A&A 370, 524–528 (2001)
DOI: 10.1051/0004-6361:20010266

Astronomy
&
Astrophysics

A speckle interferometry survey of λ Bootis stars*

E. Marchetti[1,2], R. Faraggiana[3], and P. Bonifacio[4]

[1] European Southern Observatory, Karl–Schwarzschild–Str. 2, 85748 Garching bei München, Germany
[2] Centro Galileo Galilei, Apartado de Correos 565, 38700 Santa Cruz de la Palma, Canary Islands, Spain
[3] Dipartimento di Astronomia, Università degli Studi di Trieste, Via G. B. Tiepolo 11, 34131 Trieste, Italy
[4] Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, 34131 Trieste, Italy

Received 18 December 2000 / Accepted 14 February 2001

Abstract. A search for duplicity of λ Boo stars has been made by using the speckle camera installed at the Telescopio Nazionale Galileo. The operation mode and the reduction procedure allow one to obtain not only the separation, but also the magnitude difference between the components; the latter parameter is fundamental for determining the degree of contamination from the secondary component of a binary system and thus the importance of the veiling effect that produces absorption lines weaker than normal. Two stars, HD 38545 and HD 290492, are close binaries with values of the separation and of the magnitude difference such that only a composite spectrum can be observed. For another 15 λ Boo candidates, observed with negative results, the upper limits of a possible companion separation are given.

Key words. techniques: interferometers – stars: chemically peculiar – binaries: general

1. Introduction

The limitations imposed by the atmospheric seeing is a serious problem for ground based observations. Speckle interferometry, which allows one to circumvent blurring by the Earth's atmosphere, has been known for three decades (Labeyrie 1970) and is mainly applied to the research of close binary and multiple systems (see the large series of papers by McAlister and collaborators), to the measurements of stellar diameters and to the study of the strucure of circumstellar envelopes at different wavelengths; it has been also used to evaluate sizes and shapes of the minor objects of the solar system. Unfortunately, this technique has not been widely applied so far since its major limitation lies in the relatively small dynamic range allowed for the object magnitude. However, speckle interferometry, under certain observing conditions, can still be used to retrieve the difference in magnitude between objects which are quite close in terms of relative brightness.

In spectral analysis, the flux from a composite object, when interpreted as due to a single source, will most certainly cause confusion and may originate elaborate, but unrealistic, theories. Such a confusing situation is evident in the class of the λ Boo stars, Population I, early-A, recently extended up to early-F type stars characterized by metal lines much weaker than expected for their spectral type. The wide range of the derived metal underabundances and the variety of explanations of the λ Boo phenomenon are found in the large number of recent papers on the identification and interpretation of these stars. Faraggiana & Bonifacio (1999) raised the question that undetected duplicity is a possible explanation of the peculiar Balmer profiles (shallow cores and broad wings) and of the apparent metal underabundances of several λ Boo candidates; in fact, in a composite spectrum, the veiling effect produces shallow lines which are characteristic of most λ Boo stars (see Corbally 1987).

2. Observations

The speckle camera mounted on the Adaptive Optics module (AdOpt@TNG) of the 3.5 m Telescopio Nazionale Galileo (TNG) is expected to reach the diffraction limit ($0\farcs043$ at 600 nm) and is an ideal tool for separating narrow binary systems with magnitude differences between their components of less than 3 mag, as is expected in the case of binarity of a λ Boo candidate.

The imager is an ICCD Proxitronic camera with a quantum efficiency optimized for the blue part of the visible spectrum (≈20% at 500 nm). The central part of the

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Send offprint requests to: E. Marchetti,
e-mail: `emarchet@eso.org`

* Based on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Centro Galileo Galilei of the CNAA (Consorzio Nazionale per l'Astronomia e l'Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

TV signal is digitized in a 128×128 pixel array (8 bits/px) at the standard frame rate of 25 Hz, while the single frame exposure ranges from 2 to 40 ms. An optical relay provides a scale of $\approx 0\farcs030$/px giving a field of view of $\approx 3\farcs9$. No atmospheric dispersion correction is applied.

The speckle camera computes in real–time the power spectrum of each frame and sums directly the whole set of power spectra obtained during the run. The data are then off–line corrected for the instrumental biases such as the background and detector inhomogeneities. The filter set includes some general purpose (Strömgren bands) and some narrow bandpass ones (e.g. H_α or TiO and ZrO absorption bands).

