ASYMMETRIC SURFACE BRIGHTNESS DISTRIBUTION OF ALTAIR OBSERVED WITH THE NAVY PROTOTYPE OPTICAL INTERFEROMETER

NAOKO OHISHI  
National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan; naoko.ohishi@nao.ac.jp

TYLER E. NORDGREN  
Department of Physics, University of Redlands, 1200 East Colton Avenue, Redlands, CA 92373

AND

DONALD J. HUTTER  
US Naval Observatory, Flagstaff Station, P. O. Box 1149, Flagstaff, AZ 86002-1149  
Received 2004 March 28; accepted 2004 May 5

ABSTRACT

An asymmetric surface brightness distribution of the rapidly rotating A7 IV–V star Altair has been measured by the Navy Prototype Optical Interferometer (NPOI). The observations were recorded simultaneously using a triangle with long baselines of 30, 37, and 64 m, on 19 spectral channels, covering the wavelength range of 520–850 nm. The outstanding characteristics of these observations are (1) high resolution with the minimum fringe spacing of 1.7 mas, easily resolving the 3 mas stellar disk, and (2) the measurement of the closure phase, which is a sensitive indicator of the asymmetry of the brightness distribution of the source. Uniform-disk diameters fitted to the measured squared visibility amplitudes confirm Altair’s oblate shape due to its rapid rotation. The measured observables of Altair showed two features that are inconsistent with both the uniform-disk and limb-darkened–disk models, while the measured observables of the comparison star, Vega, are consistent with the limb-darkened–disk model. The first feature is that measured squared visibility amplitudes at the first minimum do not reach zero but rather remain at $\approx 0.002$, indicating the existence of a small bright region on the stellar disk. The other is that the measured closure phases are neither $0^\circ$ nor $180^\circ$ at all spectral channels, which requires an asymmetric surface brightness distribution. We fitted the measured observables to a model with a bright spot on a limb-darkened disk and found that the observations are well reproduced by a bright spot, which has relative intensity of $4.7\%$, on a $3.38$ mas limb-darkened stellar disk. Rapid rotation of Altair indicates that this bright region is a pole, which is brighter than other part of the star owing to gravity darkening.

Subject headings: stars: individual (Altair) — stars: rotation — techniques: high angular resolution — techniques: interferometric

1. INTRODUCTION

The effect of stellar rotation on fundamental stellar parameters was originally calculated by von Zeipel (1924). He showed that the stellar radius and the surface brightness are expressed as functions of the latitude; the radius increases and the brightness decreases from the pole to the equator. The first attempt to determine the stellar oblateness owing to rapid rotation was performed with the intensity interferometer at Narrabri (Hanbury Brown et al. 1967). Although these authors mentioned the possibility of a rotationally flattened shape for Altair, their data were insufficient to decide the oblateness critically. In 2001, van Belle et al. (2001) observed Altair using two baselines of the Palomar Testbed Interferometer (PTI; Colavita et al. 1999). They calculated the apparent stellar angular diameters from measured squared visibility amplitudes using the uniform-disk model and found that the angular diameters change with position angle. This was the first measurement of stellar oblateness owing to rapid rotation. They evaluated the effect of the surface brightness distribution caused by gravity darkening on their angular diameter data. Because their simulation showed that the diameters changed by only a few percent, they neglected the gravity-darkening effect. In 2003, the large oblateness of the Be star Achernar was measured with the Very Large Telescope Interferometer (VLTI; Domiciano de Souza et al. 2003). The authors analyzed the measured deformation with the Roche model, which takes the surface brightness distribution owing to gravity darkening into account, but the deformation was too large to be explained within the range of the model. Although measurements at both the PTI and the VLTI demonstrated that stellar parameters, such as orientation of the rotation axis and the apparent oblateness, can be determined from the squared visibility amplitudes, the effect of surface brightness distribution was not determined.

