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THE STATUS OF SPECKLE IMAGING IN BINARY STAR RESEARCH

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RESUMEN

La obtención de imágenes en modo speckle continúa siendo una importante herramienta para la observación de estrellas binarias a pesar del uso de la óptica adaptativa y otras técnicas de alta resolución. En este trabajo el autor explora la última década de investigaciones con datos speckle y pone en perspectiva el sitial ocupado por esta técnica observacional. El uso de los CCD y la publicación del catálogo Hipparcos han jugado papeles fundamentales en el impulso de la técnica speckle. Las distintas posibilidades futuras de este campo observacional son discutidas también en este trabajo.

ABSTRACT

Speckle imaging continues to be an important tool in binary star research despite the rise of adaptive optics and other high-resolution techniques. The last decade of speckle work will be surveyed and a picture of where speckle sits in the broader context will be drawn. The advent of CCD-based speckle imaging and the publication of the *Hipparcos* Catalogue have played important roles in the ongoing vitality of the speckle technique. The possibilities of the future of the field will also be discussed.

Key Words: **ASTROMETRY — BINARIES: GENERAL — STARS: FUNDAMENTAL PARAMETERS — TECHNIQUES: HIGH ANGULAR RESOLUTION — TECHNIQUES: PHOTOMETRIC**

1. INTRODUCTION

Originally conceived by Labeyrie (1970), speckle interferometry was quickly seen as a very powerful tool for binary star astronomy due to the simplicity of the object (i.e. two point sources). Methods for extending Labeyrie's autocorrelation technique to true diffraction-limited imaging of general objects were followed, such as bispectral analysis (Lohmann, Weigelt and Wirnitzer, 1983), among others. Because of certain properties of the image bispectrum, bispectral analysis subsequently emerged as the most effective means of obtaining diffraction-limited images from speckle in general. Speckle imaging has been used to derive diffraction-limited images of many objects over the years.

In the field of binary star research, there is a wealth of speckle data, as evidenced by the large number of observations compiled in the 4th Interferometric Catalog[2] of Hartkopf et al. Many of these data are of course due to the work of McAlister and Hartkopf and their collaborators (e.g. Hartkopf et al. 2000, Mason et al. 2004), but there are also several other currently active binary star speckle observing efforts, such as those of Balega and collaborators (Balega et al. 2004), Docobo and his collaborators (Docobo et al. 2004), Horch, van Altena, and their collaborators (e.g. Horch, Meyer & van Altena 2004), and the PISCO team (Prieur et al. 2003).

One of the primary reasons that speckle observations remain vital is that the rise of space-based astrometry as demonstrated by *Hipparcos*. Space-based astrometry not only dramatically improves distance measures for the conversion of observed orbital and photometric parameters into astrophysical parameters such as mass and luminosity, but it also is capable of discovering many previously unknown binary systems that can be characterized in ground-based follow-up observations. This paper will focus primarily on this important connection; for more detailed information concerning the speckle process and data analysis techniques, the reader is directed toward Dainty (1984). For an excellent discussion of the value of speckle observations in binary star research, see McAlister (1985).

2. SPECKLE OBSERVATIONS AND SPACE ASTROMETRY

Visual (and by extension interferometrically resolvable) binary stars yield stellar mass information through this formulation of Kepler's 3rd Law:

$$m_1 + m_2 = \frac{a^3}{\pi^3 P^2}, \qquad (1)$$

where m_1 and m_2 are the masses of the components, a is the semi-major axis, π is the absolute trigonometric parallax, and P is the period of the system.

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[2] `http://ad.usno.navy.mil/wds/int4.html`

Of the three observables on the right-hand side of this classic equation, parallax has traditionally been the limiting factor in terms of the uncertainty of the total mass in nearly all relevant systems. In turn, this has been a fundamental constraint in the usefulness of these systems for increasing our knowledge of stellar astrophysics.

