Binary Stars as Critical Tools & Tests
in Contemporary Astrophysics
Proceedings IAU Symposium No. 240, 2006
W.I. Hartkopf, E.F. Guinan & P. Harmanec, eds.

doi:10.1017/S1743921307004164

Interferometric Constraints on Gravity Darkening with Application to the Modeling of Spica A & B

J.P. Aufdenberg[1]†, M. J. Ireland[2], A. Mérand[3] V. Coudé du Foresto[4], O. Absil[5], E. Di Folco[6], P. Kervella[4], W. G. Bagnuolo[7], D. R. Gies[7], S. T. Ridgway[1], D. H. Berger[8], T. A. ten Brummelaar[3], H. A. McAlister[7], J. Sturmann[3], L. Sturmann[3], N. H. Turner[3] and A. P. Jacob[9]

[1]National Optical Astronomy Observatory, 950 N. Cherry Ave, Tucson, AZ 85719, USA
email: aufded93@erau.edu
[2]Planetary Science, California Institute of Technology, 1200 E. California Blvd, Mail Code 150-21, Pasadena CA 91125, USA
[3]The CHARA Array, Mount Wilson Observatory, Mount Wilson, CA 91023, USA
[4]LESIA, UMR 8109, Observatoire de Paris, 5 place J. Janssen, 92195 Meudon, France
[5]Insitut d'Astrophysique et de Géophysique, University of Liège, 17 Allée du Six Août, B-40000 Liège, Belgium
[6]Observatoire de Genève, Switzerland
[7]Center for High Angular Resolution Astronomy, Department of Physics and Astronomy, Georgia State University, P.O. Box 3969, Atlanta, GA 30302, USA
[8]University of Michigan, Department of Astronomy, 500 Church St, 917 Dennison Bldg., Ann Arbor, MI 48109, USA
[9]School of Physics, University of Sydney, NSW 2006, Austrailia

Abstract. In 2005 we obtained very precise interferometric measurements of the pole-on rapid rotator Vega (A0 V) with the longest baselines of the Center for High Angular Angular Resolution (CHARA) Array and the Fiber Linked Unit for Optical Recombination (FLUOR). For the analysis of these data, we developed a code for mapping sophisticated PHOENIX model atmospheres on to the surface of rotationally distorted stars described by a Roche-von Zeipel formalism. Given a set of input parameters for a star or binary pair, this code predicts the interferometric visibility, spectral energy distribution and high-resolution line spectrum expected for the system. For the gravity-darkened Vega, our model provides a very good match to the K-band interferometric data, a good match to the spectral energy distribution – except below 160 nm – and a rather poor match to weak lines in the high dispersion spectrum where the model appears overly gravity darkened. In 2006, we used the CHARA Array and FLUOR to obtain high precision measurements of the massive, non-eclipsing, double-line spectroscopic binary Spica, a 4-day period system where both components are gravity darkened rapid rotators. These data supplement recent data obtained with the Sydney University Stellar Interferometer (SUSI). Our study follows the classic 1971 study by Herbison-Evans *et al.* who resolved Spica as a binary with the Narrabri Stellar Intensity Interferometer (NSII). We will report on our progress modeling the new interferometric and archival spectroscopic data, with the goal towards better constraining the apsidal constant.

Keywords. binaries: close, binaries: spectroscopic, methods: numerical, stars: atmospheres, stars: fundamental parameters, stars: individual (Spica, Vega), stars: interiors, stars: oscillations, stars: rotation, techniques: interferometric

† Present address: Physical Sciences Department, Embry-Riddle Aeronautical University, 600 S. Clyde Morris Blvd, Daytona Beach, FL 32114, USA

1. Introduction

The double-line spectroscopic binary Spica (α Vir = HR 5056 = HD 116658) was the second star, after Capella (see Anderson 1920 and Merrill 1922), to have its "visual" orbital elements measured interferometrically by Herbison-Evans et al. (1971). Spica is important astrophysically because it is a close (P = 4.01 d), non-eclipsing massive binary ($\sim 11\ M_{\odot} + \sim 7 M_{\odot}$) in an eccentric orbit ($e \simeq 0.1$) whose components' tidal and rotational distortions lead to the advance of its longitude of periastron with time – in other words Spica exhibits apsidal motion. The advance of periastron depends on the internal structure of the stars and therefore observationally constraining Spica's apsidal motion provides a measurement of mass distribution inside its components. The primary, Spica A, is a β Cephei non-radial pulsator (with a prominent 4-hr period) providing the potential to compare its interior structure as revealed by both aspidal motion and asteroseismology.

