RESOLVING VEGA AND THE INCLINATION CONTROVERSY WITH CHARA/MIRC

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ABSTRACT

Optical and infrared interferometers definitively established that the photometric standard Vega (= α Lyrae) is a rapidly rotating star viewed nearly pole-on. Recent independent spectroscopic analyses could not reconcile the inferred inclination angle with the observed line profiles, preferring a larger inclination. In order to resolve this controversy, we observed Vega using the six-beam Michigan Infrared Combiner on the Center for High Angular Resolution Astronomy Array. With our greater angular resolution and dense (u, v)-coverage, we find that Vega is rotating less rapidly and with a smaller gravity darkening coefficient than previous interferometric results. Our models are compatible with low photospheric macroturbulence and are also consistent with the possible rotational period of ~0.71 days recently reported based on magnetic field observations. Our updated evolutionary analysis explicitly incorporates rapid rotation, finding Vega to have a mass of 2.15+0.10−0.05 M⊙ and an age 700+75−70 Myr, substantially older than previous estimates with errors dominated by lingering metallicity uncertainties (Z = 0.006+0.003−0.002).

Key words: infrared: stars – stars: individual (Vega) – stars: rotation – techniques: interferometric

1. INTRODUCTION

The nearby hot star Vega (spectral type A0) has been used as a photometric standard for millennia. While Vega’s relatively narrow spectral lines (v sin i ~ 22 km s⁻¹) suggest slow rotation, interferometric observations instead have established Vega to be a rapid rotator viewed near pole-on (Peterson et al. 2006; Aufdenberg et al. 2006), confirming suspicions of earlier spectroscopists (Gray 1985, 1988; Gulliver et al. 1994). Rapid rotation should keep the surface material and stellar envelope well mixed, leading to the conclusion that the observed sub-solar photospheric abundance represents the bulk composition. Lower metallicity led to a revised lower mass estimate of ~2.15 M⊙ for Vega and increased age ~500 Myr (Yoon et al. 2008, 2010).

Based purely on spectroscopic analysis, Takeda and collaborators (Takeda et al. 2008a, 2008b) agree that Vega is rapidly rotating, but with a preferred set of parameters at odds with the first generation of interferometry results. The parameters most discrepant are the rotational period and inclination angle, key values for modeling line profiles and understanding its evolutionary state. Yoon et al. (2008, 2010) made the case that non-standard macroturbulence broadening of ~10 km s⁻¹ could accommodate both the observed line profile shapes and the interferometry results (Takeda et al. adopted 2 km s⁻¹ microturbulence with no additional broadening). Hill et al. (2010) carried out a similar analysis and found intermediate results for best-fitting macroturbulence and inclination angle. We refer here to this tension between models as Vega’s inclination controversy, although one might alternatively refer to it as a macroturbulence controversy.

A third observing method has recently shed new light on this touchstone system. From analysis of circularly polarized light, Lignières et al. (2009) found evidence for a weak magnetic field in Vega. Petit et al. (2010) carried out Zeeman Doppler imaging, finding a detectable weak polar field concentration (~0.6 G). Although the periodic signal is indeed weak, there is growing confidence after many years of observations that a persistent signal at 0.71 ± 0.03 days (Petit et al. 2010; Alina et al. 2012) represents the rotational period of Vega. This period is substantially longer than expected from interferometry-based models (P ~ 0.5–0.6 days) but compatible with the period range predicted using line profiles alone (P ~ 0.7–0.9 days; Takeda et al. with no excess macroturbulence).

In this Letter, we present extensive new interferometer observations of Vega using the Michigan Infrared Combiner (MIRC) on the Center for High Angular Resolution Astronomy (CHARA) Array. Our data have higher angular resolution than previous work and substantially improved Fourier coverage, allowing for a robust estimate of internal and systematic errors. Building on our recent imaging and modeling of other rapid rotators (Monnier et al. 2007; Zhao et al. 2009; Che et al. 2011), we explore a wider range of gravity darkening prescriptions. In short, we bring a new independent and critical look at the constraints interferometers can bring to Vega, particularly cognizant of parameter degeneracies and calibration systematics.