Because of the rapid rotation of Altair, where apparent rotational velocities range from $v \sin i = 190$ km s$^{-1}$ (Carpenter et al. 1984) to 250 km s$^{-1}$ (Stoeckley 1968), this star is expected to be gravity-darkened. However, the effects of the stellar surface brightness distribution on squared visibility amplitudes are small at low resolution before the first minimum. For example, the effect of limb darkening on visibilities becomes more significant after the first minimum. Consequently, in order to discuss the surface brightness distribution of rapidly rotating stars, it is indispensable to have high-resolution measurements at least over the first minimum. In 2001, the Navy Prototype Optical Interferometer (NPOI) achieved an array configuration (see § 2) that for the first time allowed for observations with a baseline as long as 64 m. With this long baseline and visible observing wavelength, the minimum fringe spacing becomes as small as 1.7 mas at the sky position of Altair. This resolution is high enough to observe this $\approx 3$ mas...
star well over the first minimum. Moreover, the NPOI is equipped with a system that enables measurement of closure phase, in addition to the squared visibility amplitudes since 1996 (Benson et al. 1997). Closure phase is a measure sensitive to the asymmetry of the brightness distribution of a source. If the gravity-darkened stellar disk is seen neither equator-on nor pole-on, the intensity distribution of the source projected on a baseline will be asymmetric. Thus, the measurement of the closure phase is useful for determining the inclination of the pole-on, the intensity distribution of the source projected on a baseline will be asymmetric. Consequently, we expect that observations of Altair with the NPOI will provide better information than earlier observations for examining the surface brightness distribution of this rapidly rotating star.

Observations were done for four nights between May 25 and June 1 of 2001, using NPOI baselines of 30, 37, and 64 m. We examine the apparent stellar diameters, reduced using a uniform-disk model, and discuss the surface brightness distribution of this star. We used all 19 scans of Altair because that star does not pass through the region close to the zenith. We also used all data of ζ Aql, and the number of scans of this star during four nights was 24.

ζ Aql was used to calibrate the measured observables of both Altair and Vega. The uniform-disk diameter of this calibration subarray one of which (W7) was in the imaging subarray. In this paper, we state the baselines as follows: OB1 (AW-AE), OB2 (W7-AW), and OB3 (AE-W7). The arrangement and the length of each baseline are shown in Table 1.

We observed Altair for four nights, May 25–27 and June 1, in 2001 and obtained 19 scans (Hummel et al. 1998) of data. Details of the observations are shown in Table 2. Interspersed with the observations of Altair were observations of the calibration star, ζ Aql, and a comparison star, α Lyr (Vega). We chose Vega as a comparison star because its spectral type, magnitude, and angular size are similar to those of Altair. In addition, Vega is a good comparison when we discuss the oblateness of Altair, because we expect negligible deformation from a circularly symmetric disk, given that its observed rotational velocity is less than 20 km s\(^{-1}\) (Freire Ferrero et al. 1983). During our observations, the measured squared visibility amplitudes of Vega showed dependence on zenith angle when the star passed within 10° of zenith. No such dependence was found outside this region. Consequently, we removed data of Vega with zenith angle smaller than 10°. Fourteen scans of Vega remained after this selection. We used all 19 scans of Altair because that star does not pass through the region close to the zenith. We also used all data of ζ Aql, and the number of scans of this star during four nights was 24.

### Table 1

Arrangement of Three Baselines Used for Observation

| Baseline | Station | \(E\) (m) | \(N\) (m) | \(Z\) (m) | Length (m) |
|----------|---------|-----------|-----------|-----------|------------|
| OB1...... | AW-AE   | −37.379245| −2.60124  | 0.000314  | 37.46964647|
| OB2...... | W7-AW   | −23.813216| −17.49076 | −0.080794 | 29.54661519|
| OB3...... | AE-W7   | 61.192461 | 20.092    | 0.08048   | 64.40661631|