The interferometric orbit for Spica from the Narrabri Stellar Intensity Interferometer (NSII) in 1971 provided an apsidal constant for this non-eclipsing system and immediately sparked theoretical investigations of Spica A's interior by Mathis & Odell (1973) and Odell (1974). These studies found that the mass distribution of Spica A from stellar interior models was less centrally concentrated than indicated by the apsidal motion constant. At the time of these theoretical studies this result held true not only for Spica, but also for many eclipsing eccentric double-line systems with more accurate radii. Over the next two decades, improvements in stellar interior models (better opacities, core overshooting, rotation effects) significantly reduced the discrepancies between theory and observation for most systems, but not for Spica (see Claret & Gimenez 1993). More recent work from Claret & Willems (2002) and Claret (2003) indicates that Spica remains one of the massive binaries for which there is still disagreement with theory.

The refinement of Spica's interferometric orbit, together with tighter constraints on the angular diameters of its components, promise to more tightly constrain our knowledge of the system's apsidal constant and provide an important check on theoretical expectations for stars in this mass range just off the main sequence. The apsidal constant is a function of the ratio of the primary radius to the semi-major axis of the orbit to the fifth power,

$$k_{2,\mathrm{obs}} \propto \left(\frac{\theta_A}{\theta_{SMA}}\right)^5, \tag{1.1}$$

thus sensitive to the angular diameter of the primary θ_{A} and the angular measure of the semi-major axis, parameters probed by an interferometer. Advances in visibility calibration for long-baseline interferometry make possible visibility measurements up to five times more precise than used to establish the original Spica interferometric orbit. Here we present a report of our first steps toward better constraining Spica's orbit and fundamental parameters using new interferometric data from the Sydney University Stellar Interferometer (SUSI) and from the Center for High Angular Resolution (CHARA) Array (see ten Brummelaar et al. 2005) using the Fiber-Link Unit for Optical Recombination (FLUOR, see Coudé du Foresto et al. 2003). The analysis of these data is tackled with state-of-the-art model stellar atmospheres for the components including rotational distortion and gravity darkening. Our model aims to predict self-consistently the interferometry, high-resolution spectroscopy and mean spectrophotometric properties of the system as an aid in constraining the system's fundamental parameters.

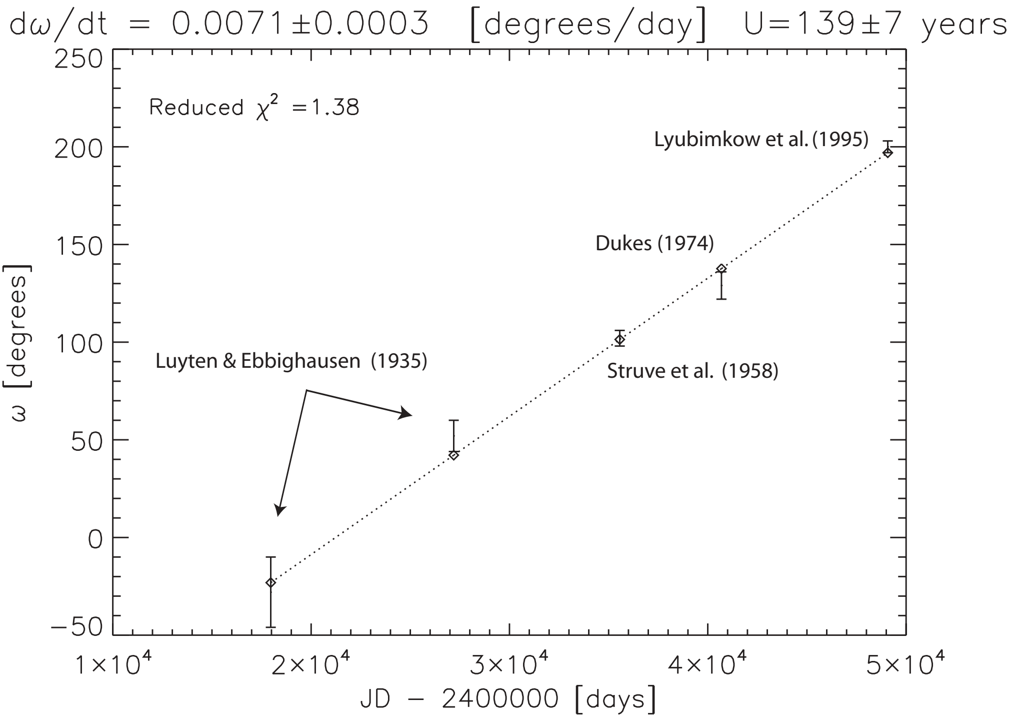

Figure 1. A linear fit to evolution of Spica's longitude of periastron with time. ω values from Luyten & Ebbighausen (1935), Struve et al. (1958), Dukes (1974) and Lyubimkov et al. (1995). The corresponding apsidal period, U, is 139±7 years.