The *Hipparcos* mission and subsequent release of the *Hipparcos* Catalogue (ESA, 1997) have substantially improved parallaxes of stars within a couple of hundred parsecs of the sun. *Hipparcos* parallaxes have typical uncertainties in the range of 2 to 5 times smaller than ground based parallax results (*i.e.* from 1 to 2 milliarcseconds [mas]). As impressive as this achievement is, the dominant source of mass uncertainty remains the parallax for most speckle binaries. For example, the well-known binary Bu 151AB (= WDS 20375+1436 = HIP 101769) has *Hipparcos* parallax of 33.49 ± 0.88 mas, and recent orbital parameters obtained from W. I. Hartkopf (private communication) give $a = 439.4 \pm 0.6$ mas and $P = 26.6327 \pm 0.0110$ years. The fractional errors in the observed quantities are therefore $\delta a/a = 0.00137$, $\delta\pi/\pi = 0.02628$, and $\delta P/P = 0.00041$. The parallax error is nearly a factor of 20 larger than the other two contributors, even for this system which is only 30 parsecs from the sun, and even post-*Hipparcos*.

However, two major satellites to be launched in the coming years will totally transform our idea of what is "nearby." These are NASA's Space Interferometry Mission (SIM, planned launch 2010), and ESA's Gaia mission (planned launch 2011). Both are being designed to determine parallaxes to better than 10 micro-arcseconds (μas), at least 100 times better than *Hipparcos*. (As of this writing, SIM's mission goals have been restructured to focus more on planet searches.) If this type of parallax precision is obtained for Bu 151AB, the fractional uncertainty $\delta\pi/\pi$ becomes 3.0×10^{-4}, and the overall error budget from the three observables would be less than 0.3%, approximately 15 times better than the current value (using the *Hipparcos* parallax) of 4.6%.

The above exercise demonstrates the importance of space-based astrometry in unlocking the power of the speckle binaries for astrophysics, and there are dozens of other bright, well-known systems awaiting this kind of revision. The binary star community owes a debt of gratitude to the visual observers, such as Wulff Heintz, Charles Worley, Geoff Douglass, Paul Couteau, their contemporaries and predecessors, as well as the sustained speckle efforts of the Center for High Angular Resolution Astronomy (CHARA) group at Georgia State University and the

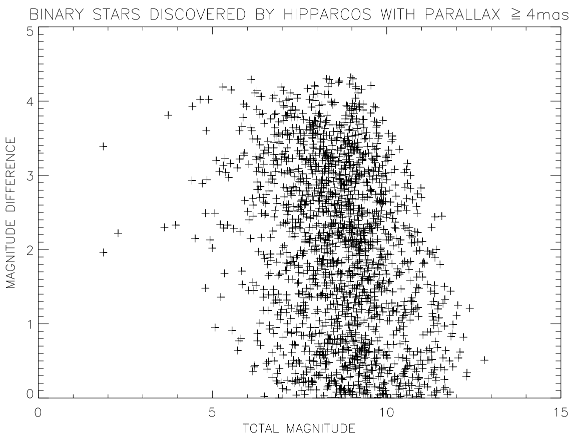

Fig. 1. Magnitude difference plotted as a function of total magnitude for the *Hipparcos* double star discoveries within 250 pc of the Sun.

U.S. Naval Observatory (USNO), who have already provided us with a wealth of orbital information: they knew long ago the demon of parallax would one day be subdued.

3. NEW BINARIES: MINING THE GOLD

In addition to the well-known binaries discussed above, *Hipparcos* discovered some 3400 new double star systems and flagged thousands of other stars as "suspected double." Figure 1 shows a representative sample of these discoveries. These objects are extremely well-suited to follow-up observations using speckle imaging, and some first results have been published recently. Horch et al. (2002) identified 19 systems as probably orbitally bound, and Balega et al. (2004) have determined orbital parameters for a couple of objects. This is just scratching the surface, however, and many more results should be forthcoming in the next decade.

