Precise Stellar Radial Velocities
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Imaging and Modeling of Double Stars with the Navy Prototype Optical Interferometer: a Continuation of the Mark III Double Star Program

Christian A. Hummel

US Naval Observatory, Washington, DC 20392, USA

Abstract.
We present results from the new Navy Prototype Optical Interferometer (NPOI) – the orbit of the double star Mizar A and measurements of Matar – which are compared to an orbit determined with the predecessor of NPOI, the Mark III Interferometer. Uncertainties of the orbital inclination are between 0.1 and 0.3 degrees; those of the semi-major axis are less than 0.5 percent. We determine the component masses and other parameters of the double star system, including relative photometry, directly through a fit to a combination of interferometric and spectroscopic data. Algorithms were developed to handle any hierarchical stellar system.

We describe plans for the study of spectroscopic double stars with NPOI, which draw from our experience with the Mark III binary program. This program yielded orbits of 26 stars, of which 17 were published with mass determinations of 24 components using spectroscopy. The accuracy of the physical parameters were often limited by the spectroscopy. We show that in order to benefit from the high precision of the interferometric observations, new high-precision spectroscopic observations, combined with improved algorithms for the detection of the secondaries, are required.

1. Introduction

Since the advent of optical long baseline interferometry, subtle shifts of the spectral lines of spectroscopic binaries are no longer the only telltale sign of their multiplicity. The very high angular resolution of multiple element interferometers has made it possible to image directly stellar systems with separations as small as a few thousandths of an arcsecond. As we will show in the following sections, high astrometric precision combined with precise radial velocities enables us to determine accurate stellar masses in non-eclipsing systems.

2. The Mark III double star program

Between 1988 and 1992, the Mark III Interferometer (Shao et al. 1988) on Mt. Wilson, California, was the first interferometer to resolve and measure systematically a large number (26) of orbits of spectroscopic binaries with good

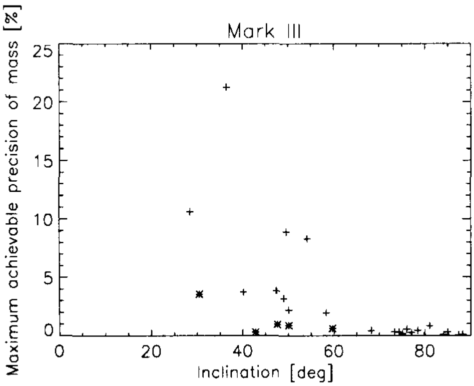

Figure 1. The distribution of orbital inclinations and the uncertainty of $(\sin i)^3$ for binaries in the Mark III program. The star symbol denotes (from left to right) η And, α Aur, θ^2 Tau, β Tri, and ζ^1 UMa.

precision. The data were combined with published radial velocity measurements to derive 24 component masses in double-lined systems. Seventeen orbits were published (see, e.g., Hummel 1997). In Fig. 1 we show orbital inclination results in a form relevant to estimating the accuracy of stellar masses achievable with the Mark III observations.

The Mark III results are so precise that in many cases the available spectroscopy was the limiting factor in the determination of stellar masses. We demonstrate this in Fig. 2.

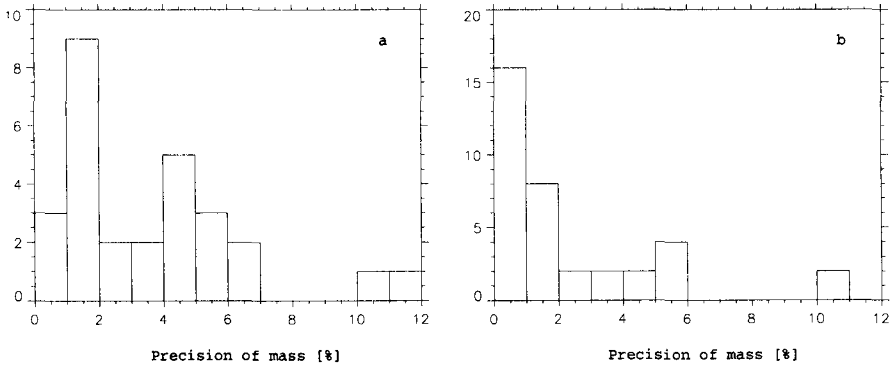

Figure 2. a: Histogram of actual precision of masses achieved by combining Mark III results and spectroscopy. b: Histogram of the precision of masses if spectroscopy were perfect.

