LETTERS

Vega is a rapidly rotating star

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Vega, the second brightest star in the northern hemisphere, serves as a primary spectral type standard[1]. Although its spectrum is dominated by broad hydrogen lines, the narrower lines of the heavy elements suggested slow to moderate rotation, giving confidence that the ground-based calibration of its visible spectrum could be safely extrapolated into the ultraviolet and near-infrared (through atmosphere models[2]), where it also serves as the primary photometric calibrator. But there have been problems: the star is too bright compared to its peers[3] and it has unusually shaped absorption line profiles, leading some[4,5] to suggest that it is a distorted, rapidly rotating star seen pole-on. Here we report optical interferometric observations that show that Vega has the asymmetric brightness distribution of the bright, slightly offset polar axis of a star rotating at 93 per cent of its breakup speed. In addition to explaining the unusual brightness and line shape peculiarities, this result leads to the prediction of an excess of near-infrared emission compared to the visible, in agreement with observations[6,7]. The large temperature differences predicted across its surface call into question composition determinations, adding uncertainty to Vega's age and opening the possibility that its debris disk[8] could be substantially older than previously thought[9,10].

Single baseline Michelson stellar interferometers measure complex 'visibilities'[11], usually recorded as amplitudes and phases, which are related to the intensity distribution of the target through a Fourier transform. Even though the phases have been shown to be very sensitive to asymmetries in the intensity distribution, they are badly corrupted by the atmosphere and have been little used in the optical. But for closure phases, the data we focus on here—which are obtained by summing the phases measured on each baseline of a triangle in an interferometric array such as the Navy Prototype Optical Interferometer[12] (NPOI)—the atmospheric contribution cancels. The use of closure phase in the radio[13] has enabled a dramatic gain in dynamic range of interferometric images made from multi-antenna arrays. In the optical[12,14], where the phase errors can reach 100 waves on long baselines, the technique enables the use of phase information in any guise. As the observations reported here were made just with a three-telescope array, the application of imaging techniques was not justified and we relied instead on fitting Roche models to the closure phase data.

The application of Roche spheroids to rotating stars was worked out 80 years ago[15]. Assuming solid body rotation and a point mass gravitational potential, a rotating star will adopt the figure of a Roche spheroid. Conservation of energy through surfaces of constant potential leads to the prediction that when the energy is transported by radiation the amount transported will vary over the surface in proportion to the effective gravity[16] (that is, gravity minus local centrifugal terms). Near breakup, the effective gravity near the equator can become quite small, leading to the prediction of a

large drop in the local temperature with a corresponding decrease in brightness, an effect referred to as 'gravity darkening'. Rapidly rotating stars seen at intermediate inclinations are therefore expected to display asymmetric intensity distributions. Altair[17,18] proved to be the first major test of this theory in an isolated rotating star, where the theory succeeded to a high degree in describing a very non-trivial brightness distribution.

The observations considered here were obtained during late May and early June 2001 on the same nights as those of Altair previously reported[17,19], where Vega served as a check star (the Vega data in machine readable form are in a separate file in the Supplementary Information). The observations and much of the data reductions are exactly as described for Altair[17], which should be consulted for details. Issues specific to the Vega data are described in the

Table 1 | Vega model and derived parameters

Quantity	Value	Errors (s.d.)*
$\omega = \Omega/\Omega_B$†	0.926	±0.021
θ_p (mas)†	2.767	0.037
T_p (K)†	9,988	61
i (deg.)†	4.54	0.33
PA (deg.)†	8.6	2.7
v_{eq} (km s^{-1})	274	14
$v_{eq,B}$‡ (km s^{-1})	356.1	2.4
Ω (d^{-1})	1.884	0.081
Ω_B‡ (d^{-1})	2.034	0.041
T_{eq} (K)	7,557	261
R_p ($R_\odot$)	2.306	0.031
R_{eq} ($R_\odot$)	2.873	0.026
θ_{min}§ (mas)	3.441	0.031
θ_{max}§ (mas)	3.446	0.031
$\log L$ ($L_\odot$)	1.544	0.018
$\log g_p$ (cm^2 s^{-2})	4.074	0.012
$\log g_{eq}$ (cm^2 s^{-2})	3.589	0.056
M‖ ($M_\odot$)	2.303	0.024
T_{eff}‖ (K)	9,306	86
Age‖ (Myr)	386	16