In addition, Mason, Hartkopf, and their collaborators have recently surveyed approximately 3,600 stars with $B - V$ colors in the range 0.5 to 1.0 for duplicity using the Kitt Peak and CTIO 4-m telescopes. A small percentage of these are double, and the colors place these objects in a range of particular interest regarding stellar astrophysics. These binaries, with separations presumably too small to have been detected by *Hipparcos*, may have shorter periods. This sample, like the *Hipparcos* double stars, is therefore waiting to be culled for the orbital and photometric information that will lead to astrophysical studies.

In view of the dramatic improvement in the distance measures to stars that can be expected over the

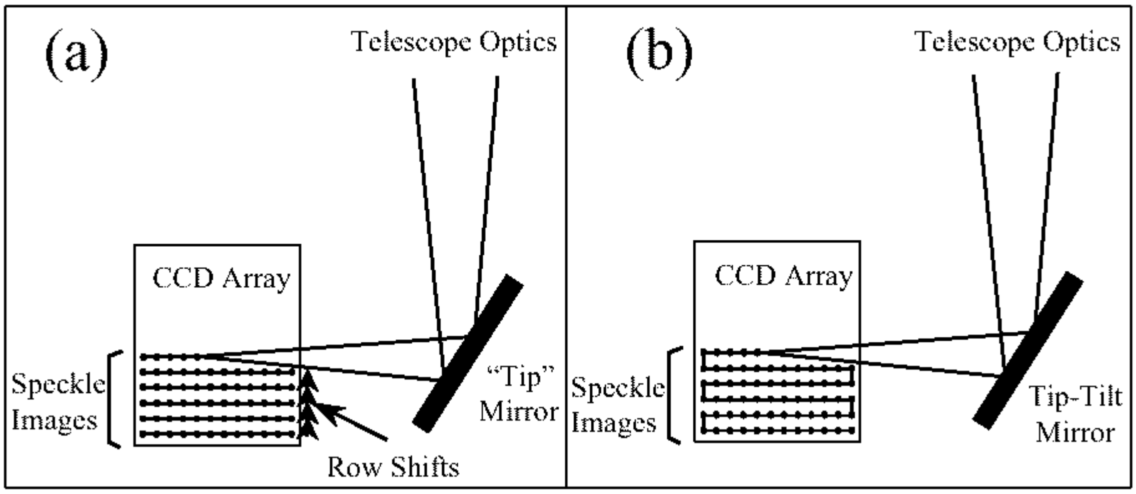

Fig. 2. Schematic of two proposed methods of filling an entire CCD array with speckle patterns. (a) a tip-only operation, where fast charge transfers move rows of speckle patterns toward the serial register, and (b) a tip-tilt operation, where the mirror provides deflection of the image to all areas of the chip. In both cases, the CCD itself is used as a memory cache of previous speckle images.

next 10 to 15 years, there is an opportunity to make dramatic gains in terms of the stellar mass information and fundamental calibrations of stellar evolution theory as well as statistical studies that would be of significant benefit for stellar astrophysics.

4. CCDS IN SPECKLE IMAGING

Large format CCDs with very low read noise (3 to 6e-) are now fairly common and increasingly affordable. Some devices still have long readout times but even this is now commonly being addressed with faster electronics and multiple-port readout. CCDs are capable of recording speckle patterns with a signal-to-noise ratio similar to photon counting cameras over a wide range of magnitudes. Horch, Ninkov, & van Altena (1998) ran a series of conservative speckle simulations which indicated that a high-quality astronomy CCD would, in fact, have comparable or higher SNR when compared to a photon counter of 10% quantum efficiency to at least magnitude 10.2.

Even a large format CCD could in principle be used in speckle imaging, if the chip area were efficiently used to store speckle patterns prior to frame readout. Speckle patterns could be collected on the chip using a movable mirror to direct the image to each portion of the detector area in a regular pattern. Figure 2 illustrates two possible techniques for using this approach. This has been the basis for the design of the Rochester-Yale Tip-tilt Speckle Imager (RYTSI), which was completed in 2001 and is currently in use at the WIYN 3.5-m Telescope[3] at Kitt Peak, Arizona (Meyer et al. in prep).

