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Invited review

BINARY STAR ASTROMETRY WITH MILLI AND SUB-MILLI ARCSECOND PRECISION

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SUMMARY: The past several decades have seen accelerating progress in improving binary stars fundamental parameters determinations, as new observational techniques have produced visual orbits of many spectroscopic binaries with a milli arcsecond precision. Modern astrometry is rapidly approaching the goal of sub-milli arcsecond precision, and although presently this precision has been achieved only for a limited number of binary stars, in the near future this will become a standard for very large number of objects. In this paper we review the representative results of techniques which have already allowed the sub-milli arcsecond precision like the optical long baseline interferometry, as well as the precursor techniques such as speckle interferometry, adaptive optics and aperture masking. These techniques provide a step forward from milli to sub-milli arcsecond precision, allowing even short period binaries to be resolved, and often resulting in orbits allowing precisions in stellar dynamical masses better than 1%. We point out that such unprecedented precisions should allow for a significant improvement of our comprehension of stellar physics and other related astrophysical topics.

Key words. binaries: visual – binaries: spectroscopic – methods: observational – techniques: high angular resolution

1. INTRODUCTION

Astrometry of binary stars is one of the oldest branches of observational astronomy. Historically, the study of binary stars has always been closely connected to high angular resolution. The discovery of new binary or multiple systems, the astrometric determination of their orbital parameters, and eventually the measurement of fundamental stellar properties such as masses and diameters: all these important achievements greatly benefit from high angular resolution.

Classical astrometry has limited precision and accuracy for several reasons, but mainly due to the effects of diffraction and turbulence in the atmosphere. Additional noise is introduced by distortions in the telescope's structure, caused by its own weight and by its thermal response. The combination of these factors prevented reaching precisions in position measurements better than one tenth of an arcsecond.

Later on, techniques such as a variety of speckle methods, lunar occultations, aperture masking interferometry, adaptive optics, and then methods such as long baseline interferometry (involving independent telescopes separated by large distances) were developed, having always binary star research as a main area of application. New techniques have continuously been introduced allowing observation of binary systems with smaller separations and increasing dynamic ranges.

Speckle interferometry, which is characterized by the diffraction limited resolution and enhanced accuracy, offers a wide range of possibilities for astrometry. Speckle applications are limited by the constraint that the observations can be carried out over isoplanatic angles (within which the perturbing effects of the atmosphere are the same) with the result that only differential, rather than absolute astrometry can be performed with this technique.

On the other hand, the technique of lunar occultations employs diffraction effects generated at the lunar limb to overcome the limitations on resolution, which affects single telescopes. In a lunar occultation event, a background source is scanned by the lunar limb, which acts as a straight diffracting edge. The result is that the light from the background source is modulated by a series of diffraction fringes, before being progressively obscured. The angular information is embedded in the amplitude of the fringes, but for sufficiently detached systems two (or more) jumps can be easily separated, corresponding to the individual components. For smaller separations, a detailed analysis is needed to separate the contribution of each component. Note that the angular resolution achievable by the Lunar Occultation (LO) technique is not directly related to the telescope diameter: for this technique, the instrument which provides the resolution is actually the lunar limb.

One of the latest technologies to be applied to binary stars, rapidly maturing over past several decades, were Adaptive Optics (AO) where the image distorting effects of atmospheric turbulence are corrected in real time producing near diffraction limited images, and the Aperture Masking Interferometry where a mask is placed over the telescope which only allows light through an array of holes which acts as a miniature astronomical interferometer, allowing the phase closure analysis. Both of these techniques have been used to obtain structures at the scale bellow the diffraction limit of a single aperture telescope, but only their merging allowed to overpass the intrinsic limitations of each of these techniques used separately.

Ground based optical interferometers use long baselines to solve the difficulties of diffraction limits, and obtain an angular resolution of milli or even micro arcseconds (mas and μas respectively). In fact, using the very short exposures, the long-baseline optical interferometry can freeze the atmosphere within seeing limits to reach the sub-mas measurement precision. This technique allows performing the astrometry of stellar fields by analyzing the fringe patterns of stars measured by the interferometer. The binary stars astrometric information can be extracted from both visibility amplitude and/or fringe phase analysis. Recently, the phase referenced astrometry became a principal tool to achieve the sub-milli arcsecond precisions.

The techniques cited above can nearly close the gap in selection space between astrometric (measuring separations and position angles) and spectroscopic (measuring Doppler shifts of spectral lines) study of binary star systems, bringing the complementary powers of astrometry and spectroscopy to bear on a complete dynamical understanding of such systems, particularly including the determination of the masses of the individual stellar components. In addition, for the cases where the angular diameters of one or more components are accessible, a complete specification of a star in terms of its mass, radius and luminosity can be made.

Binary stars provide a unique laboratory to study physical properties of individual objects, and important constraints on star formation and evolution. They are frequently the only source for the fundamental determination of the most basic property of a star, its mass. Besides gravitational microlensing (e.g. Paczynski 1986), the observation of binary systems and use of Newtonian orbital dynamics provide the only method of direct accurate measuring stellar masses. Masses of a sample of stars, when determined with sufficient accuracy, serve as crucial tests of our theoretical understanding of stellar formation, structure, and evolution.

While the optical interferometric techniques and instruments related to the present paper have been described in more detail in Jankov (2010) and astrophysical results in Jankov (2011), here we review the binary star results in the context of high resolution astrometry. The corresponding techniques are introduced in Section 1, and the results obtained from Speckle Interferometry in Section 2. The technique of Lunar Occultations is presented in Section 3., while Section 4. describes Adaptive Optics and Aperture Masking Interferometry results. The long baseline interferometry results are presented in Section 5, and finally, we conclude this review by Section 6.

2. SPECKLE INTERFEROMETRY

Speckle interferometry of close double stars avoids seeing limitations through a series of diffraction-limited high speed observations made faster than the atmospheric coherence time scale. This technique not only allowed observations of binaries (stars gravitationally bound to each other) with angular separations below the seeing limit, but the observations were generally an order of magnitude more accurate than visual observations (McAlister 1985). McAlister's early observations set the standard for the calibration and accuracy of speckle measurements, making speckle interferometry the viable and important technique as it is today for binary star astrometry.

Speckle interferometry measurements have now been made for four decades. For this reason the binaries with the highest quality orbits often have periods of 40 years or less. Due to their small separations, they have been mostly observed with speckle cameras on larger telescopes. The larger telescopes concentrate on binaries with smaller separations while smaller telescopes observe the wider pairs.

Many close binaries were discovered during the Hipparcos mission. Generally they are fast orbiting systems, i.e. with short orbital periods. Astronomers have intensified speckle interferometry observations of these binaries since they can determine orbital elements reliably in the short time interval and determine the dynamical masses. The main problem in the mass determination lies in uncertainties of the Hipparcos parallaxes. The Gaia mission (Eyer et al. 2013) is expected to result in an order of magnitude improvement in the accuracy of parallaxes. As a consequence, the accuracy of dynamical mass determination will be significantly improved.

An example that clearly shows much higher precision and accuracy of speckle interferometry observations than visual observations is η CrB (Fig. 1). The scatter of speckle interferometric measurements (filled circles) is significantly less than the scatter of visual measurements (plus signs). The orbit obtained in 1929 using visual measurements was given a grade "definitive". However, speckle interferometry allowed a correction to be made and the orbital elements were determined more accurately by Mason et al. (1999). The latest combined spectroscopic/astrometric solution was determined by Muterspaugh et al. (2010). Calculated masses are $1.243 \pm 0.054\mathcal{M}_{\odot}$ and $1.100 \pm 0.039\mathcal{M}_{\odot}$ and distance is 18.50 ± 0.22 pc.

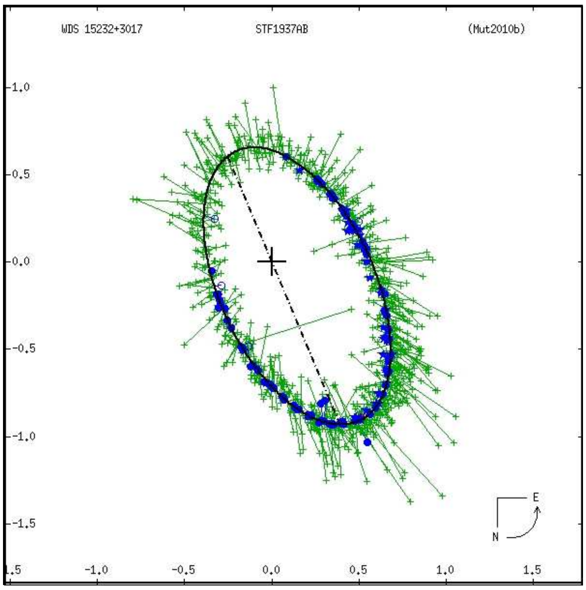

Fig. 1. *The apparent orbit for η CrB. Plus signs indicate visual (micrometric) observations and filled circles indicate speckle or other single-aperture techniques. The solid lines connect each measurement to its predicted position along the orbit. The dot-dash line indicates the line of nodes. Scales are in arcseconds, and the curved arrow at lower right indicates the direction of orbital motion.*

A large number of observations were made with the CHARA speckle camera, used on several different telescopes. The aim of these observations was to provide a high accuracy of high angular resolution measurements of binary star systems by speckle methods. An observing program was aimed at determining the properties of binaries containing very massive components and mass determination. The results of speckle interferometric measurements for such binaries are reported in Mason et al. (1997) for Be stars, Mason et al. (1998) for O-type stars and Hartkopf et al. (1999) for the brightest Wolf-Rayet stars.

Horch et al. (1999) reported the results from speckle observations taken with the Wisconsin-Indiana-Yale-National Optical Astronomy Observatories (WIYN) 3.5 m telescope located at Kitt Peak, Arizona. Speckle images were obtained using two different imaging detectors, namely, a multianode microchannel array detector and a fast-readout Charge Coupled Device (CCD). The measurement precision study was performed on a sample of binaries with very well known orbits by comparing the measurements obtained in that study to the ephemeris predictions. For the CCD, the root mean square (rms) deviation of residuals was found to be 3.5 milli arcseconds in separation and 1.2 degrees in position angle.

Horch et al. (2009) reported the first results of a new speckle imaging system, the Differential Speckle Survey Instrument (DSSI) at the WIYN 3.5 m telescope introduced in 2008. The instrument is designed to take speckle data in two filters simultaneously with two independent CCD imagers. This speckle imaging system continues to provide the majority of astrometric data for sub-arcsecond separation binary systems. This is largely due to the fact that it is a very efficient technique, permitting a large number of objects per night to be observed. In addition to accurate relative positions, magnitude differences between the components were measured and individual brightness estimates for each of them were obtained. Accurate magnitude differences can yield useful information about their luminosities and spectral types.

Since 2002 there has been progress in understanding how to obtain reliable photometry of binaries (e.g. Balega et al. 2002, Horch et al. 2004, Scardia et al. 2005, Tokovinin and Cantarutti 2008, Tamazian et al. 2008). This advance promises to be significant for our understanding of the stellar structure and evolution in the long term. To build a standard stellar structure model it is necessary to know its mass, helium abundance, metallicity and age. If well-determined magnitudes and colors can be obtained for many binaries in addition to individual masses (through orbit determinations) and system metallicity (through spectroscopic observations), then the standard stellar evolution calculations become more significant. This is an important fact for investigating the details of stellar models, which is not possible without photometric information on the components of binary systems. Such information is also very important in the investigation of binaries with nonstandard components, as shown in the work of Tamazian et al. (2008) on the flare star CR Dra.

Horch et al. (2011) presented the results of speckle observations of Hipparcos stars and other selected targets. The data were obtained using the DSSI at the WIYN 3.5 m telescope. Since the first paper in this series (Horch et al. 2009), the instrument has been upgraded so that it now uses two electron-multiplying CCD cameras. The obtained measurement precision, when compared to ephemeris positions of binaries with very well known orbits, is approximately 1-2 mas in separation and better than 0.6 degrees in position angle.

