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Reality and the speckle imaging of stellar surfaces – II. The asymmetry of Alpha Orionis

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ABSTRACT

Bispectrum image reconstructions of the red supergiant Alpha Orionis, based upon CCD observations made with the 4.2-m William Herschel Telescope in 1995 January, are presented, and the statistical significance of asymmetries across the stellar disc established at better than 99 per cent certainty. Asymmetry is present in at least two wavebands, although the statistical evidence is stronger in the continuum than within a TiO absorption band. The asymmetry may be interpreted as being due to the presence of a bright feature contributing some 15–20 per cent of the total observed disc brightness. Ambiguities present in simple limb-darkened model fits to the power spectrum are shown, and the allowed range of limb-darkening coefficients and disc diameters is given.

Key words: methods: statistical – techniques: interferometric – stars: individual: α Ori – supergiants.

1 INTRODUCTION

We apply here the methods of Klückers & Edmunds (1996, hereafter Paper I) to observations made of Alpha Orionis with the William Herschel Telescope (WHT), and establish firm evidence of asymmetry which we interpret in terms of a surface feature. Statistical significance is established by testing against simulated image reconstructions and bispectra of a circularly symmetric, plain, limb-darkened disc generated under similar observing conditions to those recorded during the real observations.

2 OBERVATIONS OF ALPHA ORIONIS

The observations of Alpha Orionis were obtained at the Ground-Based High Resolution Imaging Laboratory (GHRIL) at the WHT, during the nights of the 1995 January 19 and 20. The stellar image obtained at the Nasmyth focus was magnified by a factor of 10 and refocused upon a Tektronics TK512 CCD. The use of a CCD was favoured because of its intrinsic linearity, in contrast to previous investigations using non-linear photon counters where there have reputedly been severe problems due to the adverse response of image-reconstruction algorithms to non-linearities in the data. Also, reasonably low-noise CCDs are now available with fast readout, making them very suitable for this kind of application. Observations were made at two wavelengths, 6853 and 6709 Å, which correspond to continuum and TiO bandhead bandpasses, respectively. Both filters had a bandwidth of 15 Å.

The speckle image frames recorded were 200×200 pixel in size, with an exposure time of 30 ms, and were stored at a rate close to 1 frame per second. Tests performed on the CCD prior to the observations confirmed the high linearity of this instrument. Readout noise was relatively low (given the readout rate), being estimated at $\sim 30e^-$.

Speckle images of a calibration star α Canis Minoris (Procyon) were collected with a cycle of observations between the primary object, Alpha Orionis, and the calibration star rotated over a 35-min period – 15-min observation of each object, corresponding to 1000 images each, with a total of around 5-min acquisition time.

The image-scale at the CCD was 11.54 ± 0.15 mas pixel^{-1}, which corresponds to a resolution oversampling factor of close to 3 at the wavelengths observed. The average seeing disc recorded during the observations was around half an arcsecond. There was no need to correct for the effects of atmospheric dispersion, which was calculated to have negligible effect for these narrow bandwidths and the particular observing elevations recorded. The Nasmyth image rotator corrected for any field rotation during observations. The images were bias-subtracted and flat-fielded in the conventional manner.