### Table 2

Observation Table for Altair

| Date       | Scan | Hour Angle (hr) | P. A. (deg) | UDD (mas) | P. A. (deg) | UDD (mas) | P. A. (deg) | UDD (mas) |
|------------|------|----------------|-------------|-----------|-------------|-----------|-------------|-----------|
| May 25..... | Pt 81 | −0.470         | 182.5       | 3.10      | 211.6       | 3.23      | 195.2       | 3.16      |
|            | Pt 84 | −0.318         | 182.8       | 3.01      | 212.1       | 3.16      | 195.6       | 3.18      |
|            | Pt 87 | −0.167         | 183.2       | 2.99      | 212.7       | 3.12      | 196.0       | 3.20      |
|            | Pt 90 | −0.017         | 183.5       | 2.97      | 213.4       | 3.09      | 196.4       | 3.19      |
|            | Pt 93 | 0.132          | 183.9       | 3.08      | 214.1       | 3.17      | 196.8       | 3.15      |
|            | Pt 97 | 0.629          | 185.5       | 3.16      | 216.0       | 3.32      | 199.3       | 3.18      |
|            | Pt 100| 0.827          | 185.6       | 3.16      | 218.0       | 3.32      | 199.3       | 3.18      |
| May 26..... | Pt 30 | −0.242         | 182.0       | 3.04      | 212.4       | 3.20      | 195.8       | 3.17      |
|            | Pt 35 | 0.208          | 184.1       | 2.91      | 214.4       | 3.13      | 197.1       | 3.18      |
|            | Pt 38 | 0.775          | 185.5       | 3.20      | 217.6       | 3.44      | 199.1       | 3.19      |
| May 27..... | Pt 23 | −0.967         | 181.4       | 3.15      | 210.0       | 3.25      | 194.1       | 3.17      |
|            | Pt 30 | −0.484         | 182.5       | 3.14      | 211.5       | 3.25      | 195.2       | 3.14      |
|            | Pt 35 | −0.146         | 183.2       | 3.03      | 212.8       | 3.18      | 196.0       | 3.21      |
|            | Pt 39 | 0.142          | 183.9       | 3.08      | 214.1       | 3.28      | 196.9       | 3.18      |
|            | Pt 44 | 0.475          | 184.7       | 3.27      | 215.8       | 3.54      | 198.0       | 3.17      |
| Jun 1...... | Pt 14 | −1.041         | 181.2       | 3.18      | 209.8       | 3.26      | 194.0       | 3.12      |
|            | Pt 19 | −0.726         | 181.9       | 3.09      | 210.7       | 3.31      | 194.6       | 3.15      |
|            | Pt 24 | −0.410         | 182.6       | 3.06      | 211.8       | 3.23      | 195.3       | 3.17      |
|            | Pt 29 | −0.120         | 183.3       | 3.03      | 212.9       | 3.23      | 196.1       | 3.16      |

* Position angle, P. A., is east of north. For OB3, 180° are added. UDD is uniform disk diameter.
star is computed as 0.80 mas from its observed color and magnitude (Mozurkewich et al. 1991). This value is also used in other observations (Nordgren et al. 1999). Although the size of the star, 0.80 mas, is small compared with that of Vega and Altair, the star is partly resolved with the longest baseline; measured with the full 64.4 m baseline, its squared visibility amplitudes become about 0.7 for a perfect interferometer. Because $\zeta$ Aql is a rapidly rotating star, with $v \sin i \sim 320$ km s$^{-1}$ (Royer et al. 2002), we examined the possibility that using this star as a circular disk with a diameter of 0.80 mas biases the results for Vega and Altair. We evaluated the effect of rotation as 5% changes in diameter and 5% asymmetric brightness distribution on the star owing to gravity darkening. At the longest baseline, we found that these features change the squared visibility amplitudes by about 6% and the phase by about $3^\circ$ at most. The calculated possible errors of the squared visibility amplitudes and phase were at almost the same level as the measurement errors, which are described in § 2.2. Consequently, the effect of the rapid rotation of the calibration star is not critical to our result, but we need to be careful when we reduce precise physical parameters directly from measured observables.

Because the signal-to-noise ratio of the measured visibilities decreases as the wavelength becomes shorter, we used only the 20 reddest of the 32 spectral channels, thus covering wavelengths from 520 to 850 nm. The raw squared visibility amplitudes of the calibration star depend on the channels and baselines. The highest raw $V^2$ was 0.71 $\pm$ 0.04, at the reddest channel of OB2 ($V^2$ for a perfect interferometer on a 0.8 mas star is 0.96), and the lowest raw $V^2$ was 0.13 $\pm$ 0.01, at the bluest channel of OB3 ($V^2$ for a perfect interferometer on a 0.8 mas star is 0.6). We also removed the data obtained at the spectral channel with wavelength $\lambda = 633$ nm, because this channel contains light from the NPOI’s He-Ne metrology laser. One detector for OB3 was not available during our observations, and one other did not work on 2001 June 1. Consequently, there were 19 spectral channels $\times$ 19 scans = 361 squared visibility amplitudes on OB1 and OB2 and 18 spectral channels $\times$ 15 scans + 17 spectral channels $\times$ 4 scans = 338 squared visibility amplitudes on OB3, triple amplitudes, and closure phases. The total number of data was (361 $\times$ 2) + (338 $\times$ 3) = 1738.