The improvement in seeing that has been realized by telescopes at excellent sites, as well as at newer telescopes where dome seeing issues have been better controlled, helps the use of CCDs in speckle imaging. Better seeing means that the frame integration time can be longer, easing the bandwidth requirement of the technique. Because of better seeing and longer frame integration times, there are more photons per speckle, making it easier to record high-contrast speckle patterns above the read noise, and resulting in a fainter limiting magnitude.

The principle motivation for collecting speckle data with CCDs is differential photometry. A nagging problem in speckle work has always been the inability to determine the relative photometry of the two stars in a binary system, sometimes referred to as the "Δm" problem. Seasoned speckle observers, such as Hartkopf et al. (1996), have generally assigned uncertainties of 0.5 mag for any magnitude difference estimates. This problem appears to be due in large part to microchannel saturation, a detector non-linearity present in microchannel–plate-based devices such as the intensified-CCDs (ICCDs) used by many speckle observers. It is avoided with CCD-based speckle imaging.

[3]The WIYN Telescope is a joint facility of the University of Wisconsin-Madison,Indiana University, Yale University, and the National Optical Astronomy Observatories.

5. SPECKLE PHOTOMETRY

Horch, Ninkov, & Franz (2001) first demonstrated the successful recovery of differential photometry from CCD-based speckle data, and this work has also been continued and refined at the WIYN Telescope (Horch, van Altena, & Meyer 2004). Those authors found that in a large number of two-minute speckle observations, uncertainties in the magnitude difference were on average 0.13 magnitudes, a considerable improvement over previous attempts with ICCD cameras.

These observations provide the opportunity to test the accuracy of stellar evolution theory. An excellent example of this is the system discussed earlier, Bu 151AB. From WIYN speckle photometry obtained in several narrow pass bands and the total magnitude and color of the system known from the literature, the components of the system can now be placed on an H-R diagram. Figure 3 shows these data with 1-σ formal uncertainties in the WIYN photometry. The Yale-Yonsei isochrones (Demarque et al. 2004) for three different ages: 1.6, 1.8, and 2.0 Gyr are also shown on the plot. Only the 1.8 Gyr isochrone is consistent with both observational points. However, not only the isochrone should pass through both observational points, but the observed mass value on the isochrone (as determined from the orbital parameters) should be also obtained at that point. Figure 3 highlights the appropriate mass range for each component. From these data, it can be conservatively concluded that the theory and observation are consistent in this case, and the predicted age of the system is 1.8 ± 0.2 Gyr.

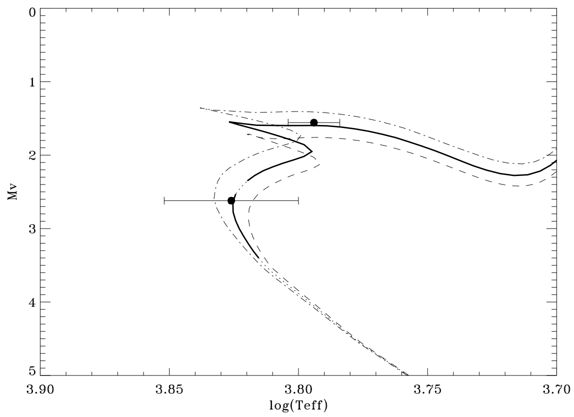

Fig. 3. Yale-Yonsei isochrones compared with observed data obtained from WIYN speckle observations of Bu 151 AB. Three isochrones are shown, all at solar metallicity: 1.6 (dot-dashed line), 1.8 (dotted line), and 2.0 (dashed line) Gyr. The mass range that must be matched with the data point for consistency with orbital parameters is shown on the 1.8 Gyr isochrone in bold.

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