Six quantities are needed to uniquely define the Roche model of a star[17]: the ratio of the angular rotation to that of breakup, $\omega = \Omega/\Omega_B$, the inclination (or tilt) of the rotational axis to the line of sight, i, the position angle, PA, of the pole on the sky, the radius of the polar axis, R_p (or equivalently, using the parallax, the polar angular diameter, θ_p), the effective temperature at the pole, T_p, and the surface gravity at the pole, g_p, or equivalently, the mass. It is then possible to calculate the radius, $R(\phi)$, of the star for a given stellar latitude, ϕ, the effective gravity and the local temperature ($T(\phi)$). For the spectral calculations we have adopted the ATLAS model atmospheres[28] and in particular the Van Hamme[29] limb-darkening parameterization of that grid. Other parameters include linear rotational velocities, v, the luminosity, L, surface gravities, g, the mass, M, and effective temperature, T_{eff}, the last referring to the entire non-rotating star. Subscripts $_{eq}$ and $_p$ specify quantities evaluated at the equator and pole, respectively.
* Uncertainties due to the parallax have not been included in the errors.
† The parameters derived from the model fit. A mass of 2.30 $M_\odot$ was assumed in the fit.
‡ Rotating at breakup but with the same mass and polar radius.
§ $\theta_{min,max}$ are the minimum and maximum projected angular diameters.
‖ The parameters of a non-rotating star from the Padova grid[26] that would reproduce the (corrected) luminosity and polar radius[17].

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Table 2 | Predicted photometric 'excesses' for Vega

Band	Wavelength (μm)	Excess (mag)
R	0.67	−0.016
I	0.86	−0.029
J	1.12	−0.052
K	2.14	−0.072
L	3.69	−0.072

The differential excesses for the model of Vega compared to a non-rotating model (both solar composition) which matches the *V* magnitude with an angular diameter of 3.24 mas (ref. 27). Until the question of composition is resolved, these values should be considered indicative.

Supplementary Information. We focus here on the closure phase data taken by NPOI on 25 May 2001, as they are the most extensive and the highest quality data of that run. We augment these with the V-band magnitude[2], $V = 0.026 \pm 0.008$, as an additional observable. The model was fitted by enforcing the usual minimum χ^2 metric using the Levenberg–Marquardt algorithm[20].

The parameters from the initial reduction are given in column 2 of Supplementary Table S1. The projected (at inclination i) equatorial velocity, v_{eq}, for this model was predicted to be $v_{eq} \sin i \approx 15 \, \mathrm{km \, s^{-1}}$, a bit below the $\sim 21.8 \pm 0.1 \, \mathrm{km \, s^{-1}}$ found from detailed profile fits using a rotating model[21]. Although it is not so far off given how close the star is to pole-on, we feel the projected velocity is sufficiently well

known that it should also be incorporated in the fit. We have therefore added as an 'observable' $v_{eq} \sin i = 22 \pm 1.0 \, \mathrm{km \, s^{-1}}$ (see Supplementary Information) and refit the data (columns 3 and 4 of Supplementary Table S1).

The Roche model provides a good fit to the augmented data set. The model parameters fitted, a number of derived quantities, and an estimate of what the main parameters of the star Vega would be, were it not rotating, are given in Table 1. The quality of the fit is illustrated in Fig. 1, and a false-colour rendering of the Vega model is shown in Fig. 2. As Vega has so many roles in astronomy, the ramifications of this result are extensive. We summarize some of the most important below.

Rotation can affect the gross spectral distribution of a star, an issue of considerable import given Vega's role as the primary flux calibrator in the ultraviolet, visible and near-infrared. To estimate the size of these effects, we have calculated the changes in the fluxes from the rotating model compared to the static case that would be measured through a series of broadband filters (Table 2). As can be seen, there is a significant, systematic increase in the infrared emission from the rotating model. This is understood as being due to the large amount of surface area predicted to be at relatively low temperatures.