2. Constraining Spica's Apsidal-Motion Constant

Our computation of Spica's mean observed apsidal motion is based on parameters from the literature and the formulae of Claret & Willems (2002). Our fit to the advance of periastron, which corresponds to $\dot{\omega} = 0.0071 \pm 0.0003$ degrees/day†, is shown in Figure 1. For computing $\log k_{2,\mathrm{obs}}$, we adopted values and uncertainties for the component masses, the orbital inclination, the component angular diameters, and the angular size of the semi-major axis from Herbison-Evans et al. (1971). The semi-amplitudes $K_{1,2}$ of the components and the eccentricity were taken from spectroscopic orbit of Shobbrook et al. (1972). The component $v \sin i$ values are from Lyubimkov et al. (1995). We find $\log k_{2,\mathrm{obs}} = -2.66 \pm 0.19$. Our value is consistent with that from Claret & Gimenez (1993). Our error bar together with Claret and Gimenez's Figure 9 shows that Spica's $\log k_{2,\mathrm{obs}}$ value is marginally consistent with theory, $\log k_{2,\mathrm{theo}} \simeq -2.4$, just outside 1 sigma. Our analysis of the error budget indicates that the uncertainty in $\log k_{2\ \mathrm{obs}}$ can be reduced from 0.19 to 0.11 if the uncertainties in the primary's (equatorial) radius, the semi-major axis, the inclination and the eccentricity can all be reduced to 1%. An additional reward from an improved orbital solution will be a precise distance estimate (via orbital parallax) independent from *HIPPARCOS*. Lastly, more tightly constraining Spica's fundamental parameters will help to better identify the primary's β Cephei pulsational modes as discussed by Smith (1985a) and Smith (1985b). Spica may prove a valuable target for on-going and upcoming space-based asteroseismology missions.

† This corresponds to $\dot{\omega} = 0.0284 \pm 0.0014$ degrees/cycle (periastron to periaston).

3. Gravity Darkening Considerations

Accurate angular diameters for Spica A & B will be model dependent because even with the CHARA Array's 313-m E1–W1 baseline the component stars themselves are not fully resolved. The components are expected to be gravity darkened, particularly Spica A with a $v \sin i$ of $\sim$ 150 km s^{-1}, 50% of the angular break-up speed for an inclination of 63.7°. Therefore the darkening is expected to deviate from standard limb darkening models and will be dependent on the orientation of the orbit and the rotation axes of the stars relative to the orbit. We assume here that the angular momentum vectors of the stars and the orbit are aligned.

Perhaps the best interferometric gravity darkening measurements on a star thus far are those obtained by CHARA/FLUOR on Vega (see Aufdenberg et al. 2006). To analyze these data we developed a code to produce synthetic visibilities for rapidly rotating stars assuming purely radiative Von Zeipel darkening (where the β exponent in the Von Zeipel relation $T_{\rm eff}/T_{\rm eff}^{\rm pole} = (g/g_{\rm pole})^{\beta}$ is 0.25). Such a model provides a very good fit to the CHARA/FLUOR visibility data for Vega, a model independently confirmed by observations from Navy Prototype Optical Interferometer at optical wavelengths (see Peterson et al. 2006). Based only on these independent interferometric data, our gravity darkening model for purely radiative stars would seem to be sufficient to apply to the Spica problem. However a closer look reveals that this model fails to reproduce aspects of the high quality spectrophotometric and high resolution spectroscopic data available on Vega. As pointed out in Aufdenberg et al. (2006), the model is too bright in the far ultraviolet, below 160 nm, suggesting a deviation from Von Zeipel.

