BINARY STAR ASTRONOMY WITH OPTICAL INTERFEROMETRY

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Abstract

The Mark III Interferometer on Mt. Wilson, a long baseline optical interferometer, was in daily operation for more than seven years. During that time it achieved milliarc second angular resolution for binary star astronomy, with sub-milliarc second accuracy. For the first time many spectroscopic binaries have been resolved, including binaries in which the companion cannot be detected with spectroscopy. The high angular resolution means that the traditional gap between visual and spectroscopic binaries has been decreased by more than an order of magnitude. In order to confirm the performance of the Mark III Interferometer, this paper uses the results of astronomical observations, and compares the Mark III Interferometer with other high resolution techniques, including astrometry, lunar occultation, photometry, speckle, and spectroscopy. Comparisons for a variety of binary stars among these techniques indicate that long baseline optical interferometry provides a reliable, fully automatic, daily accessible astronomical capability for achieving high resolution, high accuracy, high dynamic range, and high photometric measurement precision for the study of binary stars.

1 Introduction

The Mark III Stellar Interferometer[1] has made a number of important contributions to binary star astronomy. This long baseline optical interferometer was in routine operation for more than seven years during which time it resolved many close binaries with only milliarc second (mas) separations. This instrument reached a resolution of 2 mas, which is ten times better than existing techniques. With such high resolution, not only have many spectroscopic binary systems been resolved, but also some primary components themselves have had their angular sizes determined. These measurements have provided direct determination of stellar effective temperatures. In particular, the Mark III has a capability for differential photometry to better than 0.05 mag for separations less than 0.″1. This represents a turning point for the collection of photometric data for double and multiple stars because of the present dearth of photometric measurements of the individual components with such small separations. Because of the high accuracy of its fringe visibility

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measurements, the Mark III demonstrates a dynamic range of 4 mag, and makes it possible to reveal the physical characteristics of many interesting binary systems.

Some important questions to ask regarding an observation method for binary stars include: does the technique achieve the claimed resolution and accuracy; are there systematic errors which cannot be corrected; are the measured angular separations reliable for large intensity ratios; and is there cross-checking among the different techniques?

Traditionally, there are five techniques available to do binary observations beyond the limit of the seeing disk, namely, the astrometric technique (measurement of the star's position), lunar occultation, the photometric technique (observe the eclipsing of the two components), the spectroscopic method, and speckle interferometry. The Mark III Stellar Interferometer is a powerful tool to measure binary stars, and provides good examples to compare with the techniques above. These comparisons among different techniques are helpful in order to recognize the performance limits for the study of binary stars, and to find out the possible systematic errors in a particular technique. Depending on the separations between two components, there are four, three, or only two techniques available. By using observed binaries, the Mark III Interferometer is compared below with other techniques which are also capable of measuring these binaries. The final section provides a summary.

2 Comparison of Mark III results with those from astrometry, speckle, and spectroscopy

There are some binary stars with separations of $\sim$100 mas which have had orbital results from these four techniques. One examples is χ Dra.

The nearby system χ Dra (8 pc) first had its spectroscopic orbit determined by Wright in 1900, and the orbit was finalized in 1942. An astrometric orbit was completed by Alden in 1936, and the most recent analysis was done by Breakiron & Gatewood[2] in 1974, which determined an inclination $i = 56.^\circ 0 \pm 2.^\circ 1$ and semimajor axis $a'' = 0.''149 \pm 0.''01$. Using speckle observations, the first orbit was determined by Bonneau & Foy in 1980, who obtained an inclination $i = 75.^\circ 0 \pm 2.^\circ 5$. Using additional speckle data lead to an inclination $i = 79.^\circ 9 \pm 0.^\circ 9$ and $a'' = 0.''1240 \pm 0.''0029$. In 1987 the secondary's spectroscopic orbit and the speckle's visual orbit were revised by Tomkin et al[3]. Adopted orbital parameters, combining the spectroscopic and speckle results are inclination $i = 74.^\circ 9 \pm 0.^\circ 9$ and $a'' = 0.''122 \pm 0.''001$. Unfortunately, the magnitude differences between the two components can only be estimated from the spectroscopy and from theoretical considerations, and the two published values are 1.99 mag and 2.07 mag in V. With the Mark III Interferometer there are 3 years of data available using baselines from 4 m to 20 m. Because of its high resolution, these observation can cover close orbital motion, which cannot be measured by any other technique. More importantly, a high accuracy of measurement provides a good foundation in order to determine the orbital motion accurately. In addition, the direct magnitude differences and color indices are obtained for the first time, and allow the placement of the system on the H-R diagram. The results are: Δ m $= 2.02 \pm 0.06$ mag at 800 nm and Δ m $= 2.44 \pm 0.17$ mag at 550 nm, yielding bolometric magnitudes of 4.02 mag and 6.14 mag for the primary and the secondary, and color differences between 550 nm and 800 nm of +0.54 mag and +0.96 mag for two components. These physical parameters correspond to an F6-F7 primary and K3-K4 secondary, which is consistent with the spectral classification. While the primary was resolved with the Mark III, its diameter can only be estimated to have an upper limit of 2 mas. Because of its high declination ($\delta = 72°$), the longest baseline which could be used for this system is only 20 m, compared to a maximum available baseline of 31.5 m.

