ON THE HUBBLE SPACE TELESCOPE TRIGONOMETRIC PARALLAX OF THE DWARF NOVA SS CYGNI*

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ABSTRACT

SS Cygni is one of the brightest dwarf novae (DNe), and one of the best studied prototypes of the cataclysmic variables. Astrometric observations with the Fine Guidance Sensors (FGSs) on the Hubble Space Telescope (HST), published in 2004, gave an absolute trigonometric parallax of 6.06 ± 0.44 mas. However, recent very long baseline interferometry (VLBI), obtained during radio outbursts of SS Cyg, has yielded a significantly larger absolute parallax of 8.80 ± 0.12 mas, as well as a large difference in the direction of the proper motion (PM) compared to the HST result. The VLBI distance reduces the implied luminosity of SS Cyg by about a factor of two, giving good agreement with predictions based on accretion-disk theory in order to explain the observed DN outburst behavior. This discrepancy raises the possibility of significant systematic errors in FGS parallaxes and PMs. We have reanalyzed the archival HST/FGS data, including (1) a critical redetermination of the parallaxes of the background astrometric reference stars, (2) updated input values of the reference-star PMs, and (3) correction of the position measurements for color-dependent shifts. Our new analysis yields a PM of SS Cyg that agrees well with the VLBI motion, and an absolute parallax of 8.30 ± 0.41 mas, also statistically concordant with the VLBI result at the ~1.2σ level. Our results suggest that HST/FGS parallaxes are free of large systematic errors, when the data are reduced using high-quality input values for the astrometry of the reference stars, and when instrumental signatures are properly removed.

Key words: astrometry – novae, cataclysmic variables – stars: distances – stars: dwarf novae – stars: individual (SS Cyg)

1. INTRODUCTION: HST MEASUREMENTS OF TRIGONOMETRIC PARALLAXES

The Fine Guidance Sensors (FGSs) on the Hubble Space Telescope (HST) are a set of three interferometers used for guiding control of the telescope during imaging or spectroscopic observations. In addition, the FGS system itself can provide high-precision astrometry by measuring positions of a target star and several surrounding astrometric reference stars with one FGS while the other two guide the telescope. This capability of determining accurate trigonometric parallaxes, with precisions that can be better than ±0.2 mas, has been applied to a variety of astrophysical problems, such as the zero-point of the Cepheid period–luminosity relation (Benedict et al. 2007) and the ages of the oldest stars in the solar neighborhood (Bond et al. 2013).

Recently, however, the possibility of significant systematic errors in HST trigonometric parallaxes has been raised by long-baseline interferometric radio observations of the archetypical dwarf nova (DN) SS Cygni, which gave very different parallax and proper-motion (PM) results from the FGS measurement. DNe are a subclass of cataclysmic variables (CVs), which are very close binaries containing a low-mass main-sequence star that transfers material to an accretion disk surrounding a companion white dwarf. In a DN system, at semi-regular intervals, the accretion disk becomes unstable and brightens dramatically, producing a DN outburst.

2. THE DISCREPANT RADIO AND HST PARALLAXES OF SS CYGNI

SS Cyg at maximum light is one of the brightest DNe, and it is one of the best studied, having nearly continuous coverage of its optical variability since its discovery in 1896 by Louisa Wells (as reported by Pickering 1896). These brightness estimates—all of them by amateur astronomers—show that the eruptions recur about every 49 days. During its outbursts, SS Cyg becomes a detectable radio source. This property has been exploited by Miller-Jones et al. (2013, hereafter MJ13), who used very long baseline interferometry (VLBI) to obtain astrometric measurements of SS Cyg during five eruptions over the years 2010–2012. The VLBI observations, triggered by notifications of outbursts from amateur astronomers of the American Association of Variable Star Observers (AAVSO), were made with the Very Long Baseline Array and the European VLBI Network. The resulting radio-based trigonometric parallax, which is referred to extragalactic calibrators, is an absolute parallax. By contrast, FGS parallaxes from HST must be referred to nearby background stars, making it necessary to estimate the distances to the reference stars in order to convert the relative parallaxes of the target to absolute.

Harrison et al. (1999, hereafter H99) used HST to measure the trigonometric parallax of SS Cyg (and two other DNe), based on FGS data obtained in 1997 and 1998. They slightly revised their analysis of the data in a subsequent paper (Harrison et al. 2000, hereafter H00), and again 4 yr later (Harrison et al. 2004, hereafter H04). H04 give an SS Cyg parallax of 6.06 ± 0.44 mas, corresponding to a nominal distance of 165 ± 12 pc.