Far more puzzling is the failure of this interferometric Vega model to reproduce Vega's high dispersion spectrum. Work to fit Vega's high-dispersion spectrum by Hill et al. (2004) finds a much more slowly rotating Vega: $V_{\rm eq}$ = 115 km $^{-1}$ (spectroscopic) versus $V_{\rm eq}$ = 270 km s^{-1} (interferometric). Since Aufdenberg et al. (2006), we have upgraded our code to generate synthetic high dispersion spectra for rotating stars. Our own independent high-dispersion synthesis for Vega (see Figure 2) confirms the much lower equatorial speed found by Hill et al. (2004) assuming standard Von Zeipel darkening. The higher of the two equatorial speeds is favored to solve Vega's mass-luminosity problem (a bright pole explains the high apparent absolute magnitude), yet such a model implies a pole-to-equator effective temperature difference of $\sim$2000 K. Such a temperature difference is enough to expect that Vega's atmosphere near the equator may be convectively unstable, further complicating the darkening law. Furthermore, the effects of differential rotation and meridional circulation may come into play.

For the hotter early B-type atmospheres in the Spica system we assume a purely radiative von Zeipel darkening holds, but we recognize this may not be good assumption in the presence of mutual illumination and tidal distortion. We hope that including rotational distortion and gravity darkening is better than assuming spherical stars with regular limb darkening.

4. SUSI and CHARA/FLUOR Observations of Spica

The first interferometric measurements of Spica obtained with the Narrabri Stellar Intensity Interferometer (NSII) have not yet been followed up with modern long-baseline interferometry, as least in the published literature. As noted above, the uncertainty in the apsidal constant, $k_{2,\rm obs}$, is very sensitive to uncertainties in both the equatorial angular diameter of the primary star $\theta_{\rm A}$ and the angular diameter of the semi-major axis $\theta_{\rm SMA}$. Estimates for these parameters will be tied to the precision of the visibility measurements

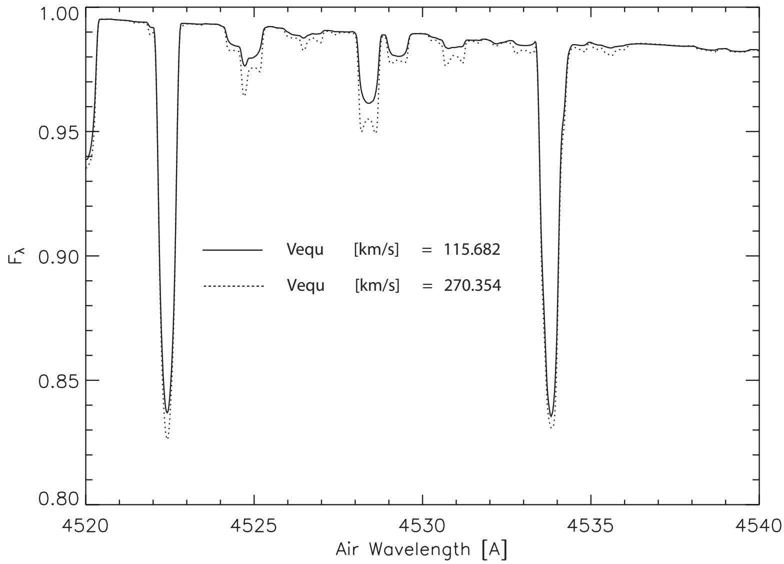

Figure 2. Two synthetic spectra for Vega with different equatorial velocities. The higher velocity model shows deeper line cores for the stronger lines and distorted, inverted line cores in the weaker lines. This distortion is due to strong darkening near the limb (Vega's equator in our pole-on view) where the local effective temperature enhances formation of these lines and the modest projected rotation velocity ($v \sin i \simeq 21$ km s^{-1}) shifts the line redward and blueward on opposite regions of the limb causing the inverted line core. The 270 km s^{-1} equatorial velocity is consistent with interferometric data (see Aufdenberg et al. 2006 and Peterson et al. 2006), while the 115 km s^{-1} best matches Vega's observed high-resolution spectrum (see Hill et al. 2004).