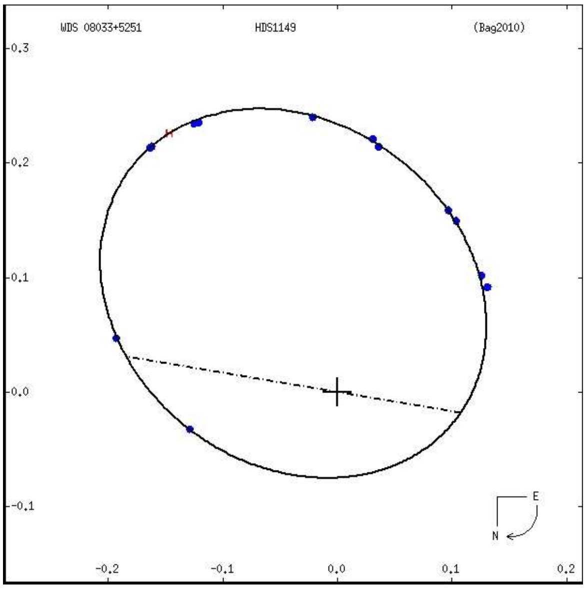

Fig. 2. *The apparent orbit for HIP 39402. Filled circles indicate speckle or other single-aperture techniques and sign "H" indicates a measurement from Hipparcos. Other designations are the same as in Fig. 1.*

The first results of the diffraction-limited optical speckle interferometry and infrared bispectrum speckle interferometry of 111 double and 10 triple systems performed in 1998-1999 with the 6-m telescope of the Special Astrophysical Observatory (SAO) in Zelenchuk (Russia) were presented in Balega et al. (2002). The observations concentrated on nearby close binaries discovered during the Hipparcos mission. Many nearby fast-orbiting low-mass binaries known before Hipparcos were also included in the program. Balega et al. (2002) were able to resolve stellar companions as close as 20 mas. The measurement precision was about 2-6 mas. Recent data on these studies and references to previous works can be found in Balega et al. (2007, 2010). An example of nearby close binary discovered during the Hipparcos mission is HIP 39402 (Fig. 2). It is a system of M dwarfs at a distance of 31 pc from the Sun. Balega et al. (2010) obtained the orbital period of 12.95 ± 0.05 years, the semimajor axis of 197.7 ± 1.6 mas and the dynamical total mass of $1.40 \pm 0.56 \mathcal{M}_\odot$.

The results of speckle observations of visual binary stars made with the Pupil Interferometry Speckle camera and COronagraph (PISCO) on the 102 cm Zeiss telescope of INAF "Osservatorio Astronomico di Brera" in Merate (Italy) are given in a series of 12 papers. PISCO was developed in France and first used at Pic du Midi from 1993 to 1998. It was moved to Merate in 2003 and used there since. The best precision was on the order of a few mas. Recent data on these studies and references to previous works can be found in Prieur et al. (2012) and Scardia et al. (2013).

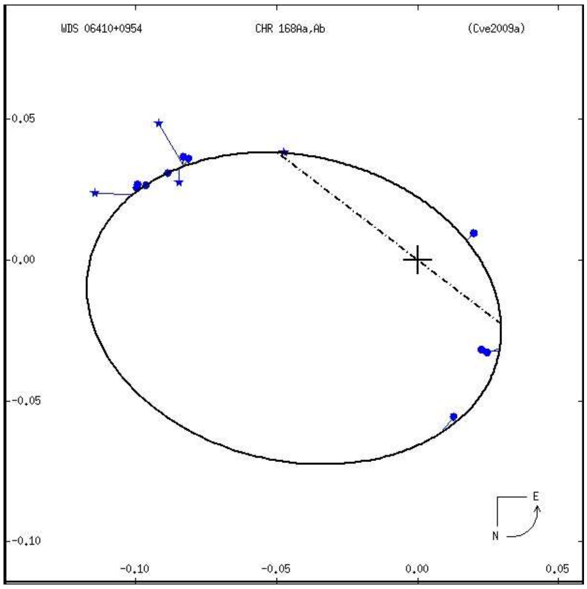

Fig. 3. *The apparent orbit for 15 Mon. Filled circles and asterisk indicate speckle or other single-aperture techniques. Other designations are the same as in Fig. 1.*

Speckle interferometry at 4-m class telescopes is an almost unique source of modern binary star measurements with high precision, the contribution from adaptive optics or long baseline interferometry being less in number (Hartkopf et al. 2012). Presently, the speckle interferometry program runs at the Blanco and SOAR 4 m telescopes in Chile. During the period 2008–2009 Tokovinin et al. (2010) produced many data (1898 measurements of 1189 pairs) and discovered 48 newly resolved pairs. The observations were performed with the high-resolution camera (HRCam), a fast imager designed to work at the SOAR telescope either with the SOAR Adaptive Module or as a stand-alone instrument. Most measurements are with better than 1 mas precision. Over 100 new southern orbits have been calculated since 2009 (cf. Hartkopf and Mason 2010, Mason et al. 2010, Mason and Hartkopf 2011a, 2011b).

A challenging target, the massive and very important speckle/spectroscopic O star binary 15 Monocerotis is a member of open cluster NGC 2264. This pair has only been resolved in 1988 by speckle interferometry with a 4-m class telescope, by Hubble Space Telescope fine guidance sensors and by long-baseline optical interferometry. The orbit (Fig. 3) of 15 Mon was determined by Cvetković et al. (2010a). The distance to this cluster was determined many times and different values were reported. By analyzing the available data Cvetković et al. (2010a) found that the distance to 15 Mon is most likely about 720 pc. The orbital elements combined with this distance yield a total mass of $59.1\mathcal{M}_\odot$ and individual masses of components of $39.4\mathcal{M}_\odot$ and $19.7\mathcal{M}_\odot$.

The multiple system V505 Sgr is composed of three components. The eclipsing/spectroscopic binary was discovered first. The existence of the third visual component was first indicated by spectroscopic measurements and later confirmed by speckle interferometry. The orbit (Fig. 4) for the visual pair obtained from speckle interferometric measurements have been reported in Cvetković et al. (2010b). Their solution yielded a mass of the third visual component of $3\mathcal{M}_{\odot}$ and a distance to the system of 103–108 pc.

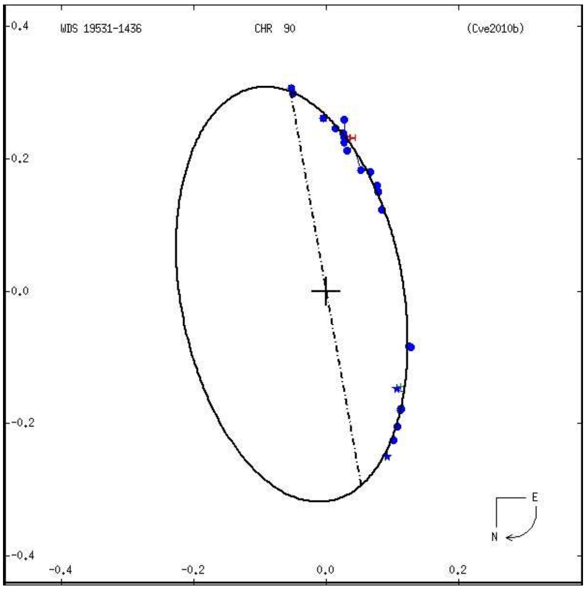

Fig. 4. *The apparent orbit for V505 Sgr. Filled circles and asterisk indicate speckle or other single-aperture techniques, multi-aperture techniques are denoted by filled squares and sign "H" indicates a measurement from Hipparcos. Other designations are the same as in Fig. 1.*

Docobo et al. (2010) presented the results of speckle interferometric observations and differential photometry for visual binaries. These observations were carried out in recent years by the research team of the R.M. Aller Astronomical Observatory of the University of Santiago de Compostela in collaboration with SAO. The goal of these studies is to obtain new orbital parameters, dynamical parallax and dynamical mass, as well as individual masses for mostly (but not only) late type close visual binaries.

3. LUNAR OCCULTATIONS

Lunar occultations (LO) are a simple and effective technique to achieve high angular resolution far exceeding the diffraction limit of any single telescope, and matched only by the long baseline interferometry which, however involves much more demanding technical requirements. The method consists of recording the signal from background stars for a few seconds around the predicted time of occultation by the Moon's dark limb. At millisecond time resolution, a characteristic diffraction pattern can be observed. Patterns for two or more sources superimpose linearly, and this property is used for detection of binary stars (Fig. 5). The detailed analysis of the diffraction fringes can be used to measure specific properties such as stellar angular size and presence of extended light sources such as a circumstellar shell.

We would like to mention that lunar occultations are the technique which has already probed the range of binary star milli arcsecond resolution and high sensitivity, despite of important limitations in the sky coverage and in the ability to choose its targets and times of observation. Therefore, this kind of measurements is ideally suited to be performed for the large interferometric facilities. Using a long baseline interferometry oriented programme, Richichi et al. (2008a, 2008b, 2010, 2011, 2014) and Cusano et al. (2012) presented lists of several hundred stars for which LO data could be recorded and analyzed. Results include the detection of new binary and multiple stars, where the projected angular separations possible to achieve were about 1 milli arcsecond and very faint sources up to 12 mag were detected.

In particular, Richichi et al. (2013) reported 25 sub-arcsecond binaries, detected for the first time by means of lunar occultations in the near-infrared as part of a long-term program using the Infrared Spectrometer And Array Camera (ISAAC) instrument at the ESO Very Large Telescope. They derived a typical frequency of binarity among field stars of $\approx$10% in the resolution range afforded by the technique (from $\approx$3mas to $\approx$500mas). In conclusion, they found from this research as well as from previous similar works, that a routine observations of random LO, with an infrared detector operated in the subarray mode at an 8 m-class telescope with time resolution of order 3 ms, can detect companions to stars in the general field down to a sensitivity K $\approx$3-12 mag, with separations as small as a few milli arcseconds (at least 10 times better than the diffraction limit of the telescope).

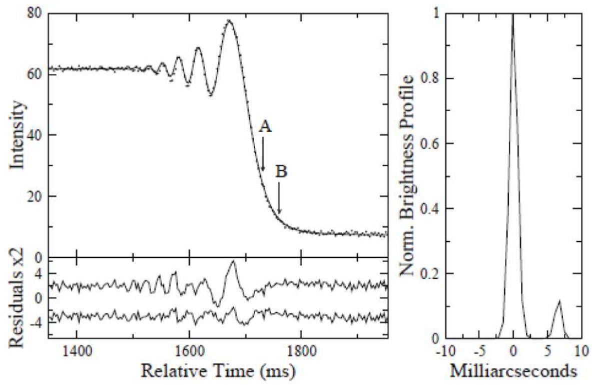

Fig. 5. *Left: light curve (dots) and best fit (solid line) for 2MASS 17073892-2554521. The lower panel shows (enlarged scale and displaced by arbitrary offsets for clarity) the residuals of fits by a point-like (above) and by a binary star model (below). Right: brightness profile reconstructed by the model-independent method.*

Finally, Richichi et al. (2014) exhausted the sample of LO observed at the VLT with ISAAC (which has been decommissioned) reporting a total of 1226 lunar occultation events recorded over 7 years. Concerning binary and multiple systems, which correspond to they observed 97 stars, a detection rate of 8% among randomly selected stars, 90 of these being the first-time detections. They concluded that the majority of observed binaries may be unresolvable by adaptive optics on current telescopes, and that they might represent a challenging task for long-baseline interferometry.

4. ADAPTIVE OPTICS AND APERTURE MASKING INTERFEROMETRY RESULTS

The technique called adaptive optics uses sophisticated, deformable mirrors controlled by computers which can correct in real-time for the distortion caused by turbulence of Earth's atmosphere, allowing to observe finer details and much fainter astronomical objects than is otherwise possible from the ground. But, the adaptive optics requires a bright reference star that is very close to the object under study in order to measure the blurring caused by the local atmosphere, so that the deformable mirror can correct for it. Since suitable stars are not available everywhere in the sky, the application of the technique was quite limited in the past. With the advent of artificial stars created by shining a powerful laser beam into the Earth's upper atmosphere almost the entire sky can now be observed with adaptive optics and this technique becomes ever more omnipresent at the world's large telescopes. Since then, the adaptive optics has continuously been used for observation of binary systems with smaller separations and increasing dynamic ranges. An example of orbit determinations using this technique can be found in Drummond (2014).

However, the sensitivity and precision of adaptive optics imaging for close companions ($<20\lambda/D$) is limited by imperfect calibration of the primary stars point spread function (PSF) used in post processing deconvolutions. The PSF width and shape change under different atmospheric conditions, and quasi-static image artifacts (speckles, which resemble faint companions) are superimposed on the image by uncorrected atmospheric turbulence and by optical imperfections in the telescope itself. Finally, it turned out to be remarkably difficult to precisely calibrate the AO PSF in practice in order to obtain sub-milli arcsecond precisions. For example, Lewis et al. (2005) reported astrometric and photometric measurements of multiple star systems with the following astrometric error bars: $\pm0\overset{''}{.}02$ for separations less than $1''$, $\pm0\overset{''}{.}01$ for separations between $1''$ and $4''$, and $\pm0\overset{''}{.}02$ for separations greater than $4''$.

