# Imaging Spotted Giant Stars

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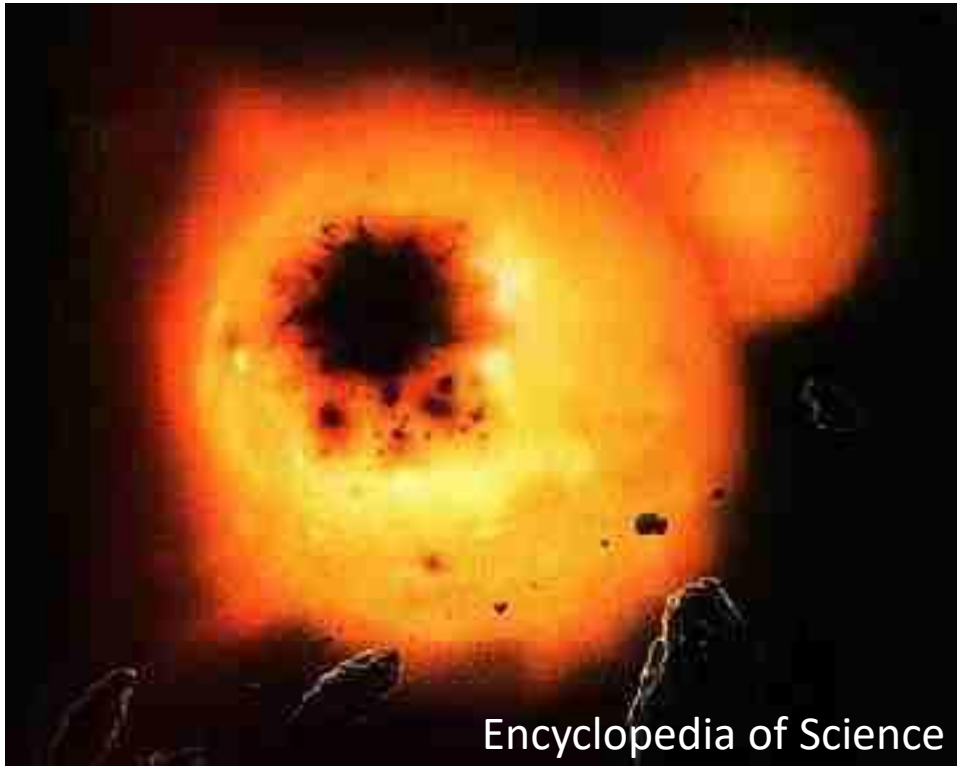
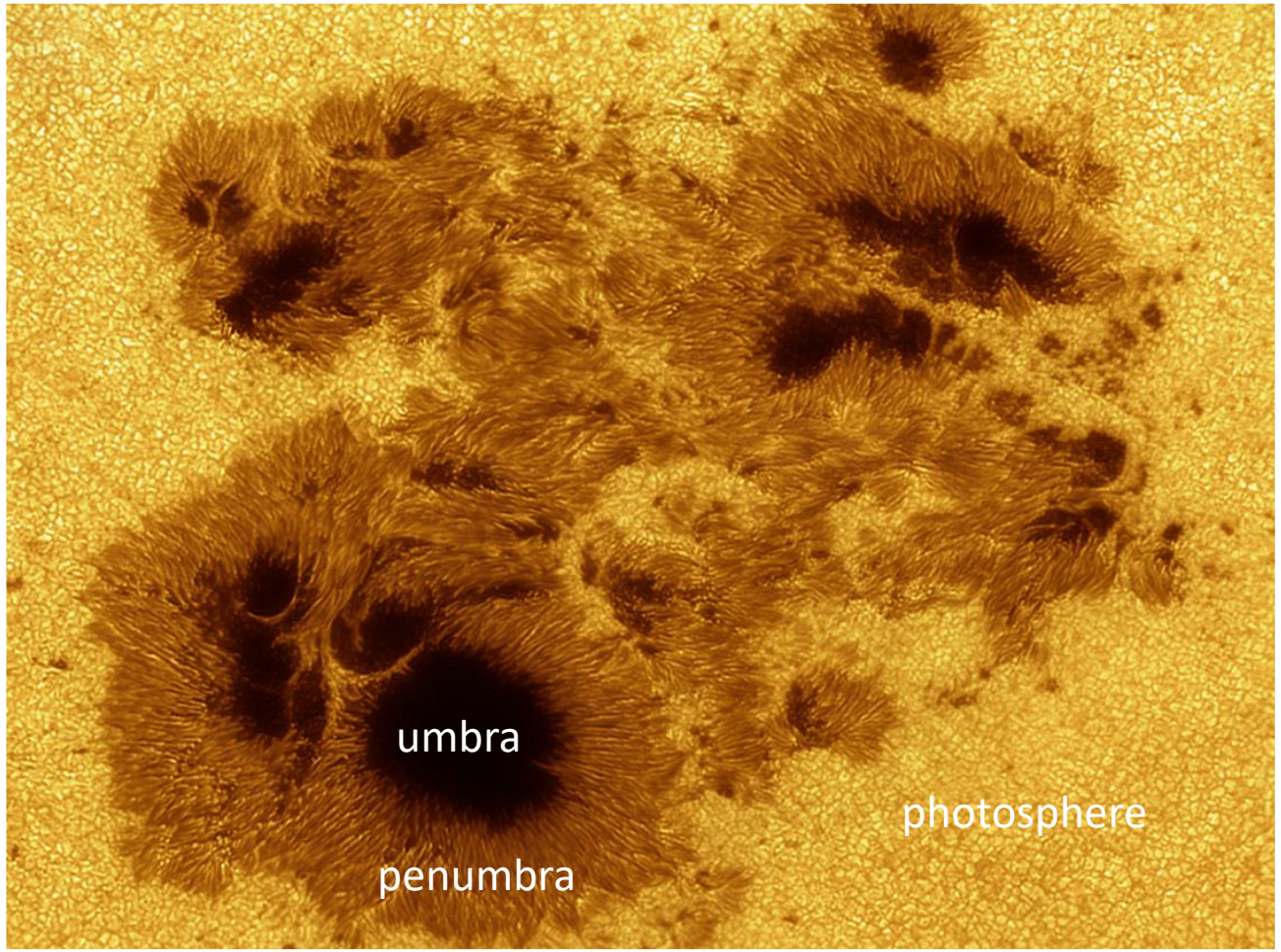
# RS Canum Venaticorum Stars

- Binary with giant primary and main sequence secondary
- Many with short orbital periods and tidally-locked
- Show photometric and Ca II H&K variability
- Spotted



# Sunspot Structure

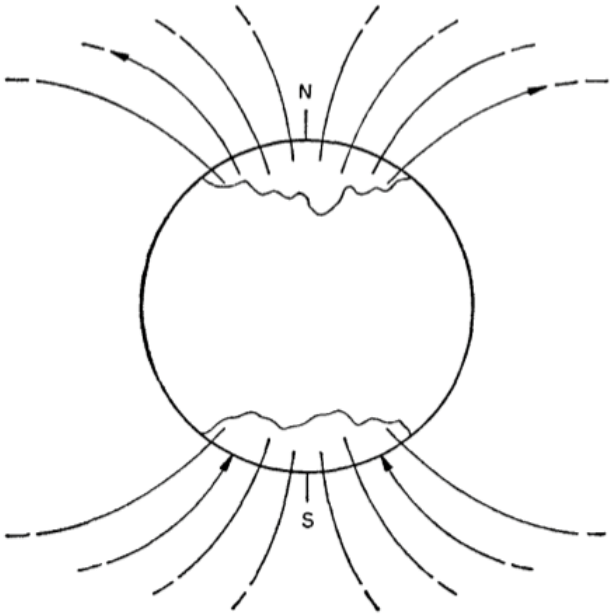
- Photosphere
  - $T_{eff}$ = 5777 K
  - $B$ ~ few G
- Penumbra
  - $T_{eff}$ ~ 5600 K
  - $B$ ~ 100 G
- Umbra
  - $T_{eff}$ ~ 4800 K
  - $B$ ~ few kG