The visual orbit of χDra is shown in Fig. 1, with the data from the speckle and the Mark III indicated as filled circles. The rms dispersions of the observations from the orbit are 0.99 mas for the Mark III and 5.5 mas for the speckle measurements. A comparison of parameters for the system determined with the four techniques are listed in Table 1. The agreement of these parameters from the Mark III and other techniques indicate that there are no systematic errors for this example, except that the astrometric method has difficulty measuring separations of ~100 mas.

Table 1. Comparison of parameters determined with the Mark III, astrometry, speckle, and spectroscopy for χDra

	Mark III		Astrometry		Speckle		Spectroscopy			
							Primary		Secondary	
P(day)	280.54	±0.03	—		280.550		280.55		280.7	
T(year)	1984.8352	±0.0019	—		1984.8360		1984.8360		1984.8283	
e	0.416	±0.003	—		0.445		0.445	±0.005	0.415	±0.008
a''(mas)	122.5	±0.2	149	±10	122	±1	—		—	
$i°$	74.76	±0.05	56.0	±2.1	74.9	±0.9	—		—	
$w°$	119.15	±0.09	—		119.2	±0.7	121.7	±1.0	292.2	±1.5
$\Omega°$	230.48	±0.12	235.5	±2.5	231.5	±0.7	—		—	
d(pc)	8.33	±0.11	7.90	±0.34	8.33	±0.10				
Δm_{800}	2.02	±0.06	—		—		—		—	
Δm_{550}	2.44	±0.17	—		—		1.99			
M_{1bol}(mag)	4.04	±0.08	—		—		—			
M_{2bol}(mag)	6.14	±0.27	—		—		—			
$Color_1$	+0.54	±0.20	—		—		—			
$Color_2$	+0.96	±0.24	—		—		—			

3 Comparison of Mark III results with those from speckle and spectroscopy

For binaries with separations of less than 100 mas, there are three techniques which are in common use: speckle, spectroscopy, and long-baseline interferometry. A good example for comparison is the star ξ Cephei.

