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Hubble Space Telescope Astrometric Observations of the Metal-poor Spectroscopic Binary HD 20039

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ABSTRACT. An attempt has been made to spatially resolve the metal-poor, double-lined spectroscopic binary HD 20039 with the *Hubble Space Telescope* Fine Guidance System. Astrometric measurements of the system to complement the spectroscopic orbit would permit the distance and the masses of the components to be determined. Observations were obtained around the times of predicted maximum separation on both sides of the orbit, but the system was not resolved. The resulting upper limit on the separation indicates that the distance to HD 20039 is significantly larger than expected from its assumed classification as a subdwarf.

1. INTRODUCTION

Stellar mass is the most fundamental parameter of stellar astrophysics, largely determining a star's internal structure and evolution. Therefore, mass determinations for types of stars where little or no data are available are of great interest. One important stellar category lacking direct mass determinations is the halo population.

Various methods exist for estimating stellar masses, but direct measurement of mass is possible only through gravitational effects, usually orbital motion in a binary system. Binaries in the halo population (defined here as stars having $[m/\mathrm{H}] < -1.0$) were practically unknown until recently, but many have now been found. Radial velocity surveys alone have identified over 100 spectroscopic binaries (see, e.g., Carney et al. 1994, hereafter CLLA). Many of these systems have well-determined spectroscopic orbits, including a few double-lined (SB2) cases. These halo-population SB2's provide the opportunity for direct mass determinations provided the inclination of the orbit can be determined.

Two ways to obtain the inclination of an SB2 are (1) to identify a system that has eclipses and observe the light curve or (2) to spatially resolve the two components and obtain the astrometric orbit. The recent development of optical high-resolution interferometric instruments has opened the door for determining the astrometric orbits, and hence the inclinations and masses, for many spectroscopic binaries (see, for example, Hummel et al. 1995).

A literature search was conducted for SB2 systems with $[m/\mathrm{H}] < -1$, well-determined orbits, and distance estimates. Those identified are listed in Table 1. The star G221-7 = HD 20039 appeared to be the best candidate for resolution. This system has a period of 114 days, and the spectroscopy and photometry (CLLA) indicate $[m/\mathrm{H}] = -1.18$, $d = 40$ pc. The orbital elements (Latham et al. 1992) and radial velocity curve are shown in Table 2 and in Figure 1. The photometric distance combined with the spectroscopic orbit yields a predicted maximum angular separation of about 0$''$.016..

2. OBSERVATIONS

The predicted maximum separation for HD 20039 is somewhat above the nominal resolution limit of the *Hubble Space Telescope* (*HST*) Fine Guidance System: 10 mas for Δmag < 4 for systems brighter than 14 mag (Space Telescope Science Institute 1994, 1995). The guidance system consists of three dual-axis Koester prism interferometers, referred to as the Fine Guidance Sensors (FGS). Operated in its TRANSfer mode, an FGS scans across the target to obtain the interference pattern, generally referred to as the "S-curve." Comparison of the observed S-curve with that for a single star—a "reference curve"—allows one to resolve and measure close binaries. Details about the use of the FGS system to measure double stars can be found in Bradley et al. (1991) and the *HST* Fine Guidance Sensor Instrument Handbooks (Space Telescope Science Institute 1995, 1998). Examples of astrometric orbits utilizing FGS data can be found in Gies et al. (1997), Hershey & Taff (1998), and Franz et al. (1998).

A proposal to carry out FGS TRANSfer-mode observations of HD 20039 during *HST* Observing Cycle 5 was approved, although the review committee noted that the