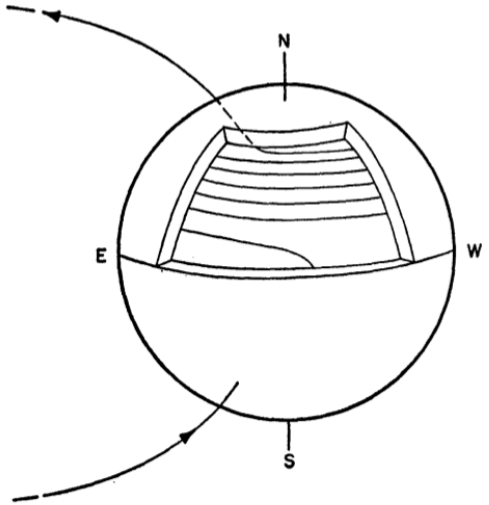


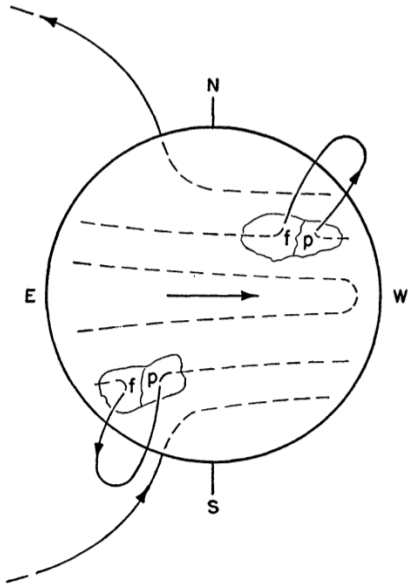

APOD/Shivak & Friedman

# Sunspot Magnetism

- Magnetic fields wrap around the surface due to differential rotation
- Starspots form where *B*-field is perpendicular to the surface



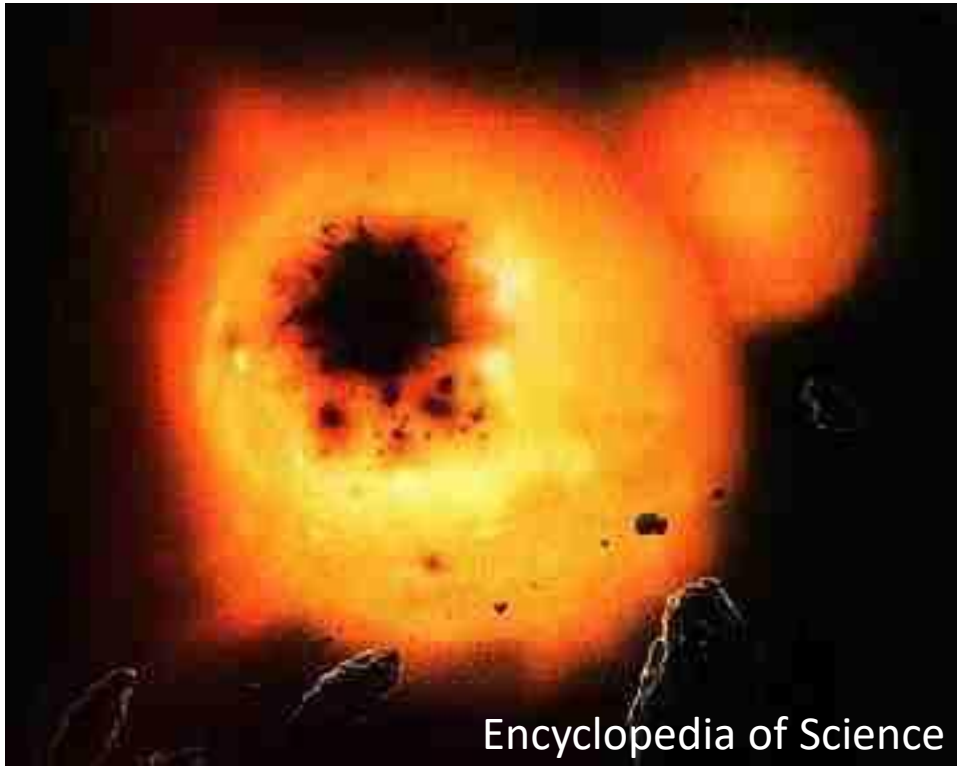




Babcock 1961

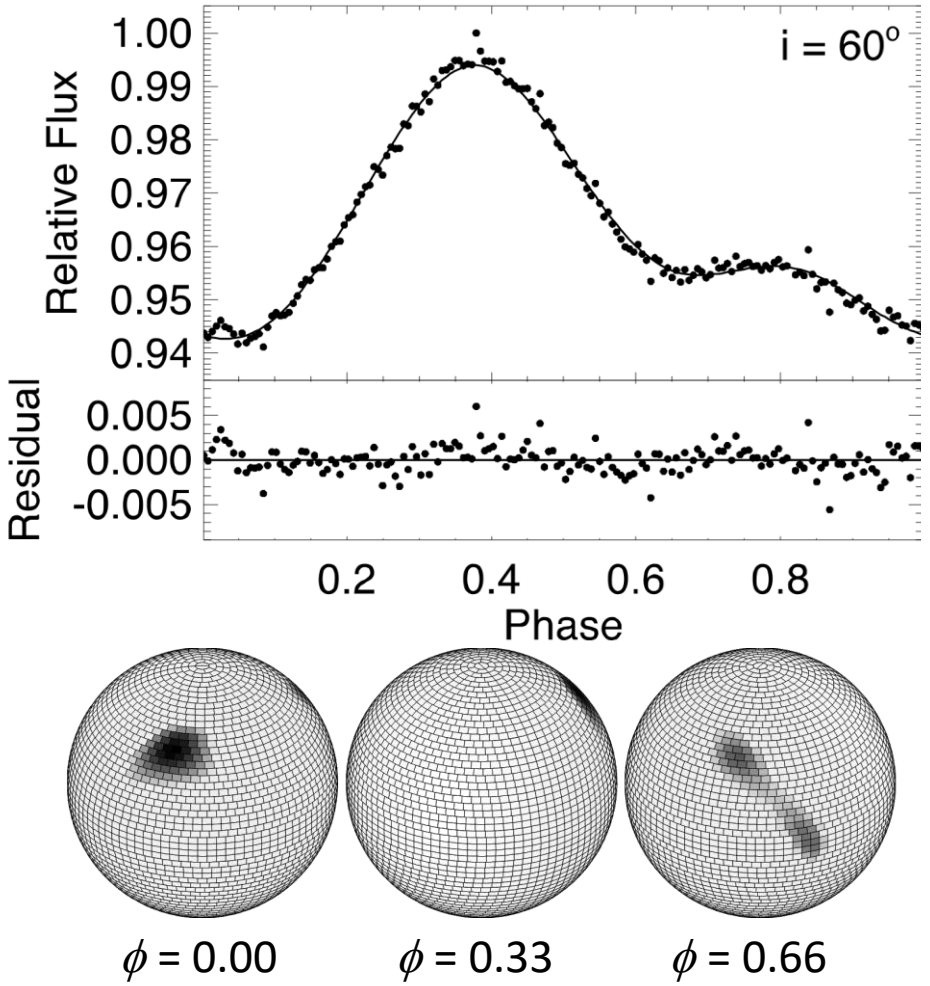
# RS CVn Imaging Campaign

- Simultaneous observing runs (photometry, spectroscopy, interferometry)
- Image data (light-curve inversion, Doppler, aperture synthesis imaging)
- Compare results