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3. NPOI observations

The Navy Prototype Optical Interferometer (NPOI), in operation since 1996 near Flagstaff, Arizona, has proven to be a powerful instrument for the observation of single and double stars with overall sizes down to a few milliarcseconds (mas). The NPOI was described in detail by Armstrong et al. 1998. First results have been published by Benson et al. (1997) and Hajian et al. (1998). As of summer 1998, the NPOI consists of three stations used simultaneously to form non-redundant non-collinear baselines of up to 37.5 m. Fringe amplitudes and one closure phase are measured for 20 channels covering the visible band from 520 nm to 850 nm. We interleave scans on the program and calibrator stars, each scan being 90 s long and yielding about 60 visibility measurements (3 baselines times 20 channels). Thus, even with only a few scans, a sizable uv-coverage can be obtained for imaging and reliable modeling.

4. Modeling

We have developed a hierarchical stellar systems model format, consisting of binary and single stellar component descriptions, which is fit directly to a combination of data from interferometry and spectroscopy. In this way, we determine the orbital elements and stellar masses, as well as the magnitude difference between the components in each wavelength channel, and the diameters of the components. This technique reduces the total number of fit parameters over the case where both data sets are modeled independently.

5. Mizar A and Matar

These spectroscopic binaries have been among the first to be observed with NPOI in order to determine orbits from NPOI data alone (Mizar A, ζ^1 Ursae Majoris), and from a combination of NPOI data and earlier (incomplete) Mark III data (Matar, η Pegasi). In both cases, published radial velocity data have been included in the fit. The orbit of Mizar A is shown in Fig. 3a; the orbital inclination is 60.5 ± 0.3 degrees, the semi-major axis is 9.83 ± 0.03 mas. In Fig. 3b, we show how well an orbit published by Hummel & Armstrong (1992) agrees with the new NPOI measurements. (For this figure, the orbital period has been adjusted, since it carried a rather large uncertainty.) It is obvious that the agreement is excellent, confirming the measurement accuracy of the two independent interferometers.

Matar consists of a G2 bright giant and a F0 dwarf. Only the giant component has been measured by spectroscopy. Therefore, the stellar masses can be determined only with additional information, for which the distance is a suitable candidate since it has been measured by the Hipparcos satellite (ESA 1997). In order to investigate how well the Hipparcos trigonometric parallaxes agree with orbital parallaxes derived with the Mark III program, we compiled the following table. The agreement is excellent, except for two cases, Capella and Mizar A.

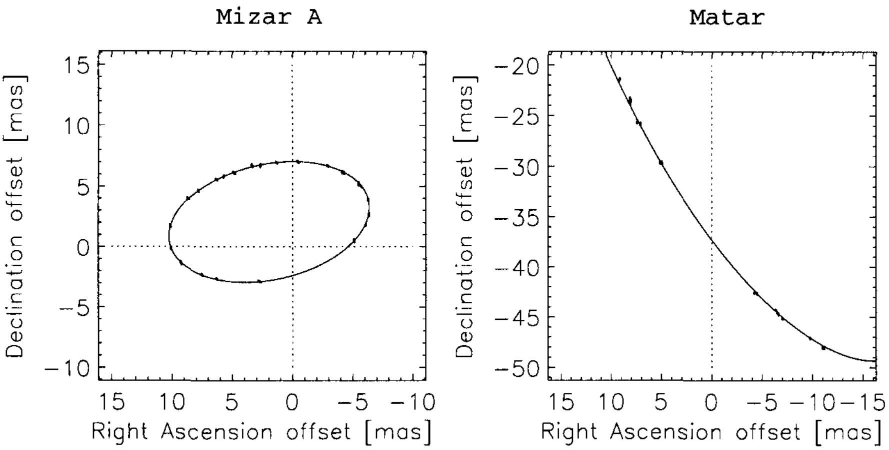

Figure 3. Apparent orbit of the secondary of Mizar A relative to the primary derived from NPOI data (left), and the Mark III orbit of Matar as published by Hummel & Armstrong (1992) superposed on new NPOI data (right). The positional uncertainty ellipses are derived from the interferometer point-spread function (or synthesized beam width) divided by 40, which give a realistic estimate for the orbit residuals. For Mizar A, the median residual is only 70 μas.