TABLE 1

Double-lined Spectroscopic Binaries with $[m/H] < -1.0$

Star	Coordinates α_{2000}	δ_{2000}	V	$B-V$	$[m/H]$	Distance (pc)	Reference	Notes
G173-10	01 36 01	49 42 44	10.13	0.51	−1.42	116	1	HIP 7452
G221-7	03 18 36	72 16 43	8.89	0.75	−1.18	40	1	HD 20039
G86-40	05 26 36	34 44 48	11.82	0.58	−1.60	218	1	
G103-50	06 40 08	28 27 12	12.07	0.86	−2.00:	107	1	
G88-10	07 10 24	24 20 48	11.87	0.44	−2.42	200	1	HIP 34630
G87-45	07 32 58	31 07 06	11.44	0.64	−1.49	123	1	
G114-26	08 59 09	−04 00 53	9.66	0.48	−1.90	86	1	HIP 44124
G161-82	09 51 27	−04 38 24	11.98	0.60	−1.43	176	2	
G66-59	15 03 49	10 44 30	13.20	0.64	−2.53	278	1	
G183-9	17 53 00	15 21 06	11.87	0.53	−1.58	204	1	
CS 22873-139	20 05 55	−59 17 12	13.83	0.37	−3.1	1000	3	

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

References.—(1) CLLA; (2) Ryan & Norris 1991; (3) Preston 1994.

TABLE 2

Orbital Data for HD 20039

Parameter	Value
P (days)	114.377
T (JD)	2,446,664.3
γ (km s^{-1})	−3.20
K_A (km s^{-1})	22.72
K_B (km s^{-1})	26.22
e	0.3809
ω (deg)	21.1
$a_A \sin i$ (Gm)	33.04
$a_B \sin i$ (Gm)	38.13
M_B/M_A	0.866

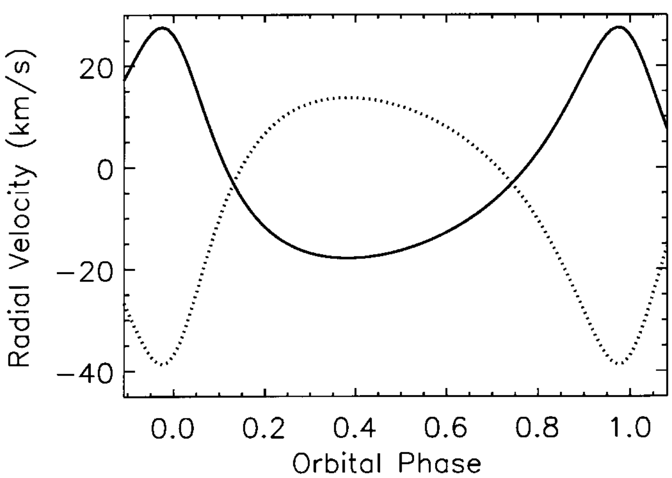

Fig. 1.—Radial velocity curves for the double-lined spectroscopic binary HD 20039.

project was "right at the limit of feasibility." Observations were successfully obtained at six selected orbital phases in the period 1995.85–1996.30.

The times of the six observations were chosen such that there would be three, separated by about 0.1 in orbital phase, covering the predicted time of maximum separation on one side of the orbit and three others providing similar phase coverage on the opposite side of the orbit. *HST* scheduling resulted in both cases in two of the three phases being observed in one orbit of the binary and the third in the following orbit. Two independent observations were made at each epoch, with a single observation consisting of 21 scans across the star using the F583W filter.

The 21 individual scans for an observation were first combined to produce high signal-to-noise S-curves for the x- and y-measurement axes. The observed S-curves were then fitted with the sum of two reference S-curves, adjusting the separation and scaling the ordinates of the two curves until the residuals were minimized. The fitting produced a separation and magnitude difference in each FGS coordinate.

Many trial solutions were done employing various software, constraints on the fits, and reference S-curves. Processing the data using the standard Space Telescope Science Institute pipeline, procedures developed at the Lowell Observatory, and our own programs produced similar results. The stability of the solutions was tested by first starting the iterative fitting with the fainter star on the left side of the brighter star and then starting with it on the right side. In most cases the "left-side" and "right-side" solutions gave similar separations but with different signs, indicating ambiguity about which component was brighter. Constraining the magnitude difference or the quadrant of

