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HUBBLE SPACE TELESCOPE FINE GUIDANCE SENSOR ASTROMETRY OF THE LOW-MASS BINARY L722-22

JOHN L. HERSHEY
Astronomy Programs, Computer Sciences Corporation, Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; hershey@stsci.edu

AND

L. G. TAFF
Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218; lgtaff@stsci.edu

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ABSTRACT

The M dwarf star L722-22 (LHS 1047, GJ 1005) was discovered to be a binary in 1979. Analysis of ground-based data indicated a mass near 0.06 $M_\odot$ for the secondary star, well below the nominal stellar mass limit of 0.08 $M_\odot$. The close, faint binary was near the limit for ground-based astrometry and was approved for *Hubble Space Telescope* Fine Guidance Sensor (FGS) observations in 1992. The relative orbital motion of the binary has been monitored using FGS "transfer" mode measurements. The trigonometric parallax and motion of the primary about the center of mass were determined from the FGS "position" mode observations. All possible background reference stars in the FGS field-of-view were used. The relative orbit and fractional masses have been determined with far higher precision and accuracy than possible with ground-based techniques for this close, faint binary. The FGS observations definitely eliminate the possibility that the secondary star is a candidate for having a substellar mass, and place its mass and lower mass error range well above the stellar mass limit. Masses of 0.179 and 0.112 $M_\odot$ have been found for the two components, with formal random errors as low as 1.5%. The mass errors resulting from the correction from relative to absolute parallax are somewhat larger.

Key words: binaries: general — binaries: visual — stars: low-mass, brown dwarfs

1. INTRODUCTION

The M dwarf star L722-22 was discovered to be a binary by Ianna (1979). The analysis of the ground-based data (Ianna, Rohde, & McCarthy 1988) indicated that the secondary had a substellar mass of 0.06 $M_\odot$. This value is well below the generally accepted nominal stellar mass limit of 0.08 $M_\odot$. The principal results of the ground-based studies of L722-22 are shown in Table 1. Because the masses of the pair were known to be near the end of the main sequence, and because of the possibility that the secondary was a "brown dwarf," the pair was approved for *Hubble Space Telescope* (*HST*) Fine Guidance Sensor (FGS) observations in 1992. Knowledge of masses at the stellar–brown dwarf boundary is important in many areas of astrophysical research, such as star formation, stellar evolution, stellar nuclear reactions, galactic age and evolution, the lower end of the stellar mass function, the total mass of clusters and the Galaxy, and so on (Stevenson 1991). The sources for general information, photometric parameters, and spectroscopic classification for L722-22 as given in Table 1 may be found in Ianna et al. (1988) and Kirkpatrick & McCarthy (1994).

The M dwarf binary L722-22, with close components of 11th and 14th magnitudes, is near the limit for double-star astrometry with ground-based techniques. The residuals of individual nights of the photographic data were at the level of 50% of the very small astrometric orbital amplitude. The few one-dimensional speckle interferometry observations yielded a blended, asymmetric image profile. Only the photographic data could provide information on the center-of-mass motion and the mass ratio. Photographic images of the pair are completely blended and the center-of-mass estimate depends on an uncertain model for the location of the photographic photocenter. Furthermore, the system is too faint to be meaningfully observed by the ESA astrometry satellite *Hipparcos*.

The results of the ground-based study, with a substellar mass for L722-22B, have appeared in a number of papers in recent years relating to low-mass stars and brown dwarfs, for example, Burrows & Liebert (1993). In general, the study of all low-mass objects near the end of the main sequence has been limited by their inherent and apparent faintness. This has made it difficult to determine fundamental astrophysical parameters such as individual masses, luminosities, and spectral or photometric indices in the few binaries where the masses can be determined dynamically.

With the advent of *HST* FGS astrometry, it became possible to perform interferometric binary star observations much fainter than any ground-based interferometers are able, and also to observe stellar motions at high resolution relative to background stars. Because of their mode of operation, utilizing background stars to provide a static reference frame is generally not possible with ground-based interferometers. These problems, coupled with the capabilities of the FGS, made the latter uniquely appropriate for determination of the individual masses of the faint binaries in the lower end of the main sequence. A proposal to use both the FGS "transfer" and "positional" observing modes was submitted for several very low mass binaries, including as high-priority requests Ross 614, Wolf 424, and L722-22. Only L722-22 was approved. After the completely successful first FGS observation of L722-22 the other binaries were given to other proposers by the *HST* Telescope Allocation Committee.