# Light-curve Inversion Imaging

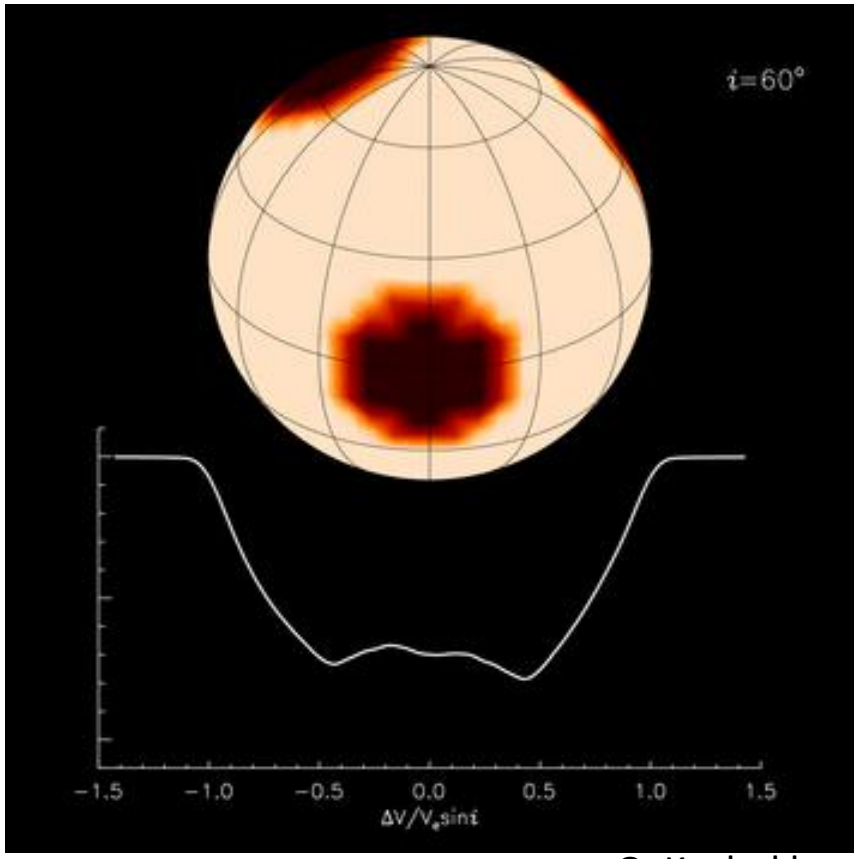
- Spots rotate in and out of view causing variability
- Advantages
  - Applied to any star
  - Constrains spot longitude
  - Requires little data
- Disadvantages
  - Poor latitude constraints
  - No inclination constraints
  - Only detects rotational modulation




Roettenbacher et al. 2013

# Doppler Imaging

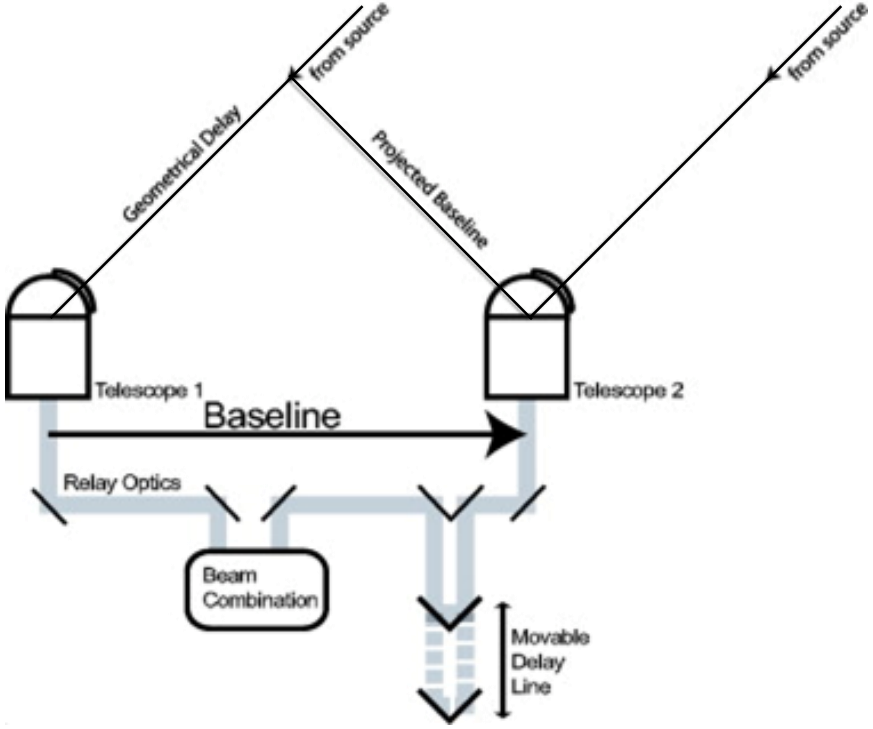
- Spots rotate in and out of view seen as distortions in absorption lines
- Advantages
  - Constrains spot latitude
  - Constrains spot longitude
- Disadvantages
  - Requires high signal-to-noise, high-resolution spectra
  - Requires good phase coverage
  - Requires rapidly-rotating stars




O. Kochukhov

# Interferometric Imaging

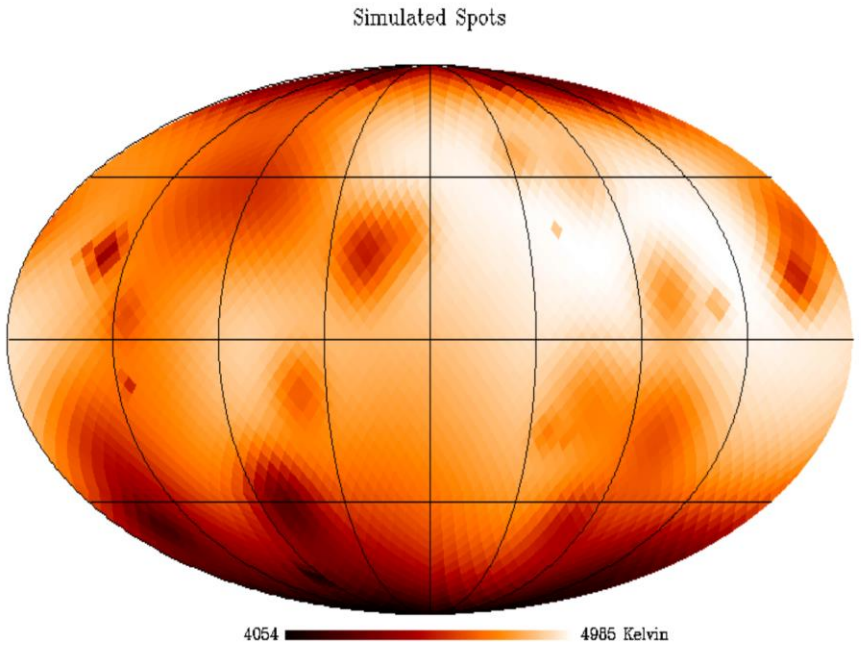
- Spots imaged directly as they appear on the surface
- Advantages
  - Determines orientation on sky, inclination
  - Accurately maps spot location
  - No fundamental limit to resolution
- Disadvantages
  - Requires large stars
  - Requires bright stars
  - Limited baseline lengths