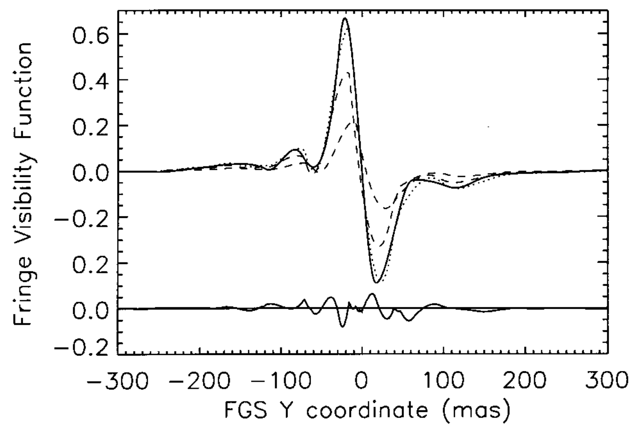

FIG. 2.—A representative fit of an observed S-curve with two scaled reference curves. The solid line is the observed S-curve. The dashed lines are the two reference curves, and the dotted line is their sum. The residuals from the fit are shown below the S-curves.

the primary had only small effects on the separations. Most trials employed reference S-curves derived from the standard single-star calibrator Upgren 69, but, because HD 20039 ($B-V=0.75$) is significantly redder than Upgren 69 ($B-V=0.5$), some were made with a red reference curve (from SAO 185689, $B-V=1.5$). As previously found (Gies et al. 1997), the derived separations for close systems are very sensitive to the adopted reference curve. Unfortunately, our reference curve calibration is weak, both because calibrations from objects of similar color to HD 20039 were not available and because the closest calibrations were obtained well outside of the interval of our observations (the closest were at 1995.70, about 2 months before our initial observations, and at 1996.81, about 6 months after the final ones).

For the final solutions we fixed the brightness ratio of the two stars at 2.0 (Δmag $= 0.75$) to insure internal consistency. The data were fitted with two Upgren 69 reference curves (*HST* observations F3H80202) expanded by amounts to correspond to the assumed $B-V$ colors of the two components of HD 20039. A typical fit is shown in Figure 2.

The separations in FGS instrument coordinates (Δx, Δy) derived from the fits were converted to separations and position angles (ρ, θ) in equatorial coordinates using the recorded *HST* roll angles. The results are given in Table 3. The formal errors of the separations are at the 1 mas level. The derived position angles have errors less than 5°, but, because in almost all cases the sign of the separations was uncertain, there was a quadrant ambiguity. We have adopted those quadrants that provided the most internal consistency between the six data sets.

3. RESULTS

If the system was indeed resolved, then the results will show (1) a 180° difference in position angle between the observations made on the two different sides of the orbit and (2) orbital motion within the data sets at each orbital extremum. Despite a great deal of experimentation with various constraints and quadrant choices, neither criterion could be satisfied. This indicates that most, if not all, of the separations that result from the S-curve fitting are spurious.

The spectroscopically well-determined small value of ω places the line of apsides close to the plane of the sky. This fact, coupled with the relatively large eccentricity, means that the projected separation at apastron will be significantly greater than at periastron. Consequently, we carefully investigated the possibility that only the apastron measures (data sets F2ZQ0401–602) were valid. Some of these S-curves do differ significantly from our single-star reference curve, but taken together the results for the three data sets are inconsistent with the known orbital motion.

TABLE 3

DERIVED SEPARATIONS AND POSITION ANGLES

Set (F2ZQ0-)	Date	*HST* Roll (deg)	Orbital Phase	Δx (mas)	Δy (mas)	ρ (mas)	θ (deg)
101	1996.297	154	0.84	+9.3	−6.2	11.2	239
102				+9.6	−6.4	11.5	239
201	1996.016	64	0.93	−3.2	+5.9	6.7	177
202				−2.0	+4.4	4.8	181
301	1996.046	69	0.03	−5.8	+4.9	7.6	151
302				−2.0	+7.6	7.9	186
401	1996.128	103	0.30	−2.7	−5.2	5.9	15
402				−1.7	−5.9	6.1	3
501	1995.847	340	0.40	+1.6	−3.6	3.9	86
502				+5.0	−4.0	6.4	58
601	1995.869	2	0.47	+4.8	−5.6	7.4	47
602				+0.9	−3.2	3.3	72