2. FGS OBSERVATIONS

The FGS as an astrometric instrument and its modes of observation have been described in detail elsewhere, both in

TABLE 1

General Data for L722-22 from Pre-1988 Ground-based Observations[a]

Parameter	Value
Designations	L722-22, LHS 1047, G158-50, GJ 1005
R.A. (J2000.0)	0 15 28
Decl. (J2000.0)	−16 08.0
Apparent V magnitudes	11.5, 14.4
Absolute parallax (arcsec)......	0.189
Spectral type	dM4.5
$B-V$	1.74
Orbit Period (yr)	4.6
Masses ($M_{\odot}$)	0.17, 0.055

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

[a] Ianna et al. 1988.

our own publications and in such papers as Bradley et al. (1991). In addition, a series of STScI FGS Instrument Handbooks, beginning in 1985, and a series of STScI FGS Instrument Science Reports cover too much material to summarize here. The Handbooks and Instrument Reports also carry many references for the instrumental properties and observational results. The *HST* Phase II Proposal Instructions for each proposal cycle also contain practical information for the use of the FGSs in their astrometric role.

The observations of L722-22 were executed in two observational modes of the FGS. One is known as "position" mode (POS) and the other is called "transfer" mode (TRANS). These are the normal manners in which the FGSs are used as science instruments. All observations were performed with FGS3, using the F583W filter. Its response is centered at 583 nm. In POS mode, the FGS follows the null of the interferometer fringe for a specified interval of time and provides a 40 Hz data stream of instantaneous positions as the FGS follows the small excursions of the star in the FGS field of view caused by photon noise in the sensors and telescope pointing variations. The time series of positions can be processed to determine a mean position of the scientific target in the FGS field of view. The positions in the FGS coordinate system must be corrected for a variety of effects, such as differential aberration relative to the *HST* guide stars in the other two FGSs. The optical aberrations of the FGS field of view must also be removed, because the reference stars are measured at a large range of positions in the FGS field of view. This occurs while traversing the observing season for any fixed target as a result of the necessity to rotate the *HST* to maintain a favorable solar array orientation. The total range exceeds 180° in the case of L722-22. This is in sharp contrast with ground-based differential astrometry, which always observes a field at the same position and orientation in the telescope focal plane. Some of the instrumental corrections vary with time and require a different set of correction constants following each set of calibration observations. Software tools have been developed at the STScI for applying the various instrumental and attitudinal corrections to the raw POS mode data.

TABLE 2

HST FGS Astrometric Observations of L722-22

Year	X	Y	$(X_A - X_B)$	$(Y_A - Y_B)$
1993.606......	−1.477	2.501	−0.330	−0.222
1994.389......	−1.082	2.115	−0.099	−0.269
1994.621......	−1.005	1.888	−0.007	−0.242
1994.789......	−1.081	1.696	0.067	−0.203
1994.916......	−1.109	1.595	0.107	−0.162
1995.481......	−0.501	1.295	0.162	0.106
1995.583......	−0.457	1.176	0.132	0.148
1995.694......	−0.456	1.048	0.091	0.184
1995.828......	−0.471	0.913	0.030	0.207
1995.943......	−0.449	0.843	−0.023	0.217
1996.421......	0.200	0.722	−0.219	0.176
1996.479......	0.256	0.679	−0.237	0.168
1996.574......	0.300	0.591	−0.268	0.147
1996.983......	0.301	0.294	−0.360	0.054
1997.493......	0.924	0.159	−0.398	−0.081
1997.859......	0.879	−0.167	−0.379	−0.158
1997.964......	0.890	−0.211	−0.366	−0.185

Note.—All positions for equator of 2000. The positional columns are in units of arcseconds.

In TRANS mode, the interferometers are scanned in two coordinates back and forth across the target in small steps, generating the "transfer function" or fringe visibility function of the target, often colloquially referred to as an "S-curve." Most of the TRANS mode observations of L722-22 included 10 scans with 1 mas steps, and they provide the information on the separation of the components of the binary. Although no correction for the *HST* primary mirror spherical aberration is in place for the FGSs, the TRANS mode observations in FGS 3 are not severely degraded by this defect, mainly because of the small arc they cover. Additionally, TRANS mode works in an interferometric way; and even though the incoming wave front reaching the FGSs is curved because of the aberrations in the primary mirror, the interferometer superposes the two halves of the wave front with the same direction of curvature, yielding nearly full fringe amplitudes. Software has also been developed at STScI for preprocessing the raw measurements' TRANS mode data into a single mean fringe function for each observation.

A total of 17 *HST* observing visits were made to L722-22 between 1993 August and 1997 December. The epochs of observation (in years) appear in the first column of Table 2. After the experience with the first few visits, an optimal observing sequence could be created. It involved first measuring the centrally placed star, L722-22, then performing one observation of each of the reference stars, then a repeat observation of the central star, followed by a TRANS mode observation of 10 scans of L722-22, then observations in POS mode of the reference stars, and finally a third observation of the central star, in POS mode. In this way both the relative and absolute aspects of the system could be reliably determined.