Another particularly successful strategy to obtain structures at the scale of diffraction limit is the Aperture Masking Interferometry, presently implemented at a host of large telescopes around the world. This was due to Baldwin et al. (1986) and Haniff et al. (1987) who showed how the aperture masking in the visible yields data identical to those expected for an imaging array, and produced images of binary stars using the closure-phase imaging. The technique of aperture masking at the Keck Telescope (Tuthill et al. 2000) presented unprecedented imaging and results from this work have led to much enthusiasm towards developing imaging capabilities for long-baseline interferometers such as CHARA and VLTI. The technique of the non-redundant aperture masking (NRM) has been well established as a means of achieving the full diffraction limit of a single telescope (e.g. Nakajima et al. 1989).

Although, at first glance, this may appear to be a direct competitor to the adaptive optics described above, it turned out that the two methods could be combined into a powerful new form which exploited the strengths of both. NRM uses a pupil-plane mask to block most of the light from a target, resampling the primary mirror into a set of smaller subapertures that form a sparse interferometric array. Rather than an image of the target, the science camera then observes its interferometric fringes. NRM allows for superior calibration of stellar primary's PSF and for elimination of speckle noise by application of interferometric analysis techniques. In particular, the measurement of closure phases allows for calibration of the stellar PSF and for the canceling of low-order phase errors that cause speckle noise in AO.

On the other hand, seeing-limited aperture masking is strictly confined to bright-target science by the requirement to freeze the atmospheric turbulence in a single exposure, so that integration times can be no more than a hundred milliseconds or so. Combining masking and AO can be thought of as a Fizeau interferometer in which the AO system performs the role of a fast fringe tracker, locking the fringe on every baseline to a phase center, now defined by the wavefront sensor. As long as the AO system is able to deliver some reasonable degree of correction on all baselines, the fringes are stabilized and one can perform arbitrarily long integrations with the science camera, thereby reaching a fainter class of targets. For example, this has been clearly shown by observation achieved with a novel combination of aperture masking interferometry and AO by Lloyd et al. (2006) who used the Palomar 200 inch telescope AO system to directly measure the astrometric brown dwarf binary GJ 802B and to derive the dynamical masses $0.175 \pm 0.021\mathcal{M}_{\odot}$ and $0.064 \pm 0.032\mathcal{M}_{\odot}$ for the primary and secondary, respectively.

5. LONG-BASELINE INTERFEROMETRY

The long baseline interferometric observations of binary and multiple stars have been incited by the Narrabri Stellar Intensity interferometer program which resulted in discovery that several stars, previously thought to be single, were in fact binary systems (Hanbury Brown et al. 1974) but the instrument lacked the capability for determining their orbits. This sample included: β Cen, λ Sco, δ Vel, ζ Ori, β Cru, σ Sgr and δ Sco. Each of these systems has subsequently had its binary nature confirmed by spectroscopy or/and interferometry. However, the decisive step forward has been achieved since the double-lined spectroscopic binary α Vir was observed in 1966 and 1970 with this interferometer to obtain the interferometric orbit for the 4.015 day period system (Herbison-Evans et al. 1971). The observations of α Vir with the Narrabri Stellar Intensity Interferometer were combined with spectroscopic and photometric data to yield mass, radius and luminosity of the primary as well as an accurate distance to the system, showing, for the first time, the power of combining interferometric, spectroscopic and photometric observations of double-lined spectroscopic binaries for determination of fundamental properties of stars.

Indeed, the spectroscopy and interferometry allow determination of some orbital parameters in common, namely the period, the longitude of periastron, and the eccentricity. However, there are also complementary parameters: interferometry provides the inclination of the orbit i, the angular size of the semi-major axis a, the brightness ratio of the two components, and the angular size of at least the primary component of the system, whereas spectroscopy provides $a \sin i$, $\mathcal{M}_\mathrm{A} \sin^3 i$, and $\mathcal{M}_\mathrm{B} \sin^3 i$ where a is the semi-major axis of the system and $\mathcal{M}_\mathrm{A}$ and $\mathcal{M}_\mathrm{B}$ are masses of the component stars. In addition it is possible to determine an accurate distance to the system through the orbital (so-called dynamical) parallax.

The long-baseline optical interferometry can nearly close the gap in the selection space between astrometric and spectroscopic detection of binaries. It unifies the complementary powers of astrometry and spectroscopy to bear on a complete dynamical understanding of such systems, including the determination of masses of individual stellar components. We list in Table 1 two important orbital parameters (together with their uncertainties) which were used in the mass calculation: the orbital period P and semi-major axis a, for binary stars described in this paper.

With routine operation of several ground-based interferometers such as Mark III, the Palomar Testbed Interferometer (PTI), the Center for High Angular Resolution in Astronomy (CHARA) array, the Sydney University Stellar Interferometer (SUSI) the Naval Prototype Optical Interferometer (NPOI), Infrared Optical Telescope Array (IOTA), Keck Interferometer (KI), and particularly with their combined results, the period overlap of spectroscopic and visual binaries has been greatly increased. The few Very Large Telescope Interferometer (VLTI) observations of binary systems that have been made so far are in general of a preliminary nature, but they demonstrated the potential of the VLTI for binary star studies.

The interferometric observations, combined with precise radial velocities, provide an opportunity to determine masses very accurately and orbital parallaxes generally more precisely than those obtained in Hipparcos mission for a significant number of systems. Fekel and Tomkin (2007) reported on a program (list of the 44 systems) to improve the orbits of known spectroscopic binaries that are potential targets for ground-based optical interferometers.

Table 1. The orbital period P and semi-major axis a with their errors for binaries referred to in this paper. Units for P are: years (y), days (d), hours (h) and minutes (m). Unit for a is mas. Data are taken from the Sixth Catalog of Orbits of Visual Binary Stars[1].

Name	P	σ_P	a	σ_a
α And	96.7015 d	0.0044	24.0	0.13
π And	143.53 d	0.06	6.69	0.05
64 Psc	13.824621 d	0.000017	6.527	0.061
η And	115.72 d	0.01	10.37	0.03
β Ari	106.9954 d	0.0005	36.1	0.3
β Tri	31.387 d	0.001	8.02	0.05
δ Tri	10.0200 d	0.0001	9.80	0.06
12 Per	330.98209 d	–	53.18	0.15
β Per Aa1,2	2.867328 d	0.00005	2.15	0.05
β Per Aa,Ab	680.168 d	0.046	93.43	0.11
27 Tau	290.984 d	0.079	13.08	0.12
V773 Tau	51.1033 d	0.0018	2.809	0.033
HD 27483	3.05911 d	0.00001	1.26	0.05
θ^2 Tau	140.7302 d	0.0002	18.91	0.06
α Aur	104.022 d	0.002	56.47	0.05
θ^1 Ori C	11.26 y	0.5	43.61	3.
ζ Ori	2687.3 d	7.0	35.9	0.2
ζ Ori A	9.442 y	0.012	44.1	1.5
β Aur	3.9600 d	0.0001	3.3	0.1
15 Mon	74.28 y	4.06	95.6	14.9
HIP 39402	12.95 y	0.05	197.7	1.6
δ Vel	45.1503 d	0.0002	16.51	0.16
HD 98800	314.327 d	0.028	23.3	2.5
o Leo	0.039694 y	–	4.46	–
93 Leo	71.69 d	0.	7.5	0.1
ζ^1 UMa	20.53835 d	0.00005	9.83	0.03
β Cen	357.00 d	0.07	25.32	0.23
12 Boo	9.604560 d	0.000004	3.4706	0.0055
η CrB	15204.9 d	1.4	862.26	0.33
δ Sco	3945.4 d	2.8	98.94	0.14
σ^2 CrB	1641.299649m	0.000115	1.225	0.013
σ Sco	33.010 d	0.002	3.62	0.06
V819 Her AB	2019.66 d	0.35	74.41	0.67
V819 Her Ba,Bb	53.511202h	0.000038	0.6631	0.0221
λ Sco	1052.8 d	1.2	49.3	0.3
HD 171779	2324. d	250.	0.160	0.048
β Lyr	12.9414 d	—	0.976	0.083
113 Her	245.52 d	0.08	10.1	0.1
HD 184467	494.16 d	0.58	84.20	0.84
V505 Sgr	94.24 y	0.72	333.0	4.0
θ Aql	17.122 d	0.001	3.2	0.1
HD 193322	312.40 d	–	3.9	1.2
WR 140	2896.35 d	0.9	8.99	0.19
HD 195987	57.32178 d	0.00029	15.378	0.027
HD 198084	523.4192 d	0.1010	65.0	1.0
α Equ	98.800 d	0.004	11.987	0.078
δ Equ	2084.03 d	0.10	231.965	0.008
η Peg	817.41 d	0.04	45.02	0.06
ζ Aur	972.183 d	–	16.2	0.1
κ Peg AB	4224.76 d	0.74	234.94	1.82
κ Peg Ba,Bb	5.971497 d	0.000001	2.520	0.026
χ Dra	280.528 d	0.02228	124.4	1.1
ϕ Cyg	434.171 d	0.015	26.9	0.75
σ Psc	3.05911 d	0.00001	1.26	0.05
ι Peg	10.213025 d	0.000002	10.329	0.016
λ Vir	206.7321 d	0.0040	19.759	0.079
μ Ori Aa,Ab	4.447585 d	0.000001	1.661	0.016
μ Ori Ba,Bb	4.783535 d	0.000003	1.688	0.013
GJ 802 B	1104. d	9.	92.9	2.1
V397 Aur	2513.813 d	2.9	25.57	0.12

[1]http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/wds/orb6

5.1. Mark III results

The baselines of the Mark III interferometer made it ideally suited to the resolution of spectroscopic binaries with intermediate periods. The instrument was productively used in that domain, clearly demonstrating the effectiveness of the long-baseline optical interferometry in complementing the spectroscopy to lead to three-dimensional orbit solutions and component masses.

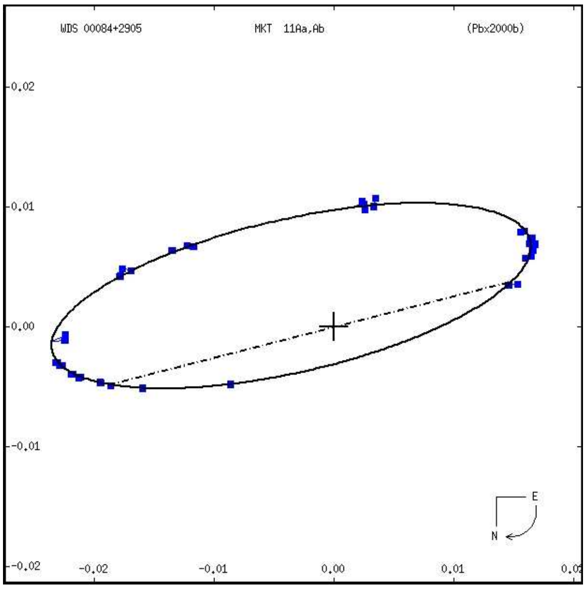

Fig. 6. *The apparent orbit for α And. Filled squares indicate multi-aperture techniques. Other designations are the same as in Fig. 1.*

The first among series of such studies concerned the spectroscopic binary α And. It is also the bright component of ADS 94. By using the Mark III Stellar Interferometer, observations of α And in 1988 and 1989 (Pan et al. 1992) clearly demonstrated the sub-milli arcsecond measurement precision at optical wavelengths. The measurements of relative coordinates (position angles and separations) with measurement precision can be found in the Fourth Catalog of Interferometric Measurements of Binary Stars (INT4)[2]. Pan et al. (1992) determined the visual orbit of this binary independently of spectroscopic data using observations from the Mark III only, and the orbital elements are in excellent agreement with the spectroscopic results. The "definitive" orbital elements were determined using both interferometric and spectroscopic observations. They obtained a semi-major axis of 24.15 ± 0.13 mas and the orbital period $P = 96.7$ days. Pourbaix (2000) gives a combined solution (Fig. 6) for this pair, yielding orbital parallaxes and component masses. Subsequently, more reliable component masses are derived: $\mathcal{M}_{\rm A} = 4.05 \pm 0.50\mathcal{M}_\odot$ and $\mathcal{M}_{\rm B} = 1.71 \pm 0.20\mathcal{M}_\odot$ (Ren and Fu 2010).