There is an extensive literature on the possibility and extent of an 'infrared excess' in the Vega spectrum[6,7]. As the issue is critical to so much of astronomy, sides have been strongly taken. Observations of
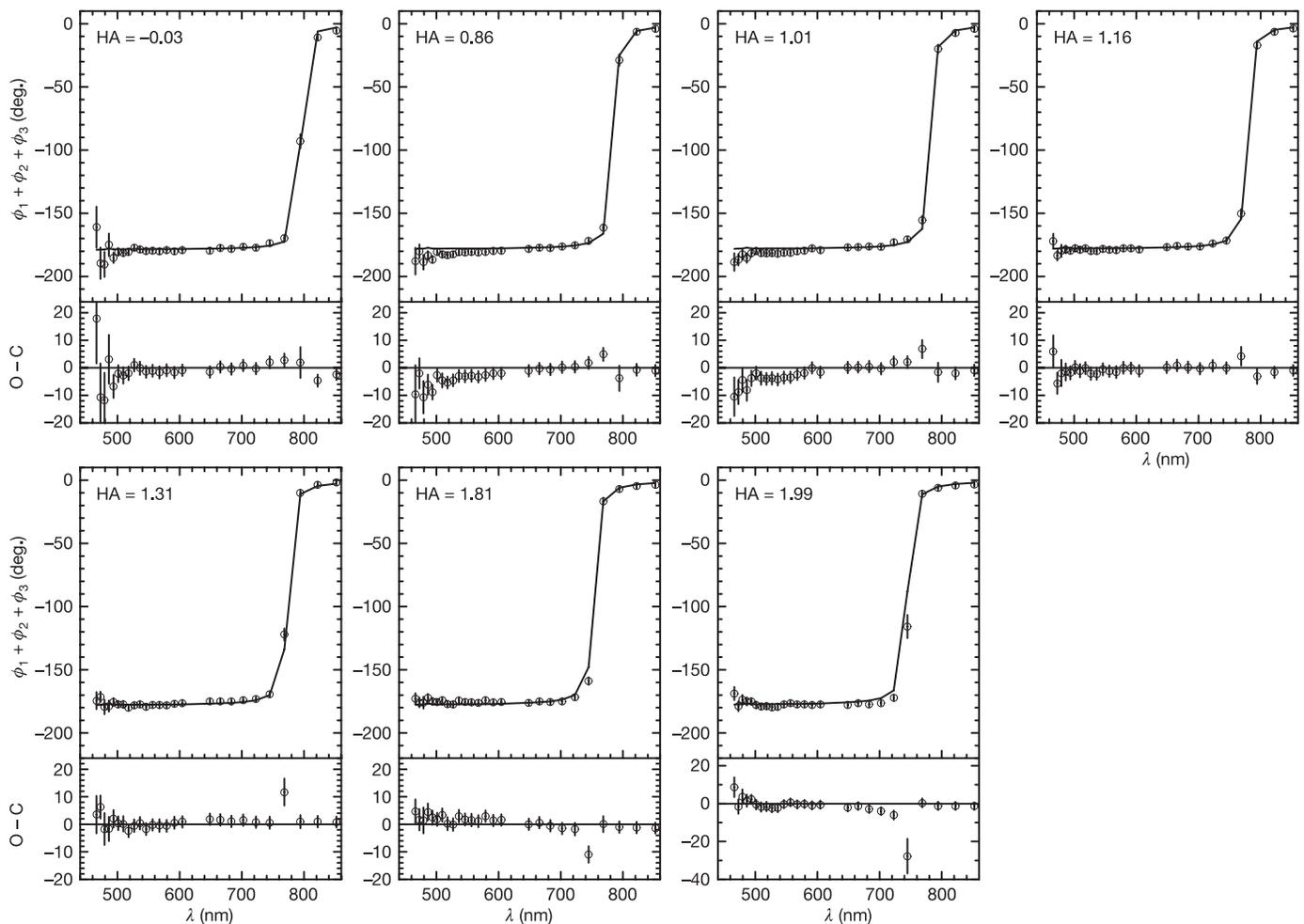
Figure 1 | Roche model fits to the closure phase data taken on 25 May 2001. The observations (open circles), estimated errors (bars, standard deviations) and model calculations (solid lines) are shown for each scan (labelled by hour angle, HA). Residuals (observed, O, minus calculated, C) are shown below each of the scans for clarity. The phases for the individual baselines, ϕ_i, and thus the closure phases, take on only two values, 0° or 180°,