3. FGS DATA ANALYSIS

3.1. *TRANS Mode Data Analysis*

The analysis of the TRANS mode data for a binary requires a fit of the observed transfer function with the sum of two single-star transfer functions. This process yields the angular separation of the components and their relative brightness. An apparently single-star transfer function is used as a "reference" transfer function. A series of reference transfer functions from calibration observations of stars believed to be single is kept at the STScI. This library includes stars of several color indices, as very red or blue color produces measurable effects in the transfer function.

The reference star used here is referred to as "Lat Col 1A" in the STScI library of reference transfer functions, with a magnitude of 9.7 and color index $B-V=1.92$, which is the nearest in color index to the L722-22 value of 1.7.

An alternative data reduction procedure is a Fourier transform deconvolution into energy profiles of the component stars (Hershey 1992). This type of analysis yields essentially the same results for separation and brightnesses as the direct transfer function fitting procedure, but serves as an aid to interpretation, especially for multiple systems where the interfering transfer functions are visually confusing (Lattanzi et al. 1994). Both methods require a fitting process for the best individual functions that sum to the observed one. Deconvolution brings in an additional mathematical process and loses some of the high-frequency information by filtering. This could cause some loss of positional information.

Whether direct or deconvolved transfer functions are used to reduce the measurements, the following equation is applicable for fitting the observed binary star data in each instrumental coordinate:

$$S(x) = B_1 S_{\rm ref}(x - x_1) + B_2 S_{\rm ref}(x - x_2) . \qquad (1)$$

Here $S(x)$ represents the observed transfer function of the two stars; B_1 and B_2 are scaling factors to be found by the fitting process related to the magnitudes of the two stars, and $S_{\rm ref}$ is a single reference star transfer function with its null at the zero point of its angular coordinate, x. The same form of equation is used for the instrumental y-coordinate. The positions of the nulls of the component transfer functions in the observed binary transfer function are represented by x_1 and x_2, and their difference is the separation of the binary star in that coordinate. If, instead, deconvolved transfer functions are used, then $S_{\rm ref}$ represents the energy profile from deconvolution of a single star.

A differential correction method for fitting the binary transfer functions or profiles with equation (1) was used. The method assumes starting values of the four constants are available that are near their correct values. The initial values are used in the fitting equation to generate a set of residuals. The residuals are represented as the total derivative with respect to all of the fitting parameters, with corrections to the parameters to be determined:

$$R(x) = \sum \frac{\partial S(x)}{\partial p_i} \Delta p_i. \qquad (2)$$

Here the p_i are the four fitting parameters B_1, B_2, x_1, and x_2 of equation (1). The derivatives with respect to B_1 and B_2 are simply the value of the reference transfer function at each distance from its null. However, the derivatives with respect to x_1 and x_2 require a numerical representation of the transfer functions, since they are not easily represented as analytic functions.

A least-squares fit is made to $R(x)$ for small corrections to each parameter and the corrections added to the parameters, allowing a new set of residuals to be computed. The iteration cycle is repeated until the corrections are a small fraction of their formal errors in the least-squares fit to the current residual series. The result of the fitting process for the binary is shown in Figure 1. Transfer functions of a representative observation of L722-22 in X and Y are shown in Figures 1*a* and 1*b* with the fits of two single-star transfer functions. Figures 1*c* and 1*d* show the deconvolution of the transfer functions in Figures 1*a* and *b* and the fits to the double-star profile with two single-star profiles.

Formal errors from the solutions for the separation of the components of L722-22 are at the fractional milliarcsecond level, in spite of the small amplitude of the transfer function of L722-22B. The small fitting error was confirmed by the repeatability of the separation measures from a series of TRANS mode observations at the same roll and successive orbits made in the 1993 visit. The standard deviation of the separation from six TRANS mode observations was 0.7 mas in one coordinate.

The external error as found from observations in a range of telescope rolls and across several years is, of course, somewhat larger. The separation of the binary is projected onto the coordinate system of the FGS, which is determined by the roll of the telescope. The separation error in each coordinate increases as the projected component of separation decreases below roughly 50 mas, because this binary has a large magnitude difference. As measured by the error of the relative orbit fit, the external error is at the 2 mas level.

3.2. *POS Mode Data Analysis*

The field of L722-22 is at high galactic latitude with very few candidate reference stars in the small FGS field of view. Two 14th magnitude stars at angular distances of 1′ and 2′ were retained as reference stars after attempts at fainter stars failed stable acquisition. Their *HST* Guide Star Catalog identification numbers are 5839511 and 5839449, with catalog magnitudes of 14.0 and 14.6. The stars were available at all telescope rolls throughout the observing season. Fourteenth magnitude stars provide a strong lock and an internal error of an observation which is smaller than the external error of a POS mode observation. The two stars are just 30° from being diametrically opposite L722-22, and thus constrain the transformation from instrumental to equatorial coordinates quite well, as may be seen from the small mass ratio and parallax errors below.