Monnier 2003
Monnier et al. 2007

# SURFING: SURFace imagING

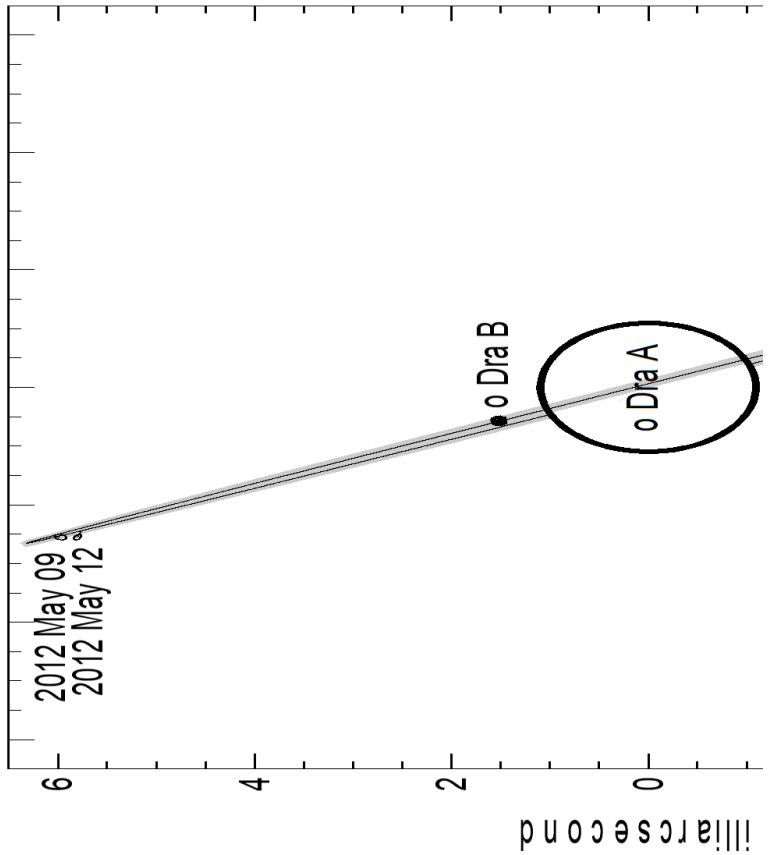
- Each pixel on the surface of a rotating star can be changed to fit multi-epoch data
- More robust than imaging single snapshots
- Analogous to technique used in Doppler imaging



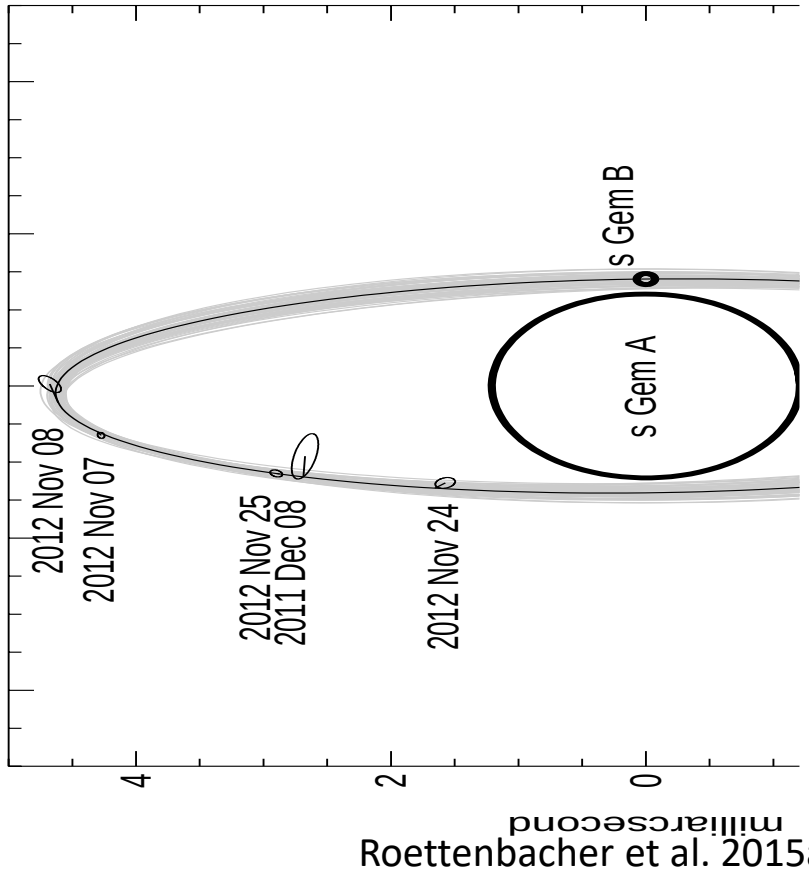

Monnier in prep.