A detailed description of the real–time speckle facility can be found in Marchetti et al. (1997) and Mallucci (1998), while the real–time data acquisition is fully described in Baruffolo et al. (1998).

A calibration run of the speckle camera of the TNG has been used to observe a sample of stars classified as λ Boo from spectroscopic observations; this sample has been extracted from the list published by Faraggiana & Bonifacio (1999) and it is shown in Table 4. We obtained speckle observations of these stars on the nights of December 20th and 21st, 1999 and on September 28th, 2000. The nights were plagued by poor seeing and as a consequence the signal to noise ratio (SNR) for most observations was not high enough to provide stringent lower limits for separation and Δm. We report here the positive results obtained for two stars, HD 38545 and HD 290492, for which we measured separation, Δm and position angle, and we give the upper limits we could attain for some other λ Boo candidates.

The filters chosen for the observation were tuned to match both the characteristics of the objects and the seeing conditions experienced during the two nights. We decided to use the intermediate band filters b and y of the Strömgren system and a narrow band H_α filter for the very bright star HD 38545.

The exposure time of each speckle frame was 20 ms for all stars observed, including those used for the field of view calibration, and runs of 3000 frames were performed, each with a total integration time of 60 s per run. Depending on seeing conditions and on the brightness of the target star, up to 10 runs per object were performed.

For each object, we selected a reference single star in order to acquire the Speckle Transfer Function (STF) needed to deconvolve the atmospheric disturbance from the power spectrum of the object. Since the behaviour of the seeing is variable with a time scale that may be of the order of minutes, and also depends on the zenith distance, we selected a suitable STF star of comparable magnitude within few degrees of each target, and we switched between them many times, thus allowing the best possible homogeneity in terms of temporal seeing variations.

We also selected two double stars having well–known orbital parameters for determining the detector's scale and orientation, namely ADS784 AB and ADS6650 AB, for which the orbital parameters are taken from Cole et al. (1992) and Söderhjelm (1999) respectively and which were observed with all the three filters mentioned above.

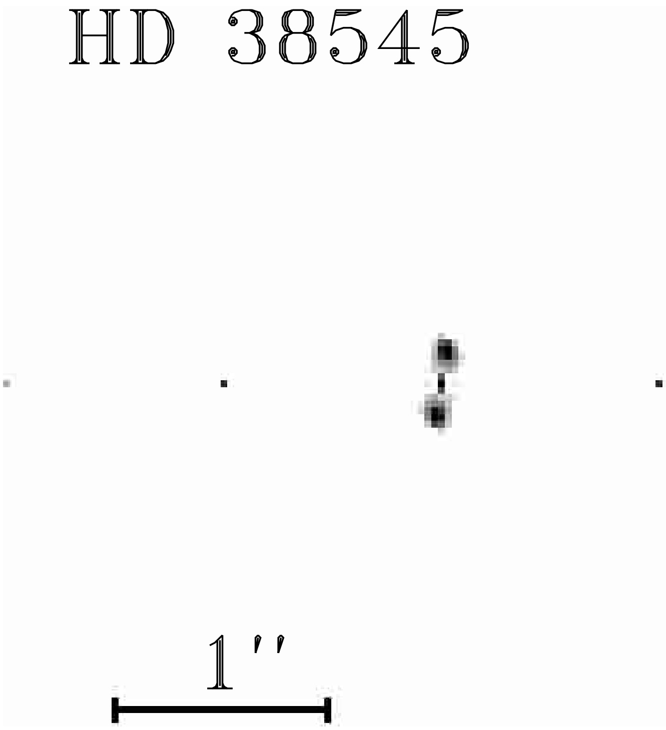

Fig. 1. Autocorrelation function of HD 38545

3. Data reduction

The speckle facility, after the end of each run, provides the accumulated power spectrum of the collected speckle frames. The power spectrum is divided by the STF obtained from observations of a nearby star, canceling out in this way the contribution of the atmospheric turbulence affecting the observation. This image pre–processing is also needed both for removing some features caused by the possible repetitive noise induced on the camera signal and to eliminate a typical cross–shaped disturbance occurring when the speckle image of the object is not entirely contained in the camera field of view. The power spectrum is then inverted via Fast Fourier Transform (FFT), and the autocorrelation function (ACF) of the brightness distribution of the astronomical target is obtained. In the case of binary stars, the ACF shows the characteristic behaviour of a central peak with two opposite and symmetric secondary peaks (see Fig. 1). The distance between the central peak and one of the secondary ones is the separation between the two components while the position angle is given by the orientation of the secondary peak with 180° uncertainty. The center of the secondary peaks is retrieved by fitting a paraboloid with a sub–pixel precision.