During most of the $4\frac{1}{2}$ years of observations the POS mode data were processed from the *HST* engineering data format, up to corrected positions in the FGS instrumental coordinate system, using STScI software as described in FGS Instrument Science Report 20 (Bucciarelli, Lattanzi, & Taff 1992).The last set of L722-22 observations occurred after a transition of the Institute POS mode software to the form developed by Space Telescope Astrometric Team (STAT) members at the University of Texas. The final POS pipeline used for all the L722-22 POS data was that of the University of Texas group. The POS mode processing output consists of sets of positions corrected from instrumental positions to relative angles on the celestial sphere in the instrument coordinate orientation.

The reference star positions were then rotated into equatorial coordinates, defined by the J2000.0 positions of the reference stars from the STScI Guide Star Catalog. The transformation found for the reference stars was applied to the central star as in a photographic plate reduction. With only two reference stars, the rotation angle and scale change of the transformation must be assumed to be common to both coordinates. The result of this stage of processing of the POS mode observations is the series of positions of the scientific target in equatorial coordinates relative to the reference stars, as shown in Table 2, columns (2) and (3) and in Figure 2*a* for star A. In spite of the small number of refer-

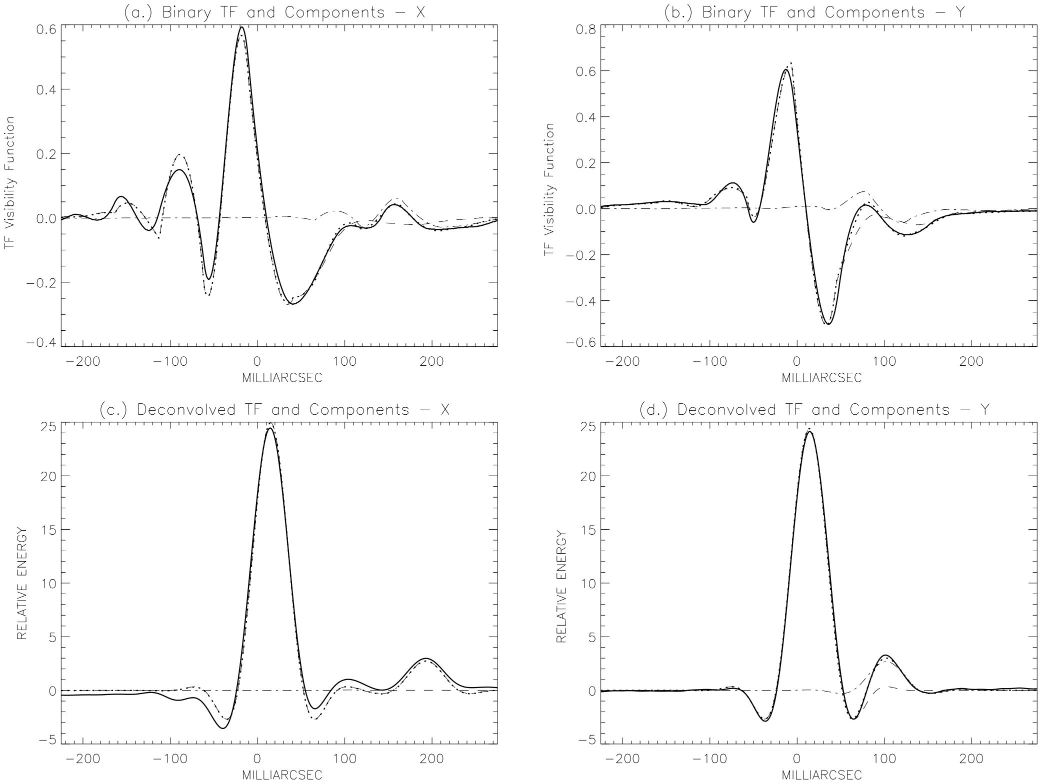

FIG. 1.—Transfer functions and fits from a representative FGS observation of L722-22. (*a*, *b*): Transfer functions in FGS3 X and Y and the fit to the binary transfer functions with two single-star transfer functions from a reference star template, respectively. (*c*, *d*): Result of the "deconvolution" of the transfer functions into energy profiles and the fit to the binary from a single-star profile template. The observed, double-star transfer functions are shown by solid lines. The fits from the sums of the two components are shown by dotted lines. The star A components are shown by dashed lines and the star B components by the dot-dashed lines. Deviations of the fits in the ordinate do not necessarily indicate a similar error in X or Y, if the fit is well centered in the abscissa.

ence stars, the positions of L722-22 in the reference frame carry an external error of only 2.6 mas and are able to yield a random error of the parallax under 1 mas.

