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MASSES AND ORBITS OF T TAURI STARS

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ABSTRACT

Binary T Tauri stars in the Taurus Star Forming region present a unique opportunity to study the evolution of low-mass stars. Using new Speckle measurements from the Keck telescopes and previously published relative orbital positions, the orbital solutions to binary systems can be determined. Due to the low orbital coverage, these results are preliminary, and include a concise error analysis. This paper presents preliminary masses and orbital solutions for GG Tau, DF Tau, FO Tau, and FS Tau.

Subject headings: binaries: general—stars: individual(DF Tau, GG Tau, FO Tau, FS Tau)—stars: pre-main-sequence

1. INTRODUCTION

Theoretical models of young, pre-main-sequence, low-mass binary systems disagree about the input physics needed to construct a star. This leads to varied predictions of mass and age when placed on a color-magnitude diagram. These models diverge, especially towards very low mass stars, leading to mass differences of a factor of two and age differences by a factor of ten. (White et al. 1999; Tamazian et al. 2002; Schaefer et al. 2003). This warrants an experimental test to the robustness and accuracy of these models. The most fundamental property of a star–its mass–must therefore be compared to the predictions based on a color-magnitude diagram.

By obtaining the relative positions of stars as projected onto the sky, it is possible to bound the mass experimentally. As discussed in section 3.1, a full 3-D orbit can be fit to these points in a χ^2 minimization routine. However, due to the absence of radial velocity measurements and no knowledge of the center of mass, only the combined mass can be determined.

2. OBSERVATIONS

Speckle interferometry yields diffraction limited, high-resolution images. Using standard reduction techniques discussed in Ghez et al. (1993); Patience et al. (1998), the relative position of the two stars are obtained. Briefly, this technique involves taking four hundred short exposure images of the binary system and a calibrator source that is assumed to be unresolved. They are treated in the traditional manner with sky-subtraction, flat-fielding, and bad-pixel removal. These images are stacked and the binary of interest is compared to the unresolved calibrator source in Fourier domain, and the properties of the power spectrum are used to determine the separation and the position angle.

The new data presented in this paper were observed at the Keck and Palomar telescopes between 1995 and 2003. The 64×64 subsection of the 256×256 SRBC InSb array was used at Palomar to make observations. Observations at Keck used the Near-Infrared Camera, as described in Matthews & Soifer (1994); Matthews et al. (1996).

3. ORBIT ANALYSIS

3.1. *Orbital Determination*

Using published astrometric measurements of the system as well as the new data presented in this paper, it is possible to determine an estimate of the true orbit using numerical simulations. However, refined error estimates must be made to account for the variety of sources and techniques used for the data. All binaries are assumed to be at a distance of 140±10 pc (Bertout, Robichon, & Arenou 1998; Kenyon, Dobrzycka, & Hartmann 1994; Wichmann, et al. 1998).

Generally, orbits are determined through a minimum χ^2 fitting routine. The first set of orbits arise from selecting orbital parameters that can vary across the entire space. Each orbit is minimized using a conjugate gradient method followed by Powell's method. The 3-σ region around each of the orbital parameters is used to construct a new set of orbits which span the space around the minimum more completely. Both sets use 25,000 fits.

GG Tau was treated slightly differently. To account for its minimal orbital coverage, the inclination was initially fixed to 37°, and the mass fixed to 1.28 solar masses to agree with data from the disk (Guilloteau et al. 1999). After the first minimization, the process is repeated with the inclination and the mass now allowed to be variable, but introducing initial guesses from the 3-σ range of fit values where the errors are fixed. This entire process is done twice: once for each set of data. The first set consists of the data already published and new data in their original form. The second set is calculated using standardized errors, much like in McCabe et al. (2002). The errors are weighted by method, with Hubble observations receiving the smallest errors, speckle imaging receiving double those errors and AO relieving four times as much[1].

3.2. *Error Analysis*

Due to the limited orbital coverage obtained for the binary systems, it is important to obtain well-determined errors on the orbital parameters. A Monte Carlo simulation determines these errors effectively by questioning the data points' uncertainties. With every iteration, all the

[1] Hubble observations recieved a separation error of 2.5 mas and a P.A. error of 0.6°.

data points are randomly redistributed within their errors according to a Gaussian distribution. Then, using the best fit solved for with the original data set as a seed, a new best fit is determined using the redistributed data. The process is iterated 10,000 times.