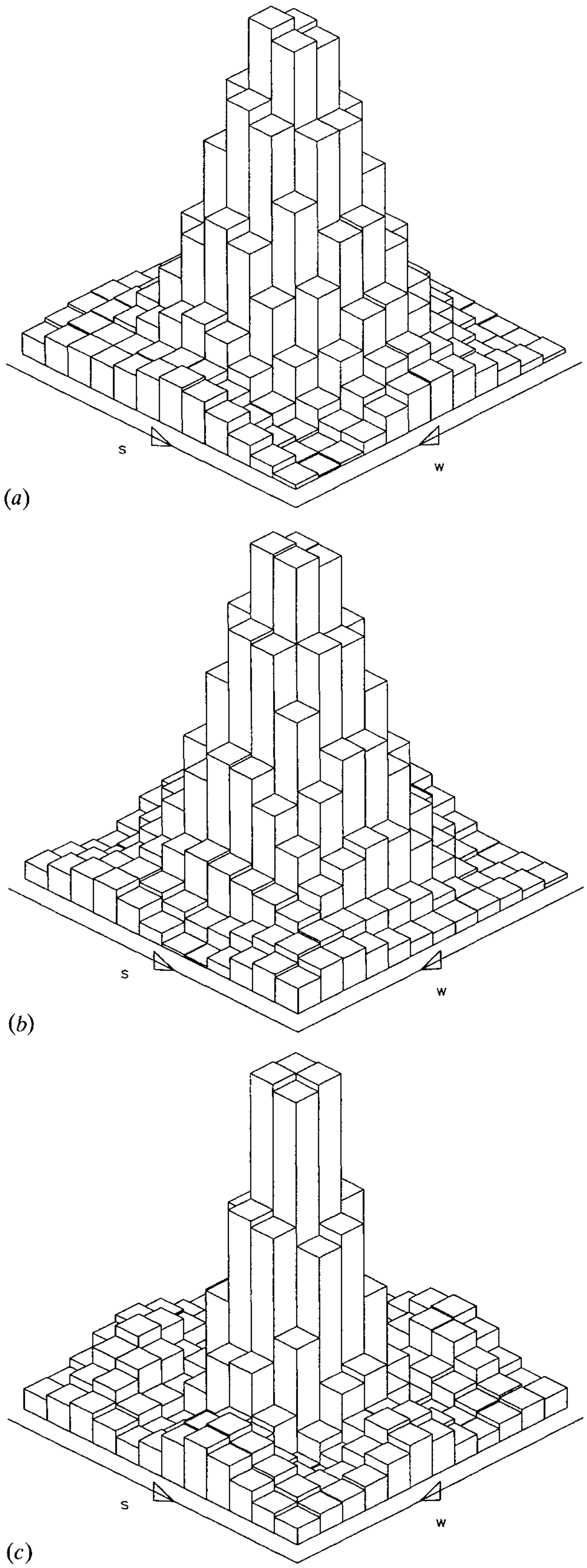

Figure 1. Three-dimensional perspective plot of the reconstructed image of (a) Alpha Orionis at 6853 Å, (b) Alpha Orionis at 6709 Å and (c) the unresolved reference star Alpha CMi. North is to the back and east to the right, and the pixel size is 11.5 mas.

3 STATISTICAL TESTING OF IMAGE RECONSTRUCTIONS OF ALPHA ORIONIS

From the data collected over the two nights of observations at the WHT, two image reconstructions of Alpha Orionis were obtained using the bispectrum phase recovery method. Image 1 was obtained at 6853 Å, by averaging two reconstructed images each of which had been obtained using 1000 speckle frames of Alpha Orionis and the same number of the calibration star. Image 2 was obtained at 6709 Å in the same way. These bispectrum image reconstructions of Alpha Orionis, suitably centroided, are shown in Figs 1(a) and (b). A reconstruction of the (unresolved) reference calibration star is shown in Fig. 1(c). As can be seen, the Alpha Orionis images are clearly resolved compared with the calibration star, and both images of the red giant show deviations from circular symmetry. The statistical significance of this asymmetry will now be examined, using the methods of Paper I.

3.1 Null-hypothesis test cases

Using a plain limb-darkened stellar disc model (as discussed in Section 2 of Paper I), the estimated power spectra of Alpha Orionis obtained at the two wavebands were modelled by varying only the apparent diameter, θ_*, and the linear limb-darkening coefficient, μ, as given in the equation

$$I(r, \mu) = I_o[1 - \mu + \mu \cos(\pi r/2R_*)], \tag{1}$$

where I_0 is the central stellar disc intensity, μ is the linear limb-darkening coefficient and R_* is the stellar radius, where θ_* is effectively $2R_*$ (Grey 1976).

Table 1 gives the best-fitting values of the model parameters, and in Fig. 2 we show the possible range of fits. The asymmetry we establish later may slightly influence these values, but the effect is probably small because (i) the level of asymmetry is relatively small and (ii) the fits are performed to a *rotationally averaged* power spectrum. The low-frequency spectra may also be 'contaminated' by the effect of an extended circumstellar envelope around Alpha Orionis. For this reason, in the modelling of the power spectra, emphasis was given to the mid-high-frequency regions which appear to be well defined. It must be noted that due to the low resolution available, the two sets of parameters given in Table 1 characterize model stellar discs which appear to be very similar within the Fourier plane – i.e. a small, almost uniform disc and a larger, heavily limb-darkened disc. Even so, however, an increase in the spatial extent of Alpha Orionis from the continuum (6853 Å) to the

Table 1. Apparent angular diameter and linear limb-darkening coefficient parameters, θ_* and μ, obtained from line fits to the power spectra of Alpha Orionis.