4. MASS DETERMINATION

4.1. *Relative Orbit*

The relative orbital positions of the binary's components are shown in Table 2 and in Figure 2. The solution for the relative orbit was carried out by the method of differential corrections, simultaneously for all seven elements. Two versions were executed, one in terms of the classical elements (P, T, e, a, i, ω, Ω) and the other using the Thiele-Innes constants for the orientation elements. The results of both are shown in Table 3. An advantage of the solution for the classical elements is the generation of a direct error for the semimajor axis. This is needed in the error analysis for the binary masses.

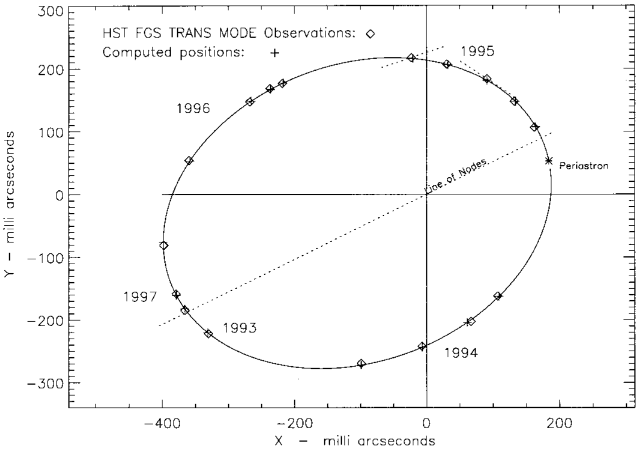

FIG. 2.—Relative orbit, L722-22B relative to L722-22A. The separation data result from FGS TRANS mode observations rotated into equatorial coordinates by the roll angle of the telescope. The two dashed lines among the 1995 observations are the indeterminate directions of observation, treated as "one-coordinate observations." The observation is allowed to be minimized along the dashed line, as explained in the text.

4.2. *Astrometric Motion of Star A*

The motion of the primary star (star A) relative to background stars is represented by

$$X_A = c_X + \mu_X t + \pi P_\alpha - \beta(X_B - X_A)\ , \qquad (3)$$

with a similar equation in Y (van de Kamp 1967, eq. [11.1]). X is the coordinate in the direction of right ascension, π is the annual parallax, P_α is the parallax factor in right ascension, β is the fractional mass, $\beta = M_B/(M_A + M_B)$, c_X is a zero-point constant, μ_X is the relative proper motion in R.A., t is the time in years, and $(X_B - X_A)$ is the separation of stars A and B in the X-coordinate.

The equations for X and Y were solved simultaneously for six constants, with π and β common to both equations. Finally, the sum of the masses is given by $(a''/\pi)^3/(\text{period})^2$, where a is the semimajor axis of the relative orbit and the individual masses are $M_A = \beta(M_A + M_B)$ and $M_B = (1 - \beta)(M_A + M_B)$. Figures 3*a*–3*d* show the observations of star A in the reference frame of the two background stars, and the fits with all parameters and with the displacements due to one or more parameters removed. Star B in Figures 3*a*–3*c* is plotted by offsetting from star A by the amount of the TRANS mode separation in equatorial coordinates. The results for the elements of the relative orbit and the constants describing the motion of star A are shown in Table 3. The proper motion and annual parallax in Table 3 are relative to the two reference stars given above.

The magnitude difference between the components of L722-22 may be found from the solutions for B_1 and B_2 in equation (1) and the corresponding equation for Y. A value of 2.42 ± 0.01 mag was found from the observations with separations greater than 100 mas in the instrumental coordinates. At this separation, the proximity effects on the transfer function fitting are negligible. The magnitude difference is in the bandpass of the FGS F583W filter. The transmission profile for the FGS F583W filter is shown in the various instrumental handbook references, and spans the ranges of the B, V, and R photoelectric filters. Thus, the magnitude difference is not directly convertible to standard photometric bands.