# MIRC Orbits of RS CVns

*H*-band flux ratio 370:1



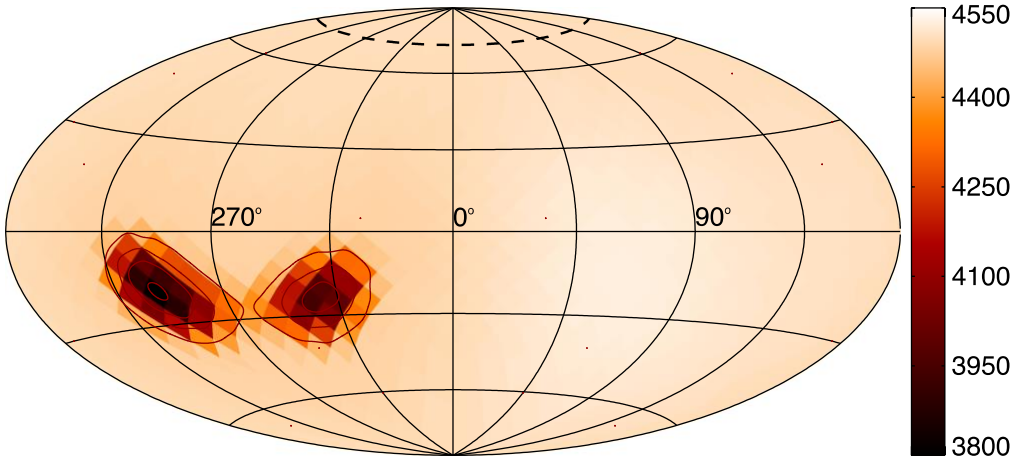

*H*-band flux ratio 270:1




Roettenbacher et al. 2015a,b

# Starspots of σ Gem

*2011*
*Imaging*

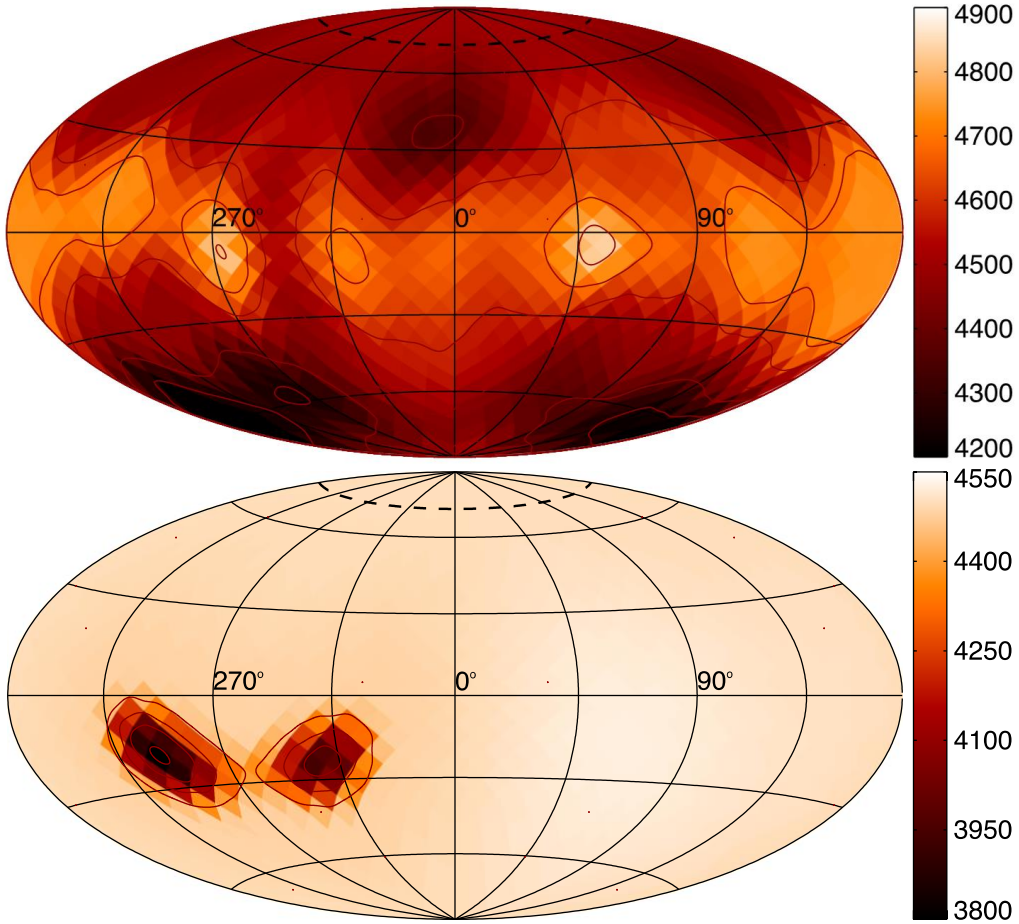



P = 19.6 days

Roettenbacher et al. 2017

# Starspots of σ Gem

*2011 Imaging*

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Roettenbacher et al. 2017

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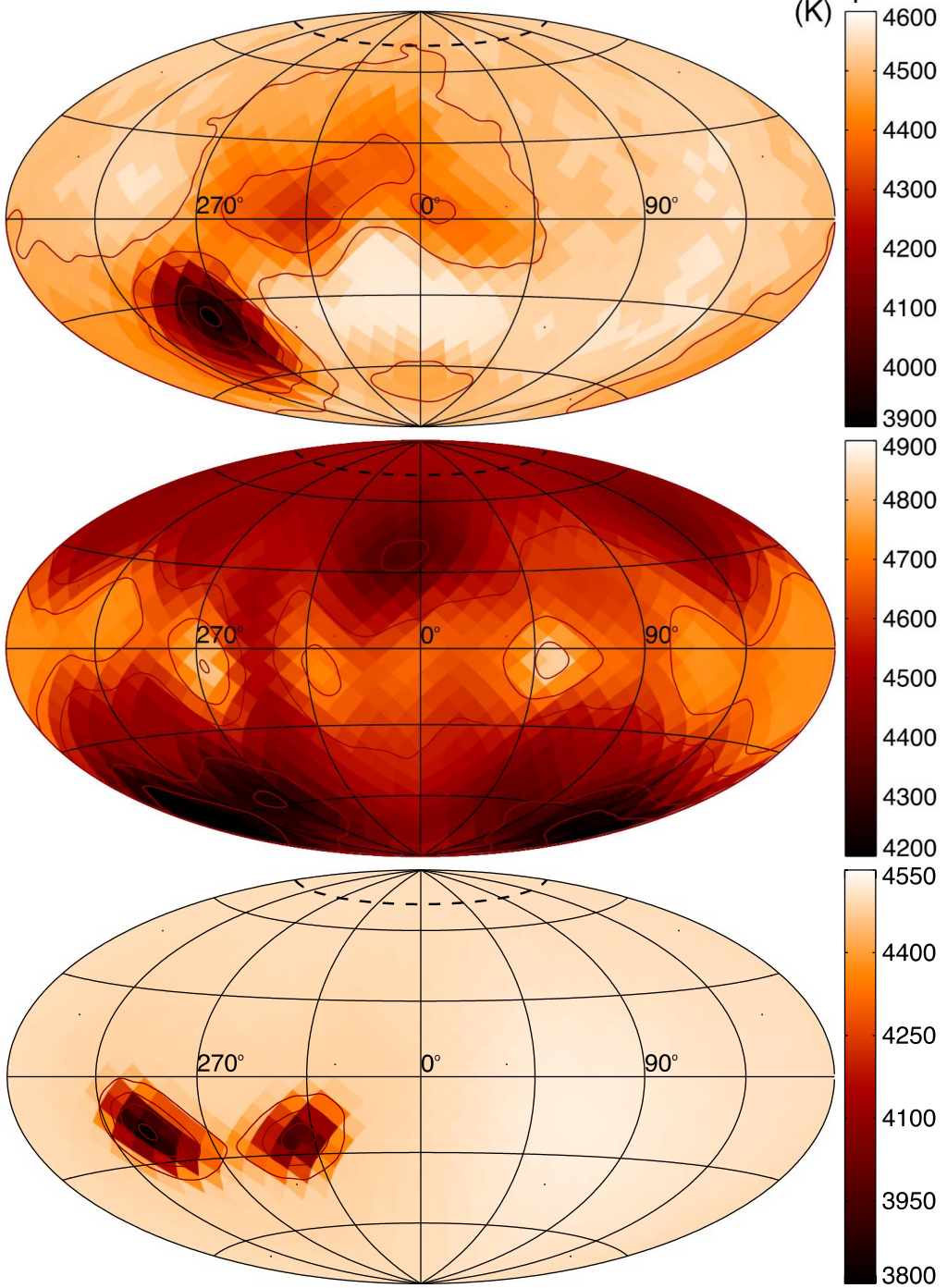
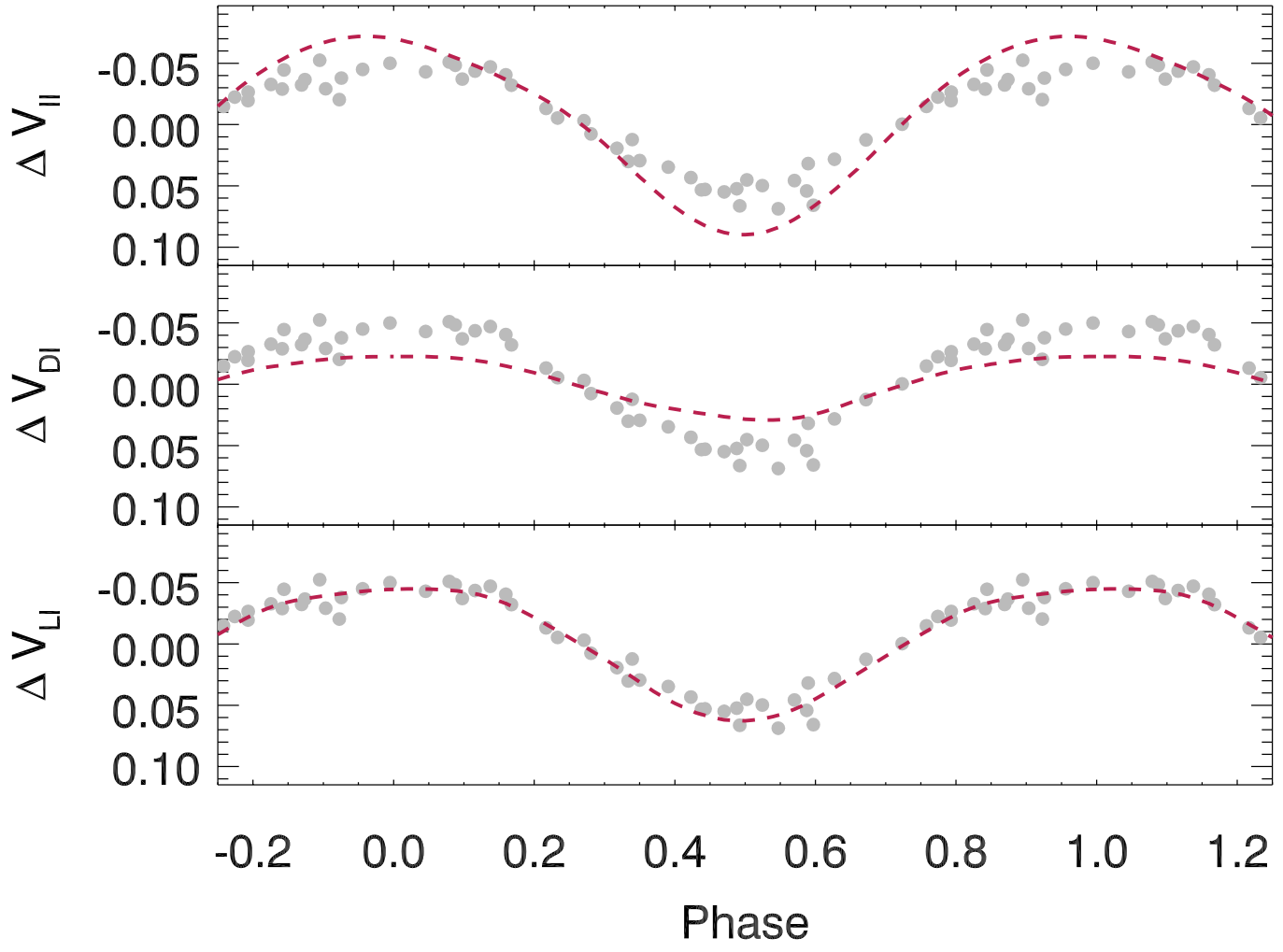
*2011 Imaging*