This triple system has a widely separated ($8''$) third body with a common proper motion. The central star was found to have a composite nature in 1938, and the spectra are classified as A5m for the primary and F2 III-IV for the secondary. Nine years of coude spectrographic observations[4] have lead to orbital elements for both components and a value of $\Delta m = 0.55 \pm 0.20$ mag in B from the spectral line luminosity ratios. In this case the measured radial velocities lead to an evolutionary puzzle: the less-massive companion appears to have evolved off the main sequence first. Although the authors presented three possible explanations for this, none appears reasonable. Speckle techniques resolved this system in 1975, and obtained its visual orbit[5] in 1980 for nearly 1.3 revolutions, yielding period $P = 2.254 \pm 0.005$ year, eccentricity $e = 0.589 \pm 0.010$, $a'' = 0.''073 \pm 0.''002$, and $i = 71.^\circ 9 \pm 1.^\circ 1$. Combining the speckle and double-line spectroscopic results, it is straightforward to derive the distance $d = 25.8 \pm 2.2$ pc, and the masses $\mathcal{M}_{Aa} = 1.00 \pm 0.11$ and $\mathcal{M}_{Ab} = 0.36 \pm 0.05 M_\odot$. Using $\Delta m = 0.5$ mag in B from spectroscopy, the absolute magnitudes are determined as $\mathrm{M}_{Aa} = 3.04 \pm 0.20$ mag and $\mathrm{M}_{Ab} = 3.35 \pm 0.20$ mag. It is obvious that both components are significantly undermassive and underluminous for their spectra types. The question arises as to whether the speckle or spectroscopic results are wrong, or is this is a unique example in which the classic stellar evolution theory cannot be applied? For this system the Mark III has had three years of observations, and the orbital parameters are determined as $i = 72.^\circ 93 \pm 0.^\circ 07$ and $a'' = 76.7 \pm 0.29$ mas. These values agree well with those from speckle. Thus, it is believed that the visual orbit is well determined. One obvious possibility for the above undermassive solution is that the spectroscopic measurements had systematic errors because of the blending of line pairs. As to the question of underluminousness, the spectroscopic estimates are definitely wrong. The Mark III provides direct measurements of magnitude differences as 1.75 ± 0.06 mag at 550 nm, and 1.62 ± 0.03 mag at 800 nm. The visual magnitudes are 4.51 mag and 6.24 mag for the primary and the secondary, and the color indices between 550 nm and 800 nm are $+0.37$ mag and $+0.51$ mag, which correspond to an A type primary and an F type secondary. This is in much better agreement with the anticipated values on the H-R diagram. Table 2 summarizes the solutions of the physical parameters from the Mark III and speckle by using existing spectroscopic data or by using assumed distances from the trigonometric parallax. It is obvious that it is necessary to redo the radial velocity measurements for both components in order finally to solve this puzzling system.

Table 2. Comparisons using spectroscopic data and the assumed distance

Parameters	Spectroscopic data Mark III	Spectroscopic data Speckle	Assumed distance Mark III	Assumed distance Speckle
distance(pc)	24.37	25.8	33	33
Δm (mag)	1.75	0.31	1.75	0.31
M_1 (mag)	2.45	3.04	1.92	2.5
M_2 (mag)	4.09	3.35	3.56	2.8
$\mathcal{M}_1(\mathcal{M}_\odot)$	0.95	1.00	2.36	2.05
$\mathcal{M}_2(\mathcal{M}_\odot)$	0.34	0.36	0.84	0.74

4 Comparison of Mark III results with those from spectroscopy

There are many interesting binaries which have separations smaller than the diffraction limit of a single telescope, or which have larger separations but have large magnitude differences, >2–3 mag, which are difficult to measure. Only two techniques, spectroscopy and long-baseline interferometry, have the possibility of determining the geometric and physical parameters for such systems. We present β Ari here as an example.

The binary star β Ari has had independently-determined orbital parameters from the Mark III without knowledge of the spectroscopic data. This binary has separations of 35 - 64 mas over most of its period. However, a large magnitude difference of 2.6 mag at 800 nm probably prevented it from being resolved with other techniques. Because of its unusually large eccentricity (e=0.9), the star has attracted much attention. The first spectroscopic orbit was obtained in 1907, and further studies in 1938 and 1970 did not show significant changes of the orbital parameters. The companion was detected spectroscopically by Tomkin & Tran[6] in 1987, and a mass ratio of 0.57 ± 0.03 was determined. With the Mark III Interferometer, both components became "visual," and the orbital parameters were determined independently from 20 nights of observations on 14 baselines from 8 m to 31.5 m. The geometric parameters determined from the Mark III agree well with those from spectroscopy. In addition, the magnitude differences were determined with the Mark III as $\Delta m = 2.63 \pm 0.22$ mag at 800 nm and 3.31 ± 0.34 mag at 550 nm. The color indices between 550 nm and 800 nm are +0.2 mag and -0.1 mag for the primary and the companion. Combining the Mark III results with those from spectroscopy leads to a direct determination of the distance, masses, and luminosities as $d = 18.87 \pm 0.61$ pc, $\mathcal{M}_1 = 2.34 \pm 0.10\mathcal{M}_\odot$, $\mathcal{M}_2 = 1.34 \pm 0.07\mathcal{M}_\odot$, and absolute bolometric magnitudes $M_{1bol} = 1.2 \pm 0.1$ mag and $M_{2bol} = 4.4 \pm 0.2$ mag. The results are found to fit well on the empirical mass-luminosity relation. The ephemeris of the star β Ari from the newly determined orbit from the Mark III indicates that the maximum separation between the two components is ≈ 64 mas, and the angular separation is more than 35 mas for ≈ 83 days of each 107 days period. It is a good target star to test the resolution and the dynamic range for any type of high resolution instrument since this very bright system (2.64 mag at V) has separations between two components changing from 2 mas to 64 mas every 107 days.