4.3. *Special Investigations*

As shown in Figure 1, the amplitude of the transfer function of star B is very small, and its position is affected by minute instrumental and photon noise departures of the

TABLE 3

ASTROMETRIC RESULTS AND MASSES FOR L722-22AB

Parameter	Value
Orbital elements:	
P (yr)	4.566 ± 0.009
e	0.364 ± 0.001
T_0	1995.366 ± 0.003
a (arcsec)	0.3037 ± 0.0007
i (deg)	146.0 ± 0.3
Ω[a] (deg)	62.6 ± 0.6
ω (deg)	−13.6 ± 0.6
Thiele-Innes constants (arcsec):	
B	0.2894 ± 0.0007
G	−0.0492 ± 0.0015
A	0.0831 ± 0.0010
F	0.2522 ± 0.0007
Relative proper motion:	
μ_X (arcsec yr^{-1})	0.6009 ± 0.0006
μ_Y (arcsec yr^{-1})	−0.5993 ± 0.0005
Relative parallax (arcsec)	0.1656 ± 0.0008
Absolute parallax (arcsec)	0.1666
Sum of masses ($M_\odot$)	0.291 ± 0.004
Fractional mass, β	0.3844 ± 0.0027
Masses ($M_\odot$):	
Star A	0.179 ± 0.003
Star B	0.112 ± 0.002

[a] Node, equator of 2000.

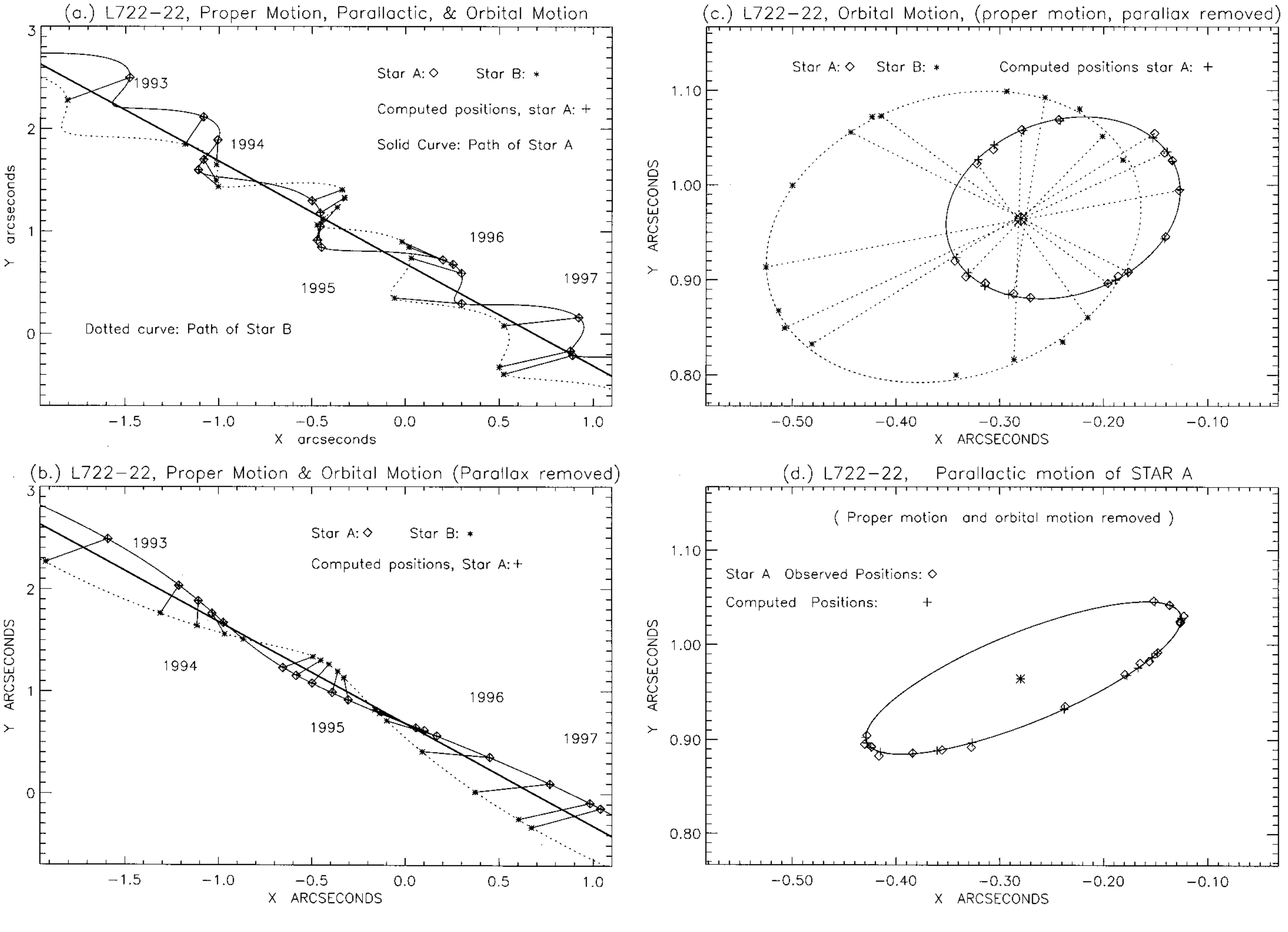

FIG. 3.—Motions of L722-22 in the reference frame. The title of each panel indicates the aspect of the motion displayed. In (*a*)–(*c*), the positions of star B are offset from star A by the amount of the TRANS mode separation observed. In (*c*), only alternate pairs of observations of star A and B are connected with dashed lines. In all panels, the fitting residuals are represented by the offsets of the diamonds and plus signs.