P = 19.6 days

Roettenbacher et al. 2017

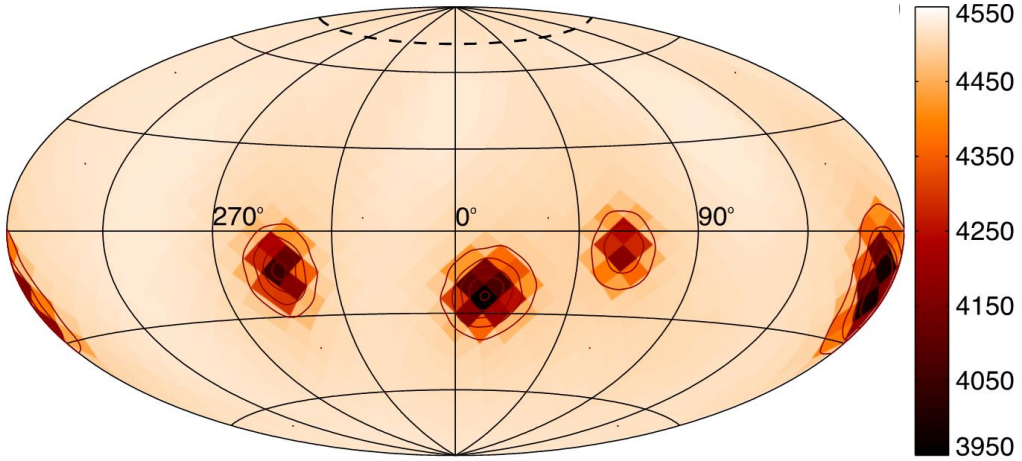
# 2011 σ Gem Light Curve Comparison




Roettenbacher et al. 2017

# Starspots of σ Gem

*2012*
*Imaging*

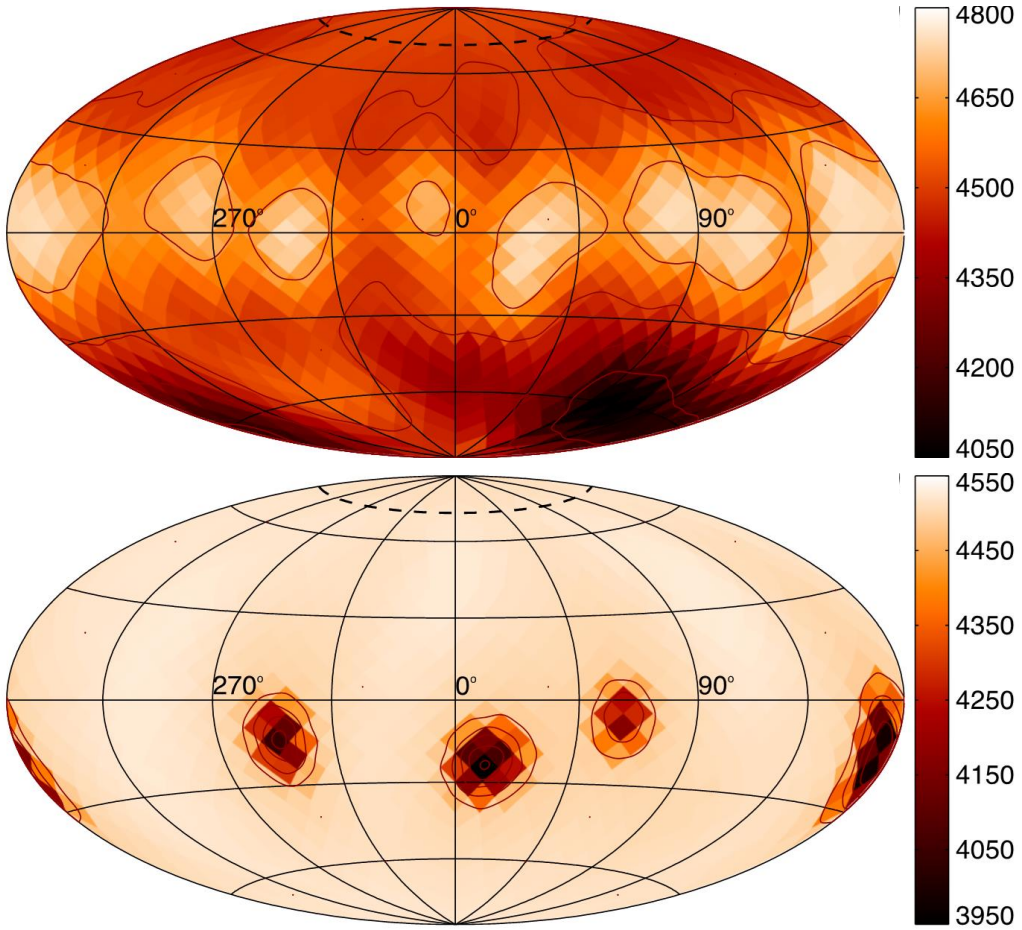



P = 19.6 days

Roettenbacher et al. 2017