Table 1. Parallaxes [mas] from the Mark III optical interferometer and spectroscopy (Mizar A with NPOI) compared to Hipparcos.

Star	HIC	Mk. 3	±	Hip.	±
θ Aquilae	99473	13	1	11.4	0.9
β Aurigae	28360	40	1	39.7	0.8
93 Leonis	57565	13.8	0.5	14.4	0.9
η Andromedae	4463	13.1	0.3	13.4	0.7
β Arietis	8903	53	2	54.7	0.8
β Persei	14576	35.4	1.1	35.1	0.9
α Equulei	104987	18.1	0.8	17.5	0.9
ζ Aurigae	23453	3.8	0.1	4.1	0.8
ϕ Cygni	96683	12.4	0.3	13.0	0.6
θ 2 Tauri	20894	21.2	0.8	21.9	0.8
Capella	24608	75.1	0.5	77.3	0.9
Mizar A	65378	39.4	0.3	41.7	0.6

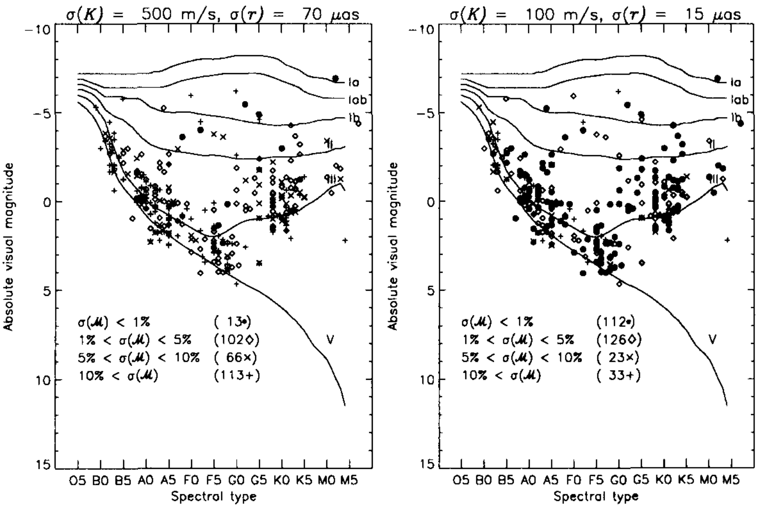

Figure 4. The location of about 300 primaries in the HR diagram, from a sample of bright binaries observable with NPOI. The left plot gives information on the distribution of mass uncertainties which could be achieved with a current typical accuracy of 500 m/s for the velocity amplitude and 70 μas for the relative astrometry. On the right, the change of the distribution is shown for measurement accuracies 5 times better.

6. A Bright Binary Catalog

We have compiled a catalog of about 300 double stars brighter than $V = 6$, north of $\delta = -20°$, and with estimated semi-major axes between 1 mas and 200 mas, based on the Batten et al. (1989) catalog of spectroscopic binaries. In Fig. 4 we plot the location of the primaries in the HR diagram, coded according to the uncertainty with which their masses could be determined given the measurements accuracies of spectroscopy and interferometry. However, we have not accounted for the influence of the apparent magnitude and the spectral type of the stars on the measurement accuracies, so that these plots can serve only to show the good coverage of the HR diagram with this sample of double stars, and the improvement of the measurement precision necessary to bring about a significant increase in the number of stars with high-precision mass determinations.

7. Outlook

Future tasks include the systematic extension of the binary modeling procedure to include photometry in addition to spectroscopy, interferometry, and astrometry. Already underway is the extension of the NPOI array to baseline lengths of up to 437 m and the simultaneous operation of up to six siderostats. These developments will then enable the modeling and imaging of truly complicated stellar systems, e.g., interacting binaries.

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Discussion

Larson: Your computer movie of the orbit of Mizar A is really great. Like most of us in this room, I wear two hats, the second being that of a teacher. The educational potential of tyhe images is *extremely* high, and I would like to know if the "movie" will be released for educational purposes.

Hummel: This is a good idea; we will make it available as soon as possible.

Brown: What developments are necessary to improve the accuracy of relative separations from the present 70 μas to the desired 10 μas?

Hummel: We will increase the baselines by a factor of 10 in length, and we will improve the visibility calibration as well.