observed transfer function from the reference transfer function. Two TRANS mode observations showed outlier residuals because of the close projection of the separation in one FGS coordinate. These residuals were at the level of 4 σ in the FGS X-coordinate, regardless of the technique of transfer function solution. One was the case of smallest separation near 20 mas, but the other was near 40 mas. The transfer functions in the X-coordinate of FGS 3 are distorted, as may be seen in Figures 1*a* and 1*b*, where the Y-coordinate is close to an ideal transfer function. Although other cases near 40 mas fit very well, some small systematic effect in the X-coordinate made the solution vulnerable at this separation and large magnitude difference in which secondary transfer function lobes of star A are comparable in size to the primary transfer function lobes of star B. Residuals of this size at these moderately small separations would likely not have arisen in a binary with nearly equal magnitudes.

Regardless of the cause, these two observations were treated as one-coordinate, Y only, FGS observations; namely, those obtained at 1995.69 and 1995.94. In equatorial coordinates, the FGS coordinates may lie at any angle. A doubly iterative solution was developed that, after each orbit solution, moved the position in equatorial coordinates along the indeterminate FGS coordinate for a minimum residual in the problematic FGS coordinate. The orbit was then solved again and the process repeated until convergence was obtained. The two observations so treated and the direction of the indeterminate FGS coordinate are shown by the short dashed lines in Figure 2. The single coordinate observations meaningfully contribute to the solution, since the intersection of the indeterminate FGS coordinate with the orbit must meet a time constraint and thus the residuals in the indeterminate FGS coordinate are not generally zero.

The effect of the two corrections is mainly cosmetic, and maintains the standard error of the relative orbit fit consistent with the precision of the main body of the observations. Experiments in orbit determination with and without the one-coordinate corrections showed very little effect on period and semimajor axis, the parameters that determine the mass. When the two one-coordinate observations were included, the small change they induced resulted in changes to the period and the semimajor axis smaller than their errors. The insensitivity of the orbital elements to a few large residuals is caused by the strong observational coverage throughout the orbit.

The analysis for the motion of star A in the reference frame of the two background stars assumes that the POS mode observations are following the null of star A and are unaffected by the presence of star B. Plans had been made to correct star A's coordinates, if necessary, for any positional effect of star B (because light from star B might have systematically biased the derived null position for star A). However, the brightness of star B is only 11% of star A in the FGS bandpass. By inspection of the fitting plots, the effect on star A is certainly zero for projected separations of 100 mas or more. Large-scale plots of the fitted transfer function components at closer separations show the TRANS mode primary-star transfer function lying on the observed transfer function at the null. As a comprehensive check, a feature was added to the fitting program to locate the nearest point to the null for the fitted primary and for the sum of the primary and secondary fitted components. In nearly all cases the two points were the same in the 1 mas grid. A few 1 and 2 mas differences appeared, but they were not at the small projected separations and are apparently a random error phenomenon. One case at the smallest separation showed an effect on the primary null of several milliarcseconds, but that separation is one that appears as an outlier in the relative orbit fit and was regarded as a one-coordinate observation, as explained above. In the solution of star A positions for parallax and fractional mass, the observation in question was corrected for the null shift found in the solution before rotation into equatorial coordinates. However, the solution for the positions by equation (3) was degraded by this "correction," perhaps because the transfer function solutions are incorrect in this close case, as evidenced by the outlier in the TRANS mode data. No other cases were available for comparison, and thus no corrections to the POS mode observations were made for blending caused by star B.

Investigations have been made into an instrumental effect seen in a wide binary (Whipple 1997). The separation was reported to depend on the FGS position angle of observation. The effect has been ascribed to very small misorientations of the interferometer prisms. The effect was modeled for the observations of L722-22 and solutions made for the amplitude of this instrumental error. The separations of L722-22 range from $0''.2$ to $0''.4$ throughout its orbit, and the effects of this instrumental error are expected to be small. Fits did not indicate an effect above 1 mas, and since neither the sign nor magnitude of the error in the two prisms have yet been calibrated, no correction for this effect has been applied. The instrumental position angle of a binary cycles on a 1 yr period because of *HST* rolls. The orbital period of L722-22 is over 4 yr, thus an error owing to instrumental position angle would appear in the relative orbit as a quasi-random effect, and would not produce a direct systematic effect.