2. OBSERVATIONS AND DATA REDUCTION

We have used CHARA array in conjunction with the MIRC combiner to measure visibilities (V²) and closure phases (CP) of Vega across the near-infrared H band. The CHARA
Array was built and is operated by Georgia State University on Mt. Wilson, California. CHARA is the longest baseline optical/infrared interferometer in the world with six fixed 1 m telescopes and a maximum baseline of 330 m (ten Brummelaar et al. 2005).

The MIRC image-plane combiner was used for all observations presented here. Before 2011, MIRC was used to combine four telescope beams, allowing 6 V^2 and 4 CP measurements at a time. Following a major upgrade in 2011, MIRC now combines all six CHARA telescopes, resulting in up to 15 V^2 and 20 CP measurements simultaneously. MIRC splits the H-band light (\(\lambda_0 = 1.65 \, \mu m\)) into eight spectral channels (\(\lambda/\Delta \lambda \sim 42\), with absolute wavelength precision of \(\pm 0.25\%\) based on measures of \(\epsilon\) Peg using the orbit of Konacki et al. (2010). Further instrument details can be found in a series of SPIE papers (Monnier et al. 2004, 2006, 2010; Che et al. 2010, 2012).

Using Fourier transform techniques, the V^2 are measured, averaged, and corrected for biases. The bispectrum is formed using the phases and amplitudes of three baselines that form a closed triangle (Monnier 2007). Amplitude calibration was performed using real-time flux estimates derived from choppers (before 2010) or through use of a beam splitter following spatial filtering for improved performance (after 2010; Che et al. 2010).

Lastly, observations of reference calibrators throughout the night allowed for correction of time-variable factors such as atmospheric coherence time, vibrations, differential dispersion, and birefringence in the beam train. Additional pipeline details can be found in earlier papers (e.g., Monnier et al. 2007; Zhao et al. 2009; Che et al. 2011).

For this work we have evolved our calibration model to better account for systematics. Firstly, we include two types of calibration error for V^2—multiplicative errors associated with the transfer function and additive errors associated with correcting biases at low fringe or bispectrum amplitude. Based on calibrator studies, the former has been estimated to be 20% (6.6%) for 2007 (2012) data while the additive systematic error is \(\Delta V^2 = 2 \times 10^{-4}\) (for both epochs). For triple amplitudes ("T3amp"), the corresponding multiplicative errors are 30% (10%) for 2007 (2012) and additive errors are \(1 \times 10^{-5}\). A detailed study by Zhao et al. (2011) suggests that CPs have an error floor of 1' for the observing modes adopted here. To avoid our model fits being trapped by systematics, we also include two new types of CP errors associated with low signal-to-noise ratio (S/N) data near visibility null crossings. Because correlated camera readout noise dominates the CP measurements at low S/N, we enforce minimum CP errors when the S/N_{T3amp} \(\lesssim 1\). In addition, we account for finite time-averaging and spectral bandpass effects by including an error term proportional to \(\Delta CP\) across each spectral channel. Formally, these two terms are only important right at the null crossings and appear in the following noise floor formula: \(\sigma_{CP} > \text{MAX}((30'/S/N_{T3amp})^2, 0.2\Delta CP_s)\).

Here we present data for Vega from three nights in 2007 (MIRC4) and two nights in 2012 (MIRC6). Data on four additional nights of MIRC4 were recorded in 2007 and 2010, but were discarded due to calibration problems. Table 1 includes detailed observing information including the calibrators and their adopted sizes; reduced data are available in OI-FITS format (Pauls et al. 2005) upon request.