The spectroscopic binary β Ari has been directly resolved with the Mark III (Pan et al. 1990). Observations in 1988 with the sub-milli arcsecond measurement precision are given in the INT4. They are combined with spectroscopy by Pan et al. (1990) to determine visual orbit (Fig. 7), masses, and distance. The obtained semi-major axis is 36.1 ± 0.3 mas and the orbital period is $P = 107$ days; masses $\mathcal{M}_{\rm A} = 2.34 \pm 0.10\mathcal{M}_\odot$ and $\mathcal{M}_{\rm B} = 1.34 \pm 0.07\mathcal{M}_\odot$ and parallax 53 ± 2 mas.

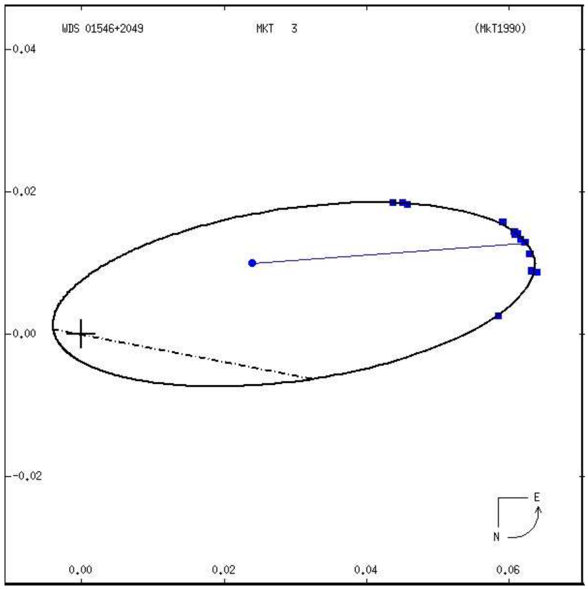

Fig. 7. *The apparent orbit for β Ari. Filled circle indicates speckle techniques and multi-aperture techniques are denoted by filled squares. Other designations are the same as in Fig. 1.*

For ϕ Cyg, Armstrong et al. (1992a) determined the distance $d = 80.8 \pm 1.8$ pc and component masses $\mathcal{M}_{\rm A} = 2.536 \pm 0.086\mathcal{M}_\odot$, $\mathcal{M}_{\rm B} = 2.437 \pm 0.082\mathcal{M}_\odot$, while for α Equ, Armstrong et al. (1992b) determined the distance $d = 55.3 \pm 2.3$ pc and component masses $\mathcal{M}_1 = 2.13 \pm 0.29\mathcal{M}_\odot$, $\mathcal{M}_2 = 1.86 \pm 0.21\mathcal{M}_\odot$.

Other Mark III studies were completed for more binaries. An example can be found in Bennet et al. (1996) where the spectroscopic and eclipsing binary ζ Aur (Fig. 8) is considered and they found $\mathcal{M}_{\rm A} = 5.8 \pm 0.2\mathcal{M}_\odot$ and $\mathcal{M}_{\rm B} = 4.8 \pm 0.2\mathcal{M}_\odot$ for the component masses and 261 ± 3 pc for the distance of system to ζ Aur. Another example is the system η And (Fig. 9) considered by Hummel et al. (1993). They found $\mathcal{M}_{\rm A} = 2.59 \pm 0.30\mathcal{M}_\odot$ and $\mathcal{M}_{\rm B} = 2.34 \pm 0.22\mathcal{M}_\odot$ for the component masses and 76 ± 2 pc for the distance to η And.

[2]http://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/wds/int4

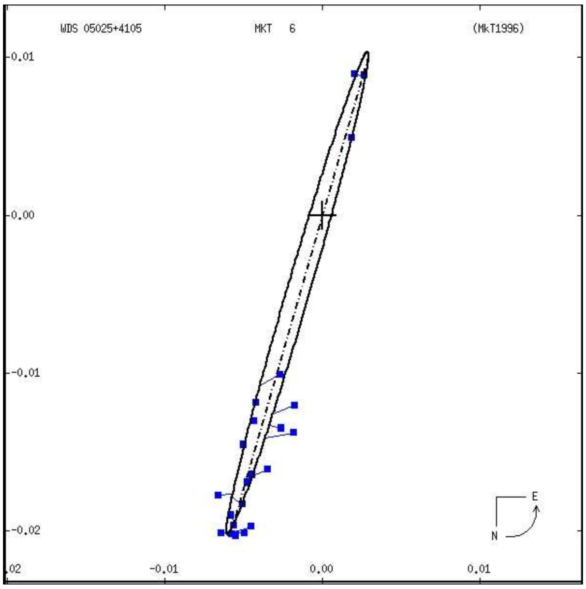

Fig. 8. *The apparent orbit for ζ Aur. Filled squares indicate multi-aperture techniques. Other designations are the same as in Fig. 1.*

Combined Mark III and NPOI analyses were completed for: ζ^1 UMa or Mizar (Fig. 10) and η Peg (Fig. 11) by Hummel et al. (1998) and, in another joint Mark III and NPOI venture targeting the Hyades binary, θ^2 Tau (Fig. 12) by Armstrong et al. (2006). θ^2 Tau is a detached and single-lined interferometric and spectroscopic binary as well as the most massive binary system of the Hyades cluster. The system revolves in an eccentric orbit with a periodicity of 140.7 days. Its light curve shows a complex pattern of δ Scuti type pulsations. In order to refine the orbital solution for θ^2 Tau, by performing a combined astrometric and spectroscopic analysis based on the new spectroscopy and long-baseline data from the Mark III optical interferometer, Torres et al. (2011) determined a new orbit for θ^2 Tau, an orbital parallax of 20.90 ± 0.14 mas and component masses $\mathcal{M}_{\rm A} = 2.86 \pm 0.06\mathcal{M}_\odot$ and $\mathcal{M}_{\rm B} = 2.16 \pm 0.02\mathcal{M}_\odot$, the mass ratio being in good agreement with the older estimates of Peterson et al. (1991), Peterson et al. (1993), but the mass of the primary being 15–25% higher than the more recent estimates by Torres et al. (1997) and Armstrong et al. (2006).

Torres et al. (2011) determined a new orbit for θ^2 Tau, an orbital parallax of 20.90 ± 0.14 mas and component masses $\mathcal{M}_{\rm A} = 2.86 \pm 0.06\mathcal{M}_\odot$ and $\mathcal{M}_{\rm B} = 2.16 \pm 0.02\mathcal{M}_\odot$.

Hummel et al. (1995), determined visual orbits of several spectroscopic binaries with semimajor axes ranging from 3 mas to 10 mas which provided the component masses for θ Aql ($\mathcal{M}_{\rm A} = 3.6 \pm 0.8\mathcal{M}_\odot$, $\mathcal{M}_{\rm B} = 2.9 \pm 0.6\mathcal{M}_\odot$), β Aur ($\mathcal{M}_{\rm A} = 2.41 \pm 0.03\mathcal{M}_\odot$, $\mathcal{M}_{\rm B} = 2.32 \pm 0.03\mathcal{M}_\odot$), 93 Leo ($\mathcal{M}_{\rm A} = 2.25 \pm 0.29\mathcal{M}_\odot$, $\mathcal{M}_{\rm B} = 1.97 \pm 0.15\mathcal{M}_\odot$), ζ^1 UMa ($\mathcal{M}_{\rm A} = 2.51 \pm 0.08\mathcal{M}_\odot$, $\mathcal{M}_{\rm B} = 2.55 \pm 0.07\mathcal{M}_\odot$), β Tri ($\mathcal{M}_{\rm A} = 3.7 \pm 0.4\mathcal{M}_\odot$, $\mathcal{M}_{\rm B} = 1.6 \pm 0.2\mathcal{M}_\odot$), and δ Tri ($\mathcal{M}_{\rm A} = 0.6 \pm 0.4\mathcal{M}_\odot$, $\mathcal{M}_{\rm B} = 0.5 \pm 0.3\mathcal{M}_\odot$), while for π And and 113 Her the mass determination required additional observations.

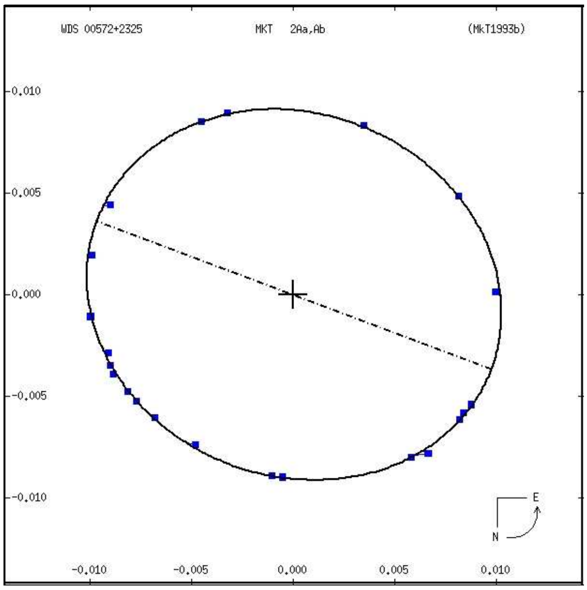

Fig. 9. *The apparent orbit for η And. Filled squares indicate multi-aperture techniques. Other designations are the same as in Fig. 1.*

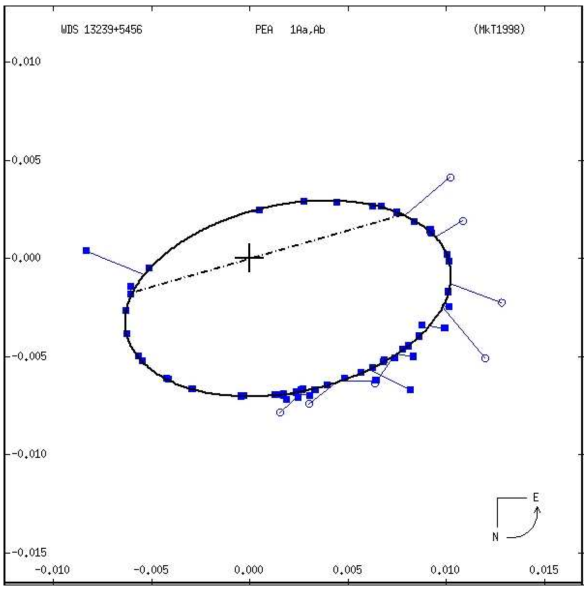

Fig. 10. *The apparent orbit for ζ^1 UMa. Filled squares indicate multi-aperture techniques, and eyepiece interferometric observations are represented by open circles. Other designations are the same as in Fig. 1.*

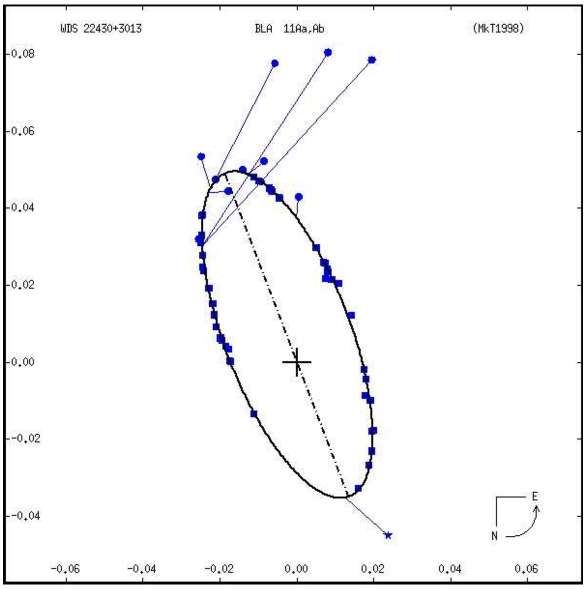

Fig. 11. *The apparent orbit for η Peg. Filled circles and asterisk indicate speckle or other single-aperture techniques, multi-aperture techniques are denoted by filled squares. Other designations are the same as in Fig. 1.*

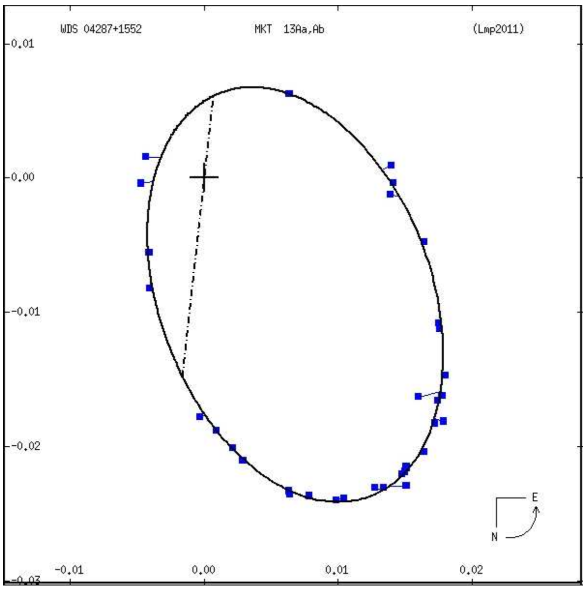

Fig. 12. *The apparent orbit for θ^2 Tau. Filled squares indicate multi-aperture techniques. Other designations are the same as in Fig. 1.*

The Pleiades star Atlas or 27 Tau primary component (A) is a spectroscopic binary Aa1, Aa2. The orbit of Pan et al. (2004), based on Mark III and PTI measurements, provided a distance in contradiction with the early Hipparcos result (118.3 ± 3.5 pc), about ten percent smaller than the accepted value. The discrepancy generated a spirited debate because the implication was that either the current stellar models were incorrect by a surprising amount or Hipparcos was giving incorrect distances. Nearby open clusters of stars (those that are not gravitationally bound) have played a crucial role in the development of stellar astronomy because, as a consequence of its stars having a common age, they provide excellent natural laboratories to test theoretical stellar models. The results of Pan et al. (2004) who derived a firm lower bound for the distance $D > 127$ pc, with the most likely range being $133 < D < 137$ pc were very important because they reaffirmed the validity of current stellar models. This result was confirmed by the distance derived from the orbit of Zwahlen et al. (2004), based on published Mark III and PTI measurements, plus the additional NPOI astrometric data, as described in Section on NPOI results.