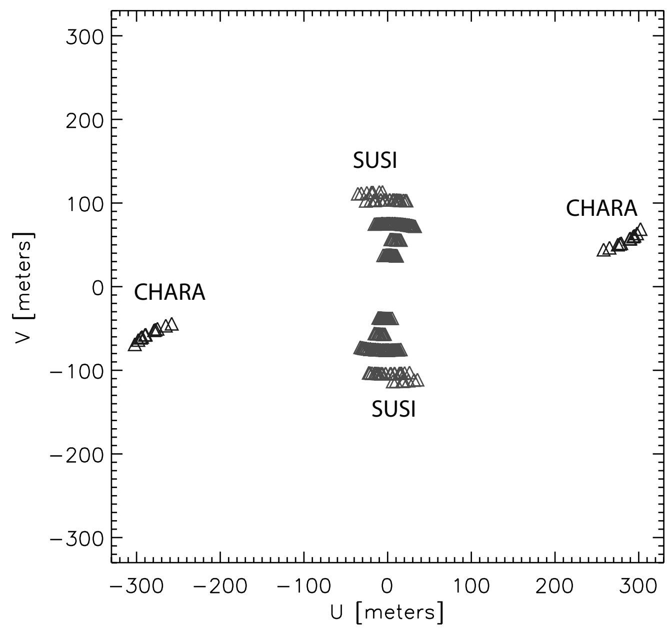

Figure 3. Baseline and position angle coverage of Spica from the CHARA/FLUOR and SUSI inteferometers mapped on the U-V plane. CHARA's long east-west projected baselines at K-band have equivalent resolving power to SUSI's longest baselines at 700 nm.

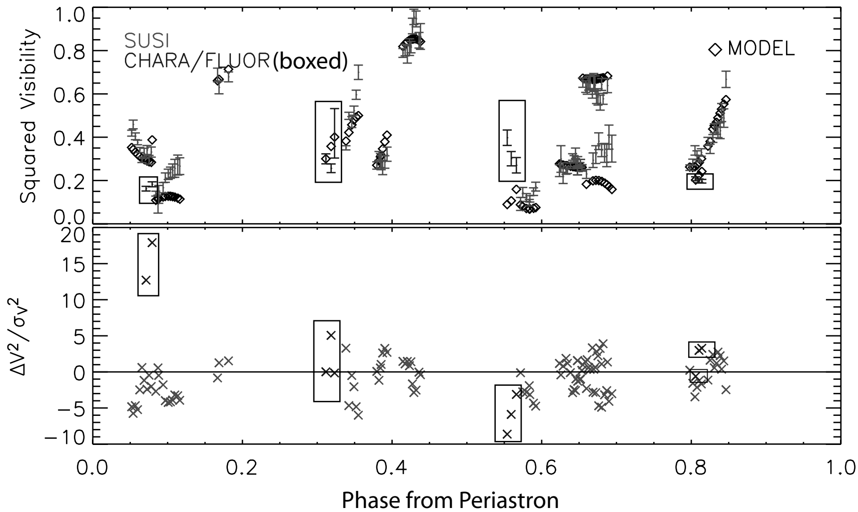

Figure 4. A preliminary comparison of model visibilities (diamonds) to the SUSI data (error bars) and CHARA/FLUOR data (error bars in boxes) on Spica. The residuals are shown in the lower panel. Our preliminary model matches these data best near phases 0.3 and 0.8 (relative to periastron), while the largest deviations occur near phases 0.1 and 0.6. At these latter pair of phases the two stars are near their minimum angular separation on the sky according the model.

and the model chosen to interpret them. While the Herbison-Evans et al. (1971) visibilities have uncertainties of $\simeq \pm 10\%$, the best data from our first season (2006) of CHARA/FLUOR observations are at the level of 5%. Visibilities at the level of 1-2% have been demonstrated with FLUOR on Vega by Aufdenberg et al. (2006), and we hope to obtain data of this precision on Spica with CHARA/FLUOR in the coming season. For our initial analysis we are combining our CHARA/FLUOR data with 112 squared visibility points obtained by Ireland (2005) at SUSI. These data, on a north-south baseline, nicely complement the CHARA data obtained on its longest (313 meter) east-west baseline. While the CHARA baseline is at least three times longer than the SUSI baselines, the SUSI data were obtained at a wavelength of 700 nm, roughly three times shorter than the FLUOR K-band. Figure 3 shows the baseline coverage in the U-V plane for CHARA and SUSI data sets. The corresponding squared visibility data are shown in Figure 4, along with preliminary model points. The model points are based on synthetic images of the Spica system which are Fourier transformed to yield synthetic visiblities. One synthetic image and Fourier map is shown in Figure 5 at phase 0.30 from periastron. For this same model, two high-dispersion spectra have been synthesized and compared to archival echelle data from the University of Toledo's Ritter Observatory (see Figure 6). Lastly, the same model is compared to archival spectrophotometry of Spica from the far ultraviolet to the K-band in Figure 7.

At this time we can say that present constraints on Spica's orbit and components are sufficient to yield reasonable synthetic matches to high dispersion spectroscopy, the spectrophotometry, and the interferometry at several phases at two wavelengths. A comparison of our preliminary model against the CHARA/FLUOR data at phases 0.1 and 0.6 (see Figure 4) indicates some important deficiency or deficiencies. Whether the resolution to this problem lies in further iteration of the system's orbital parameters or more realistic models for the system's components remains to be seen. High precision interferometry appears to be key to revising our model for the system.