The new set of best fit solutions is then analyzed in two steps. First, the minimum χ^2 solutions is ordered and put into a histogram. Then, for each orbital parameter, the median is calculated. The one-σ error on each side of every parameter is calculated by including 34% of the data on either side of the median. This is done to account for non-Gaussian distributions, where the data may be skewed to one side.

4. ORBITAL SOLUTIONS AND THEORETICAL MODELS

Table A1 summarizes the orbital parameters computed from the dataset in table A3. Graphically, the results are shown in Figure A1. Using Kepler's law, the semi-major axis and the period determine the combined mass of the system, shown in table A2. This mass is compared to the theoretical predictions of the combined mass determined using a color-magnitude diagram. A specific position on a color-magnitude diagram yields a unique mass and age for a given star. However, various theoretical models of low-mass, pre-main-sequence stars determine these positions differently based on the construction of the model. It is, therefore, necessary to use experimental evidence to decide which model most accurately represents nature.

In order to test our system masses to the models, a temperature and luminosity are required for each star. The data obtained by Hartigan & Kenyon (2003) yields accurate spectra of each of the individual stars. These will be combined for each binary to determine the total mass of each system. The models included in this survey are Baraffe et al. (1998, hereafter BCAH), D'Antona & Mazzitelli (1997, hereafter DM), Siess et al. (2000, hereafter SDF), and Palla & Stahler (1999, hereafter PS).

The two datasets for GG Tau produce similar orbits with differing masses. They span about 23° of the orbit, but exhibit very little change in separation; therefore, there is very little curvature in the system, and it becomes important to accurately represent the errors in the system to determine a proper orbit. Another justification for forcing the errors is the χ^2 statistic. When using the published errors, the best fit orbit has a reduced χ^2 of 3.16; thus, the errors are underestimated. After standardizing the errors, the new reduced χ^2 becomes a far more reasonable 1.57. The results for the forced data support the BCAH model, whereas the published errors solution is closer to the PS and SDF models.

Data for DF Tau spans about 90° and has adequate regular sampling to produce a a well-defined curvature. Although this may result in large errors for some parameters, the mass will be well constrained. The orbital solution has a reduced χ^2 of 1.22. The orbital solution yields a mass of 0.81 solar masses, most closely resembling the SDF model.

FO Tau has the lowest mass of the survey. It is regularly sampled, spanning an orbit of about 27°, with a 12% change in separation. The orbit of FO Tau has a reduced χ^2 statistic of 3.37, leading to the belief that the uncertainties are underestimated. The mass derived from the orbit is 0.56 solar masses, agreeing well with both the SDF and the DM models.

FS Tau is poorly sampled but has a measured orbit spanning 34° and a 14% change in separation. The uncertainties in FS Tau also seem underestimated due to a reduced χ^2 statistic of 3.05. It seems unreasonable to do the same error standardization to this system because of the lack of regular sampling. It also has very few data points, and the error correction would result in dropping the occultation measurement. The same analysis can be done to this system after a few more years' worth of observations. Currently, this system favors the BCAH model followed by the SDF.

Each of the models can be ranked based on a reduced χ^2 scale where the dynamical mass is compared to the theoretical mass. Due to the two solutions for GG Tau, the model is compared with each and both results are given. For the forced errors, the SDF model fits the data best, followed by the BCAH model with a reduced χ^2 value 1.2 times larger. The PS model is 1.7 times larger, and the DM model is 2.6 times larger. The published errors also have the SDF model as the best fit. This is followed by the PS model with a reduced χ^2 2.5 times larger, then the BCAH at 3.2 times larger. DM still has the worst fit with a χ^2 value 4.7 times larger.

5. DISCUSSION

Having well studied properties based on disk dynamics, GG Tau has a known inclination and system mass (Guilloteau et al. 1999). Compared alongside values obtained astrometrically, a distance to the system can be inferred. The total mass inferred via disk dynamics scales proportionally to the distance to the object. Astrometrically, it scales as the distance cubed; therefore, a distance can be determined by equating the two methods: $M_d*(d/140)=M_t=M_a*(d/140)^3$, where M_d is the mass of the disk, M_t is the true mass, and M_a is the astrometrically obtained dynamical mass.