2.1. Detector Dead-Time Correction

Before calibrating the measured observables, we corrected the effect of detector dead time. When we observe bright stars such as Altair and Vega, the effect of detector dead time, $t_d$, is not negligible. The dead time of the detectors used at the NPOI is approximately 200 ns. The number of photons counted per unit cycle (500 Hz) at the detectors of the red spectral channels becomes about 800 in the case of Vega; one photon is detected per approximately 2.5 $\mu$s. In such a case, the number of photons counted at the detectors becomes less than the number of incident photons, and the response of the detector becomes nonlinear. This is a well-known effect, and we calculate the actual photon count rate, $CR_a$, using measured photon count rate, $CR_m$, as follows:

$$CR_a = \frac{CR_m}{1 - t_d CR_m}.$$  

Here the count rate is the number of photons counted per second.

We calculated the actual visibility $|V_a|$, using the measured visibility $|V_m|$ as follows:

$$|V_a| = \frac{|V_m|}{1 - t_d CR_m (1 - |V_m|^2)}.$$  

This correction changed the squared visibility amplitudes of Vega up to 20%. In this paper, we treat the detector dead-time correction as described above. Triple amplitudes are also corrected using equation (2).

2.2. Measurement Errors

The statistical errors of measured quantities are calculated and recorded for each scan. However, actual measurement errors are sometimes dominated by long-term errors, rather than by statistical errors within short-term measurements (Wittkowski et al. 2001). Generally, it is not easy to evaluate long-term systematic errors. In this paper, we calculate the variance of calibrated quantities, $\sigma^2_{\text{cal}}(t_i, \lambda_j)$, for the calibration star as long-term errors and the estimated errors of measured squared visibility amplitudes, $\sigma^2_{\text{vs}}(t_i, \lambda_j)$, as follows:

$$\sigma^2_{\text{vs}}(t_i, \lambda_j) = \sigma^2_{\text{vstat}}(t_i, \lambda_j) + \sigma^2_{\text{vcal}}(\lambda_j)$$

$$= \frac{\sigma^2_{\text{vstat}}(t_i, \lambda_j)}{\left| V(t_i, \lambda_j) \right|^2} \times \frac{\sum_{j=0}^{N-1} \left| V_{\text{cal}}(t_i, \lambda_j) \right|^2}{N}.$$  

Here $t_i$ is the time at the $i$th scan, $\lambda_j$ is the wavelength at the $j$th spectral channel, $\sigma^2_{\text{vstat}}(t_i, \lambda_j)$ is the statistical error, $\sigma^2_{\text{vcal}}(\lambda_j)$ is the calibrated squared visibility amplitude of the source, $|V(t_i, \lambda_j)|^2$ is the calibrated squared visibility amplitude of the calibration star, and $N$ is the number of scans. We also estimated the measurement errors of triple amplitudes as in equation (4).

$$\sigma^2_{\text{cp}}(t_i, \lambda_j) = \sigma^2_{\text{cpstat}}(t_i, \lambda_j) + \sigma^2_{\text{pcal}}(\lambda_j).$$  

The ratios of the errors calculated using equations (3) and (4) to the statistical errors were 4.8 (for the squared visibility amplitudes at OB1), 15.4 (for those at OB2), 1.4 (for those at OB3), 2.7 (for triple amplitudes), and 1.1 (for closure phases). This means that the measurement errors of these observations are nearly dominated by the long-term errors, rather than by the short-term statistical errors. Even if the measurement errors are dominated by the long-term errors, it is confirmed that data obtained at NPOI show no systematic error compared with data obtained at other interferometers (Nordgren et al. 2001).