Table 3. Stellar Parameters from the Mark III and spectroscopy

Parameters	Mark III	Spectroscopy
P(days)	106.952 ± 0.077	106.9954 ± 0.0005
e	0.900 ± 0.008	0.895 ± 0.003
i°	46.07 ± 0.57	—
a''(mas)	37.02 ± 0.23	—
M_1 (mag)	1.31 ± 0.1	—
M_1 (mag)	4.61 ± 0.2	—
mass ratio	—	0.57 ± 0.03

The Mark III and spectroscopy represent two completely different techniques, and demonstrate agreement of better than 1% for the common orbital parameters. The differential photometry from Mark III yields color indices of both components which are consistent with their spectral classifications. Their measured luminosities from the Mark III fit very well to the H-R diagram. These facts indicate that the Mark III interferometer is reliable and accurate for the study of close binary stars.

5 Comparison of Mark III results with those from photometry and spectroscopy

Eclipsing binary stars are of great importance in astronomy, and have long been studied to accurately determine their periods, inclinations, radii, masses, and other physical parameters. These stars also offer an unique opportunity to verify the performance of the Mark III Interferometer with respect to its resolving power and its measurement precision of differential photometry. There are 5 eclipsing binaries observed on the Mark III. We are going to present the results for the star β Aur here for the purpose of comparison.

The eclipsing binary β Aur has two almost identical components, each of which is a main sequence A0 type star. Their radial velocities were obtained by Baker and Smith in 1910 and 1948, respectively, and are in good agreement. However, measurements in 1968 by Galeotti & Guerrero were $\sim$ 7 % smaller, and caused the masses to decrease $\sim$ 20 %. The new observations in 1970 by Popper & Carlos[7] confirmed the older values, and the orbital parameters from spectroscopy are: $P = 3.9600421 \pm 0.0000013$ days, $e = 0.011 \pm 0.004$, and $w = 204.^\circ 35 \pm 34.^\circ 8$. Although the eclipses are very shallow for this system, the photometric observations in eight colors determined the inclination $i = 77.^\circ 8 \pm 0.^\circ 2$. This binary has a short period with only a few milliarc second separation all of the time. However it is not difficult to resolve it with the Mark III Interferometer because of its small magnitude difference, which is determined directly as 0.04 ± 0.06 mag. An inclination of $76.^\circ 2 \pm 2.^\circ 7$, semi-major axis of 4.76 ± 0.23 mas, and distance of 17.2 pc were determined. By using the linear radius from photometry, the angular diameters of the two components can be calculated as 1.3 mas. From the results of the Mark III, the angular separations during the eclipses are $\approx$ 1.2 mas. The stellar parameters from these three techniques are compared in Table 4.

Table 4. Stellar Parameters from the Mark III, photometry, and spectroscopy

Parameters	Mark III	Photometry	Spectroscopy
i°	76.2 ± 2.7	77.8 ± 0.2	—
w°	183.7 ± 2.5	—	204.35 ± 34.8
a''(mas)	4.76 ± 0.23	4.73 ± 0.02	—
a(a.u.)	0.082 ± 0.004	0.081 ± 0.0003	—
d(pc)	17.2 ± 0.8	—	—
$\mathcal{M}_1(\mathcal{M}_\odot)$	2.40 ± 0.3	2.35 ± 0.03	—
$\mathcal{M}_2(\mathcal{M}_\odot)$	2.31 ± 0.3	2.27 ± 0.03	—

6 Comparison of Mark III results with those from lunar occultation and spectroscopy

Despite its dependence on the Moon and its limited sky coverage, the lunar occultation technique has directly measured many stellar diameters down to the milliarc second level. The technique can also measure the projected separations of a binary system to a precision of a few mas. In particular, the occultation measurements can provide direct determination of magnitude differences between the two components. It is interesting to compare the results from the Mark III with those from lunar occultation. A good example is binary star θ^2 Tau.