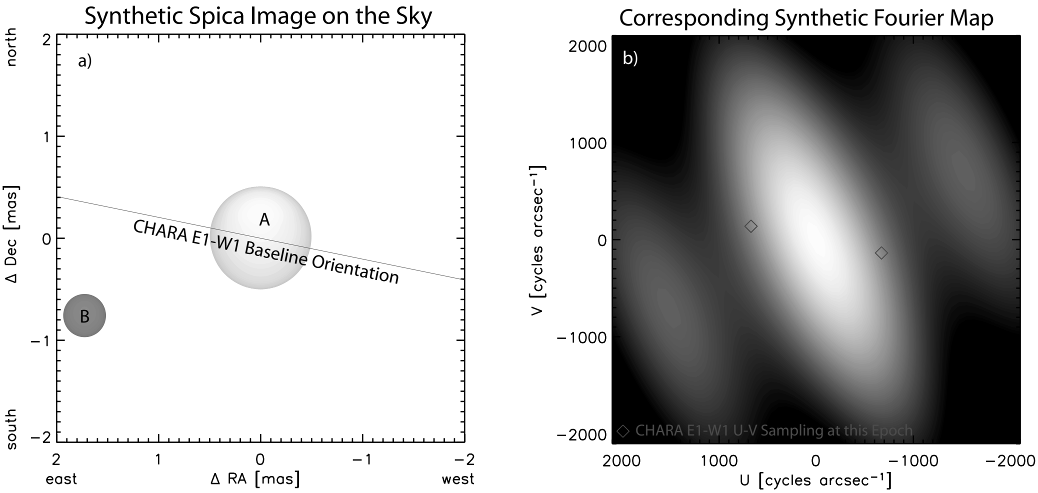

Figure 5. Panel a) shows a synthetic image of Spica A & B at phase 0.30, along with the orientation of the CHARA baseline. Both stars are limb and gravity darkened, however the dynamic range in the image makes Spica B appear as a uniform disk. Panel b) shows the Fourier map of the image; the brightness corresponds to the value of the squared visibility. The system is most resolved in a direction along a line connecting the two stars, and least resolved perpendicular to this line. As a result the CHARA/FLUOR squared visibility is ~ 0.4 as seen in Figure 4 at phase 0.30. The diamonds show the snapshot U-V sampling of the two telescope E1-W1 baseline at this single epoch.

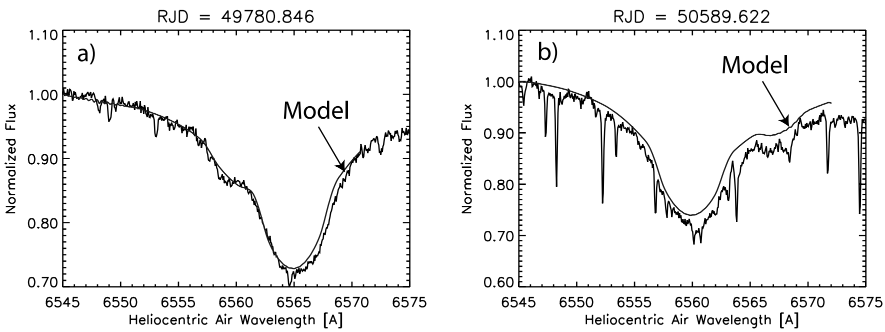

Figure 6. Two archival spectra of Spica from Ritter Observatory at phases a) 0.415 and b) 0.873 compared with the same model used to generate the synthetic squared visibilities shown in Figure 4. Strong telluric lines affect the spectrum in panel b). The Hα components of both the primary and the secondary can been discerned on opposite sides in the two panels. The model comparison isn't too bad considering the model was not fit to these data (apart from the flux normalization), only to the interferometry. Simultaneous fitting to both the spectroscopy and interferometry will hopefully lead to a more consistent model for Spica.