A large number of comparisons of direct transfer function fitting and the fitting of deconvolved profiles were made by processing all observations both ways and using the separations of each for relative orbit determinations. Variations on each method were tried. Both methods result in semimajor axes and orbital periods that lie well within the respective errors, as shown in Table 3. Direct transfer function fitting held a slight edge in the standard error of fit of the relative orbit. After extended experimentation, the final data for orbit determination and display in Table 2 were formed by taking the mean of four sets of separations. Each method was also executed on two observations of the reference star (*HST* Data Archive designations F2U0102 and F3H50102). The errors from the means of separations originating from the two reference stars was reduced compared with the separate sets, indicating a random component was removed by the means. The standard error resulting for the orbital fit to the TRANS mode data per *HST* visit was 1.9 mas.

5. CONCLUSION

The parallax found by the FGS analysis is given in Table 3 and is 12% smaller than the ground-based value of Ianna et al. (1988). Recently the ground-based plate data of the 1988 study have been remeasured and more recent observations have been included that now yield a value in good agreement with the *HST* FGS value (P. A. Ianna 1996, private communication). The smaller parallax is the primary reason for the larger masses found for the components of L722-22 in the present study. The reduction in parallax of 12% translates into a 45% increase in the masses through the third power in Kepler's third law.

The correction from relative to absolute parallax remains problematic. Statistics cannot be applied reliably on a sample of two reference stars. If both are giants with absolute magnitudes near zero, then the correction of the relative parallax to absolute is a fraction of a milliarcsecond. If, in contrast, both are main-sequence objects, in the A and F spectral-type region, then the correction would approach 1 mas. The separations of the reference stars in the FGS have been followed for over 4 years, and show evidence of a small change with time, but no relative parallactic motion. It is possible that both are distant or that both have significant, but nearly equal, parallaxes and proper motions. The motion of L722-22 relative to the two reference stars agrees at a level of $0\farcs030$ yr^{-1} with the ground-based proper motion based on 12 reference stars ranging in magnitude from 10 to 13. Therefore, the proper motion of the reference stars is likely at or below the level of $0\farcs03$ yr^{-1} and both stars are likely distant. Finally, if both reference stars are late F to G main-sequence objects, then the correction could reach somewhat over 1 mas. A 1 mas overcorrection would reduce the mass of star B by 0.002 $M_{\odot}$, equal or less than the formal error of its mass. A token correction to absolute parallax of 1 mas has been applied to the relative parallax to yield the absolute parallax reported in Table 3. If the correction were 3 mas instead of 1, then the masses would reduced by 3.5%. Observations of spectral type and luminosity class could reduce the uncertainty of the distance of the reference stars.

The errors given in Table 3 for the masses of stars A and B are at the 1.5% level (with four-decimal-place calculations), but they are strictly formal random errors. The error convolution was computed with a simulator that added an error distribution to the parallax, semimajor axis, period, and fractional mass, computed the masses many times, and then computed a mean from the resulting masses. The result is close to a simple error budget that convolves errors by vector addition on each algebraic operation. The uncertainty in masses resulting from systematic instrumental effects is difficult to assess at this stage in the use of the FGSs.

Whatever calibration problems may remain in reducing FGS data, this orbit is sufficiently well-covered that unmodeled instrumental changes that are functions of seasonal *HST* attitudinal effects should appear as quasi-random residuals when spread across the $4\frac{1}{2}$ yr orbit. An overall scale error for the FGS coordinate system would be a hidden systematic effect throughout the entire analysis. It is believed to be at the level of one part in 10^4 and so would affect the masses by much less than their random errors. The data for L722-22 are in the *HST* Archive under proposal numbers 4283, 5510, 6063, and 6641 and can be reprocessed later if better calibrations and analysis techniques become available.

The primary advantages of FGS TRANS mode over ground-based interferometry are its ability to provide separate positions of a close, faint binary in a background reference frame that speckle interferometry is unable to do, and to reach stars too faint for present long-baseline interferometry. The determination of the relative orbit and individual masses for L722-22 demonstrates an advance in binary star measurements over ground-based observations of factors of roughly 10 to 30 (depending on the basis of estimation) for this faint, close pair. Whether the errors in the masses is 1.5% or 4% in L722-22, they are at the level of the best ground-based determinations for bright stars. The accuracy of the masses is far higher than any ground-based mass determination for the low-mass stars near the end of the main sequence.

Barbara McArthur of the University of Texas processed the data through the POS mode pipeline developed there. A number of STScI staff have been involved in various ways and at various times throughout the past 10 years in the creation of the Institute astrometry software, including B. Bucciarelli, S. Holfeltz, and M. Lattanzi. The work has been based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. Support for this work was provided, in part, by NASA through grant numbers 4283, 5510, 6063, and 6641 from the Space Telescope Science Institute.

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