The VLBI parallax of SS Cyg reported by MJ13, which is 8.80 ± 0.12 mas (d ∼ 114 ± 2 pc), is significantly larger than the HST value reported by H04. MJ13 discuss several possible reasons for this large discrepancy, including very large errors in one or more of the estimated parallaxes of the HST background reference stars, and statistical biases in the HST parallax measurement. MJ13 point out that their 114 pc distance is in excellent agreement with a distance predicted on the basis of models of unstable accretion disks, whereas at the larger distance found by H04, with the implied doubling of the system
the PM and parallax of each star. These reductions are carried out using the least-squares program GAUSSFIT (Jefferys et al. 1988). We input the estimated reference-star parallaxes and PMs as observations with errors, allowing the GAUSSFIT model flexibility to adjust their values within the errors to minimize the solution’s global errors. The output parallax for SS Cyg is thus absolute. No priors were assumed for SS Cyg itself. Our analysis differed from that of H04 in several additional respects, as follows.

3.1. Input Estimated Parallaxes of the Reference Stars

The five reference stars lie within a few arcminutes of SS Cyg. We use the designations that were assigned in the original proposal; the formatted HST proposal listings4 may be consulted for the coordinates and other details of the reference stars and observations.

H00 gave ground-based VRI photometry for the reference stars. However, there is additional photometry available in the literature for these stars, from the following sources: (1) AAVSO charts and associated magnitude sequences5 (two stars), (2) the AAVSO Photometric All-Sky Survey6 (APASS; Henden et al. 2012; all five stars), (3) Grant & Abt (1959; one star), (4) Henden & Honeycutt (1997; three stars), (5) Misselt (1996; two stars), and (6) the Tycho catalog (Høg et al. 2000; one star).

We averaged the $B$, $V$, and $I$ magnitudes from these sources, giving equal weight to each publication. Table 2 lists the star designations, the $V$ magnitudes, and the $B - V$ and $V - I$ colors, in Columns 1–4, and the sources of the photometry in Column 5. Spectral types were determined by H99 and H00 for the five reference stars, based on spectroscopic observations obtained by their team. Because of several issues raised in our reanalysis (see below), we requested new observations with the queue-scheduled Hobby–Eberly Telescope (HET; Shetrone et al. 2007) and its Low-Resolution Spectrograph. These data, covering 4330–7280 Å at a resolution of 5.8 Å, were obtained on 2013 June 12 and 13. By comparison of our spectra with those of classification standards, we modified the spectral types of three of the reference stars; details are given in Column 6 and a footnote in Table 2. We then estimated the interstellar reddening, $E(B - V)$, of each reference star by comparing the observed $B - V$ with the intrinsic $(B - V)_0$ for the indicated spectral type, as given in a literature compilation7 assembled by E. Mamajek.

### Notes

1. Photometry sources: 1. AAVSO chart. 2. APASS. 3. Grant & Abt (1959). 4. H00. 5. Henden & Honeycutt (1997).
2. Misselt (1996). 7. Tycho catalog (Høg et al. 2000).
3. Omitted from solution; see the text.
for dwarfs, and by Drilling & Landolt (2000) for giants. Our adopted reddenings are given in Column 7 of Table 2.

**H99** and **H00** estimated the absolute magnitude of each reference star using a calibration of $M_V$ versus spectral types. Our approach for dwarfs is to use the photometric measurements, once the luminosity class and reddening have been established from the spectral classification. We estimated the distances to these reference stars using a calibration of the visual absolute magnitude, $M_V$, against reddening-corrected $B - V$ and $V - I$ colors, derived through polynomial fits to a large sample of nearby main-sequence stars with accurate photometry and *Hipparcos* or USNO parallaxes. Our procedure is described in more detail in Bond et al. (2013). This algorithm corrects for effects of metallicity. For giants, we used the $M_V$ values tabulated by Drilling & Landolt (2000). Our final estimated parallaxes are listed in Column 8 of Table 2. For comparison, the parallaxes estimated by H00 are given in Column 9.