# Starspots of σ Gem

*2012 Imaging*

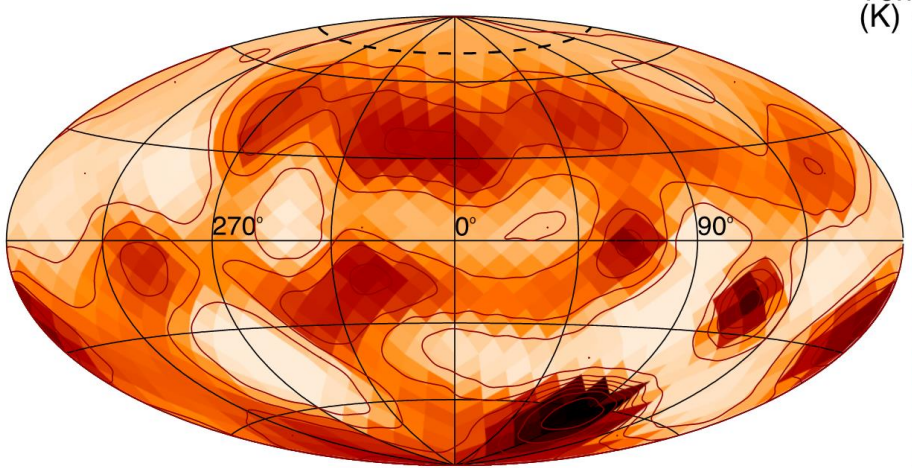


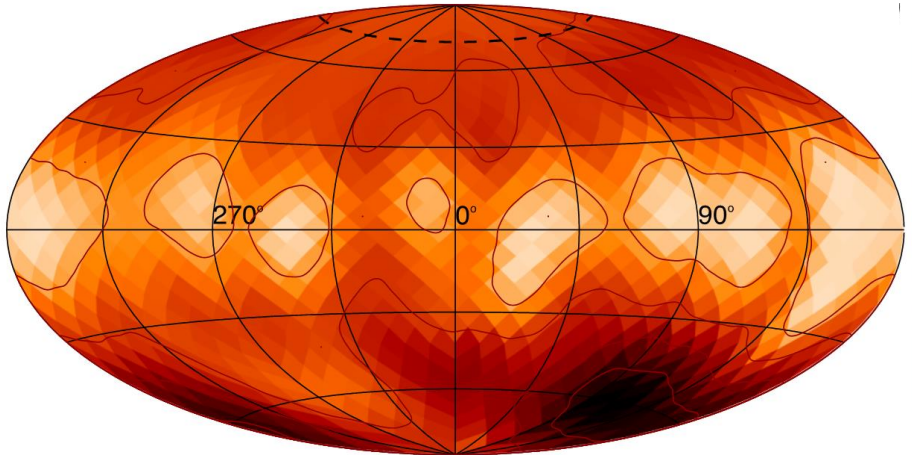

P = 19.6 days

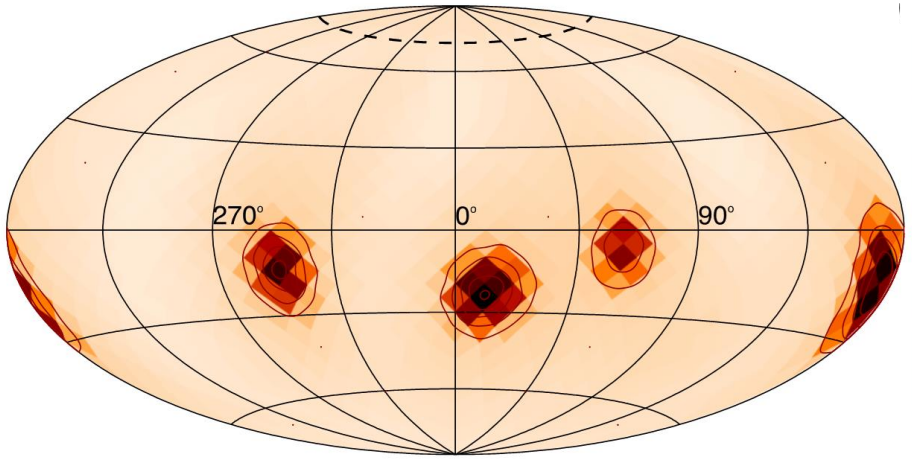
Roettenbacher et al. 2017

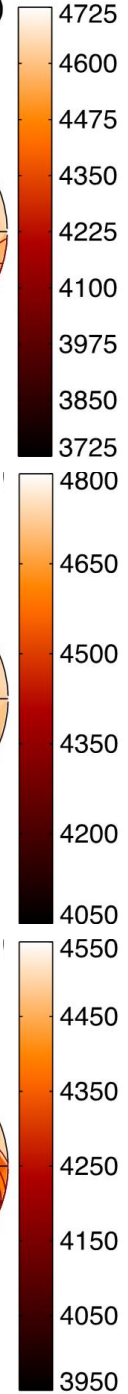
# Starspots of σ Gem

*2012 Imaging*