This implies that:

$$d = 140\sqrt{\frac{M_d}{M_a}}. \quad (1)$$

Using the astrometric results from table A1. and combining it with the mass determined by disk dynamics of 1.28±0.07 (Guilloteau et al. 1999). Propagating errors results in an inferred distance of 137.3±4.0 pc for the forced error calculations and 157.6±4.6 pc for the published errors.

The forced error calculations agree with the distance to the Taurus region of 140±10 pc. Although this is an argument for the validity of the forced calculation, these results are still preliminary due to many factors. First, although the published error calculation produces a result outside the errors of both measurements, this can be due to extra mass inside the disk but outside the binary system(Hartigan & Kenyon 2003), which would reduce the mass obtained through the disk. This scenario, however, is not very plausible due to the dynamics of binary stars. If a substantial fraction of the total mass of the binary system were to be present as dust near the orbit, it would be ejected very early in its lifetime and would be gone by the time the stars reach an equilibrium, as they do now. This extra mass does not include circumstellar disks, as they are accounted for in both methods of obtaining mass.

The disk measurement results also yield a robust value of 37±1°. This value agrees well with the forced error value of 143.5±0.1° (degenerately equivalent to 36.5±0.1°). The value obtained with the published errors differs greatly, with a value of 154.9±0.2° (degenerately equivalent to 25.1±0.2°). Compared to the results of Tamazian et al. (2002), using a technique separate from the one described above, both the forced error calculations and the published error calculations are within their error bars. However, all the orbital parameters–besides the period–resemble the forced error calculations much more closely. Although inconclusive, the forced error solution is the most probable because of these reasons.

The differing techniques of χ^2 minimization presented here, in Tamazian et al. (2002), and Schaefer et al. (2003) all produce similar results for DF Tau. Although Schaefer et al. (2003) derived a broad range of values, this could be due to the determination of errors. They computed the errors by calculating solutions within a reduced χ^2 value of 1, rather than a χ^2 value of 1. Regardless, the central peak of 0.81 agrees exactly with what is presented here. The Tamazian et al. (2002) data does as well with a system mass of 0.82±0.24 solar masses; however, the only other parameter that coincides with the values in this paper is the inclination.

The masses derived for FO Tau and FS Tau in Tamazian et al. (2002) agree within error to the results in this paper; yet, none of the other orbital parameters agree. This is reasonable because these two systems have very little orbital coverage and the least amount of data points in this survey. These results show that it is possible to get a well constrained mass without a well constrained orbit.

6. SUMMARY

The mass of a star is crucial to the understanding of its formation and evolution. It is also measurable in binary systems, creating a test for various theoretical models of formation. For low-mass pre-main-sequence stars, there are four important models: BCAH, SDF, PS, and DM.

New and published data for the relative positions of four T-Tauri stars yield a well constrained computed orbit. The mass relating to this orbit fits best with the SDF model, regardless of which of the GG Tau orbits is correct. These results are preliminary, and a larger range of binaries as well as masses for the individual stars in the binary are required for a more concrete statement.

This work made use of the W. M. Keck Observatory, operated under a scientific partnership between the California Institute of Technology, The University of California, and the National Aeronautics and Space Administration, and funded by the W. M. Keck Foundation. We are grateful for the assistance of the staff at the Keck and Palomar Telescopes.