3. RESULTS

The squared visibility amplitudes on three baselines, the triple amplitudes, and the closure phases on about 19 channels were obtained simultaneously for each scan in our observation. The visibility measured at a projected baseline, $B_p$, of a stellar interferometer, which is the Fourier transform of the brightness distribution of the source, is written as follows:

$$V(kB_p) = \frac{\int I(x) \exp(-ikB_px) \, dx}{\int I(x) \, dx},$$  

where $I(x)$ is the brightness distribution projected to the baseline and $k = 2\pi/\lambda$ is the wavenumber. For example, the
The visibility of the uniform disk with an angular radius of $r_{UD}$ is written as follows:

$$V_{UD}(r_{UD}) = \frac{2J_1(kB_{pUD}r_{UD})}{kB_{pUD}}.$$  \hspace{1cm} (6)

The visibility of the limb-darkened disk with an angular radius of $r_{LD}$ and a linear limb-darkening coefficient of $u(k)$ is written as follows:

$$V_{LD}(r_{LD}) = \frac{6}{3 - u(k)} \left\{ 1 - u(k) \frac{2J_1(kB_{pLD}r_{LD})}{kB_{pLD}} \right\} + u(k) \sqrt{\frac{x}{2}} \left( \frac{kB_{pLD}r_{LD}}{x} \right)^{3/2}. \hspace{1cm} (7)

(Quirrenbach et al. 1996).

The triple product is the product of the visibilities on three baselines that form a triangle:

$$V_{TP} = |V_1| \exp(-i\Phi_1)|V_2| \exp(-i\Phi_2)|V_3| \exp(-i\Phi_3). \hspace{1cm} (8)$$

The triple amplitude is the absolute value of the triple product,

$$|V_{TP}| = |V_1||V_2||V_3|,$$  \hspace{1cm} (9)

and the closure phase is the phase of the triple product,

$$\Phi_c = \Phi_1 + \Phi_2 + \Phi_3.$$  \hspace{1cm} (10)

As we can see from equation (5), if the brightness distribution of the source projected to a baseline, $l(x)$, is symmetric with $x$, the imaginary part of the visibility is zero, and the phase of the visibility is 0° or 180°. If the brightness distribution of the source is asymmetric, the imaginary part of the visibility becomes nonzero, and the phase is neither 0° nor 180°. Generally, it is not easy to measure the phase of visibility with a ground interferometer because of atmospheric turbulence. However, the closure phase cancels the effect of atmospheric turbulence, and so source information is obtainable. Consequently, the closure phase is a useful interferometric observable for discussing the asymmetry of the brightness distribution of the source.
3.1. Measured Squared Visibility Amplitudes, Triple Amplitudes, and Closure Phases

Vega was chosen as a comparison star because of its similarities in size, spectral type, and magnitude to Altair, but it lacks the high observed rotational velocity that would lead to apparent oblateness. Figure 1 shows the squared visibility amplitudes and the triple products measured during the night of 2001 May 25 for Vega. Figure 2 shows the observables for Altair measured on the same night. The dashed lines show the uniform-disk model with fitted angular diameters of $2\alpha_{UD} = 3.17$ mas for Altair and 3.11 mas for Vega. The solid lines show the limb-darkened–disk model with fitted angular diameters of $2\alpha_{LD} = 3.32$ mas for Altair and 3.22 mas for Vega. In order to calculate the limb-darkened model, we used linear limb-darkening coefficients calculated by Van Hamme (1993) with the parameters $T_{eff} = 7750$ K and $\log g = 4.0$, for Altair, and $T_{eff} = 9500$ K and $\log g = 4.0$, for Vega.

The measured observables of Vega are better fitted with the limb-darkened model ($\chi^2 = 7.5$) than with the uniform-disk model ($\chi^2 = 17.2$). The limb-darkened–disk diameter of Vega, measured at the PTI, was 3.28 ± 0.01 mas (Ciardi et al. 2001), and the diameters are consistent with about 2% error. However, Altair was not well fitted with either the uniform-disk model ($\chi^2 = 150$) or the limb-darkened model ($\chi^2 = 154$). Altair’s large inconsistency between the measured observables and models is mainly owing to the fact that (1) the squared visibility amplitudes at OB3 and the triple amplitudes around the first minimum do not decrease to zero and that the closure phases are neither 0° nor 180° at all spectral channels. In addition, the measured squared visibility amplitudes at OB1 are slightly bigger than those for the circular
uniform disk model, while those at OB2 are slightly smaller than the model’s. The discrepancies of measured squared visibility amplitudes and triple amplitudes from the model around the first minimum indicate that there is a small, bright component on the stellar disk, which is not resolved even with the longest baseline. A closure phase of neither 0° nor 180° means that the brightness distribution of the source is asymmetric.

