Interferometric Observations and Modeling of the Close Binary Star Spica (Alpha Virginis)

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What’s to Come....

- Rapidly Rotating Stars: A hot topic in astronomy!
- What characterizes the surface of a rapid rotator?
- Vega: a pole-on view of a rapid rotator
- Spica: Rapid rotation times two!

  History of Spica
  Spica’s a binary!
  Apsidal Motion: What’s that?!
  Spica components resolved!
  Building a model of Spica
  Preliminary Analysis
  Conclusions
Resolved Rapid Rotators from Interferometry

*Disk of Altair (A7 V) resolved as ellipsoid by the Palomar Testbed Interferometer (van Belle et al. 2001). Axial ratio: 1.140±0.029

*Disk of Alderamin (A7 IV-V) resolved as an ellipsoid by CHARA (van Belle et al. 2006). Axial ratio: 1.298±0.051

*Disk of Regulus (B7 V) resolved as ellipsoid by CHARA (McAlister et al. 2005). Axial ratio: 1.32±0.02

*Disk of Achernar (B3 Vpe) resolved as ellipsoid by VLTI (A. Domiciano de Souza et al. 2003). Axial ratio: 1.56±0.05

Interferometric Observations and Modeling Spica (α Vir)
A Pole-on Rapid Rotator: Vega

- Polar effective temperature: $10150 \pm 100$ K
- Equatorial effective temperature: $7950 \pm 350$ K
- Pole-on view (Earth view)
- Equator-on view
- Polar diameter: $2.26 \pm 0.07$ $D_\odot$
- Equatorial diameter: $2.78 \pm 0.02$ $D_\odot$
- Rotation period: $12.4 \pm 0.6$ hours
- Inclination: $4.7 \pm 0.3$ degrees

The Sun
**Rotating Stars: Limb Darkening and Gravity Darkening**

**Rapidly Rotating Model with both Limb and Gravity Darkening**

**Limb darkening:** An observer-dependent effect in which the intensity across a stellar surface varies due to a radial or depth-dependent temperature gradient. Measured on the Sun in the late 19th century.

**Gravity darkening:** Intrinsic to the star, a pole to equator effective temperature gradient resulting from rapid rotation. Local surface temperature correlates with local gravity. First worked out by Hugo Von Zeipel in 1924. Observation evidence in the 1930s.


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Why not try two rapidly rotating stars at once!

SPICA

Now for some background ...
Spica (from the Latin for ‘ear of wheat’) lies in the zodical constellation Virgo and appears near the Sun during harvest time. Hipparchus (190 BC - 120 BC) used observations of Spica is discover the precession of the equinoxes.
Spica announced as binary star (radial velocity variable) in 1890 by H.C. Vogel. Spectrum of second star confirmed by A.C. Maury in 1897.
Fig. 1.—Radial velocities of α Virginis derived from the 1956 material. The velocity-curve is that of Struve and Ebbighausen (1934).
Spica and other bright and/or nearby stars on a theorician’s Hertzsprung-Russell diagram.
Fig. 1.3. Orbital plane and the tangent plane to the sky illustrating the significance of the orbital elements.
Orbital elements are not constant if stars are not point masses or more precisely if they are not spherical.

Rotation distorts stars, close stars distort each other.

So... $\omega$ advances with time. Both non-relativistic and relativistic terms.

$\omega$ = longitude of periastron
= direction of the major axis
= lines of apsides
For one thing*, these stars aren’t spherical!

*Other complexities include:
Asynchronous rotation, mutual irradiation, limb and gravity darkening, non-radial oscillations in Spica A
Apsidal Motion Theory

Potential of distorted star 1 at the center of 2,

\[
\left\{ \frac{R_1}{a} \right\}^5 k_{12} \left\{ \frac{G m_2}{R^6} + \frac{\omega_1^2}{3 R^3} \right\}
\]

\[k_{12} = \frac{3 - \eta_2(r_1)}{4 + 2 \eta_2(r_1)}\]

\[r \frac{d \eta_2}{dr} + \eta_2^2 - \eta_2 - 6 + \frac{6 \rho}{\bar{\rho}} (\eta_2 + 1) = 0\]

\[
\frac{\Delta \omega}{2\pi} = k_{12} \left[ \frac{m_2}{m_1} \left( \frac{R_1}{a} \right)^5 f(e) \right]
\]

\[k_{12} \text{ tells you about the run of density with stellar radius}\]
Apsidal Motion Observation

\[ \frac{d\omega}{dt} = 0.0071 \pm 0.0003 \text{ [degrees/day]} \quad U = 139 \pm 7 \text{ years} \]

Reduced \( \chi^2 = 1.38 \)

Luyten & Ebbighausen (1935)
Dukes (1974)
Lyubimkow et al. (1995)
Struve et al. (1958)

\[ \omega \text{ [degrees]} \]

\[ \text{JD} - 2400000 \text{ [days]} \]
Why Binaries Are So Important: Masses and Radii

Don’t know $a^3$ if you don’t know the inclination.