The high resolution of the Mark III naturally led to significant improvement of orbital elements of α Aur or Capella first resolved in 1919 with the 20-foot beam interferometer on Mount Wilson observatory (Anderson 1920). First orbit of Capella was calculated in 1922, when it had completed almost 3 full revolutions. The orbit update of McAlister (1981) has been done when Capella had gone around over 217 times. Nearly 50 additional revolutions occurred before the data from Mark III were used to further refine the period (Hummel et al. 1994) and the new orbit is given in Fig. 13. The later observations from the upgraded IOTA interferometer, the WIYN 3.5m telescope and 4m telescope at Kitt Peak National Observatory and Cerro Tololo Inter-American Observatory have almost no residuals from the orbit of Hummel et al. (1994). Torres et al. (2009) derived

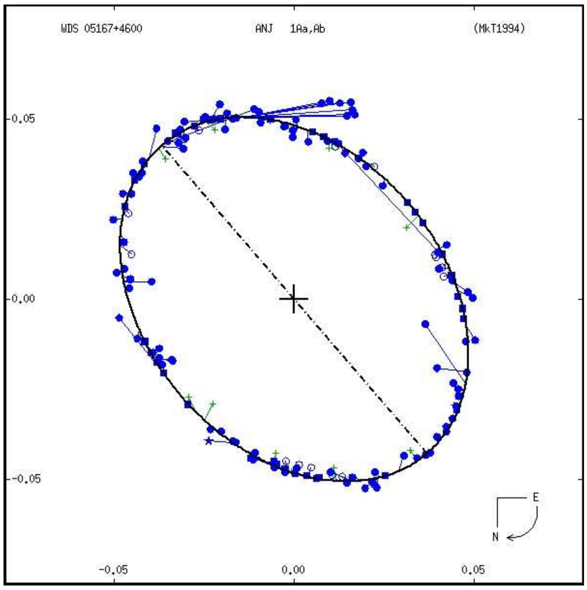

Fig. 13. *The apparent orbit for α Aur. Plus signs indicate visual (micrometric) observations, eyepiece interferometric observations are represented by open circles, filled circles and asterisk indicate speckle or other single-aperture techniques and multi-aperture techniques are denoted by filled squares. Other designations are the same as in Fig. 1.*

a new combined spectroscopic/interferometric orbit. They determined an orbital parallax of 76.67 ± 0.17 mas and masses of components: $2.466 \pm 0.018\mathcal{M}_\odot$ and $2.443 \pm 0.013\mathcal{M}_\odot$. Weber and Strassmeier (2011) derived new spectroscopic elements, assuming the period determined by Torres et al. (2009). The new solution yielded masses of $\mathcal{M}_\mathrm{A} = 2.573 \pm 0.009\mathcal{M}_\odot$ and $\mathcal{M}_\mathrm{B} = 2.488 \pm 0.008\mathcal{M}_\odot$.

The legacy of the Mark III interferometer is an important one because that instrument not only brought interferometry into the modern world but it set an excellent standard for the application of this technique to binary stars.

5.2. Palomar Testbed Interferometer results

The Palomar Testbed Interferometer (PTI) was specifically designed to perform differential astrometry in a "narrow angle" mode employing two delay lines per telescope. While astrometric precision at the arcsecond scale significantly improved, the small field of view working angles practically limited observations to arcsecond scale binaries. A method to increase this field was presented by Shao and Colavita (1992). In this narrow-angle astrometric scenario the fringes on multiple stars are tracked simultaneously to take advantage of significant correlation in the atmospheric phase noise over an isoplanatic angle (30-50 arcseconds at a typical site). The simultaneous fringe tracking requirement necessitates multiple beam combiners in a single facility, and guided the dual-fringe tracker design of PTI (Colavita et al. 1999).

The first orbit of the visual orbit of the double-lined spectroscopic binary system (SB2) based on PTI observations was that of i Peg (Boden et al. 1999a) from which the masses of the two components are determined to be $1.326 \pm 0.016\mathcal{M}_\odot$ and $0.819 \pm 0.009\mathcal{M}_\odot$, respectively, and the orbital parallax of the system is determined to be 86.9 ± 1.0 mas. There quickly followed the report on determination of the visual orbit of the SB2 system 64 Psc (Boden et al. 1999b) which is a nearly equal-mass system whose spectroscopic orbit was well known. The derived 64 Psc orbit was in good agreement with the spectroscopic results, and the physical parameters implied by a combined fit to the interferometric visibility data and radial velocity data resulted in precise component masses that agree well with their spectral type identifications. In particular, the orbital parallax of the system was determined to be 43.29 ± 0.46 mas, and masses of the two components are determined to be $1.223 \pm 0.021\mathcal{M}_\odot$ and $1.170 \pm 0.018\mathcal{M}_\odot$, respectively.

In an analysis of the equal mass system 12 Boo, Boden et al. (2000) came to a remarkable conclusion that one component was significantly more luminous than the other. They have estimated the visual orbit from PTI interferometric visibility data, fitted both separately and in conjunction with archival radial velocity data. The derived 12 Boo orbit was in good agreement with the spectroscopic results, and the physical parameters implied by a combined fit to visibility data and radial velocity data resulted in precise component masses. In particular, the orbital parallax of the system was determined to be 27.09 ± 0.41 mas, and masses of the two components were determined to be $1.435 \pm 0.023\mathcal{M}_\odot$ and $1.409 \pm 0.020\mathcal{M}_\odot$, respectively. Even though the two components are of nearly equal mass, the system exhibits a significant brightness difference between the components in the near infrared and visible. They attributed this brightness difference to the evolutionary differences between the two components in their transition between the main-sequence and giant evolutionary phases, and based on theoretical isochrones they could estimate the system age. This finding was confirmed five years later after the incorporation of additional visibilities and new radial velocities by Boden et al. (2005a) as described in Section NPOI results.

Boden et al. (2006) reported interferometric and spectroscopic observations of the high-proper motion double-lined binary system HD 9939, with an orbital period of $\approx$25 days. By combining the PTI visibility and spectroscopic radial-velocity measurements they estimated the system physical orbit and derived dynamical component masses $\mathcal{M}_\mathrm{A} = 1.072 \pm 0.014\mathcal{M}_\odot$ and $\mathcal{M}_\mathrm{B} = 0.8383 \pm 0.0081\mathcal{M}_\odot$; fractional errors of 1.3% and 1.0%, respectively. They also determined a system distance of 42.23 ± 0.21 pc, corresponding to an orbital parallax of $\pi_\mathrm{orb} = 23.68 \pm 0.12$ mas. Comparison of deduced stellar parameters with stellar models suggested the HD 9939 primary has evolved off the main sequence and appears to be traversing the Hertzsprung gap as it approaches the red giant phase of its evolution, providing new empirical constraints on stellar models during this particularly dynamic evolutionary phase.

Other PTI work on spectroscopic binaries allowed to determine astrometric orbits, which, when combined with the radial velocity measurements, determine all orbital parameters resulting in the mass determination for HD 195987 ($\mathcal{M}_\mathrm{A} = 0.844 \pm 0.018\mathcal{M}_\odot$, $\mathcal{M}_\mathrm{B} = 0.665 \pm 0.008\mathcal{M}_\odot$) by Torres et al. (2002), as well as for two double-lined spectroscopic binaries: σ Psc ($\mathcal{M}_\mathrm{A} = 2.65 \pm 0.27\mathcal{M}_\odot$, $\mathcal{M}_\mathrm{B} = 2.36 \pm 0.24\mathcal{M}_\odot$) and HD 27483 ($\mathcal{M}_\mathrm{A} = 1.38 \pm 0.13\mathcal{M}_\odot$, $\mathcal{M}_\mathrm{B} = 1.39 \pm 0.13\mathcal{M}_\odot$) by Konacki and Lane (2004) for which the latter had the smallest semi-major axis yet determined by the long base interferometry (1.2 mas).

The ability of PTI to perform differential astrometry in a "narrow angle" mode employing two delay lines per telescope permitted the instrument to undertake a program of very precise astrometry of binaries that are otherwise too wide for the long base interferometry. The performance of the method for differential astrometry of sub-arcsecond scale binaries has been clearly shown by Lane and Muterspaugh (2004) who attained an accuracy of $\pm 16\mu$as for the system HD 171779. Accuracies approaching that quality have subsequently been attained for wider binary systems as δ Equ and κ Peg (Muterspaugh et al. 2008) for which the respective orbits provided: $\mathcal{M}_\mathrm{A} = 1.192 \pm 0.012\mathcal{M}_\odot$, $\mathcal{M}_\mathrm{B} = 1.187 \pm 0.012\mathcal{M}_\odot$ (for δ Equ) and $\mathcal{M}_\mathrm{A} = 1.533 \pm 0.050\mathcal{M}_\odot$, $\mathcal{M}_\mathrm{Ba+Bb} = 2.472 \pm 0.078\mathcal{M}_\odot$ (for κ Peg). The high-precision differential astrometry measurements by the Palomar High-precision Astrometric Search for Exoplanet Systems (PHASES) have been collected for μ Orionis which was identified by spectroscopic studies as a quadruple-star system. Muterspaugh et al. (2008) derived the orbit which provided masses: $\mathcal{M}_{\rm Aa} = 2.38 \pm 0.11\mathcal{M}_\odot$, $\mathcal{M}_{\rm Ab} = 0.652 \pm 0.097\mathcal{M}_\odot$, $\mathcal{M}_{\rm Ba} = 1.389 \pm 0.019\mathcal{M}_\odot$, $\mathcal{M}_{\rm Bb} = 1.356 \pm 0.019\mathcal{M}_\odot$, so the component masses have relative precisions of 5% (component Aa), 15% (Ab), and 1.4% (Ba and Bb each). The median size of the minor axes of the uncertainty ellipses for this measurements was 20μas. Note that such astrometric precision allows not only monitoring binaries that fall within the separation regime of speckle interferometry, but also enables the planet-search programs.

V819 Her was identified by spectroscopic studies as a triple star system. The wide pair AB of this system has been resolved by speckle interferometry by McAlister et al. (1983) and since then, this system has been well-studied for years. It consists of a wide pair with 5.5 year period, one component of which is a 2.2 day period eclipsing single-line spectroscopic binary. Muterspaugh et al. (2006) derived the orbit for which semi-major axes of the wide and narrow orbits: $a_{A-B} = 73.9 \pm 0.6$ mas and $a_{Ba-Bb} = 108 \pm 9$ μas provided $\mathcal{M}_{\rm A} = 1.765 \pm 0.095\mathcal{M}_\odot$, $\mathcal{M}_{\rm Ba} = 1.430 \pm 0.041\mathcal{M}_\odot$ and $\mathcal{M}_{\rm Bb} = 1.082 \pm 0.033\mathcal{M}_\odot$. Further PHASES measurements of V819 Her have been continued during the 2004-2007 observing seasons. The updated orbital solution for the close pair V819 Her Ba-Bb has been derived by Muterspaugh et al. (2008) providing the improved masses: $\mathcal{M}_{\rm A} = 1.799 \pm 0.098\mathcal{M}_\odot$, $\mathcal{M}_{\rm Ba} = 1.469 \pm 0.040\mathcal{M}_\odot$ and $\mathcal{M}_{\rm Bb} = 1.090 \pm 0.030\mathcal{M}_\odot$.