	Image 1 (6853Å)	Image 2 (6709Å)
θ_*	56 mas	70 mas
μ	0.1	0.9

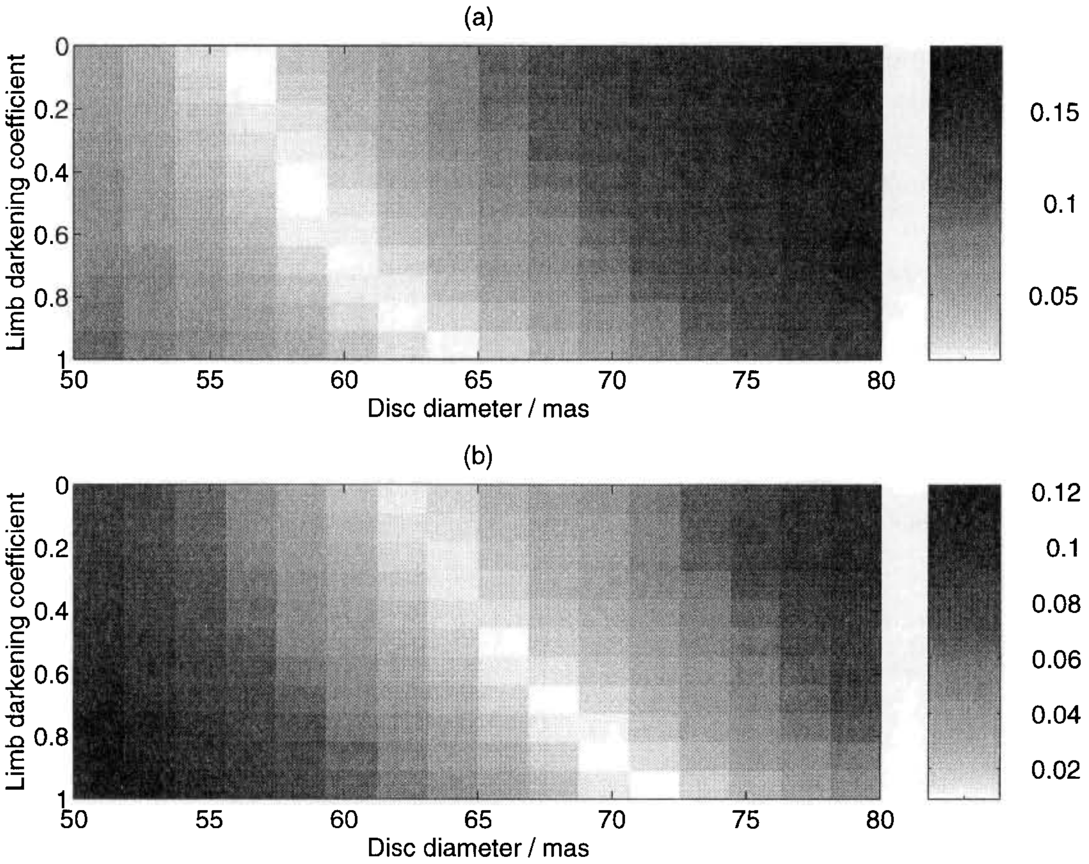

Figure 2. Model fits to stellar disc diameter and linear limb-darkening coefficient (a) at 6853 Å and (b) at 6709 Å. The numerical values correspond to the rms error of the model fit to the rotationally averaged observed power spectrum.

TiO bandhead at 6709 Å does appear to have been identified, as is clearly visible between Figs 2(a) and (b), and as is expected from stellar atmosphere models (Scholz & Takeda 1987).

For the purposes of testing the statistical significance of the apparent asymmetries within the image reconstructions of Alpha Orionis, we adopt the values of the model parameters given in Table 1 for 6853 Å as the form of the null-hypothesis test object for both Image 1 and Image 2. Any differences between the limb-darkening and the radius at the two wavelengths are sufficiently small to cause negligible error in the asymmetry testing at the level of resolution available.