5. Future Work

In addition to pursuing the collection of more precise interferometric measurements on Spica with CHARA/FLUOR, we will be comparing our code to the large database of echelle spectra from Georgia State University first analyzed by Riddle et al. (2001). Improvements to our model for Spica are now underway. Our code to generate synthetic interferometry, synthetic spectrophotometry, and synthetic high-resolution line profiles for Spica does not yet include the effects of tidal distortions or the effects of mutual illumination and heating. Tidal distortion is evident in ellipsoidal light curve variations

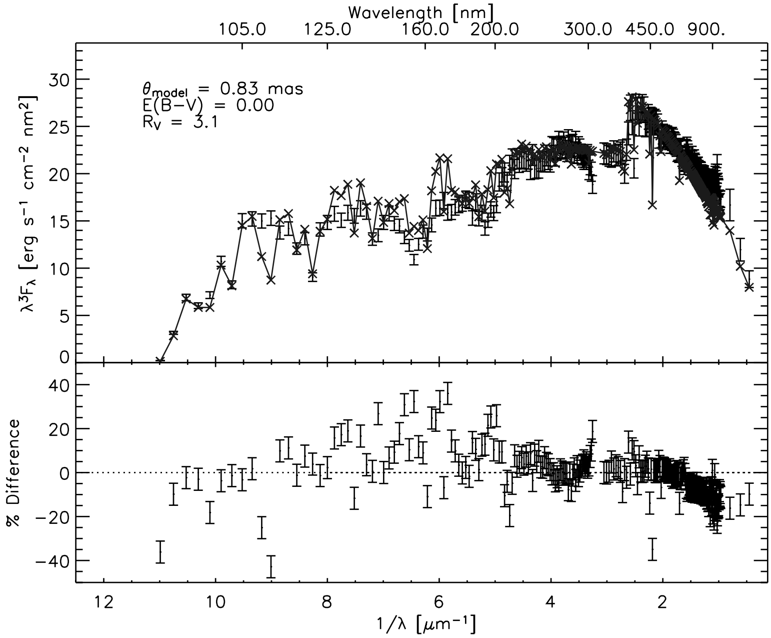

Figure 7. Top panel shows non-contemporaneous absolute spectrophotometry of Spica (error bars) compared with the model used to generate the synthetic squared visibilities shown in Figure 4. $\theta_{\rm model}$ refers to the model angular diameter of Spica A. Data in the far ultraviolet from Morales et al. (2001), in the ultraviolet from the *International Ultraviolet Explorer* (rebinned high dispersion spectra SWP33082RL and LWP12841RL), optical data from Glushneva et al. (1992) and Glushneva et al. (1998), and J, H, K fluxes from Ducati (2002). The lower panel shows the percentage difference between the model and data. The comparison in the near-IR suggests the temperature and/or radius of the secondary may need to be adjusted. We seek to simultaneously fit these spectrophotometric data along with the interferometric and high-dispersion spectroscopic data to arrive at a best model for Spica components.

($\Delta V \simeq 0.03$, see Dukes 1974) due to the changing projection of the tri-axial primary on the sky throughout the orbit. Our plan is to take the tidally distorted Roche surfaces from D.H. Bradstreet's Binary Maker 3.0 software and map our PHOENIX model radiation field grids onto this geometry. The reflection effect will change the brightness ratio of the components as a function of phase an thus effect the squared visibility. To treat this effect in the code we plan to use the approach of Cranmer (1993). While the observations and modeling of Spica which lie ahead are quite challenging, we hope to better constrain the system's fundamental parameters, thus further constraining Spica's apsidal-motion constant, thus providing a probe of the primary's interior which can be independently probed in turn via asteroseismology.

Acknowledgements

JPA thanks the Michelson Fellowship Program (under contract with the Jet Propulsion Laboratory, which is funded by NASA, and managed by the California Institute of Technology) for three years of generous support. JPA also thanks NOAO (operated by AURA, Inc, under cooperative agreement with the National Science Foundation), for hosting my Michelson Postdoctoral Fellowship in Tucson. The CHARA Array has been supported by National Science Foundation, Georgia State University, and W. M. Keck Foundation.

References

Anderson, J.A. 1920, *ApJ*, 51, 263

Aufdenberg, J.P., Mérand, A., Foresto, V.C.d., Absil, O., Di Folco, E., Kervella, P., Ridgway, S.T., Berger, D.H., ten Brummelaar, T.A., McAlister, H.A., Sturmann, J., Sturmann, L., & Turner, N.H. 2006, *ApJ*, 645, 664

ten Brummelaar, T.A., McAlister, H.A., Ridgway, S.T., Bagnuolo, W.G., Turner, N.H., Sturmann, L., Sturmann, J., Berger, D.H., Ogden, C.E., Cadman, R., Hartkopf, W.I., Hopper, C.H., & Shure, M.A. 2005, *ApJ*, 628, 453