5.3. CHARA array results

Since the CHARA Catalog of Orbital Elements of Spectroscopic Binary Stars has been published by Stuart et al. (2003), considering that the longer base lines such as at CHARA and NPOI will allow measurements in binary systems that was not possible with shorter baseline instruments, a number of new results have emerged:

In the paper by Bagnuolo et al. (2006), first results from the CHARA Array are given. They have obtained high-resolution orbital data for the bright star 12 Persei, a resolved double-lined spectroscopic binary. This star was resolved by speckle interferometry by McAlister (1977). The solution of Bagnuolo et al. (2006) combines speckle data with the data from the CHARA Array and gives orbital parallax 41.19 ± 0.21 mas, masses $1.382 \pm 0.019\mathcal{M}_\odot$ and $1.240 \pm 0.017\mathcal{M}_\odot$, and a magnitude difference 0.409 ± 0.013 mags.

Zhao et al. (2008) presented the first resolved images of the eclipsing binary β Lyrae, obtained with the CHARA Array interferometer and the MIRC combiner in the H band. The images clearly show the mass donor and the thick disk surrounding the mass gainer at all six epochs of observation. Image analysis and model fitting for each epoch were used for calculating the first astrometric orbital solution for β Lyrae, yielding precise values for the orbital inclination and position angle. The derived semi-major axis 314 ± 17 pc and orbital parallax of the star together with the inclination from the models ($i = 92.25 \pm 0.82$ degrees), allowed to obtain mass of the gainer, $12.76 \pm 0.27\mathcal{M}_\odot$ and mass of the donor $2.83 \pm 0.18\mathcal{M}_\odot$.

Raghavan et al. (2009) presented an updated spectroscopic orbit and a new visual orbit for the double-lined spectroscopic binary σ^2 Coronae Borealis based on spectroscopic radial velocity measurements and interferometric visibility measurements at the CHARA Array. σ^2 CrB is composed of two Sun-like stars of roughly equal mass in a circularized orbit with a period of 1.14 days. The long baselines of the CHARA Array have allowed to resolve the visual orbit for this pair, the shortest-period binary yet resolved interferometrically, enabling to determine component masses of $1.137 \pm 0.037\mathcal{M}_\odot$ and $1.090 \pm 0.036\mathcal{M}_\odot$.

Farrington et al. (2010) presented the modification of the orbits of χ Draconis and HD 184467, and a completely new orbit for HD 198084, including data taken at the CHARA Array. These data were obtained using a modification of the technique of separated fringe packets (SFPs). The accuracy of the SFP data surpasses that of the data taken by speckle, but the technique is much more time and labor intensive. Additionally, using SFPs with the CHARA Array, it was possible to obtain separations below the detection range of speckle interferometry (≈30 mas), and above the range in classic long-baseline interferometry where fringes from a binary overlap are no longer separated (≈10 mas). The derived stellar parameters $\pi_{\rm orb}$ (mas), $\mathcal{M}_{\rm A}(\mathcal{M}_\odot)$ $\mathcal{M}_{\rm B}(\mathcal{M}_\odot)$ are 123.4 ± 1.9, 0.96 ± 0.03, 0.75 ± 0.03 (χ Draconis), 59.2 ± 2.04, 0.82 ± 0.09, 0.77 ± 0.09 (HD 184467) and 39.8 ± 4.8, 1.071 ± 0.037, 1.047 ± 0.037 (HD 198084), respectively.

ten Brummelaar et al. (2011) combined published speckle interferometric measurements with CHARA separated fringe packet measurements to improve the visual orbit for the wide Aa,Ab binary HD 193322. In addition, they used measurements of the fringe packet from Aa to calibrate the visibility of the fringes of the Ab1,Ab2 binary and analyzed these fringe visibilities to determine the visual orbit of the close system. The two most massive stars, Aa and Ab1, have masses of approximately 21 and 23 $M_\odot$, respectively,

As described in the previous section, consistent orbital solutions for the triple star system V819 Her have been derived for both the wide (AB) and close (Ba-Bb) pairs through the speckle interferometry (Scarfe et al. 1994) and differential astrometry (Muterspaugh et al. 2006, 2008). O'Brien et al. (2011) derived the new orbit for V819 Her Ba-Bb by performing a χ^2 fit to interferometric visibility measurements from observations of fringe packets at the CHARA Array. New orbital elements are in agreement with the orbital elements derived by Muterspaugh et al. (2008) within the 1σ error bars. The exception is the inclination, for which there is a 1.3σ deviation from the value of Muterspaugh et al. (2008). An important result of the new orbit for V819 Her Ba-Bb is the mutual inclination of the system. It was found to be 33.5±9.3 degrees, consistent with observations of other triple systems. Combined with spectroscopy by Scarfe et al. (1994), O'Brien et al. (2011) derive masses for A, Ba, and Bb of $2.566 \pm 0.274\mathcal{M}_\odot$, $1.488 \pm 0.181\mathcal{M}_\odot$ and $1.079 \pm 0.148\mathcal{M}_\odot$, respectively. Parallax is 14.5 ± 0.2 mas, yielding a separation between Ba and Bb of 0.04573 ± 0.00163 AU. The age of the system is estimated at 1.9 ± 1.1 Gyr.

Algol (β Per) is an extensively studied hierarchical triple system whose inner pair is a prototype semi-detached binary with mass transfer occurring from the sub-giant secondary to the main-sequence primary. Baron et al. (2012) presented the results of Algol observations made between 2006 and 2010 at the CHARA interferometer with the Michigan Infrared Combiner in the H-band. The use of four telescopes with long baselines allowed to achieve better than 0.5 mas resolution and to unambiguously resolve the three stars. The inner (Fig. 14) and outer (Fig. 15) orbital elements, as well as the angular sizes and mass ratios for the three components, are determined independently from previous studies. State-of-the-art image reconstruction algorithms are used to image the full triple system. In particular, an image sequence of 55 distinct phases of the inner pair orbit is reconstructed, clearly showing the Roche-lobe-filling secondary revolving around the primary, with several epochs corresponding to the primary and secondary eclipses.

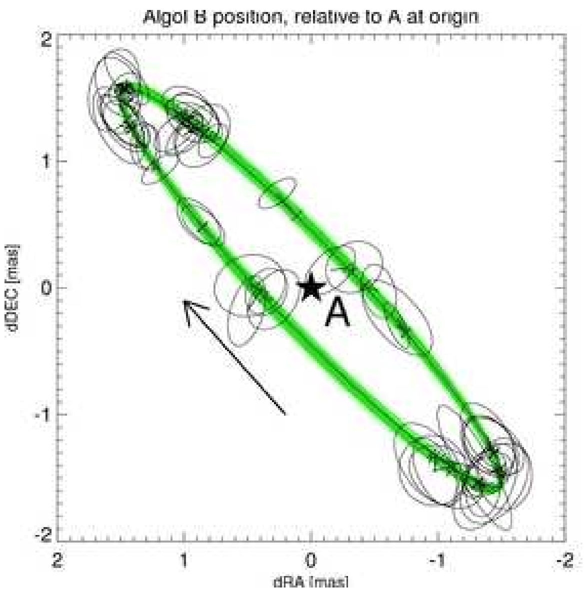

Fig. 14. *Algol, orbit of the inner binary: the band of allowed orbits at 3σ for Algol B relative to Algol A (gray), and the best fit solution (solid line inside this band); the error ellipses for each epoch are derived from the χ^2 distribution maps obtained when fitting a uniform brightness model.*

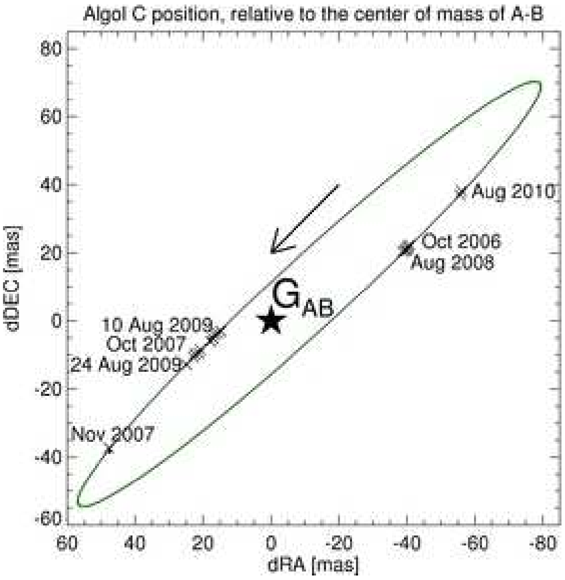

Fig. 15. *Algol, orbit of the outer binary: the band of allowed orbits at 3σ for Algol C relative to the center of mass of the inner binary A+B (gray), and the best-fit solution (solid black line).*

5.4. SUSI results

The first-ever binary system orbit obtained with the long baseline interferometry (α Vir) was derived from observations made from the Southern Hemisphere with the Narrabri Stellar Intensity Interferometer (NSII). Presently, the SUSI array at the Narrabri Observatory is being used to determine interferometric orbits for some of the binary systems discovered with the NSII.

Also, the first interferometric observations of the double-lined spectroscopic binary system γ^2 Vel were made with the NSII in 1968 (Hanbury Brown et al. 1970), but the complete orbital solution has been obtained from the SUSI measurements of the squared visibility V^2 completed over a total of 24 nights. From the orbital solution in combination with the radial-velocity results, North et al. (2007a) deduced $\mathcal{M}_\mathrm{A} = 28.5 \pm 1.1\mathcal{M}_\odot$, $\mathcal{M}_\mathrm{B} = 9.0 \pm 0.6\mathcal{M}_\odot$, a distance of 336^{+8}_{-7} pc, significantly larger than the Hipparcos estimation. The VLTI has observed γ^2 Vel and produced a single angular separation and position angle (Millour et al. 2007), yielding a distance of 368^{+38}_{-13} pc for the binary system, also significantly larger than the Hipparcos value of 258^{+41}_{-31} pc.

For σ Sco, North et al. (2007b) found that the orbital solution, when combined with radial velocity results, yields the primary and secondary masses $\mathcal{M}_\mathrm{A} = 18.4 \pm 5.4\mathcal{M}_\odot$, $\mathcal{M}_\mathrm{B} = 11.9 \pm 3.1\mathcal{M}_\odot$ and a distance of 174^{+23}_{-18} pc, which is consistent with, but more accurate than the Hipparcos value.

The bright southern binary β Cen was observed with SUSI from 1997-2002. Using measurements which have sub-milli arcsecond measurement precision, Davis et al. (2005) determined an interferometric orbit (Fig. 16). The interferometric results (Davis et al. 2005) were combined with the spectroscopic results (Ausseloos et al. 2002) to determine orbital elements, masses and distance. Using the spectroscopic data obtained over 12 years and applying the new methodology to derive high-precision estimates of the fundamental parameters of double-lined spectroscopic binaries, Ausseloos et al. (2006) refined the component masses to 1% precision resulting in $\mathcal{M}_{\rm A} = 10.7 \pm 0.1 \mathcal{M}_{\odot}$ and $\mathcal{M}_{\rm B} = 10.3 \pm 0.1 \mathcal{M}_{\odot}$.

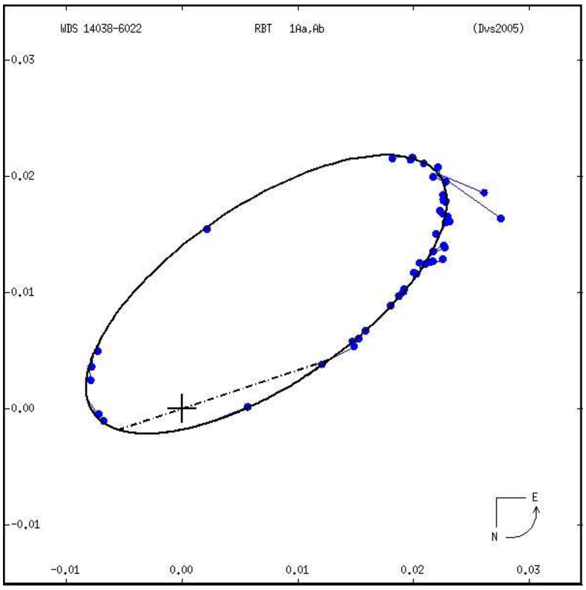

Fig. 16. *The apparent orbit for β Cen. Filled circles indicate speckle or other single-aperture techniques. Other designations are the same as in Fig. 1.*

λ Sco is a well known spectroscopic binary with a low mass companion orbiting primary with a period of about 6 days. The detection of the third component has been confirmed by radial velocity measurements (Uytterhoeven et al. 2004a, 2004b) and by SUSI. Tango et al. (2006) have combined the SUSI results with the spectroscopic results and determined the orbital elements (Fig. 17). The third component is a B star orbiting the primary with a period of about 2.9 years. They also found that the inclination of the wide orbit is consistent with the inclination previously found for the orbit of the close companion and that the wide orbit also has a low eccentricity, suggesting that the three stars were formed at the same time. The dynamic parallax from deduced stellar masses $\mathcal{M}_{\rm A} = 10.4 \pm 1.3 \mathcal{M}_{\odot}$ and $\mathcal{M}_{\rm B} = 8.1 \pm 1.0 \mathcal{M}_{\odot}$ provided the distance 112 ± 5 pc, which is approximately a factor of 2 closer than the Hipparcos value of 216 ± 42 pc.