Table 2 gives the various observing criteria that were applied to the simulated null-hypothesis image reconstructions. The difference in both the mean and standard deviation value of Fried's parameter, r_0, between the observations of Alpha Orionis and the comparison star was small enough to be neglected, and Fig. 3 shows an example of the distribution of the estimated values of r_0 during a typical observation.

Table 2. Simulated observing criteria applied to the null-hypothesis image reconstructions.

Pupil plane sampling	4.8 cm pix^{-1}	
Telescope diameter	4.2m	
Telescope resolution limit	37.0 mas	
Image plane sampling	11.5 mas pix^{-1}	
Oversampling factor	3.2	
Object	Alpha Orionis	Calibration star
No. of speckle frames	1000	1000
Fried's parameter, r_0	22 cm	22 cm
σ_{r_0}	3 cm	3 cm
Photon count frame^{-1}/10^5	4.0	1.9
σ_{ccd}/e^-	30	30

3.2 Statistical significance of asymmetry

We test for asymmetry in two ways. For the first method, 30 image reconstructions of the null-hypothesis object were generated. As explained fully in Paper I, the *asymmetry measure*, $\mathscr{E}_A(x,y)$, of each pixel within the central 4 × 4 array of each image reconstruction is calculated by dividing the array by its rotationally averaged values. By considering all of the simulated images, the standard deviation of each $\mathscr{E}_A(x,y)$ can be found and these values are combined to obtain a single standard deviation value for each pixel group within this region, $\sigma_{,A}$, (as defined in Paper I). For the null-hypothesis data sets here (for 1000 frames),

$$\sigma_{g=1,3} = [1.0\%, 2.0\%, 2.0\%]. \quad (2)$$

The two available independent image reconstructions of Alpha Orionis at each wavelength have been averaged, and the σ_g values (equation 2) scaled accordingly (i.e. divided by

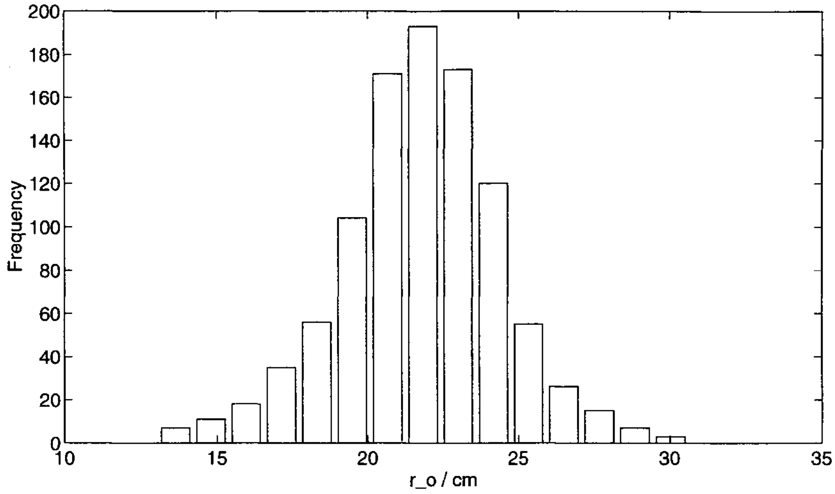

Figure 3. Distribution of the estimated r_b values during a typical 15-min observation.

Table 3. Asymmetry measure values for Image 1 (6853 Å), expressed as a factor of σ_g – the corresponding null-hypothesis pixel group standard deviations.

+7.1	+3.7	-0.3	-2.2
+4.4	+4.9	-1.1	-2.4
+0.2	-0.1	-3.7	-2.8
-3.4	-1.3	-1.5	-1.5

Table 4. Asymmetry measure values for Image 2 (6709 Å), expressed as a factor of σ_g – the corresponding null-hypothesis pixel group standard deviations.

+2.1	+2.4	+0.2	-1.2
+1.3	+2.8	-2.1	-2.0
+0.3	+1.7	-2.5	-2.0
+0.1	+0.5	-0.7	-1.0

$\sqrt{2}$), as justified in Paper I. The asymmetry measure values within the central 4×4 array of the centroided image reconstructions of Alpha Orionis divided by the pixel group standard deviations from the null-hypothesis case, σ_g, associated with each pixel element are shown in Tables 3 and 4 for the two wavelength regions. Table 3 shows clear evidence of significant asymmetry – with excess flux in the north-west segment. The deviation of the brightest central pixels implies over a 4σ significance, and the global pattern of the sign of deviation is clear. This implies that we have confidence in the existence of an asymmetry across the disc of Alpha Orionis at better than the 99 per cent level. In Table 4, the asymmetry is again apparent, and in the same direction, but with rather lower significance (2σ to 3σ within each pixel).