3.2. Apparent Stellar Diameters Reduced from the Uniform-Disk Model

Before considering the discrepancy from the uniform-disk model, we first examine whether the uniform-disk angular diameter reduced from the squared visibility amplitudes changes with position angle and whether the change is consistent with the PTI result. We consider the diameter change assuming the elliptical shape of the stellar disk. The brightness distribution of a uniform ellipse projected to a baseline with position angle \( \phi \) becomes the same as that of the circular uniform disk with angular radius \( r(\phi) \),

\[
r(\phi) = \sqrt{a^2 \sin^2(\phi - \phi_0) + b^2 \cos^2(\phi - \phi_0)},
\]

where \( a \) is the angular radius at the major axis, \( b \) is the angular radius at the minor axis, and \( \phi_0 \) is the orientation angle of the ellipse on the sky, where \( \phi_0 = 0 \) corresponds to the minor axis pointing to the north on the sky. As a result, the squared visibility amplitude becomes the same as that from equation (6) with the angular radius \( r(\phi) \). Consequently, in order to determine the parameters of the ellipse, we reduce the data using the following procedure: First, calculate the angular diameters at a position angle by fitting the squared visibility of each scan at each baseline with equation (6); then compare the reduced diameters with equation (11). Notice that \( r(\phi) \) is a little different from the intercept of an ellipse at an angle \( \phi \).

Although the errors of the fitted angular diameters are calculated from the errors of the visibilities, we found that the scatter of the diameters were a few times larger than the calculated errors at OB1 and OB2. Thus, we define the errors of the fitted angular diameters in another way. Considering the small change of position angle at each baseline—4° (OB1), 5° (OB2), and 8° (OB3) (Table 2)—during the observation, we regard the change in the angular diameter of the ellipse with position angle as small, compared to the scatter of the fitted angular diameters. We therefore use the variance of the fitted angular diameters at each baseline—0.09 mas (OB1), 0.11 mas (OB2), and 0.02 mas (OB3)—as errors of the fitted angular diameters. The error of the fitted angular diameters on OB3 is smaller than that on OB1 or OB2. We consider this fact as owing to the fact that the measured visibilities cover the first minimum at OB3 and the position of the first minimum improves the precision of the fitted diameters.

Figure 3 shows fitted angular diameters, with a horizontal axis of position angle. The reduced \( \chi^2 \), which is calculated based on the scatter of the diameters of Altair, is 1.5 with the circular uniform disk model. When we allow the diameter of Altair to change with position angle, the reduced \( \chi^2 \) is improved to 0.95. The parameters fitted with equation (11) become \( 2a = 3.31 \pm 0.09 \) mas, \( 2b = 2.93 \pm 0.17 \) mas, and \( \phi_0 = 35° \pm 18° \). In our case, the uniform-disk model estimates the angular diameters of Altair as about 0.14 mas smaller than the limb-darkened model. The resultant parameters, corrected for the limb-darkening effect, are consistent with the PTI result (van Belle et al. 2001): \( 2a = 3.461 \pm 0.038 \) mas, \( 2b = 3.037 \pm 0.069 \) mas, and \( \alpha_0 = 25° \pm 9° \). For comparison with those of Altair, the fitted diameters and errors calculated from the scatters of the fitted diameters on each baseline of Vega are shown in Figure 3. The diameter fitted with the circular uniform-disk model is \( 2r_{\text{UD}} = 3.11 \pm 0.01 \) mas, \( \chi^2 = 1.0 \), and the value of \( \chi^2 \) does not change when we use the elliptical model.

We found that Altair is well explained by the ellipse rather than the circular disk, while Vega is well explained as the circular disk. The dependence of fitted diameters of Altair on the position angle was similar to PTI’s.

3.3. A Small Bright Region on the Limb-darkened Disk

In this section, we examine whether the two features of the measured observables of Altair that are inconsistent with both the uniform-disk and the limb-darkened–disk models are reproduced with the model of a single bright region on the limb-darkened disk. When a bright spot with a relative intensity of \( I_p \) is located at \( (r_p, \phi_p) \), in polar coordinates, on a limb-darkened disk with an angular radius of \( r_s \), the visibility is written as follows:

\[
V_{\text{model}}(I_p, r_s, r_p, \phi_p) = (1 - I_p) V_{\text{LD}}(r_s) + I_p \exp[-ikB_p r_p \cos(\phi - \phi_p)],
\]

With this model, the visibility amplitude at the first minimum becomes \( I_p \). We can see that the value of the squared visibility
amplitudes around the first minimum is about 0.002 and expect that $I_p/\epsilon_{24}$.