The current main beam combiner in SUSI is the Precision Astronomical Visible Observation (PAVO), a multi-axially aligned Fizeau-type interferometer, but unlike a typical Fizeau interferometer, PAVO forms spatially modulated interference fringes in a pupil plane and then spectrally disperses the fringes. Joining it is the recently installed the Microarcsecond University of Sydney Companion Astrometry (MUSCA) beam combiner instrument. MUSCA is designed to operate alongside PAVO for high precision narrow-angle astrometry, and should significantly increase the astrometric precision of the SUSI interferometer.

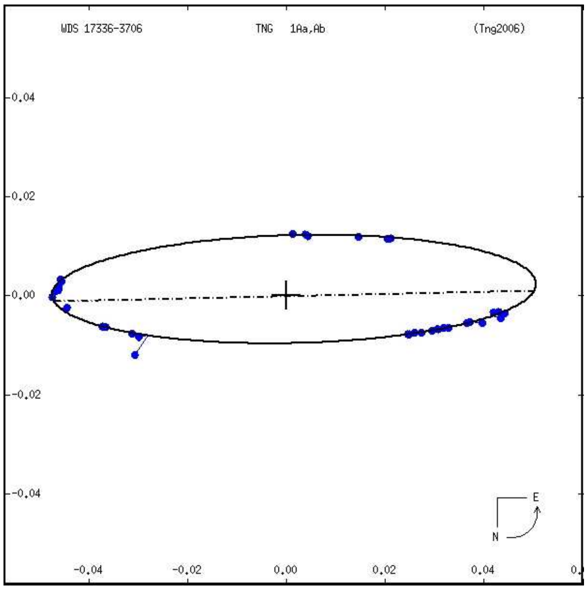

Fig. 17. *The apparent orbit for λ Sco. Filled circles indicate speckle or other single-aperture techniques. Other designations are the same as in Fig. 1.*

5.5. NPOI results

The main advantage of NPOI with respect to previously reported Mark III and PTI results, is that it measures closure phases which have been proven to improve the results significantly. Using the data from NPOI, Zwahlen et al. (2004) presented the measurements of the double star Atlas (27 Tau), which permitted, with the addition of published spectroscopic radial velocity data, to precisely derive the orbit (Fig. 18) and parameters of the binary system including the masses of individual components ($\mathcal{M}_1 = 4.74 \pm 0.25 \mathcal{M}_{\odot}$, $\mathcal{M}_2 = 3.42 \pm 0.25 \mathcal{M}_{\odot}$). Although their data were less numerous than those published by Pan et al. (2004) on the basis of observations with the Mark III stellar interferometer and with the PTI, these collected with the NPOI had the advantage of being free from any ambiguity on the orientation of the orbit. The precision was comparable with that reported by Pan et al. (2004), so they could merge both samples together and obtain an improved estimate of orbital parameters. The derived semi-major axis, compared with its measured angular size, allowed to determine distance to Atlas of 132 ± 4 pc in a purely geometrical way. Under the assumption that the location of Atlas is representative of the average distance of the Pleiades cluster, they confirmed the distance of Pan et al. (2004), i.e. the distance value generally obtained through main sequence fitting.

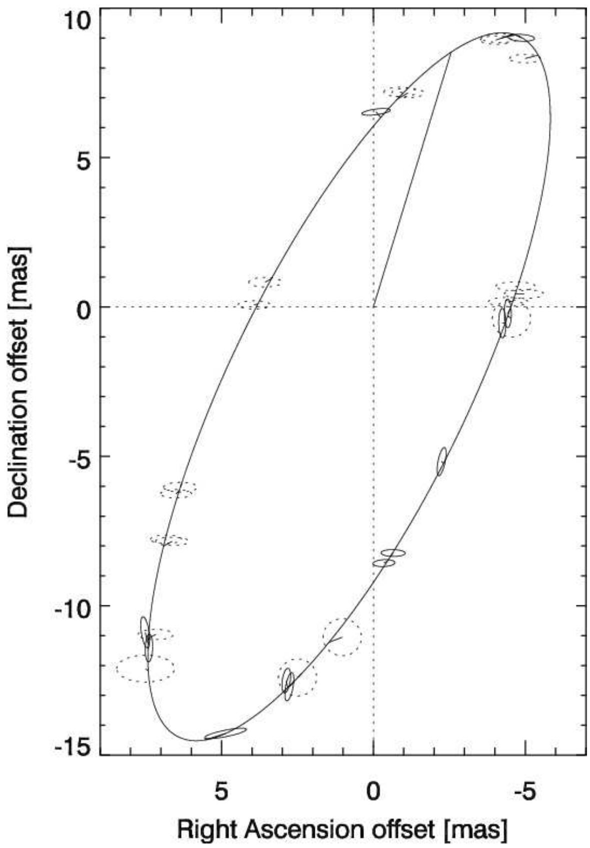

Fig. 18. *The astrometric orbit with published data from Pan et al. (2004) (dotted error ellipses) and new data from Mark III and NPOI (full lines). The ellipses indicate the errors on each axis, while the full straight line denotes the periastron. (Taken from Zwahlen et al. (2004))*

Boden et al. (2005a) reported on a significantly improved determination of the physical orbit of the double-lined spectroscopic binary system 12 Boo. They used the interferometric data from the Navy Prototype Optical Interferometer, as well as data set spanning 6 years with the PTI and a radial velocity data set spanning 14 yr from the Harvard-Smithsonian Center for Astrophysics. The orbital parallax of the system is determined to be 27.72 ± 0.15 mas, and masses of the two components are determined to be $1.4160 \pm 0.0049\mathcal{M}_\odot$ and $1.3740 \pm 0.0045\mathcal{M}_\odot$, respectively. These mass determinations are more precise than those in the previous report by a factor of more than 4. As reported in the previous paper (Boden et al. 2000), even though the two components are nearly equal in mass, the system exhibits a significant brightness difference between the components in the near-infrared and visible, indicating that the system has apparently been caught at an instant when the slightly more massive component is entering into its red giant phase and evolving rapidly from the main sequence, temporarily leaving behind its companion. They also could estimate the system's age to approximately 3.2 Gyr.

Armstrong et al. (2006) measured the visual orbit of θ^2 Tau with the Mark III optical interferometer and the Navy Prototype Optical Interferometer, and combined it with the Hipparcos proper-motion-based parallax to find a total system mass of $4.03 \pm 0.20\ \mathcal{M}_\odot$, while the masses of the components of that Hyades spectroscopic binary were determined to be $\mathcal{M}_\mathrm{A} = 2.15 \pm 0.12\mathcal{M}_\odot$, $\mathcal{M}_\mathrm{B} = 1.87 \pm 0.11\mathcal{M}_\odot$.

A close companion of ζ Orionis A was found in 2000 with the NPOI, and was shown to be a physical companion. Because the primary is an O-type supergiant, for which dynamical mass measurements are very rare, the companion was observed with the NPOI over the full 7-year orbit (Hummel et al. 2013). The resulting masses for components Aa of $14.0 \pm 2.2\mathcal{M}_\odot$ and Ab of $7.4 \pm 1.1\mathcal{M}_\odot$ are low compared to theoretical expectations, with a distance of 294 ± 21 pc which is smaller than a photometric distance estimate of 387 ± 54 pc based on the spectral type B0III of the B component.

5.6. IOTA results

The small scale of the double-lined spectroscopic binary λ Vir orbit ($\sim$ 20 mas) was well resolved by the IOTA interferometer, allowing to determine its elements, as well as the physical properties of the components, to high accuracy (Zhao et al. 2007). The masses of the two stars are determined to be $\mathcal{M}_\mathrm{A} = 1.897 \pm 0.016\mathcal{M}_\odot$, $\mathcal{M}_\mathrm{B} = 1.721 \pm 0.023\mathcal{M}_\odot$, respectively, and the two stars are found to have the same temperature of 8280 ± 200 K. The accurately determined properties of λ Vir allowed comparisons between observations and current stellar evolution models, and reasonable matches are found.

Monnier et al. (2011) presented IOTA + CHARA observations of WR 140 in 2003, 2004, and 2005, obtained with the IOTA interferometer in order to determine first visual orbit of a colliding-wind binary WR 140. High resolution Astronomy interferometers resolved the pair of stars in each year from 2003 to 2009, covering most of the highly eccentric, 7.9 year orbit. Combining their results with the recently improved double-line spectroscopic orbit they found that the WR 140 system is located at the distance of 1.67 ± 0.03 kpc, and composed of a WR star with MWR = $14.9 \pm 0.5\mathcal{M}_\odot$ and an O star with MO = $35.9 \pm 1.3\mathcal{M}_\odot$.

The IOTA interferometer (as well as other above mentioned instruments) has been used not only in a simple two-way conjunction, but also in three or/and multiple-way partnerships. The examples of such complex partnerships of high angular resolution instruments are shown in the following section.

5.7. Combined long baseline interferometry

The brightest star in the Orion Nebula Cluster is the massive O7-O5.5 type star θ^1 Ori C, which is known to be a close visual binary system. After the discovery of the companion at a separation of 33 mas with the near-infrared (NIR) bispectrum speckle interferometry by Weigelt et al. (1999), Schertl et al. (2003) presented further observations and reported the first detection of orbital motion. Kraus et al. (2007) presented the first speckle observations at visual wavelengths, the first NIR long-baseline interferometric observations of θ^1 Ori C using the IOTA interferometer, and produced an aperture-synthesis image of the system. They also performed a joint analysis of all existing interferometric measurements that covered a period of more than 9 years and clearly revealed the orbital motion. After reaching the maximum value of 42 mas in 1999, the separation of the system steadily decreased to 13 mas in 2005. A detailed modeling of these data yielded a preliminary orbit solution with a high eccentricity ($e \sim 0.91$) and a period of 10.9 yrs. According to this solution, the periastron passage should have occurred around July 2007 with a closest separation of less than 2 AU. Patience et al. (2008) recently presented additional interferometric observations of θ^1 Ori C obtained with NPOI at visual wavelengths. Extending the orbital coverage by about 1.2 yrs, they measured a companion position which deviates ~ 4 mas from the position predicted by the orbital solution of Kraus et al. (2007) and concluded that the orbit has a considerably lower eccentricity ($e \sim 0.16$) and a longer period (~ 26 yr).

Based on new astrometric measurements, Kraus et al. (2009a, 2009b) provided a more accurate orbit solution (Fig. 19). The companion has nearly completed one orbital revolution since its discovery in 1997. The derived orbital elements imply a short-period ($P = 11.26 \pm 0.5$ yr) and high-eccentricity orbit ($e = 0.592 \pm 0.07$) with periastron passage at 2002.57 ± 0.5. The new orbit is consistent with recently published radial velocity measurements by Balega at al. (2014), from which one can also derive the first direct constraints on the mass ratio of the binary components. Also, Kraus et al. (2009b) derived the system mass ($\mathcal{M} = 44 \pm 7\mathcal{M}_\odot$) and the dynamical distance ($d = 410 \pm 20$ pc), which is in a remarkably good agreement with recently published trigonometric parallax measurements obtained with radio interferometry.