The magnitude difference is estimated by comparing the intensities of the secondary and the central peaks. The energy contained in the two secondary peaks is computed by integrating the ACF signal delimited by the

Table 1. Speckle results for HD 38545

Filter	Separation	Position angle	Δm
H_α	$0\farcs136 \pm 0\farcs005$	$192\fdg7 \pm 1\fdg9$	0.61 ± 0.20
y	$0\farcs145 \pm 0\farcs005$	$191\fdg4 \pm 1\fdg9$	0.63 ± 0.20
b	$0\farcs145 \pm 0\farcs005$	$189\fdg5 \pm 1\fdg9$	0.57 ± 0.20

paraboloidal fitting, and the same procedure is applied to the central peak with its proper paraboloidal fitting. The central pixel of the ACF is affected by a large amount of spurious signal given by the correlation of the noise and the background. In the integration process, its value has been substituted with that estimated by the fitted paraboloid at the same position. Finally, the comparison between the energies of the secondary peaks and that of the central one gives the magnitude difference. The relative errors are computed using the errors of the paraboloidal fitting.

The unfavourable weather conditions (poor seeing and strong wind) during the observations seriously affected the instrument performance. Even if the speckle interferometry is not as sensible to the seeing as other high angular resolution techniques (i.e. Adaptive Optics), the low SNR achieved surely compromised both the possibilty to detect very close binary systems (separation $<0\farcs1$), and the accuracy of the magnitude difference measurements. However, the obtained data are quite encouraging and demonstrate that also when seeing conditions are not the most favourable for high angular resolution observations, it is still possible to attain significant results.

4. Results for HD 38545

This star (=HR 1989 =131 Tau) was classified as λ Boo by Gray & Garrison (1987) and, since then, it has been accepted as belonging to this class by all authors, except for Abt & Morrell (1995) who classified it as a shell star.

The observed spectrum mimics quite well that of a single star, as shown by the abundance analysis by Stürenburg (1993) and by the line profile discussion by Bohlender & Walker (1994), who confirm the atmospheric parameters, T_{eff} and log g derived by the former author. The star's shell lines are discussed by Bohlender & Walker (1994), Andrillat et al. (1995), Grady et al. (1996), Hauck et al. (1998), Holweger et al. (1999), but none of these authors could find any spectroscopic signature suggesting that the star is not a single object.

Since this star is quite bright ($V = 5.725$) it was observed with 3 filters: H_α, y an b. Our results are given in Table 1 and the autocorrelation function is shown in Fig. 1. There is good agreement between the present results and those obtained by the Hipparcos experiment (separation $0\farcs155$, $\Delta H_{\mathrm{p}} = 0.64$).

The duplicity of HD 38545 was discovered using speckle interferometry by McAlister et al. (1993) and measured again by Hartkopf et al. (2000). Of the 4 above measurements of the CHARA group, the separations in three cases are quite close together ($\approx 0\farcs170$ in 1995.7686, 1996.8717 and 1997.1311), while the separation measured by McAlister et al. (1993) in 1988.1729 is $0\farcs071$, i.e. over a factor of two smaller than the others. The position angles measured by the CHARA group are all close to 190° and slightly decreasing, as in our case, and this fact suggests that the orbit is seen nearly edge–on. Although the amount of data is too small to retrieve the orbital parameter of this binary, a rough estimation of the orbital period can be made in the approximate assumption that the inclination is $i = 90°$ and the orbit is circular ($e = 0$). We fitted the separations vs. the epoch of the interferometric observations with a sinusoid and we found a good agreement for $P = 43.5$y and $a = 0\farcs171$ (see Fig. 2). Using the Hipparcos parallax from Table 4 we give an estimation for the total mass of the system $M = 5.7 \pm 2.3\ M_{\odot}$.

