al. 1999).

Relative parallaxes of the three DNe were derived using two different astrometric techniques: (1) assuming that the parallaxes and proper motions of the reference stars sum to zero, and (2) that the reference frame is fixed (i.e., no motions are allowed in either parallax or proper motion). Method 1 is the technique preferred by the STAT and is that used in normal ground-based parallax solutions. In all cases, however, both solutions were remarkably similar, producing relative parallaxes that differed by only a few percent. This result suggests that the motions of the reference stars were not significant. With the small number of reference stars used in our program, however, a single reference star with a large parallax, or proper motion, could dramatically effect the parallax of the program object. To evaluate each of our reference stars, we treated them as the target and performed a solution to determine whether they exhibited large parallaxes or proper motions. In no cases were large motions found, and the largest relative parallax for a reference star was 2 mas. The final relative parallaxes for the DNe are presented in Table 2. The precision of these parallaxes, near ± 0.5 mas, exceeded the expected precision by a factor of 2. This added precision turned out to be especially important given the larger than expected distances of the program DNe.

To convert the relative parallaxes to absolute parallaxes requires knowledge of the mean parallax of the reference frame. To estimate this quantity, two techniques are available. The first is to determine the spectroscopic parallaxes for each reference star and average the results to determine the reference frame parallax. The second technique relies on a model of the parallaxes for stars at specific galactic coordinates and within the magnitude ranges of the reference stars. Both techniques were employed in this study.

To determine the spectral types of the reference stars, moderate-resolution (1.5 Å pixel^{-1}) optical spectroscopy of each object was obtained using the Double-Beam Spectrograph on the 3.5 m telescope at Apache Point Observatory. These spectra were then compared to the digital atlas of MK standard spectral types by Jacoby, Hunter, & Christian (1984). The estimated spectral type for each reference star is listed in Table 1. To derive spectroscopic parallaxes, optical *VRI* photometry was obtained to determine the visual magnitude and reddening for the reference stars. These data were acquired using the Clyde Tombaugh Observatory 16″ Meade telescope located on the New Mexico State University campus. This telescope is equipped with a Santa Barbara Instrument Group ST-8 CCD camera with the standard Harris *UBVRI* filter set. All three DN fields were observed on photometric nights along with Landolt standards. Standard techniques were used to derive the photometry of the reference stars listed in Table 1. A small number of *BVR* secondary standards, set up by Misselt (1996), are located within each DN field, and several of these happened to be reference stars in our program (identified in the last column of Table 1). Differential photometry was performed to check that our photometric solution reproduced the published values for these secondary standard stars. Using the spectral types and photometry, the visual extinction for each star was determined (very low in nearly all cases) and a spectroscopic parallax was estimated (final column of Table 1). The average values of these spectroscopic parallaxes are listed in the third column of Table 2 as the observed reference frame parallax for each DN field (we have assumed a 10% error in the value of these parallaxes).

In order to compare our spectroscopic parallaxes with those predicted from the Yale model (van Altena, Lee, & Hoffleit 1995), we derived the reference frame parallaxes for all three DN fields. These results, listed in column four of Table 2, are in good agreement with the observed reference frame parallaxes computed from Table 1.

5. RESULTS

We derive the absolute parallaxes for each DN by correcting the FGS relative parallax by the observed reference frame parallax. The final results are listed in the penultimate column of Table 2. We convert these parallaxes to distances in the final column of Table 2. For SS Cyg, we derive a distance of 166.2 ± 12.7 pc. This should be compared to published values of 30 ± 10 pc (Strand 1948), 50 ± 15 pc (Kamper 1979), 76 pc (Warner 1987), greater than 90 pc (Wade 1982), 95 pc (Bailey 1981), greater than 95 pc (Berriman, Szkody, & Capps 1985), and 111–143 pc (Kiplinger 1979). The Strand & Kamper results are astrometric parallaxes, while the other estimates used variations on the spectroscopic parallax of the secondary star. For U Gem, we find a distance of 96.4 ± 4.6 pc. Previous estimates were 76 pc (Wade 1979), 78 pc (Bailey 1981), 81 pc (Warner 1987), 100 ± 120 pc (van Maanen 1938), and 140 ± 70 pc (Berriman 1987). The van Maanen value is an astrometric parallax, while the other estimates used the photometric properties of the secondary star. For SS Aur, we measured a distance of 200.0 ± 25.7 pc. This should be compared with a parallax-based distance of 100 ± 40 pc (Vasilevskis et al. 1975), spectroscopic parallaxes of greater than 80 pc (Wade 1982) and greater than 152 pc (Szkody & Mateo 1986), and a moving group parallax of 200 pc (Warner 1987).

It is clear that previous quotes for the astrometric parallaxes of these three DNe were not significant. The parallax quoted with the greatest precision, that for SS Cyg by Kamper (1979), is clearly incorrect. The parallax of SS Cyg is much too small to have been detected using classical photographic astrometry. Additionally, the published parallax measurements for U Gem and SS Aur had such large error bars that they did not constitute actual detections of the parallax for those objects. *Thus, we consider the three parallaxes listed in Table 2 to be the first true trigonometric parallaxes of any dwarf novae.*

The parallaxes derived here supply the first direct tests of the accuracy of secondary distance indicators in CVs. Except for Warner's estimate for the distance to SS Aur and Kiplinger's estimate for SS Cyg, none of secondary methods provided distance estimates consistent with the astrometric parallaxes. By moving the spectroscopic parallax technique to the infrared, where contamination of the systemic luminosity by the white dwarf and accretion disk is weaker, more precise spectroscopic parallaxes might be obtained. We examine the technique of infrared spectroscopic parallax for our program DNe elsewhere (Harrison et al. 1999). Using new infrared data and more recent calibrations of the infrared luminosities of low-mass stars, we obtained accurate distance estimates for both SS Aur and U Gem. The infrared luminosity of SS Cyg, however, is apparently dominated by emission from the accretion disk.

We have used the FGS on *HST* to measure the first trigonometric parallaxes of any dwarf novae. This modest program, consuming six *HST* orbits for each object, has produced parallaxes with ±0.5 mas precision. This increased precision over that foreseen when the proposal was submitted resulted from improved planning of the way the astrometric data is obtained with the FGS, along with a greater understanding of how it should be to reduced. There is not a competing system in existence that can provide parallaxes of greater precision on objects this faint in such a small amount of time. Clearly, the FGS on *HST* will not be supplanted as an astrometer until the development of the *Space Interferometry Mission.*

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