if an object is centro-symmetric. Closure phase measurements showing departures from this simple 'abrupt transition' behaviour provide potentially very sensitive measurements of asymmetry in an object. The soft transition at the points of the 180° phase changes here give a clear signal of the asymmetry in the intensity distribution. (Note the scale change for the residuals of the last scan.)
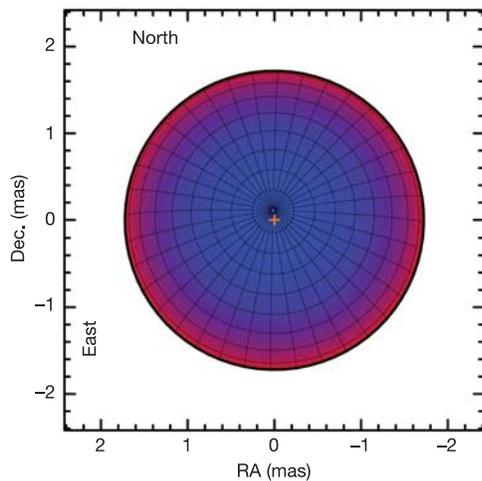
Figure 2 | A false-colour model of Vega as it appears from Earth. (Blue is bright, red is faint, and the orange '+' is the subsolar point.) The temperature drops more than 2,400 K from pole to equator, creating an 18× drop in intensity at 500 nm. Limb-darkening in a non-rotating model predicts only a 5-fold drop in intensity. Although the projected outline is almost perfectly circular, the polar diameter is only 80% of the equator. Dec., declination; RA, right ascension.

other A stars showed that Vega's colours appear sensibly normal[7], which led some authors[7,22] to wonder whether the problem was with the model atmospheres. Others[23] argued that, because the hydrogen absorption coefficient completely dominates the spectra of A stars and is so well known, it was unlikely that the model atmospheres were wrong, an argument that seems to have carried the day. Rapid rotation provides a simple resolution to this controversy—Vega is best modelled as a composite of model atmospheres. The star should have 'normal' infrared colours, as most normal A stars are rapid rotators, and there is no need to question the quality of the individual atmosphere models.

One important aspect to this model is the near pole-on orientation of the rotational axis. Vega is surrounded by a large infrared-emitting disk of material, a 'debris disk', which presents an essentially circular profile. We do not expect perfect coupling between orbiting material and the central star. But, if the poles of the disk and Vega coincide and the disk is thin, we would predict 0.3% flattening, which is unlikely to be detectable, as seems to be the case[24].

Related to the orientation of the pole is the inferred equatorial velocity, $v_{eq} = 272 \, \text{km s}^{-1}$ (Table 1). Among the Vega-like stars, Vega itself has been anomalous in displaying a very low projected rotational velocity[10]. The present determination strongly supports the view that the Vega-like stars are rapid rotators, consistent with the large amounts of angular momentum in the surrounding dust clouds.

Vega's rotational state also affects inferences about its debris disk. It is well known that rotation results in the apparent brightness, and in turn the deduced luminosity, being inclination-dependent[25]. Song et al.[10], for example, have gone to some lengths to characterize the uncertainty introduced by this effect in the Vega-like stars. It is straightforward to calculate the total luminosity of a Roche spheroid (Table 1). Further, one can apply small corrections[17] to the luminosity and polar radius to obtain the corresponding values that would apply to a non-rotating star of the same mass. Using the Padova[26] models, we derive a mass $M = 2.303 \, M_\odot$ (where $M_\odot$ is the solar mass) and an age of $386 \pm 16 \, \text{Myr}$, on the high side of recent estimates of $354^{+29}_{-87} \, \text{Myr}$ (ref. 10) and $347^{+43}_{-37} \, \text{Myr}$ (ref. 9).

Unfortunately, Vega's composition enters the age determination rather critically. The star is currently viewed as underabundant in heavy elements compared to the Sun[27], $[\text{Fe/H}] \approx -0.5$, which clearly needs to be revisited, given the 2,400 K temperature drop

now predicted across its surface. Previous age determinations have implicitly or explicitly assumed solar metallicity, the argument being that compositional peculiarities among the slowly rotating stars in this part of the Hertzsprung–Russell diagram are probably limited to the outer envelope, and normal composition models are therefore appropriate for estimating bulk properties. In our interpretation that argument fails, because at these rotational velocities meridional circulation will keep the bulk of the star well mixed.

Proceeding as above, we estimate $M = 2.11 \, M_\odot$ and an age of 572 Myr, using the metallicity $Z = 0.008$ ($[\text{Fe/H}] \approx -0.4$) Padova models[26]. It is clear that a full abundance analysis incorporating rotation needs to be performed to remove this uncertainty. In the meantime this range, 386–572 Myr, is probably a more realistic estimate of the uncertainty in the evolutionary age of Vega and its debris disk.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.