Two of the reference stars deserve special comment. (1) In the FGS reduction process, the GAUSSFIT program made a substantial modification of the parallax of REF-6, changing it from an input value near 0.7 mas to an output value of about 4 mas. This value is too large for an M0 giant at 12th mag, but if the star were actually a misclassified M dwarf, its parallax would be another order of magnitude even larger. A possible explanation of the implausible FGS parallax may be that REF-6 is a partially resolved binary with a separation slightly less than the width of the FGS3 interference fringes ($\lesssim$40 mas). If so, the measured position on the FGS detector can depend upon the telescope orientation, in effect introducing a parallax-like displacement in the solution (see Nelan 2012, Section 4.4.1, for examples of how close binary systems impact the observed interference fringes). Since the FGS parallax is discrepant from any astrophysically reasonable value, we omitted REF-6 from the solution. (2) REF-12 was classified as a K0 V dwarf by H00. However, both its $B - V$ and $V - I$ colors are much redder than those of a K0 V star. H00 attributed the red color to a large interstellar reddening of $E(B - V) = 0.65$. It would be surprising for such a nearby star ($d \simeq 288$ pc according to the parallax of 3.47 mas estimated by H00) to be so reddened, given that the more distant REF-3 and REF-14 are only moderately reddened. SS Cyg itself is little reddened, with $E(B - V) = 0.04$ according to Godon et al. (2012). Moreover, the total reddening of very distant objects in this direction is only $E(B - V) = 0.45$, according to Schlafly & Finkbeiner (2011). Interstellar extinction in the direction of SS Cyg has also been discussed by Voikhanskaya (2012), who likewise concludes that the reddening within a few hundred parsecs is minimal. These issues would be alleviated if REF-12 were instead a giant. Then it would be at a distance of $\sim$5 kpc, with a parallax of $\sim$0.2 mas, and its reddening would be $E(B - V) \simeq 0.3$; such a value would be reasonably consistent with the run of extinction versus distance presented by Voikhanskaya (2012).

Motivated by these considerations, we obtained a new spectrum as described above, which confirms that the star is a giant of about spectral type K2 III. (Unlike REF-6, REF-12 lies at the periphery of the reference-star frame, and thus the GAUSSFIT solution is unable to put an independent tight constraint on its parallax.)

The mean parallax for the four retained reference stars according to our estimates is 1.92 mas; in spite of the individual differences, this is fairly close to the mean parallax of 2.23 mas adopted by H00, but actually slightly smaller. In the analysis by H99 and H00, they forced the sum of the parallaxes of the reference stars to be zero, and then added the mean of the estimated parallax values to the relative parallax calculated for SS Cyg, in order to convert it to absolute. In our analysis, as noted above, we treat each input reference-star parallax as an observation with an error, so that the parallax we compute for SS Cyg is absolute.

### 3.2. Input Proper Motions of the Reference Stars

GAUSSFIT also requires input values of the PMs of the reference stars. H99 and H00 constrained the sum of the reference-star PMs to be zero, but in the reanalysis by H04 they state that they used USNO-B PMs as observations with errors. For our new analysis, we adopted input ground-based PMs as given in the recently available UCAC4 catalog (Zacharias et al. 2013), which are tied to an inertial extragalactic frame.

### 3.3. Lateral Color Effect

The FGS3 optical train includes refractive elements that introduce an astrometrically significant color-dependent shift in observed stellar positions. This “lateral color effect” must be accounted for in the analysis, especially since SS Cyg is blue; in particular, during outbursts, it is bluer than all of the reference stars. Moreover, *HST* parallax observations require a $\sim$180° change in telescope roll angle at the two extremes of parallax factor, making the lateral shifts go in opposite directions on the sky (as does parallactic displacement). Observations providing a calibration of lateral color effect for FGS3 were carried out in 1994, with results reported by Benedict et al. (1999), and confirmed independently by us for the present work. The corrections are defined as functions of the $B - V$ color of each star. H99 and H00 did not apply such corrections, but H04 did.

The $B - V$ colors of the (non-variable) reference stars are available (Column 3 of Table 2). For SS Cyg itself, the color varies with its magnitude level, becoming considerably bluer during outbursts. Observations of the $B - V$ color of SS Cyg at various magnitude levels have been provided by Grant & Abt (1959) and Hopp & Witzigmann (1980). Based on the magnitudes of SS Cyg reported by the AAVSO light-curve generator8 at the exact times of the *HST* observations, as listed in Column 2 of Table 1, we estimated what its $B - V$ color would have been, using the data from these two papers. We also list, in Column 3, the $V$ magnitudes derived directly from the FGS observations, transformed from the FGS instrumental magnitudes using the relation of Bucciarelli et al. (1994); these magnitudes are in good agreement with the AAVSO values. The implied colors are listed in Column 4 of Table 1, and were used as input values in our FGS analysis. SS Cyg was in outburst (and thus very blue) during the 1997 December observations, but in quiescence (and redder) at the other four *HST* visits.

### 4. PARALLAX AND PROPER MOTION OF SS CYGNI: VLBI AND HST/FGS ARE STATISTICALLY CONSISTENT

Our resulting PM components and absolute parallax for SS Cygni are given in Column 2 of Table 3. For comparison, the VLBI astrometric results are given in Column 3, and the *HST* results from H00 (for the PM) and from H04 (for the parallax) in Column 4.