θ^2 Tau is the brightest binary in the Hyades cluster. Its predicted separation of 21 mas excludes resolution with speckle. The spectroscopic orbital parameters from three investigators agree well (Plaskett 1915, Petrie 1940, Ebbighausen 1959). Unfortunately, no secondary has been detected throughout those 44 years of spectroscopic observations. In the early 1980's, lunar occultation observations detected the secondary for the occultation of Jan. 27, 1980, the magnitude differences were determined as $\Delta m = 0.61 \pm 0.09$ mag at 467 nm and 0.96 ± 0.17 mag at 547 nm by Evans & Edward[8]. Another lunar occultation of this system was observed by Peterson[9] on Aug. 5, 1980, and the results are as follows: Δ m $= 1.07 \pm 0.04$ mag at 440 nm, 1.18 ± 0.05 mag at 630 nm, and 1.04 ± 0.06 mag at 790 nm. These results yield $\Delta m = 1.10 \pm 0.05$ mag at 550 nm, primary magnitude V= 3.75 mag, color index B-V = 0.17 mag, secondary magnitude V = 4.85 mag, and color B-V = 0.16 mag. The derived separations are 11.6 mas and 20.8 mas for Jan. 27 and Aug. 5, 1980, respectively. With the Mark III Interferometer the visual orbit[10] of θ^2 Tau was determined in 1991. The magnitude differences between the two components are Δ m $= 1.15 \pm 0.07$ mag at 800 nm, 1.18 ± 0.10 at 550 nm, and 1.16 ± 0.13 at 450 nm. These results from the Mark III and those from lunar occultation are consistent to within their stated error bars. The calculated separations from the Mark III's visual orbit for those two nights on which the lunar occultations were observed are 25.3 mas and 23.8 mas, respectively. The separations from the two lunar occultation events represent minimum separations between the two components, and in fact they are all smaller than the calculated separations from the Mark III. This example shows that the two different techniques both have high photometric accuracy.

7 Conclusion

It is a challenging task to study binary systems with a long baseline interferometer. Fast star and fringe searching, automatic fringe tracking and sampling, and sufficient u-v coverage are all critical for extracting and interpreting the characteristics of binary stars in a quantitative fashion.

Seven years of observations with the Mark III Interferometer demonstrates that long baseline optical interferometry provides a reliable, fully automatic, daily accessible astronomical technique with milliarc second resolution and accuracy for the study of binary stars and other scientific projects.

Observational results from the Mark III compared with those from astrometry, photometry, lunar occultation, speckle interferometry, and spectroscopy have confirmed its high resolution, high accuracy, high dynamic range, and high differential-photometric precision. With the Mark III Interferometer there are more than 40 spectroscopic binaries which have been resolved for the first time. These observations significantly increase our knowledge of the accurate H-R diagram, particularly for the evolved stars. The number of accurate masses on the H-R diagram has been increased by 25 %, covering the spectral range from B to G. Table 5 presents the statistics[11] of stars with accurate mass, which are contributed by the Mark III and other techniques. Right now the problem is that the secondary stars can be "seen" with the Mark III Interferometer, but cannot be detected spectroscopically. We hope future improvements in spectroscopy will change this situation.

Table 5. Stars of accurately known mass and contributions from the Mark III Interferometer

Spectral Class	Luminosity Class V		IV		III		II		I	
	Others	MK3	Others	MK3	Others	MK3	Others	MK3	Others	MK3
O	4	0	0	0	0	0	0	0	0	0
B	31	4	0	2	0	2	0	0	0	0
A	18	6	0	3	0	2	0	0	0	0
F	40	1	0	0	0	0	1	0	0	0
G	7	2	1	0	2	4	3	0	0	0
K	7	0	0	0	0	0	0	0	0	0
M	14	0	0	0	0	0	0	0	0	0

Now a new infrared interferometer, the ASEPS-0 interferometer testbed, is under construction by JPL for NASA for installation at Palomar Mountain. With new observation modes and a 100 m baseline, we anticipate many new types of results for binary star astronomy, in addition to beginning a search for extra-solar planets.