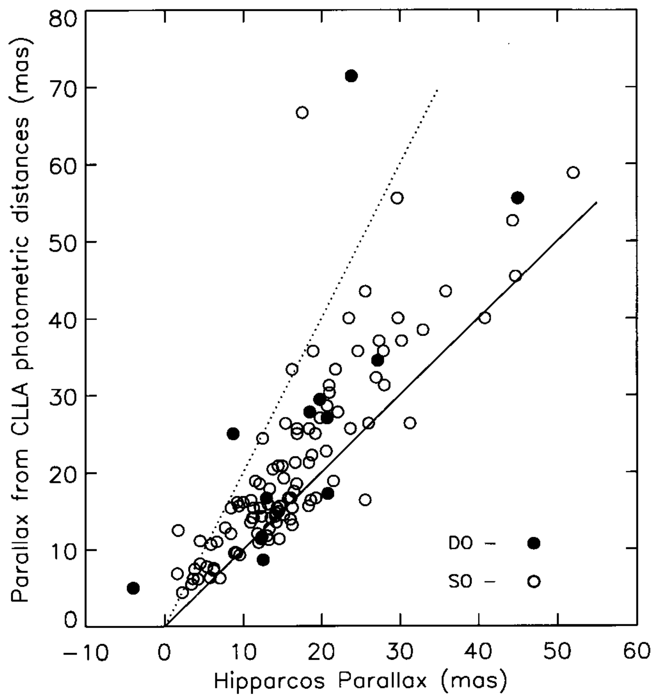

FIG. 3.—Comparison of *Hipparcos* parallaxes with those from the photometric distances for the spectroscopic binaries in the CLLA data set. SB2 systems are indicated by solid symbols. The solid line represents exact agreement and the dotted line a factor of 2 difference in parallax.

We suspect that the differences from a single-star curve resulted from temporal changes in the S-curve shapes. S-curve variations up to 2% have been reported for FGS3 (Space Telescope Science Institute 1998).

Further evidence that the system has not been resolved comes from the recent *Hipparcos* parallax of 8.7 ± 1.0 mas. The corresponding distance is 115 pc, about 3 times more distant than the photometric value used in selecting this star for observation. This distance is so large that the system would be below the FGS resolution limit even at apastron, but one must then explain the large discrepancy with the photometrically derived distance of CLLA.

We feel the most likely explanation is that the photometric distance is in error. The one ground-based parallax determination is old but gave $\pi_{\rm Abs} = 7 \pm 12$ mas (Dyson 1925; van Altena, Lee, & Hoffleit 1995). This is in agreement with the *Hipparcos* value, but the large uncertainty does not make it incompatible with the CLLA result. *Hipparcos* parallaxes were used to recompute the absolute magnitudes of the stars that form the basis of the CLLA distance calibration, but this did not produce a significant change in the photometric distance to HD 20039. Furthermore, while an independent distance calibration employed by Sandage & Fouts (1988) and Ryan & Norris (1991) does give distances 20%–25% larger for metal-poor stars, this is insufficient to resolve the discrepancy and, in fact, lends some support to CLLA's distances.

CLLA discuss several potential pitfalls in applying their calibrations to double-lined spectroscopic binaries. As an example, their distance scale (Laird, Carney, & Latham 1988) includes corrections for metal abundance, but two overlapping spectra can produce an apparent weakening of lines and hence an underestimate of the metallicity for an SB2. Also, HD 20039 has been assumed to be a subdwarf, but there is no modern spectral classification. At our request N. Houk (1998, private communication) examined the spectrum of HD 20039 on the objective prism plates being used for the revision of the HD and classified it as G8/K0 V. She did not note any metal weakness. A normal dwarf at the apparent magnitude of HD 20039 would be at a distance of about 80 pc, double the CLLA value but still not in accord with the *Hipparcos* result. Inverting the problem, the *Hipparcos* parallax indicates a combined $M_V = 3.6$, or about $M_V = 3.9$ and 5.1 for two main-sequence components. These values are inconsistent with the absolute magnitudes for normal dwarfs and for both subdwarfs and subgiants with $[m/\mathrm{H}] = -1.1$. The derived absolute magnitude is, however, in acceptable agreement with theoretical predictions for a system with an old, solar abundance subgiant (D. VandenBerg 1998, private communication; Yale Isochrones 1996[1]). If HD 20039 does indeed contain a subgiant, then the CLLA metallicity estimate, as well their photometric distance, would be invalid.