Using the granulation models of Paper I, it has been found that a single, circularly symmetric spot, contributing 18 ± 3 per cent to the total observed stellar flux and with a FWHM diameter of $(0.5 \pm 0.1)\, R_*$, can fit the observed asymmetry of Image 1 to within 1σ per pixel. A fully resolved version of this model is shown in Fig. 4. We emphasize that this represents an example solution only, since at these resolution levels the data does not necessarily exclude either asymmetric or multiple-spot configurations. A second method of testing for asymmetry avoids the whole apparatus of image reconstruction, centroiding and definition of pixel groups. This is to test the bispectrum phases – or rather, as explained in Paper I, a high signal-to-noise ratio subset of

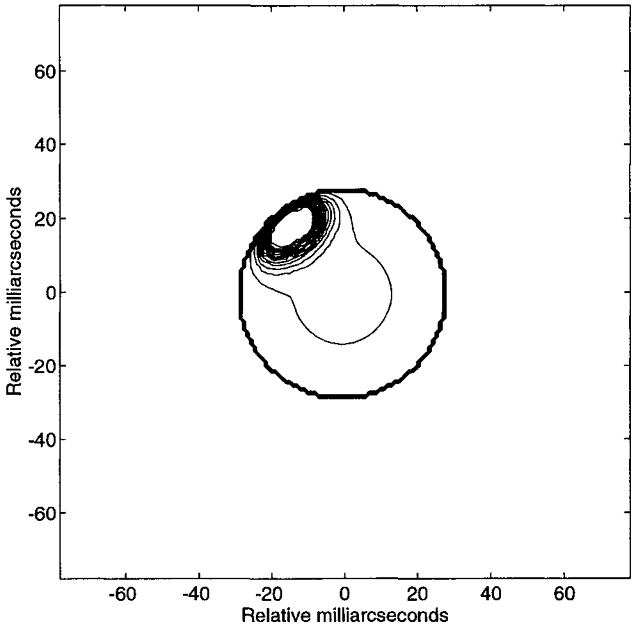

Figure 4. An example single-spot solution for the asymmetry apparent within Image 1. The feature contributes 18 per cent to the total observed stellar flux and has an FWHM diameter of $0.5R_*$. The stellar disc diameter is 56 mas and the linear limb-darkening coefficient is 0.1. North is up and east is to the right. Contour lines are at intervals of 4 per cent the peak brightness.

the phases. For this the standard deviation, $\sigma_\beta(\boldsymbol{u},\boldsymbol{v})$, of each bispectrum phase element selected, $\beta(\boldsymbol{u},\boldsymbol{v})$, is calculated in the simulation, and used in comparison with those bispectrum phase elements obtained from the observed Alpha Orionis data. Fig. 5(a) shows a histogram of the Alpha Orionis bispectrum phase values for Image 1 divided by their associated $\sigma_\beta(\boldsymbol{u},\boldsymbol{v})$ values. As can be seen a significant number of these elements have a value very much larger than the standard deviation for these elements, clearly indicating the reality of the asymmetry apparent within the reconstructed image of Alpha Orionis. For comparison, Fig. 5(b) shows a histogram of the *simulated* bispectrum phase data also divided by the standard deviation values. Although, as one would expect, the effect of the various sources of noise has resulted in a number of phase elements taking non-zero values, the spread of this distribution is much less marked than that for Fig. 5(a).

4 CONCLUSIONS

Two bispectrum image reconstructions of the red supergiant Alpha Orionis have been presented and the statistical