APPENDIX

APPENDICIAL MATERIAL

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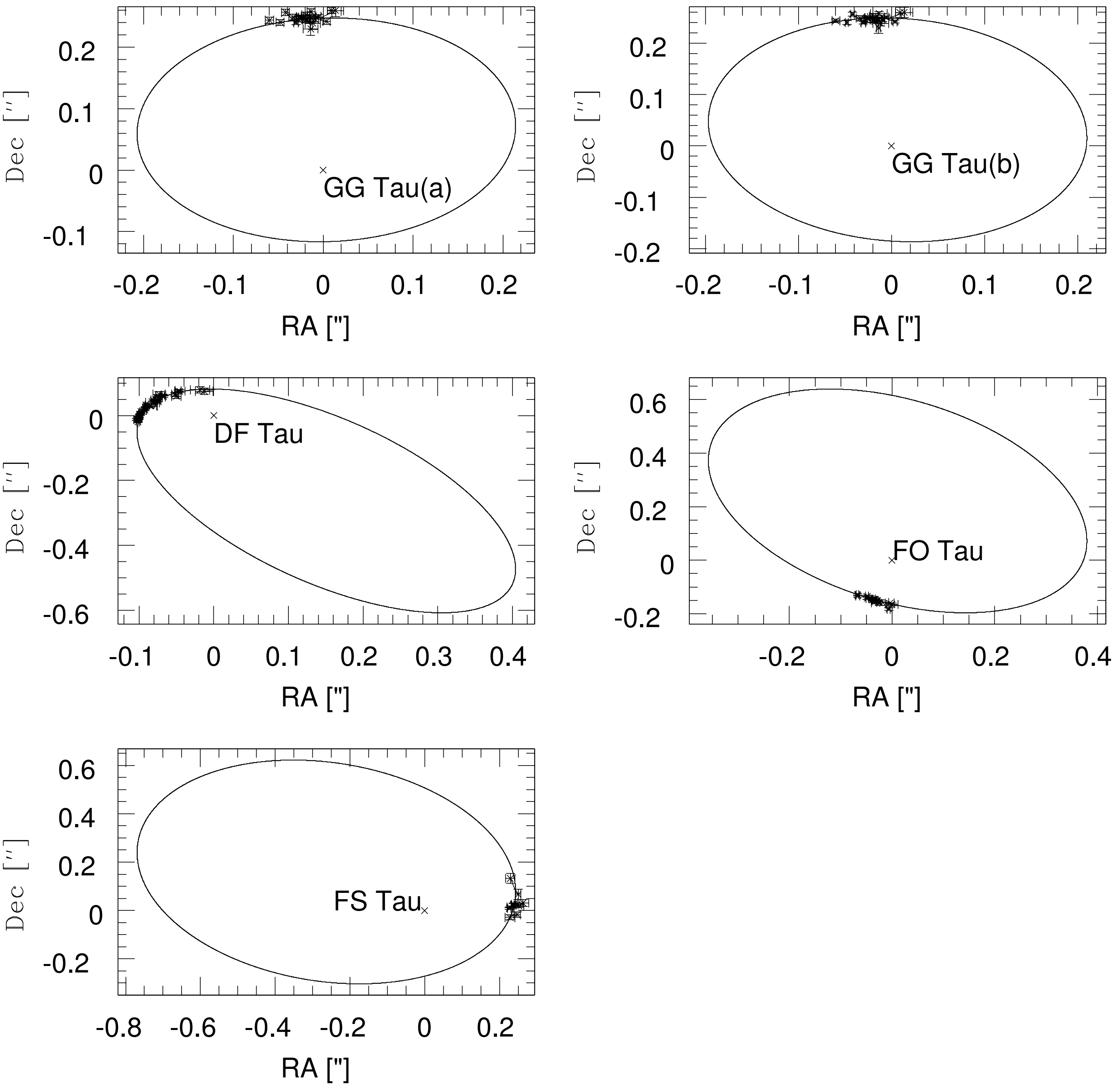

FIG. A1.— These are the calculated orbits for each binary star.

Table A1

Orbital Parameters

Star	a (AU)	e	i (deg)	w	W	T0	P
GG Tau[a]	31.8 ± 0.2	0.36 ± 0.01	143.5 ± 0.1	264.1 ± 0.1	85.8 ± 0.3	2068.8 ± 0.1	154.9 ± 0.1
GG Tau[b]	31.1 ± 0.1	0.15 ± 0.01	154.9 ± 0.2	318.9 ± 0.1	153.4 ± 0.2	2072.1 ± 0.1	172.8 ± 0.1
DF Tau	55.2 ± 0.3	0.78 ± 0.01	136.1 ± 0.4	171.1 ± 0.1	154.2 ± 0.4	1990.9 ± 0.1	456.8 ± 0.1
FO Tau	74.6 ± 0.4	0.58 ± 0.01	51.6 ± 0.1	62.9 ± 0.1	132.5 ± 0.3	1991.8 ± 0.1	857.3 ± 0.3
FS Tau	74.7 ± 2.3	0.58 ± 0.01	6.9 ± 2.6	89.0 ± 0.1	32.2 ± 1.0	2011.1 ± 0.8	652.1 ± 2.6

[a]Forced uncertainties

[b]Published uncertainties

Note. — These are the orbital parameters and the associated uncertainties for the four stars in our survey. These values represent the median values of the solutions to the Monte-Carlo simulations with a 34% spread on either side.