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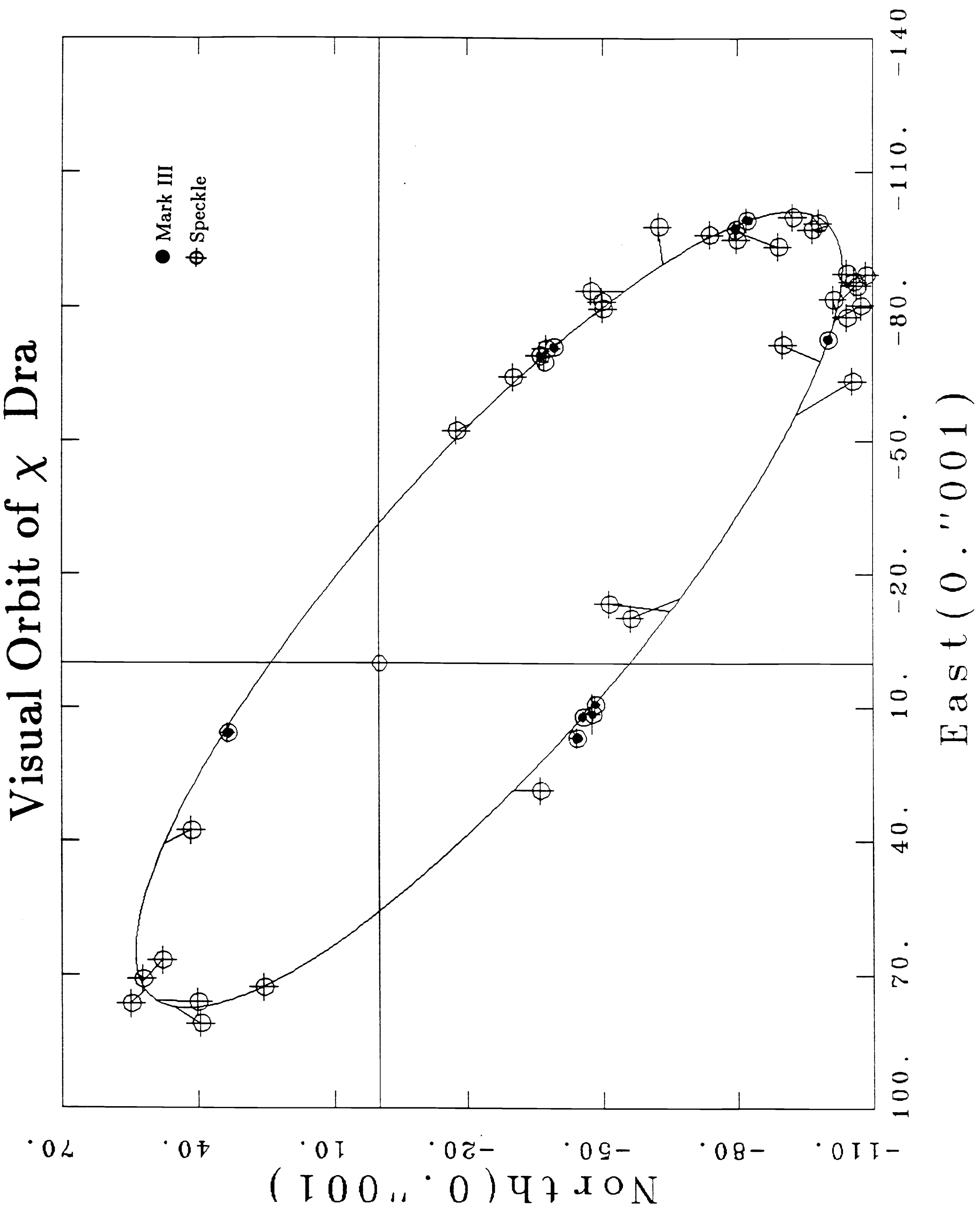

Visual Orbit of χ Dra
Mark III
Speckle
East (0.″001)
North (0.″001)
100.
70.
40.
10.
-20.
-50.
-80.
-110.
-140.