Although the existence of a bright spot changes the stellar diameter $2r_s$, we expect that the change of $2r_s$ from $2r_{LD} = 3.32$ mas is small. We searched for the optimal position of the spot ($r_p = 0$, $\Delta r_p = 0.01r_s$, $\phi_p = 0' - 360'$, $\Delta \phi = 1'$) for each set of ($I_p$, $2r_s$) in the range ($I_p = 0.034$–$0.06$, $2r_s = 3.25$–$3.51$ mas). As a result, we found that the set of parameters ($I_p = 0.047$, $r_s = 3.38$ mas) gives the best $\chi^2$, 7.3. The $\chi^2$ value of 7.3 means that this model reproduces the measured observables at the same level as the limb-darkened model for Vega. While $\chi^2$ improved from 1.5 to 0.95 when oblateness was taken into account, $\chi^2$ was improved from 150 to 7.3 by taking into account a bright spot on the circular limb-darkened disk. This means that the surface brightness distribution is more essential than the oblateness for our data. A spot on the circular limb-darkened disk model gives a $\chi^2$ of the squared visibility amplitudes at OB1 and OB2 similar to that from the elliptical limb-darkened–disk model.

Figure 4 shows the $\chi^2$ map as a function of ($I_p$, $2r_s$) and the $\chi^2$ map of ($r_p$, $\phi_p$) at ($I_p = 0.047$, $2r_s = 3.38$ mas). Although the parameters $I_p$ and $2r_s$ converge, $r_p$ and $\phi_p$ are not determined independently.

![Figure 4](image1)

![Figure 5](image2)
These two parameters appear in the second term of equation (12). The equation indicates that a small change of the position angle at OB3 during the observation makes it difficult to determine \( \rho_p \) and \( \phi_p \) independently. Consequently, measurements of this star with a wider range of position angle, or with an additional long baseline located perpendicular to OB3, will be needed to determine the position of the bright region accurately.

4. DISCUSSION

The measured observables are well reproduced with a bright spot on the circular limb-darkened disk model. Because Altair is a single star (van Belle et al. 2001) and is well known as a rapidly rotating star, it is natural to consider that this spot is a bright pole of the gravity-darkened star. Van Belle et al. (2001) simulated the effect of the gravity darkening as a region an additional 25% brighter, covering 20% of the surface of the star on the limb-darkened disk. The relative intensity of the additional bright region is 5%, which is not far from our result of 4.7%. Considering it as a gravity-darkened star, we expect that it is better to take the effect of oblateness, in addition to the surface brightness distribution, into account. Then we replaced \( r_s \) in equation (12) with \( r_s(\phi) \) (eq. [11]) and fitted the measured observables with a model in which a bright spot is on the minor axis of an elliptical limb-darkened disk.

Fixing the relative intensity of the spot, \( I_p = 0.047 \), we searched the optimized set of \( (\rho_p/b, \phi_p) \) for each set of \( (2a = 3.43 - 4.25 \text{ mas}, \Delta 2a = 0.02 \text{ mas}; 2b = 2.96 - 3.45 \text{ mas}, \Delta 2b = 0.01 \text{ mas}) \). We found that the minimum \( \chi^2 \) decreases only a little, to 7.0, which is given with the set of parameters \( (2a = 3.77 \text{ mas}, 2b = 3.29 \text{ mas}) \). Figure 5 shows the \( \chi^2 \) map of \( (2a, 2b) \) and the \( \chi^2 \) map of \( (\rho_p/b, \phi_p) \) at \( (2a = 3.77 \text{ mas}, 2b = 3.29 \text{ mas}) \). It is worth considering the region where \( (2a, 2b) \) gives smaller \( \chi^2 \) than \( \chi^2_c \), because the number of parameters is increased. Two parameters, \( \rho_p/b \) and \( \phi_p^2 \), converge better than in the former model when parameters \( 2a \) and \( 2b \) are...
The values $v \sin i = 190 \text{ km s}^{-1}$ (Carpenter et al. 1984) and $250 \text{ km s}^{-1}$ (Stoeckley 1968), determined from spectroscopy, are close to but do not exceed the $v_c \sin i$. The apparent brightness distribution with these parameters is shown in Figure 7.