Table A2
Mass Comparisons

Star Name	Dynamical	BCAH	DM	PS	SDF
GG Tau[a]	1.35 ± 0.03	1.25 ± 0.15	0.86 ± 0.15	0.98 ± 0.15	0.98 ± 0.15
GG Tau[b]	1.01 ± 0.03	1.25 ± 0.15	0.86 ± 0.15	0.98 ± 0.15	0.98 ± 0.15
DF Tau	0.81 ± 0.02	1.20 ± 0.16	0.53 ± 0.07	0.66 ± 0.12	0.73 ± 0.13
FO Tau	0.56 ± 0.01	0.72 ± 0.14	0.41 ± 0.05	0.39 ± 0.11	0.58 ± 0.10
FS Tau	0.99 ± 0.04	1.02 ± 0.10	0.92 ± 0.12	0.82 ± 0.11	0.89 ± 0.12

[a]Forced uncertainties

[b]Published uncertainties

Table A3
Astrometric Data for Stars

Year	ρ (arcsec)	$\delta\rho$	P.A. (deg)	δP.A.	Technique	Reference
GGTau						
1990.835	0.2550	0.0100	9.000	2.0	1D Speckle	1
1991.799	0.2880	0.0060	3.000	2.0	Speckle	2
1991.802	0.2600	0.0100	2.000	1.0	Speckle	3
1993.988	0.2600	0.0100	3.000	2.0	AO	4
1994.071	0.2460	0.0040	357.8	0.4	Speckle	5
1994.561	0.2502	0.0026	358.8	0.5	HST[a]	6
1994.728	0.2580	0.0040	357.0	2.0	Speckle	3
1994.794	0.2420	0.0030	0.900	0.5	Speckle	3
1994.977	0.2390	0.0050	357.2	2.0	AO	4
1995.767	0.2470	0.0040	356.9	0.7	Speckle	5
1995.888	0.2300	0.0100	356.5	0.5	AO	4
1996.742	0.2450	0.0040	355.5	0.4	Speckle	5
1996.822	0.2530	0.0050	355.6	1.0	Speckle	7
1996.928	0.2436	0.0046	354.9	1.3	Speckle	8
1996.928	0.2487	0.0046	357.2	1.0	Speckle	8
1997.738	0.2500	0.0020	354.3	1.0	HST[a]	9
1997.772	0.2480	0.0020	353.9	0.4	HST[a]	10
1997.772	0.2510	0.0020	353.8	0.3	HST[a]	10
1997.772	0.2570	0.0030	353.6	0.8	HST[a]	10
1997.873	0.2470	0.0050	353.6	0.1	Speckle	5
1998.225	0.2415	0.0025	352.8	0.6	HST[a]	11
1998.772	0.2600	0.0040	350.7	0.4	Speckle	5
1998.885	0.2510	0.0050	352.3	1.0	Speckle	7
2001.06	0.2480	0.0140	348.6	2.4	STIS[b]	21
2001.110	0.2450	0.0040	348.7	0.3	Speckle	12
2003.948	0.2510	0.0030	346.2	1.0	Speckle	7
DFTau						
1986.800	0.0760	0.0100	350.4	9.0	Occultation	13
1989.840	0.0820	0.0100	347.0	9.0	Speckle	14
1990.857	0.0880	0.0020	329.0	5.0	Speckle	2
1990.857	0.0900	0.0020	328.0	3.0	Speckle	3
1991.730	0.0840	0.0070	322.0	1.0	Speckle	14
1991.743	0.0777	0.0065	320.0	4.8	Speckle	7
1992.776	0.0980	0.0080	312.0	5.0	Speckle	3
1993.733	0.0890	0.0020	311.2	1.3	HST[a]	15
1993.815	0.0930	0.0020	313.1	1.3	HST[a]	15
1993.901	0.0960	0.0040	309.5	0.7	Speckle	3
1994.567	0.0871	0.0038	301.2	2.0	HST[a]	8
1994.797	0.0890	0.0020	302.0	3.0	Speckle	3
1994.820	0.0912	0.0020	302.1	1.3	HST[a]	15
1994.940	0.0940	0.0020	300.6	2.5	Speckle	14
1994.966	0.0890	0.0010	301.0	1.0	Speckle	3
1995.053	0.0916	0.0020	302.6	1.3	HST[a]	15
1995.570	0.0907	0.0020	302.3	1.3	HST[a]	15
1995.841	0.0910	0.0100	296.0	2.0	Speckle	7
1996.814	0.0900	0.0100	289.0	3.0	Speckle	7
1996.928	0.0896	0.0079	290.2	1.2	Speckle	8
1997.019	0.0948	0.0020	288.6	1.3	HST[a]	16
1997.706	0.0949	0.0020	285.4	1.3	HST[a]	16
1997.885	0.0950	0.0010	286.2	0.7	Speckle	7
1998.164	0.0936	0.0020	280.5	1.3	HST[a]	16
1998.775	0.0960	0.0020	277.6	1.2	HST[a]	17