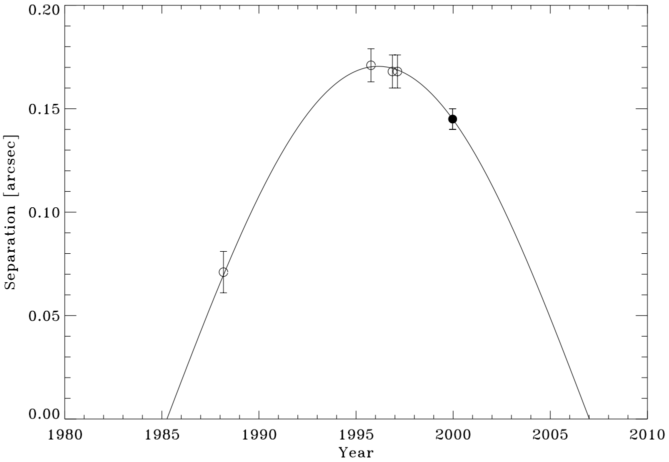

Fig. 2. Interferometric measurements of HD 38545 fitted with a sinusoid: the empty circles are the CHARA data and the filled circle is our y measurement. The fitting is made under the assumption $i = 90°$ and $e = 0$

According to the spectral analysis by Stürenburg (1993), the two components are expected to have similar masses of about 2.5 $M_{\odot}$. In fact, the absolute magnitude of this object corresponds to that of a star lying more than one magnitude above the ZAMS if the duplicity is not taken into account, and therefore its position on the HR diagram given by Paunzen (1997), Paunzen et al. (1998) (who also computed a wrong value of M_V) and, on the colour-magnitude diagram, by Bohlender et al. (1999) is misleading.

5. Results for HD 290492

The characteristics of this binary system reported in the Washington Double Star (WDS) catalogue are $\Delta m = 1.4$ and $d = 0\farcs6$, while medium-resolution spectroscopic observations allowed Paunzen & Gray (1997) to resolve the system; in fact they claim to have measured $\Delta m = 0.9$ and a separation of $2''$. The data of the WDS catalogue are based on 3 visual observations made by R. A. Rossiter at the Lamont-Hussey Observatory of Bloemfontein, South Africa, with a 27 1/2-inch refractor especially constructed by Zeiss for double star observation. The data from

Table 2. HD 290492 data from the literature

Date	Separation	Position angle	m_1–m_2
1943.026	$0\overset{\prime\prime}{.}64$	$65\overset{\circ}{.}6$	9.8–11.2
1943.205	$0\overset{\prime\prime}{.}60$	$69\overset{\circ}{.}4$	9.8–11.1
1950.174	$0\overset{\prime\prime}{.}64$	$67\overset{\circ}{.}8$	9.7–11.2

Table 3. Speckle results for HD 290492

Filter	Separation	Position angle	Δm
b	$0\overset{\prime\prime}{.}739 \pm 0\overset{\prime\prime}{.}005$	$63\overset{\circ}{.}9 \pm 1\overset{\circ}{.}9$	0.63 ± 0.20

Rossiter (1955) are collected in Table 2, and demonstrate the remarkable accuracy which may be obtained visually by an experienced observer with an appropriate instrument.

The star is not present in the Hipparcos catalogue, but is found in the Tycho catalogue. The transit data (37 accepted transits for the photometry) have been searched for binarity but none was detected. There is also no variability flag, although the scatter in the V_{T} magnitude is 0.234.

We observed the binary only with a Strömgren b filter and our results are summarized in Table 3. There is good agreement with the measurements of Rossiter, but not with the estimate of Paunzen & Gray (1997).

6. Stars observed with negative result

Other λ Boo candidates have been observed in poor weather conditions. For all the observed stars we list in Table 4 the parallax and its error given by the Hipparcos catalogue and, in the last column, the upper limit on the possible separation derived from considerations on seeing and SNR; the error is evaluated to be about ± 10 mas. For the two stars for which the separation has been measured, this upper limit is smaller than the measured separation. Taking into account the degradation of the fringe contrast in the object power spectra due to the bad seeing, we were not able to separate stars closer than $\approx 0\overset{\prime\prime}{.}10$ also considering the brightest objects and/or a small magnitude difference between the components. They deserve further observations for more stringent separation values.

We add here only a few comments on the duplicity of HD 153808, the star which has the lowest upper limit on the possible separation of a companion. Controversial visual binary detections are reported in the literature for this star. Its duplicity is measured by Isobe et al. (1990, 1992) from speckle observations, which are not confirmed by other authors (Miura et al. 1992, 1995; McAlister et al. 1993; Kuwamura et al. 1993). This star has been observed by Hipparcos, but no sign of duplicity has been detected and no mention of its duplicity is given in the Hipparcos Input Catalogue (Turon et al. 1993).