A second possible, but we feel less likely, explanation for the distance discrepancy is that the astrometric orbital motion of the binary has somehow affected the *Hipparcos* parallax. Figure 3 shows how the *Hipparcos* parallaxes compare with those corresponding to the photometric distances for other spectroscopic binaries in the CLLA data set. One sees that CLLA distances yield parallaxes systematically larger. Nevertheless, they average only about 25% greater, and of the 108 stars with *Hipparcos* parallaxes greater than 5 mas, only for HD 20039 and two other stars do the values differ by more than a factor of 2.

In summary, we conclude that our FGS observations failed to resolve HD 20039. Despite our best efforts, there remains unexplained a large discrepancy between the photometric distance, on which our resolution attempt was based, and the *Hipparcos* parallax for this star.

4. FINAL REMARKS

The fact that HD 20039 was not resolved by our observations yields an upper limit on the projected maximum

[1] The Yale Ischrones 1996 have been determined by P. Demarque, B. Chaboyer, D. Guenther, M. Pinsonneault, L. Pinsonneault, and S. Yi and may be found at Sukyoung Yi's WWW Homepage (http://shemesh.gsfc.nasa.gov/iso.html).

TABLE 4

ORBITAL DATA FOR HD 195987

Parameter	Latham et al. 1988	Latham 1997[a]	Duquenoy & Mayor 1991	*Hipparcos* Catalogue
P (days)	57.325	57.3298	57.324	57.3240
T (JD)	4990.8	6080.2	3328.589	3327.5890[b]
γ (km s^{-1})	-5.56	-5.59	-6.13	...
e	0.316	0.308	0.306	0.3060
ω (deg)	355.9	357.1	356.8	356.80
$a \sin i$ (Gm)	21.65	...	21.57	...
$f(M_1, M_2)$	0.1225	...	0.1219	...
K_{AB} (km s^{-1})	28.89	...	28.73	...
K_A (km s^{-1})	...	29.16	...	...
K_B (km s^{-1})	...	34.61	...	...
Ω (deg)	...	...	...	327.66
i (deg)	...	...	...	89.50 ± 8.4
a (mas)	...	...	...	5.24
π (mas)	...	...	...	44.99[c]

[a] Latham 1997 = D. W. Latham 1997, private communication.

[b] Erroneous; should agree with Duquenoy & Mayor 1991 value.

[c] Corresponding distance is 22 pc, compared with CLLA distance of 18 pc.

separation of the binary and hence on its distance. FGS3 is now known to have an actual resolution limit of about 18 mas for stars with small magnitude differences, as is the case for HD 20039 (Space Telescope Science Institute 1998). Because our apastron measurements were made at three different telescope roll angles, even the worst case of projection of FGS measurement axes on the orbit does not permit the apastron separation to be greater than 20 mas or the two components would have been separated. This gives a lower limit to the distance of 50 pc, significantly larger than expected if HD 20039 is indeed a subdwarf. The possibility that the system contains a subgiant calls for a more thorough spectroscopic investigation. Our results suggest that an order-of-magnitude increase in spatial resolution is needed to reliably determine the astrometric orbit of HD 20039.

We also note that our search for *Hipparcos* parallaxes for the spectroscopic binaries in the CLLA list identified one SB2 (HD 195987, $V = 7.06$, $[m/\mathrm{H}] = -0.60$) with a *Hipparcos* photocentric astrometric orbit. The orbital data from four sources are compared in Table 4. Combining the results from the astrometric and spectroscopic orbit solutions yielded the following masses for the two components: $M_A = 0.70\ M_\odot$ and $M_B = 0.60\ M_\odot$. A more complete study of this system is warranted.

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