Table A3—*Continued*

Year	ρ (arcsec)	$\delta\rho$	P.A. (deg)	δP.A.	Technique	Reference
1998.885	0.0980	0.0020	277.1	0.7	Speckle	7
1998.900	0.0990	0.0140	273.4	6.1	STIS[b]	21
1999.695	0.0985	0.0020	272.2	1.2	HST[a]	16
1999.888	0.0990	0.0020	271.4	0.8	Speckle	7
2000.241	0.1004	0.0020	267.5	1.2	HST[a]	16
2000.671	0.1009	0.0020	266.8	1.2	HST[a]	16
2000.882	0.1010	0.0020	264.0	1.0	Speckle	7
2000.937	0.1040	0.0040	263.0	1.6	Speckle	7
2001.063	0.1005	0.0020	267.9	1.2	HST[a]	16
2001.164	0.1005	0.0020	265.1	1.2	HST[a]	16
2001.937	0.1030	0.0020	259.0	1.0	Speckle	7
2002.129	0.1021	0.0020	262.3	1.2	HST[a]	16
FSTau						
1989.195	0.2590	0.0050	75.00	5.0	Occultation	13
1989.717	0.2650	0.0050	60.00	5.0	Occultation	18
1996.068	0.2390	0.0050	84.00	1.5	HST[a]	19
1996.739	0.2380	0.0040	84.40	1.6	Speckle	5
1996.909	0.2650	0.0150	83.30	3.0	Speckle	5
1996.925	0.2530	0.0130	85.90	1.4	Speckle	8
1997.178	0.2276	0.0071	86.60	0.3	HST[a]	8
1997.876	0.2480	0.0050	84.30	1.5	Speckle	5
1997.925	0.2266	0.0045	87.90	1.2	Speckle	8
1997.925	0.2300	0.0130	97.10	2.4	Speckle	8
2000.950	0.2420	0.0140	93.70	2.5	STIS[b]	21
2001.110	0.2480	0.0090	94.00	2.7	Speckle	12
FOTau						
1991.715	0.1650	0.0050	180.0	4.0	Speckle	20
1991.794	0.1610	0.0010	181.7	3.0	Speckle	2
1993.758	0.1830	0.0050	182.0	0.9	Speckle	5
1994.799	0.1530	0.0020	190.6	0.4	Speckle	3
1994.950	0.1590	0.0040	189.7	0.9	Speckle	5
1994.964	0.1540	0.0020	191.2	0.4	Speckle	3
1995.796	0.1560	0.0040	193.1	1.3	Speckle	5
1996.736	0.1520	0.0040	194.3	0.9	Speckle	5
1996.909	0.1430	0.0040	200.0	1.1	Speckle	5
1996.925	0.1499	0.0069	193.7	1.0	Speckle	8
1996.928	0.1600	0.0100	188.4	5.9	Speckle	8
1997.175	0.1525	0.0029	194.7	0.4	HST[a]	8
1997.873	0.1500	0.0050	198.9	0.8	Speckle	5
1998.885	0.1540	0.0010	201.0	0.2	Speckle	7
1999.790	0.1460	0.0014	203.8	4.1	STIS[b]	21
2001.107	0.1450	0.0040	207.6	0.6	Speckle	12
2001.838	0.1490	0.0040	206.7	1.3	Speckle	12

[b]Hubble Space Telescope

[b]Space Telescope Imaging Spectrograph

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