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8 Available at [http://www.aavso.org/lcg](http://www.aavso.org/lcg).
The *HST* observations of 1997–98 were less than optimal in two regards. (1) Only five reference stars were observed, although more were available in the surrounding field. Unfortunately, one of the five caused difficulties and had to be eliminated from our solution, as described in Section 3.1. Only one of the chosen reference stars lies to the northwest of SS Cyg, with the other four lying to the southeast. This limits the usefulness of a test in which each reference star is examined as if it were the program star, in order to assess the consistency of its input estimated parallax with the output parallax found in the solution. (In the present case, only REF-6 could be examined in this way, as the other reference stars were on the outer edges of the field.)

The small number of reference stars also limits the utility of another standard test, in which each star is dropped in turn from the solution to identify problem objects (e.g., close binaries). (2) Observations were made at only three epochs, with the first and third being at opposite parallax factors. It is preferable to have the initial and final observation be made at the same parallax factor, as this allows for a better separation between parallax and PM. Of course, it is also preferable to obtain more than the minimum of three epochs needed for parallax determination.

Nevertheless, as shown in Table 3, our reanalysis of the 1997–1998 *HST* data has produced statistical agreement with the VLBI parallax. We find a parallax of \(8.30 \pm 0.41\) mas, differing formally by about 1.2 \(\sigma\) from the VLBI value of \(8.80 \pm 0.12\) mas. Our error estimate for the FGS parallax includes the effects of uncertainties in the reference-star parallaxes. The remaining difference in parallax between our result and that of MJ13 is plausibly a residual systematic error, due to having only three epochs of *HST* observations rather than the now-standard five epochs for FGS parallax programs, along with having only four usable reference stars. We also note that these older observations from 1997 and 1998 used FGS3, which has since been replaced by the more capable and better-calibrated FGS1R.

The uncertainties listed for our PMs are the internal (random) errors. For the PM of SS Cyg, there will be an additional systematic offset in the zero-point of the PMs (i.e., a bulk linear motion of the reference frame relative to an inertial one) due to errors in the input PMs of the reference stars. For the UCAC4 catalog, individual PMs are uncertain at about 4 mas yr\(^{-1}\). Thus, with four reference stars, the PM zero-point error would be of the order of 2 mas yr\(^{-1}\). We find that our PM for SS Cyg in right ascension agrees with the VLBI value within the errors; the declination PM is slightly discordant, at nearly 3\(\sigma\), but well within the expected systematic error.

\(H00\) and \(H04\) reported smaller parallaxes (6.27 \(\pm\) 0.47 mas and 6.06 \(\pm\) 0.44 mas, respectively) of SS Cyg. We attempted to reproduce their parallax and PM results by inputting the reference-star parallaxes stated in \(H00\) and employing the methodologies they used at the respective dates, but were unable to do so. The PM position angle they report differs from that in USNO-B, UCAC4, MJ13, and the present work by about 36°. In fact, the PM of SS Cyg measured over six decades ago on photographic material at the Yerkes Observatory by Strand (1948) also agrees remarkably well with the modern VLBI and *HST* values in size and position angle, as does the more recent photographic determination by Dahn et al. (1982).

In summary, we find reasonable statistical agreement between our reanalysis of the *HST*/FGS parallax and the precise results from VLBI interferometry. This reinforces our confidence that FGS astrometry does not suffer from large systematic errors. This should be especially true when at least five epochs of observations and a well-chosen and well-calibrated reference frame are used.

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**Facilities:** AVASO, HET, HIPPARCOS, *HST* (FGS)

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**Table 3**

| Parameter | HST/FGS (This Paper) | VLBI (MJ13) | HST/FGS (H00, H04) |
|-----------|---------------------|-------------|-------------------|
| Proper motion in R.A. (mas yr\(^{-1}\)) | 112.23 \(\pm\) 0.75 | 112.42 \(\pm\) 0.07 | 73.9 \(\pm\) 0.4 |
| Proper motion in declination (mas yr\(^{-1}\)) | 35.24 \(\pm\) 0.65 | 33.38 \(\pm\) 0.07 | 98.0 \(\pm\) 1.2 |
| Absolute parallax (mas) | 8.30 \(\pm\) 0.41 | 8.80 \(\pm\) 0.12 | 6.06 \(\pm\) 0.44 |

**Notes.**

a Miller-Jones et al. (2013).

b Proper motions from Harrison et al. (2000), parallax from Harrison et al. (2004).
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