The projection of the ‘true ellipse’ on the sky is the apparent ellipse. Binary orbit must be resolved!
Spica’s Components Resolved by the Intensity Interferometer in 1971

Hebrison-Evans et al. (1971)

*Spica, the second spectroscopic binary to be resolved interferometrically (Capella 1st)*

*Find inclination ~ 63°, semi-major axis, a ~ 1.8 mas, distance = 80 parsec = 261 light-years*

*Massive components: Spica A ~11 Msun and ~7 Msun*
How Does an Interferometer See a Single Star?

On the Sky Intensity Map

Intensity

Dec [milliarcsec]

RA [milliarcsec]

Fourier Map

Fringe Contrast

spatial frequency [1/arcsec]

spatial frequency [1/arcsec]

Bird's Eye View of Fourier Map

U [cycles arcsec\(^{-1}\)]

V [cycles arcsec\(^{-1}\)]

Model Curve, 3.356±0.006 milliarcsecond diameter

Squared Visibility

low contrast

high contrast

very low contrast

Projected Baseline

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How Does an Interferometer See a Double Star

Image/SkyPlane

Fourier Plane

Visibility (Correlation)

Hour Angle

Interferometric Observations and Modeling Spica (α Vir)
Spica just agrees with theory, but the error bar is big!

We want to reduce the observational error bar. This means a better interferometric orbit and more sophisticated analysis.

Figure adapted from Claret and Gimenez (1993), adding Spica with the NSII 1971 orbit.
New Observations! Fourier Coverage of Spica from SUSI and CHARA

Sydney University Stellar Interferometer
North–South Baselines (up to ~ 100 m)

Center for High Angular Resolution Astronomy Array East–West Baseline (~ 313 m)

Fourier Plane

Interferometric Observations and Modeling Spica (α Vir)
Preliminary Model Comparison to SUSI+CHARA Visibility Data

![Graph showing squared visibility vs phase and ΔV²/σ² vs phase from periastron for SUSI, CHARA/FLUOR, and MODEL data.]

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Building a Binary Model for Spica

very preliminary values

$\omega$ Fraction of the angular break-up speed [0.50, 0.25]

$\theta_{\text{equ}}$ Equatorial angular diameter [1.076 mas, 0.45 mas]

$T_{\text{pole}}$ Effective temperature at the pole [25900 K, 20850 K]

$g_{\text{pole}}$ Surface gravity at the pole (Spica A) 3.67

$\beta$ Von Zeipel exponent [0.25, 0.25]

$P$ Period (periastron to periastron) 4.01459 days

$T_0$ Epoch of periastron 2440678.09

$\omega_0$ Longitude of periastron at $T_0$ 138°

$U$ Apsidal period 116 years

$i$ Orbital inclination 63.7°

$\Omega$ Longitude of the line of nodes 121.3°

$\theta_{\alpha}$ Angular size of the semi-major axis 1.82 mas

$K_1$ Semi-amplitude velocity of Spica A 124 km/s

$K_2$ Semi-amplitude velocity of Spica B 199 km/s

$\gamma$ Radial velocity of the center of mass -5.8 km/s

$\pi$ Orbital parallax (distance) 13.3 mas

\[ \frac{T_{\text{eff}}(\vartheta)}{T_{\text{eff}}^\text{pole}} = \left( \frac{g(\vartheta)}{g_{\text{pole}}} \right)^\beta \]

The intensity at each latitude, longitude point is interpolated from a grid of ~200 1-D non-LTE PHOENIX (Hauschildt et al.) model atmosphere radiation fields.

Interpolate $I_\lambda$ at each $T_{\text{eff}}, \log(g), \lambda, \mu$
Computation of Synthetic Images
including rotational distortion, limb and gravity darkening

Specific Fourier components of this synthetic image are computed for a visibility simulation.
Interferometric Simulation

CHARA E1-W1 Baseline Orientation

Phase = 0.07

Phase = 0.30

Interferometric Observations and Modeling Spica (α Vir)
Interferometric Simulation

Phase = 0.55

Phase = 0.80
Modeling the Orbital and Rotational Velocity Field
including rotational distortion, limb and gravity darkening

Rest frame wavelengths on the stars are mapped to observer’s frame for a high dispersion spectrum simulation.
Model Comparison to High Dispersion Spectroscopy

RJD = 49780.846

Normalized Flux

Heliocentric Air Wavelength [Å]

Phase = 0.415

RJD = 50589.622

Normalized Flux

Heliocentric Air Wavelength [Å]

Phase = 0.873

RJD = 50596.611

Normalized Flux

Heliocentric Air Wavelength [Å]

Phase = 0.627

Data: Ritter Astrophysical Observatory (U. of Toledo)

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Finally, A Model Comparison to Spectral Energy Distribution

Data: EURD, IUE, Glushneva et al., JHK

$\theta_{\text{model}} = 0.83$ mas
$E(B-V) = 0.00$
$R_V = 3.1$

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2-D atmospheric surface effects are beginning to be probed in binaries with long-baseline interferometry.

**Detailed atmospheric modeling required for analysis.**

Rich interferometric data sets (such as Spica) to have great potential for increasing our fundamental knowledge of close binaries and their internal structure.

**Next steps:**
1) including tidal distortion and irradiation effects
2) complete spectroscopic analysis, refine orbital parameters
3) reduce error bar on apsidal constant $k_{12}$
4) compare results with asteroseismology!