Claret, A. 2003, *A&A*, 399, 1115

Claret, A. & Gimenez, A. 1993, *A&A*, 277, 487

Claret, A. & Willems, B. 2002, *A&A*, 388, 518

Coudé du Foresto, V., Borde, P.J., Merand, A., Baudouin, C., Remond, A., Perrin, G.S., Ridgway, S.T., ten Brummelaar, T.A., & McAlister, H.A. 2003, in Interferometry for Optical Astronomy II. Edited by Wesley A. Traub. Proceedings of the SPIE, Volume 4838, 280–285

Cranmer, S.R. 1993, *MNRAS*, 263, 989

Ducati, J.R. 2002, VizieR Online Data Catalog, 2237, 0

Dukes, R.J. 1974, *ApJ*, 192, 81

Glushneva, I.N., Doroshenko, V.T., Fetisova, T.S., Khruzina, T.S., Kolotilov, E.A., Mossakovskaya, L.V., Ovchinnikov, S.L., & Voloshina, I.B. 1998, VizieR Online Data Catalog, 3208, 0

Glushneva, I.N., Kharitonov, A.V., Knyazeva, L.N., & Shenavrin, V.I. 1992, *A&AS*, 92, 1

Herbison-Evans, D., Hanbury Brown, R., Davis, J., & Allen, L.R. 1971, *MNRAS*, 151, 161

Hill, G., Gulliver, A.F., & Adelman, S.J. 2004, in: J. Zverko *et al.* (eds.), *The A-Star Puzzle.*, Proc. IAU Symposium No. 224 (San Francisco: ASP), p.35

Ireland, M. 2005, PhD thesis, University of Sydney

Luyten, W.J. & Ebbighausen, E. 1935, *ApJ*, 81, 305

Lyubimkov, L.S., Rachkovskaya, T.M., Rostopchin, S.I., & Tarasov, A.E. 1995, *Astron. Rep.*, 39, 186

Mathis, J.S. & Odell, A.P. 1973, *ApJ*, 180, 517

Merrill, P.W. 1922, *ApJ*, 56, 40

Morales, C., Orozco, V., Gómez, J.F., Trapero, J., Talavera, A., Bowyer, S., Edelstein, J., Korpela, E., Lampton, M., & Drake, J.J. 2001, *ApJ*, 552, 278

Odell, A.P. 1974, *ApJ*, 192, 417

Peterson, D.M., Hummel, C.A., Pauls, T.A., Armstrong, J.T., Benson, J.A., Gilbreath, G.C., Hindsley, R.B., Hutter, D.J., Johnston, K.J., Mozurkewich, D., & Schmitt, H.R. 2006, *Nature*, 440, 896

Riddle, R.L., Bagnuolo, W.G., & Gies, D.R. 2001, American Astronomical Society Meeting, 199

Shobbrook, R.R., Lomb, N.R., & Herbison Evans, D. 1972, *MNRAS*, 156, 165

Smith, M.A. 1985a, *ApJ*, 297, 206

—. 1985b, *ApJ*, 297, 224

Struve, O., Sahade, J., Huang, S.-S., & Zebergs, V. 1958, *ApJ*, 128, 310

Discussion

Izold Pustylnik: It is known from classical papers that for rapid rotators the meridional circulation can be important. Do your models take this effect into account, and do you see from CHARA data any evidence on that?

Aufdenberg: Our models do not take meridional circulation into account. From the CHARA data alone, a standard (purely radiative) von Zeipel gravity darkening law fits the data very well in the case of Vega. This also appears to be the case with the optical interferometric data from the Navy Prototype Optical Interferometer, the work of Peterson *et al.*. What we don't understand is why the model fits the interferometric data well, yet poorly reproduces aspects of the spectrophotometric data and very high resolution spectral line profile data. Meridional circulation may well play a role in the resolution of the problem.

Juan Manuel Echevarria: Can you further comment on the rotational velocity difference from spectroscopy and interferometry in Vega?

Aufdenberg: The work of Hill *et al.* shows that particular weak metal lines can be fit with a von Zeipel darkened model not exceeding an equatorial velocity of 115 km/s. We have independently confirmed this with our model. Above this velocity, in particular a velocity of 270 km/s which best matches our interferometric data, these lines show a reversed core (as in Figure 2) indicating the darkening is too strong near the equator. A more sophisticated model is needed to find a consistent set of parameters to match both the spectroscopic and the interferometric data. Such a model might include differential rotation such as in the recent work by Jackson, MacGregor, and Skumanich on rapidly rotating main-sequence stars.