Inspection of CPs shows nearly all values to be at zero or 180° as expected for a point-symmetric intensity distribution. Figure 1 shows the visibility data and the (u, v)-coverage (inset) for our data sets, split into three chunks of similar quantity: 2007, 2012 June 9 and 2012 June 13. The data were azimuthally averaged and compared to uniform disk and power-law limb-darkened disk (\(I = I_0 \mu^\alpha\)) models. As expected, the data are not consistent with a uniform disk and we find a best-fit limb-darkened diameter of 3.324 mas with power law \(\alpha \sim 0.277\)—more limb-darkened than expected for a non-rotating star (\(\alpha \sim 0.11\), Kurucz). We note variation between epochs due to calibration errors. Measuring precise limb-darkening requires controlling systematics at the few percent level, a goal for CHARA/MIRC but one that still proves challenging to attain during all observing conditions.

Internal diagnostics demonstrate that the best calibration is from 2012 June 13. This night had the best flux calibration, the greatest on-source integration time, and also employed the maximum number of simultaneous telescopes. The 2007 data, while extensive, were taken before our photometric channel upgrade and suffer from larger calibration errors. For the detailed modeling in the next section, we limited our fits to the 2012 June 13 data set.

3. MODELING

Our group has been a leader in the field of modeling rapid rotators, based largely on our unique and extensive interferometry data from CHARA/MIRC. Our series of papers (Monnier et al. 2007; Zhao et al. 2009; Che et al. 2011) contains the first images of main-sequence stars beyond the
Sun and has determined precise stellar parameters for rapidly rotating stars from early \( F \) to late \( B \). The basic physical model consists of a star with uniformly rotating surface layers, distorted by centrifugal forces acting under point-gravity with a surface temperature following the gravity-darkening law \( T = T_{\text{pole}}/g_e^{\beta} \), where \( g \) is the effective surface gravity. Based on our full data set, Che et al. (2011) argued that the observed gravity darkening deviates from the canonical value of \( \beta = 0.25 \) advocated by von Zeipel (1924a, 1924b) and instead we find empirically a lower characteristic value of \( \beta = 0.19 \). For our work here, we will again consider a range of possible \( \beta \) coefficients. Details of our calculations can be found in these earlier papers which followed the method of Aufdenberg et al. (2000; Alina et al. 2012) into the fit as priors.

### Table 1

| Date                  | Interferometer (Configuration) | Number of \( y^2 \) | Number of Closure Phases | Calibrator Information |
|-----------------------|---------------------------------|---------------------|--------------------------|------------------------|
| 2007 Jul 5            | S1–E1–W1–W2                    | 168                 | 104                      | \( \sigma \) Cyg, \( T \) Peg\(^b\) |
| 2007 Jul 8            | S1–E1–W1–W2                    | 96                  | 64                       | \( \gamma \) Lyr, \( Y \) Peg |
| 2007 Jul 13           | S1–E1–W1–W2                    | 144                 | 96                       | \( \sigma \) Cyg |
| 2012 Jun 9            | S2–S1–E1–E2–W2                 | 200                 | 144                      | HD 167304\(^d\) |
| 2012 Jun 13           | W1–S2–S1–E1–E2–W2              | 560                 | 640                      | \( \gamma \) Lyr |

**Notes.**

- \(^a\) Adopted \( \sigma \) Cyg UD diameter 0.54 \( \pm \) 0.02 mas (Barnes et al. 1978).
- \(^b\) Adopted \( \gamma \) Lyr UD diameter 0.99 \( \pm \) 0.02 mas (new CHARA/MIRC measurement).
- \(^c\) Adopted \( \gamma \) Lyr UD diameter 0.737 \( \pm \) 0.015 mas based on independent measurements by CHARA/MIRC (UD\(_H\) = 0.723 \( \pm \) 0.025 mas) and CHARA/PAVO (UD\(_H\) = 0.744 \( \pm \) 0.019 mas derived from UD\(_{DD}\) = 0.755 \( \pm \) 0.019 mas).
- \(^d\) Adopted HD 167304 UD diameter 0.69 \( \pm \) 0.05 mas (Bonneau et al. 2006).