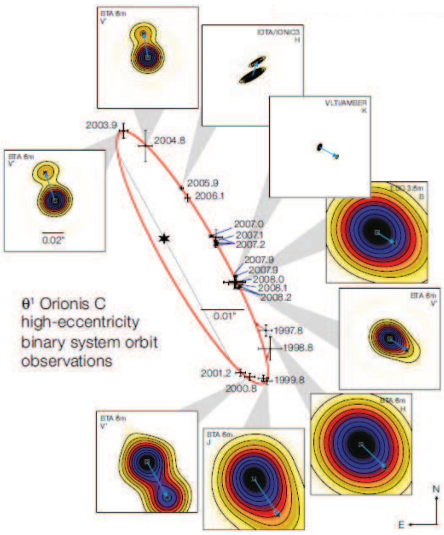

Fig. 19. *The apparent orbit for θ^1 Ori C. Selection of interferometric images of the θ^1 Ori C system obtained between 1997 and 2008, revealing the orbital motion of the companion, is presented as well. For each image, 10% intensity level contours are shown. The picture is taken from Kraus et al. (2009a).*

The highly eccentric Be binary system δ Sco is a very good example of use of different high angular techniques and instruments. The binary nature of δ Sco was first reported by Innes (1901) who observed it during a lunar occultation in 1899. It was rediscovered to be a binary using lunar occultation (Dunham 1974), by interferometry with the Narrabri Stellar Intensity Interferometer (NSII) (Hanbury Brown et al. 1974) and by speckle interferometry (Labeyrie et al. 1974). Bedding (1993) observed δ Sco with the Masked Aperture-Plane Interference Telescope (MAPPIT). Using his measurement and the measurements previously obtained with speckle interferometry, he was able to calculate an orbit for the system. The MAPPIT data were also used to estimate the brightness ratio of the two components. The orbital elements were recalculated by Hartkopf et al. (1996). Tango et al. (2009) have determined a consistent set of orbital elements by simultaneously fitting all the published interferometric and spectroscopic data, as well as the data obtained with SUSI. The resulting elements and the brightness ratio for the system measured prior to the outburst in 2000 have been used to estimate masses of the components: $\mathcal{M}_\mathrm{A} = 15 \pm 7\mathcal{M}_\odot$ and $\mathcal{M}_\mathrm{B} = 8.0 \pm 3.6\mathcal{M}_\odot$. The dynamical parallax is estimated to be 7.03 ± 0.15 mas, which is in a good agreement with the revised HIPPARCOS parallax.

δ Sco reached the periastron in early July 2011, when the distance between the primary and secondary was a few times the size of the primary disk in the H band. This opened a window of opportunity to study how the gaseous disks around Be stars respond to gravitational disturbance. Che et al. (2012) refined the binary parameters with the best orbital phase coverage data from the Navy Precision Optical Interferometer. They presented the first imaging results of the disk after the periastron (Fig. 21), based on seven nights of five telescope observations with the MIRC combiner at the CHARA array. The timing of the periastron passage has been revised to UT 2011 Jul 6±2 days. The expected minimum separation at the closest approach is predicted to be 6.14 ± 0.07 mas (14 stellar radii). Che et al. (2012) derive an orbit of δ Sco (Fig. 20) based on the data from NPOI and CHARA Array. A total mass of $28 \pm 11\mathcal{M}_\odot$, with a large error bar results from the uncertainty in the parallax estimate. Individual masses are estimated $13.9\mathcal{M}_\odot$ (from photometry

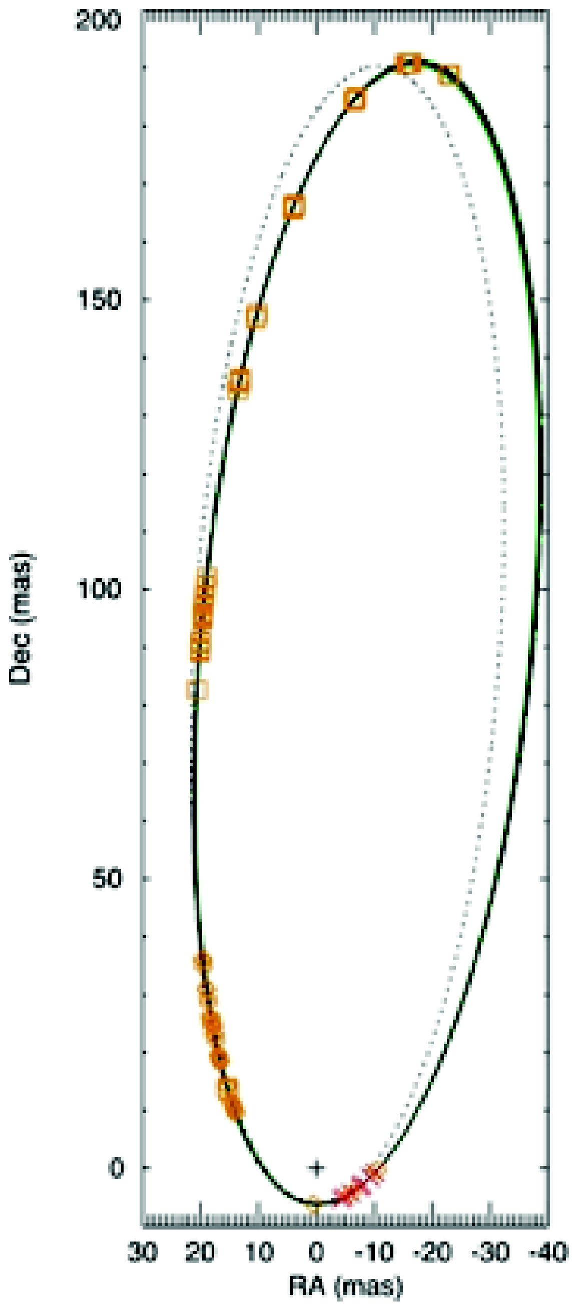

Fig. 20. *δ Sco, the squares and diamonds on the orbit are the NPOI data. The crosses on the orbit are MIRC/CHARA astrometric measurements from July 2011. The plus sign is the fixed primary. The solid lines are the binary orbits from global model fitting to both the NPOI and MIRC data. The dotted line represents the orbit from Tango et al. (2009). The dot-dashed line is the orbit from model fitting to both the new and old NPOI data. (Figure taken from Che et al. (2012))*

and spectroscopy) and $\approx 6\mathcal{M}_\odot$ (based on mass ratio from RV measurements during periastron). The binary star δ Sco was also observed by Meilland et al. (2011) with the CHARA interferometer, using the newly available VEGA instrument in order to study the disk geometry and kinematics before the 2011 periastron.

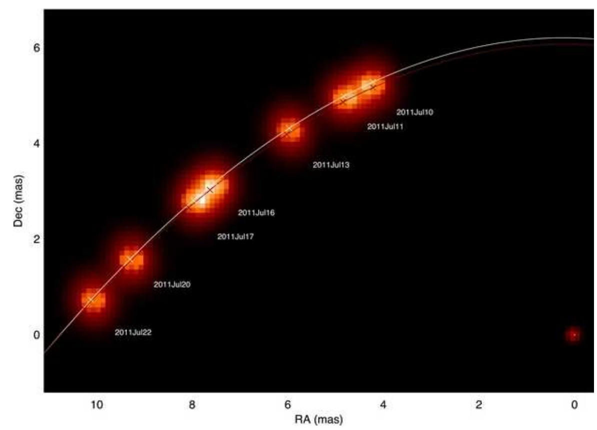

Fig. 21. *δ Sco images from the global model fitting of seven nights of the MIRC/CHARA observations. The secondary (at bottm right) is fixed at the origin for all seven nights, and the primary along with its disk changes position relative to the secondary from night to night. The white solid line is the predicted its orbit and primary positions on those seven nights from the global model. (Figure taken from Che et al. (2012))*

The o Leonis primary is a giant of type F9 and the secondary is an A5m dwarf, for which Hummel el al. (2001) presented a three-dimensional solution for the orbit. This study stands out because it combines the interferometry data from the Mark III, NPOI, and PTI interferometers, as well as the radial velocity data, resulting in mass uncertainties of only $\approx 0.5\%$. Stellar evolution isochrones can be put to a serious test for this system. They derive masses of $2.12\pm0.01\mathcal{M}_\odot$ and $1.87\pm0.01\mathcal{M}_\odot$, respectively. The distance to the binary is determined to be 41.4 ± 0.1 pc.

5.8. Keck interferometer

The large apertures of each of the two Keck telescopes are ideally suited for speckle, aperture masking and adaptive optics high angular resolution astrometry of binary stars, as well as long baseline interferometry when the telescopes operate in that mode, and it has produced plentiful of results in the field. Here are several examples:

Boden et al. (2005b) reported on KI observations of the double-lined binary B component of the quadruple pre-main-sequence (PMS) system HD 98800. With these interferometric observations, combined with astrometric measurements made by the Hubble Space Telescope Fine Guidance Sensors and published radial velocity observations, they have estimated preliminary visual and physical orbits of the HD 98800 B subsystem, in particular the component masses of $0.699 \pm 0.064\mathcal{M}_\odot$ and $0.582 \pm 0.051\mathcal{M}_\odot$ for the Ba (primary) and Bb (secondary) components, respectively. The modeling of the subsystem component temperatures and luminosities are in agreement with previous studies, and coupled with the component mass estimates allowed for comparison with the pre-main-sequence models in the low-mass regime.

Boden et al. (2007) reported on interferometric and radial velocity observations of the double-lined 51 day period binary (A) component of the quadruple pre-main-sequence (PMS) system V773 Tau. With these observations they have estimated preliminary visual and physical orbits of the V773 Tau A subsystem. Among other parameters, their orbit model included an inclination of 66.0 ± 2.4 deg, and allowed to infer the component dynamical masses and system distance. In particular, they find component masses of $1.54 \pm 0.14\mathcal{M}_\odot$ and $1.332 \pm 0.097\mathcal{M}_\odot$ for the Aa (primary) and Ab (secondary) components, respectively. The modeling of the subsystem component spectral energy distribution finds temperatures and luminosities consistent with previous studies and, coupled with the component mass estimates, allows for comparison with the PMS stellar models in the intermediate-mass range.

As part of the continuing campaign to measure the masses of PMS stars dynamically and thus to assess the reliability of the discrepant theoretical calculations of contraction to the main sequence, Simon et al. (2013) presented new results for V397 Aur, a visual and double-lined spectroscopic binary in the Taurus star-forming region. The new high angular resolution astrometry and high spectral resolution spectroscopy at Keck Observatory led to a significant revision of previously published orbital parameters. In particular, the masses of the primary and secondary, $0.86 \pm 0.11\mathcal{M}_\odot$ and $0.55 \pm 0.05\mathcal{M}_\odot$, respectively, are smaller than previously reported, and the system lies 158.7 ± 3.9 pc from the Sun, further than previously reported.

6. CONCLUSION

The dynamic parallaxes derived from orbital solutions of binary stars proved to be very important in many cases when the Hipparcos parallaxes challenged the existing models of stellar internal structure and evolution. Despite the fact that the obtained dynamic parallaxes generally confirm the existing astrophysical models, we expect that the era that we are just entering, when the sub-milli astrometric precision will become a standard, should significantly advance our knowledge not only quantitatively but also qualitatively. The much more precise dynamic parallaxes, complemented with the GAIA satellite parallaxes, the augmented sensitivity which will increase the number of accessible targets and stellar types, and particularly stellar masses derived from better orbital solutions will significantly enhance our understanding of stellar formation, structure and evolution, as well as of considerable number of astrophysical topics which are related to stellar physics.

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АСТРОМЕТРИЈА ДВОЈНИХ ЗВЕЗДА СА ПРЕЦИЗНОШЋУ ОД ХИЉАДИТОГ И ВЕЋОМ ОД ХИЉАДИТОГ ДЕЛА ЛУЧНЕ СЕКУНДЕ

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Прегледни рад по позиву

Неколико протеклих декада сведоче о убрзаном процесу побољшавања одређивања основних параметара двојних звезда, након што су нове посматрачке технике дале визуелне орбите многих спектроскопских двојних звезда са прецизношћу од хиљадитог дела лучне секунде. Модерна астрометрија се брзо приближава циљу прецизности веће од хиљадитог дела лучне секунде, и мада је тренутно та прецизност постигнута само за ограничени број двојних звезда, у блиској будућности то ће постати стандард за врло велики број објеката. У овом раду дајемо преглед репрезентативних резултата техника које су већ омогућиле прецизност бољу од хиљадитог дела лучне секунде: оптичка интерферометрија са дугачким базама, уз технике као што су спекл интерферометрија, адаптивна оптика и апертурно маскирање које омогућавају корак напред од прецизности са хиљадитим делом лучне секунде ка прецизности већој од хиљадитог дела лучне секунде, дозвољавајући да се раздвоје чак и краткопериодичне двојне звезде, и често резултујући орбитама које омогућавају прецизности динамичких маса звезда боље од 1%. Наглашавамо да таква висока прецизност мора довести до значајног побољшавања нашег разумевања физике звезда и повезаних астрофизичких тема.