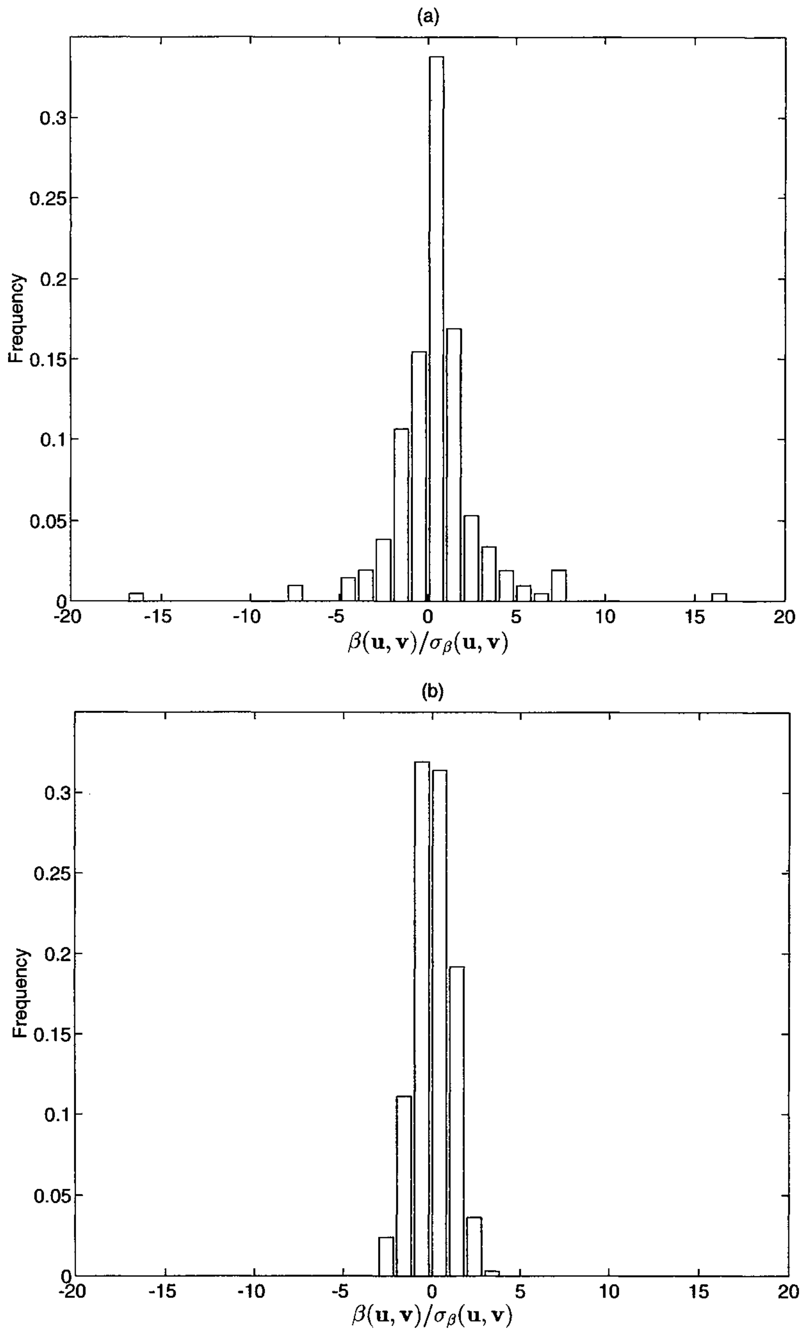

Figure 5. (a) The probability distribution of the selected bispectrum phases, $\beta(\boldsymbol{u},\boldsymbol{v})$, of the Image 1 data expressed as a multiple of the standard deviation of the bispectrum phase as calculated from the simulations, $\sigma_\beta(\boldsymbol{u},\boldsymbol{v})$. (b) For comparison, the probability distribution of the selected bispectrum phases of the simulated data also expressed as a multiple of their associated standard deviation. Both distributions have been normalized to unit area.

significance of the apparent asymmetries across the stellar disc have been tested. For the image obtained within the continuum waveband at 6853 Å, a statistically significant asymmetry could be established. The asymmetry is also present (at a somewhat lower level) in the image within a TiO bandhead at 6709 Å. A single hotspot accounting for 15–20 per cent of the total brightness of the disc could explain our observations.

We suggest that the null-hypothesis of no asymmetry across the disc of Alpha Orionis at 6853 Å can be rejected with at least 99 per cent confidence. Further observation and monitoring of time-varying resolved structure on Alpha Orionis will be worthwhile. The potential for speckle image reconstruction (and resolution of structure) on Betelgeuse will be greatly enhanced by the advent of 8-m telescopes, where statistical testing of details of the surface features will be possible. Faster readout low-noise cameras are certainly possible, and will allow high-accuracy reconstructions from only a few minutes worth of data.

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