### Table 2

| Model Parameters\(^a\) | Model 1 | Model 2 | Model 3 | Concordance\(^b\) |
|------------------------|---------|---------|---------|------------------|
| \( \beta = 0.25 \)     |         |         |         |                  |
| \( \beta = 0.19 \)     |         |         |         |                  |

**Notes.**

- \(^a\) Other parameters: distance 7.68 pc (van Leeuwen 2007), \( V \) mag 0.03 \( \pm \) 0.05 (Mermilliod et al. 1997), \( H \) mag 0.00 \( \pm \) 0.05 (Kidger & Martin-Luis 2003), [Fe/H] = \(-0.5\) (Yoon et al. 2008).
- \(^b\) The Concordance Model incorporated the observed \( v \sin i = 22 \pm 2 \) km s\(^{-1}\) (Takeda et al. 2008a) and period estimate 0.71 \( \pm \) 0.03 days (Petit et al. 2010; Alina et al. 2012) into the fit as priors.
- \(^c\) Geneva stellar evolutionary tracks (C. Georgy et al. 2012, submitted; Ekström et al. 2012) were used assuming \( \alpha/\alpha_{\text{cut}} = 0.8 \) and covering the range \( Z = 0.006^{+0.003}_{-0.002} \).
the more limited data sets of these workers led to underestimates of systematic errors, although we can not rule out certain physical explanations (time variability, spots, non-standard gravity darkening).

Constrained by only interferometry data, our parameters of Models 1 and 2 span a larger range than earlier estimates, limiting our constraints on key stellar properties. We can reduce our errors by including constraints on the period (0.71 ± 0.03 days; Petit et al. 2010; Alina et al. 2012) and $v \sin i$ (22 ± 2 km s$^{-1}$; Takeda et al. 2008a, 2008b) as statistical priors during the Markov Chain calculation. We call Model 3 our “Concordance Model,” a set of parameters that agrees with CHARA/MIRC interferometry, the spectral energy distribution (SED), $v \sin i$, and rotational period estimates. Table 2 contains these results, showing much smaller error bars with only a minimal increase in normalized $\chi^2$ (0.89–0.90). In this model we allowed gravity darkening to be free and find $\beta = 0.231 ± 0.028$, a bit higher than the 0.19 preferred by Che et al. (2011), but, interestingly, consistent with the reparameterization of $\beta$ by Espinosa Lara & Rieutord (2011), who argue that $\beta$ depends on the rotation rate, matching 0.25 only for slow rotators becoming smaller as the star spins up.

As a side note, we found that the basic parameters of the Concordance Model can be determined simply and robustly without a complicated calculation. First, the projected equatorial diameter can be deduced from basic visibility fitting (see Figure 1) to be 3.32 mas. This diameter can be turned into an equatorial velocity ($v_{eq} = 195$ km s$^{-1}$) using the estimated period and distance. Finally, the inclination angle must be $\sim 6.5^\circ$ to match the observed $v \sin i$. Indeed, these “back-of-the-envelope” estimates match quite closely the Concordance Model results in Table 2.

One way to view these results is to compare our parameters with the family of SED solutions outlined by Takeda et al. (2008a). Figure 2 shows our interferometric-based models (along with those of Peterson et al. and Aufdenberg et al.) plotted in $\omega$-inclination space next to Takeda’s Models 1–9.11 Takeda et al. (2008a) went further and used the line profile shapes to select best Models 3, 4, and 5, corresponding to $\sim 7^\circ$ inclination. We see our Models 1 and 2 are just consistent with the Takeda results at the $\sim 1\sigma$ level, while our Concordance Model strongly selects Takeda Model 5 as the optimal choice. Indeed, this diagram further reinforces that a true concordance does exist between the SED and line profile fitting of Takeda, the putative rotational period from Petit et al. and the CHARA/MIRC interferometric observations in the near-infrared.