Table 4. Upper limits on the separation achieved for each of the program stars; the separation of the companion of the stars marked with $\star$ is given in the previous sections

HD	V	π	$\sigma(\pi)$ (mas)	upper limit (mas)
3	6.70	6.66	0.75	155
11503	4.64	15.96	0.85	124
23392	8.7	3.25	1.08	310
38545*	5.72	7.72	0.93	124
39421	5.97	8.60	0.92	124
64491	6.23	16.55	0.92	124
74873	5.87	16.38	1.16	124
84123	6.81	9.09	0.90	155
84948	8.1	4.97	1.14	284
90821	9.2	—	—	310
91130A	5.93	13.33	0.76	124
98772	5.98	11.58	0.56	124
105058	8.91	5.32	1.04	310
153808	3.92	20.04	0.65	93
192640	4.97	24.37	0.55	124
204041	6.46	11.46	0.99	155
290492*	9.27	–	–	310

It is discussed as spectroscopic binary by Petrie (1939) who classified the two components as A0 and A2, computed a magnitude difference of 1.5 and showed, in Fig. 5 of his paper, the line profiles of three lines at different phases. Batten et al.'s (1989) catalogue gives the orbital elements ($a \sin i$ being 3.91 10^6 and 6.2 10^6 km for the two components) and Hipparcos measured the parallax $\pi = 20.04 \pm 0.65$ mas. According to these data the angular separation of the two components of the spectroscopic binary system should be not higher than 0.13 mas and so these stars cannot be identified with those detected by the speckle observations. This low expected value of the angular separation explains the lack of duplicity detection by the Hipparcos experiment as well as by our TNG observations. This demonstrates that when the the separation is too small to be detected by direct imaging and the spectral lines are too broad to separate the components by spectroscopic observations, it is impossible to establish the binary nature of a system.

7. Discussion

The characteristics of the λ Boo stars are still not yet explained, in spite of the numerous efforts made, especially in the last two decades. The inhomogeneous properties of the members of this class represent the most intriguing aspect of the problem and the large area these stars occupy on the HR diagram represents a serious problem for the determination of their evolutionary stage. We recall that no systematic search for binaries has been made for these objects and we consider this point as the first to be clarified before any study can be initiated (see Faraggiana & Bonifacio 1999).

Our search for binaries with the TNG speckle camera has been severely limited by poor weather conditions, but it allowed us to confirm that two λ Boo stars HD 38545 and HD 290492 must be removed from this class of objects.

Before making any detailed analysis of peculiar objects and elaborating theories on their characteristics, a rigorous selection of true single objects is required. This may prove to be impossible from spectroscopic data alone.

For example, the duplicity of HD 38545 is now well established, thanks to speckle and astrometric observations, while it had never been suspected from the several analyses of its spectrum.

The case of HD 153808 represents an opposite example: high quality spectra revealed, over 60 years ago, that the star is a binary, while the present speckle observations and the Hipparcos experiment did not succeed in detecting its duplicity. The dubious visual duplicity found by previous speckle observations may suggest the presence of a third body, which, however, cannot be responsible for the SB2 system.

These two objects clearly show that a single best method to detect binaries does not exist; this is confirmed by the fact that the positive duplicity detection has been obtained for two stars which are not the brightest, nor the nearest objects (see V and π values in Table 4) and not even those observed under the best conditions. We cannot guess which observing approach, direct imaging or spectroscopy, is more suitable for duplicity detection; only coordinated efforts using different observational techniques will be efficient in revealing new binaries which produce a composite spectrum.

8. Conclusions

We performed a search of duplicity among λ Boo candidates using the speckle camera of the Galileo telescope. We have been able to confirm the separation and Δm for two of the program stars; for the others we were able to place stringent upper limits on the separation of a possible companion. The use of this instrumentation is promising mainly because it allows the determination of both separation and Δm, which is not always possible by the speckle approach. Due to the poor weather conditions we were not able to assess if the theoretical diffraction limit may be actually achieved nor could we establish the limiting magnitude and maximum Δm for successful binary detection.

Although we have shown that the speckle camera can work even under bad weather conditions, the observations would greatly benefit from a good seeing. In such conditions, the speckle camera should allow to reach an angular resolution which is almost an order of magnitude better than that obtained by classical ground based instruments and comparable with that of space instrumentation.

Acknowledgements. We thank the Referee, Dr. Y. Y. Balega, for the useful suggestions and for pointing out a serious error in the first version of the manuscript. We also thank Dr. R. Ragazzoni for the useful discussions of the results and Dr. A. Ghedina for the invaluable support during the observations.

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