5. CONCLUSION

We observed Altair with high resolution, including the measurement of the triple product using three long baselines of the NPOI for four nights. Measured observables indicate the asymmetric surface brightness distribution of this star; the asymmetry is deduced directly from the definition of the visibility and is not model-dependent. Although the measurement of the structure of the surface brightness distribution has been reported for evolved stars (Tuthill et al. 1997), this is the first time that the asymmetric surface brightness distribution for a main-sequence star has been found from direct measurements using interferometry. The measured observables are well reproduced with a model having a bright spot of relative intensity 4.7% on the limb-darkened disk with an angular diameter of 3.38 mas. The rapid rotation of the star indicates that the bright spot is a bright pole of the gravity-darkened star. Although we could not determine the position of the pole, owing to insufficient data, we expect that additional observations with sets of long baselines covering a wider range of position angles will solve this problem. More sophisticated gravity- and limb-darkening modeling of a rapidly rotating star (Domiciano de Souza et al. 2002) will also help in the determination of physical parameters when we have sufficient multibaseline data. We expect that these kinds of observations will be realized with current and future interferometers and that the study of rapidly rotating stars will progress with further observations by interferometers.

N. Ohishi acknowledges C. A. Hummel for supporting the use of data reduction system, OYSTER. The Navy Prototype Optical Interferometer is a joint project of the Naval Research Laboratory and the US Naval Observatory, in cooperation with Lowell Observatory, and is funded by the Office of Naval Research and the Oceanographer of the Navy.

REFERENCES

Armstrong, J. T., et al. 1998, ApJ, 496, 550
Benson, J. A., et al. 1997, AJ, 114, 1221
Carpenter, K. G., Slettebak, A., & Sonneborn, G. 1984, ApJ, 286, 741
Ciardi, D. R., van Belle, G. T., Akeson, R. L., Thompson, R. R., Lada, E. A., & Howell, S. B. 2001, ApJ, 559, 1147
Colavita, M. M., et al. 1999, ApJ, 510, 505
Domiciano de Souza, A., Kervella, P., Jankov, S., Abe, L., Vakili, F., di Folco, E., & Parese, F. 2003, A&A, 407, L47
Domiciano de Souza, A., Vakili, F., Jankov, S., Janot-Pacheco, E., & Abe, L. 2002, A&A, 393, 345
Freire Ferrero, R., Gouttebroze, P., & Kondo, Y. 1983, A&A, 121, 59
Gray, D. F. 1976, The Observation and Analysis of Stellar Photospheres (New York: Wiley-Interscience)
Hanbury Brown, R., Davis, J., Allen, L. R., & Rome J. M. 1967, MNRAS, 137, 393
Hummel, C. A., Mozurkewich, D., Armstrong, J. T., Hajian, A. R., Elias, N. M., II, & Hutter, D. J. 1998, AJ, 116, 2536
Mozurkewich, D., et al. 1991, AJ, 101, 2207
Nordgren, T. E., Sudol, J. J., & Mozurkewich, D. 2001, AJ, 122, 2707
Nordgren, T. E., et al. 1999, AJ, 118, 3032
Quirrenbach, A., Mozurkewich, D., Buscher, D. F., Hummel, C. A., & Armstrong, J. T. 1996, A&A, 312, 160
Royer, F., Grenier, S., Baylac, M.-O., Gómez, A. E., & Zorec, J. 2002, A&A, 393, 897
Stoeckley, T. R. 1968, MNRAS, 140, 121
Tuthill, P. G., Haniff, C. A., & Baldwin, J. E. 1997, MNRAS, 285, 529
van Belle, G. T., Ciardi, D. R., Thompson, R. R., Akeson, R. L., & Lada, E. A. 2001, ApJ, 559, 1155
Van Hamme, W. 1993, AJ, 106, 2096
von Zeipel, H. 1924, MNRAS, 84, 665
Wittkowski, M., Hummel, C. A., Johnston, K. J., Mozurkewich, D., Hajian, A. R., & White, N. M. 2001, A&A, 377, 981