We end this section with a note of caution. The deviation from centro-symmetry on the surface of Vega is quite subtle, amounting to a pole offset of just $\sim 0.2$ mas, roughly five times smaller than the fringe spacing from our longest baseline. Model-fitting different MIRC epochs can yield pole position angles (PAs) as different as $90^\circ$, and results from our best epoch (see Table 2) are discrepant with results from Peterson et al. (2006). We have searched extensively for the explanation for the fragile constraints on the pole PA, including physical causes (faint close-by companion, magnetic spots, non-radial pulsations; see also Rogers et al. 2012) and calibration-related problems (fringe cross talk, detector noise, bispectrum bias, time-averaging). After an exhaustive series of tests, none of the more limited data sets of these workers led to underestimates of systematic errors, although we can not rule out certain physical explanations (time variability, spots, non-standard gravity darkening).

Note: Takeda’s curve was slightly shifted here to account for fact that we use $2.15 M_\odot$ instead of $2.3 M_\odot$; $\sin i_{\text{new}} = \sqrt{M_{\text{takeda}}/M_{\text{new}}(\sin i_{\text{takeda}})}$. 

these hypotheses could convincingly explain the variations. We urge follow-up observations, especially at visible wavelengths where gravity darkening effects are strongest. Fortunately, the conclusions from our work here depend mostly on $V^2$ and not CPs, and the pole PA is not of paramount physical importance.

4. DISCUSSION AND CONCLUSIONS

We can now use our modeling results to assess the evolutionary state of Vega. We have used the most recent evolutionary tracks from the Geneva group that explicitly incorporates the
effects of rapid rotation (C. Georgy et al. 2012, submitted; Ekström et al. 2012). We considered metallicity range $Z = 0.006^{+0.003}_{-0.002}$ appropriate for $\text{[Fe/H]} = -0.5$ under the range of currently considered chemical abundances of the Sun (Anders & Grevesse 1989; Asplund et al. 2005, 2009)—note that Yoon et al. (2010) recommend $Z = 0.009$ corresponding to the upper range we considered. Because rapid rotation makes a star’s position on the traditional Hertzsprung–Russell (H-R) diagram ($L$ vs. $T_{\text{eff}}$) to be viewing-angle-dependent (see e.g., Zhao et al. 2009), we instead present stellar evolutionary tracks in units of total bolometric luminosity and stellar polar radius. Figure 3 shows our modified H-R diagram for $Z = 0.006$ including the effect of rotation. Our best models have $\omega/\omega_{\text{crit}} \sim 0.8$ and we show these isochrones in the figure. We conclude that Vega has a mass of $2.15^{+0.10}_{-0.15} M_\odot$ and age of $700^{+75}_{-150}$ million years for $Z = 0.006^{+0.003}_{-0.002}$, with errors dominated by the metallicity assumption not random errors. While our mass estimate is similar to those of Yoon et al. (2010), our age estimate is significantly higher, mostly due to including the effect of rotation and less so because of the lower mean metallicity $Z$ we have adopted.

In conclusion, we have presented modeling of the photometric standard star Vega using new interferometric data from CHARA/MIRC. The large quantity and high angular resolution of our data allow for precise constraints on the geometry and surface temperatures of Vega. We find Vega rotating more slowly than previous interferometer results, consistent with the putative rotation period observed by Alina et al. (2012) and compatible with the observed line profiles without excess macroturbulence. The differences with previous interferometry results could be from under-estimates of errors in earlier work or may suggest subtle deficiencies in the physical models. Our “Concordance Model” and its placement on a new H-R diagram represent the best global model for Vega to date, but there is still room for improvement. In addition to confirmation of the rotation period through photometry, we recommend additional visible-light interferometry data spanning the first three visibility lobes with $<5\%$ precision on $V^2$ to definitively establish the tilt angle of the pole and to pinpoint the true level of gravity darkening.

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**Facility:** CHARA

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