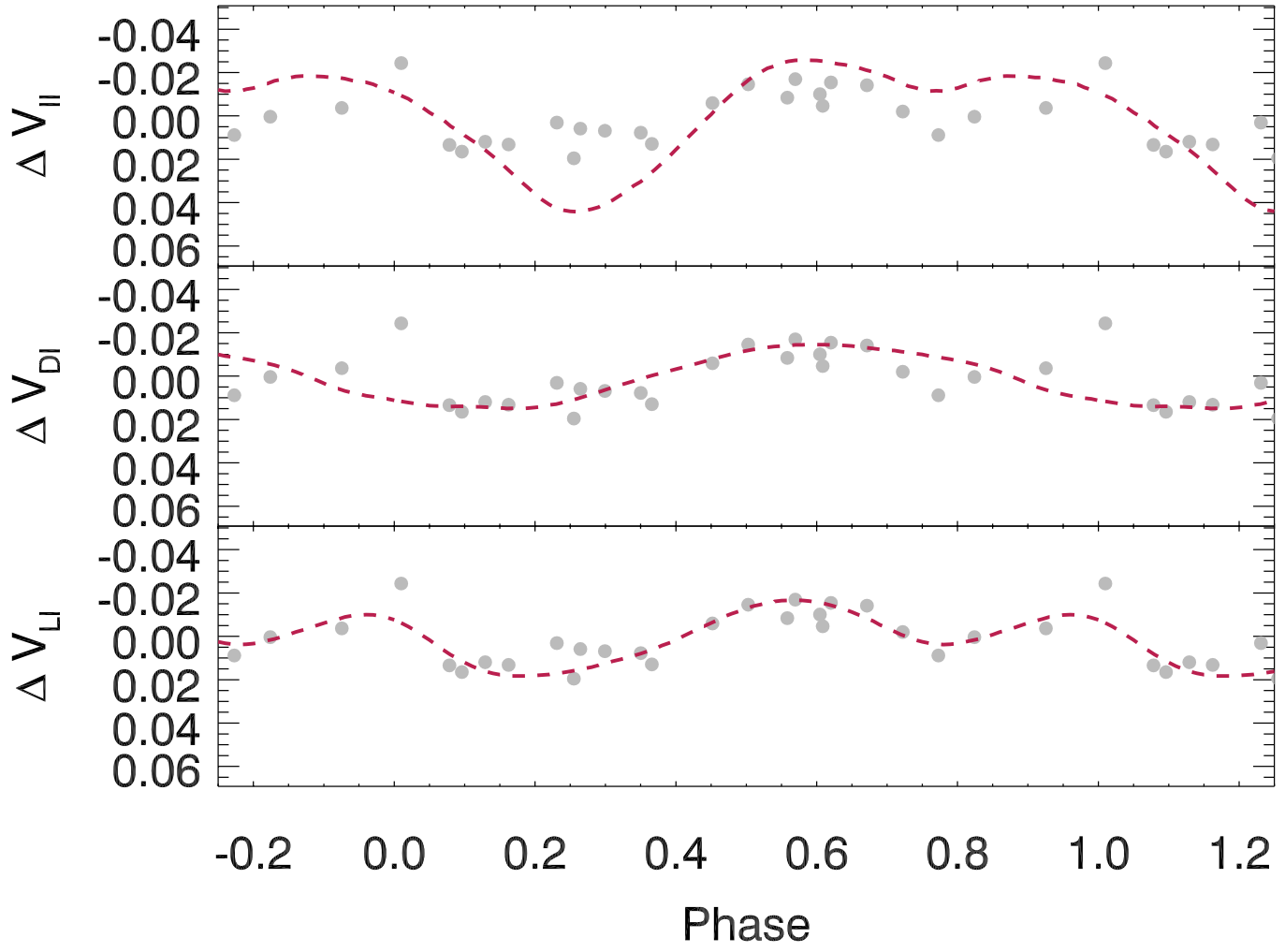




P = 19.6 days

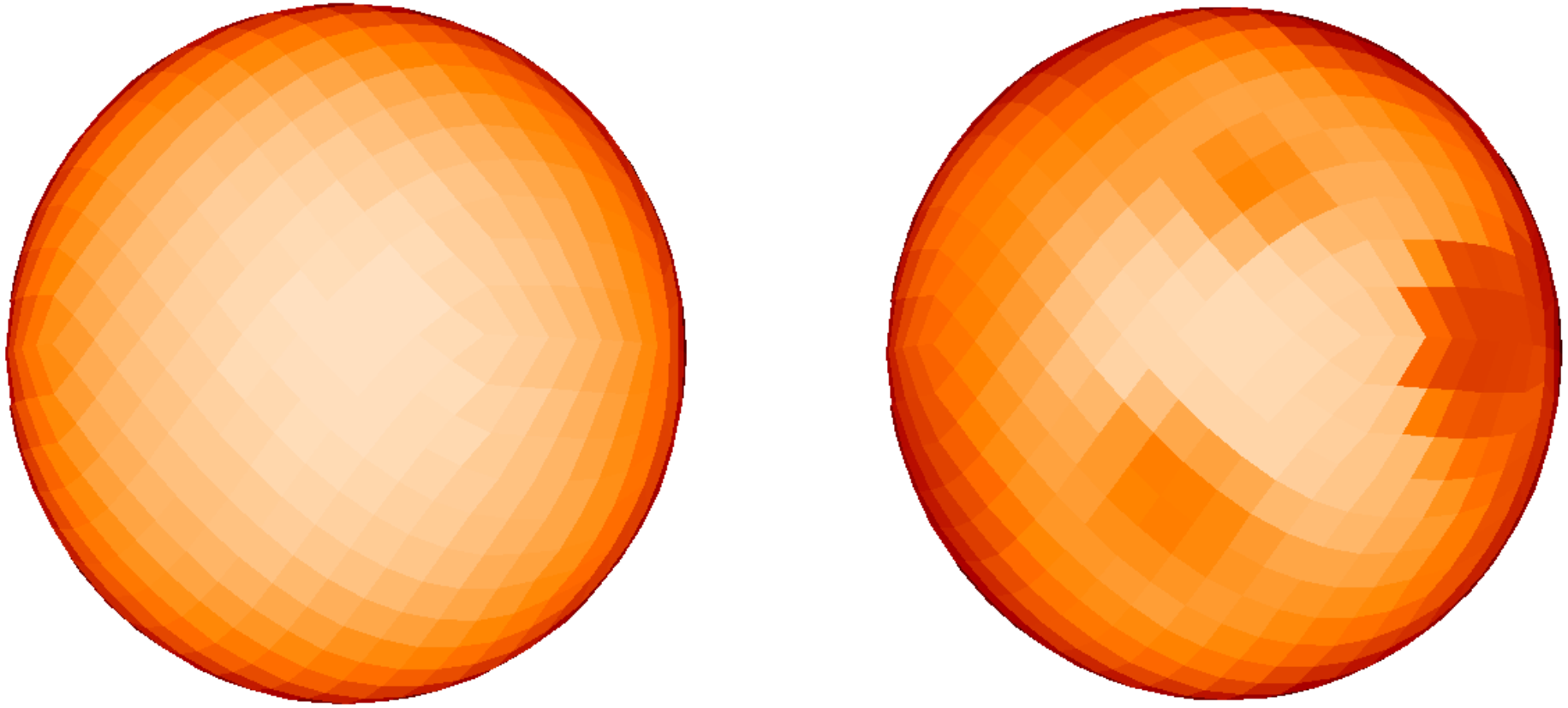
Roettenbacher et al. 2017

# 2012 σ Gem Light Curve Comparison




Roettenbacher et al. 2017

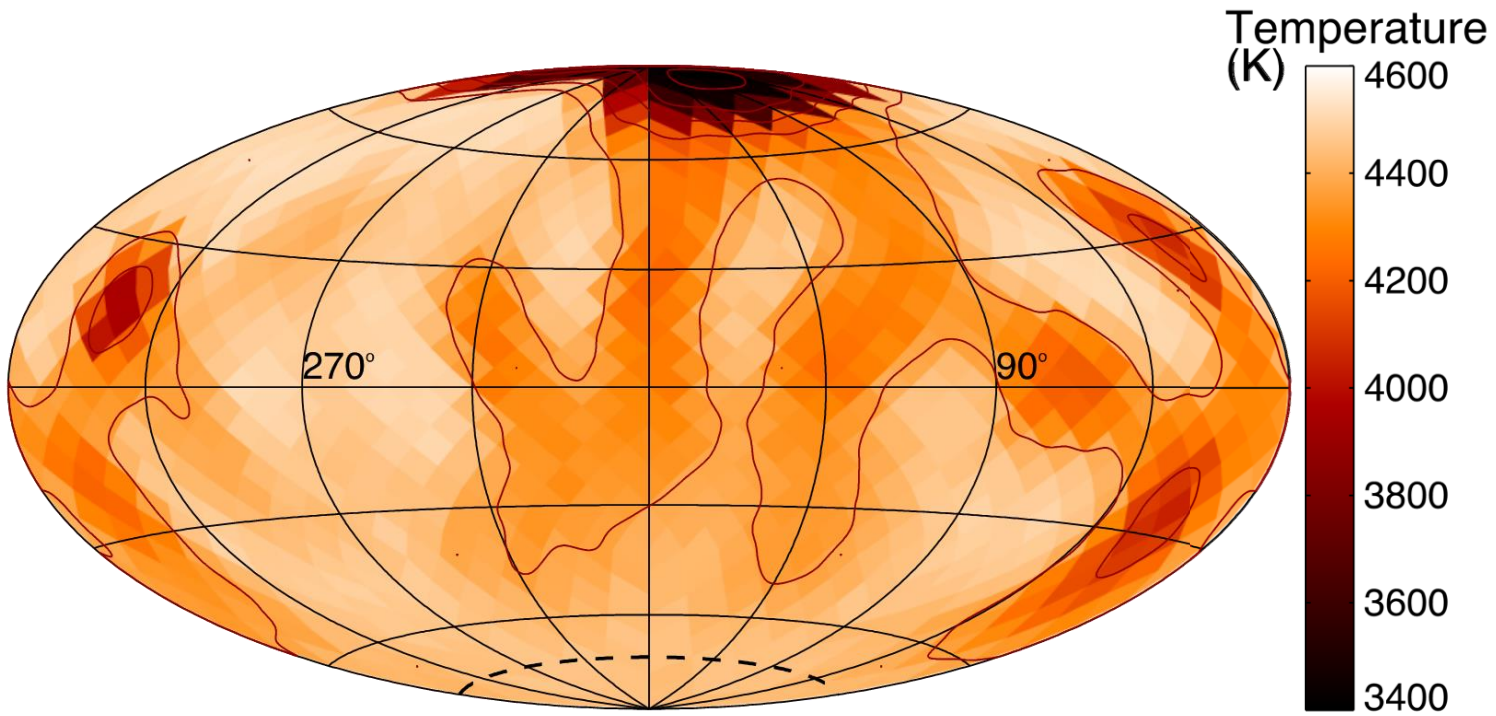
# σ Gem in *H*-band



2011 2012

Roettenbacher et al. 2017

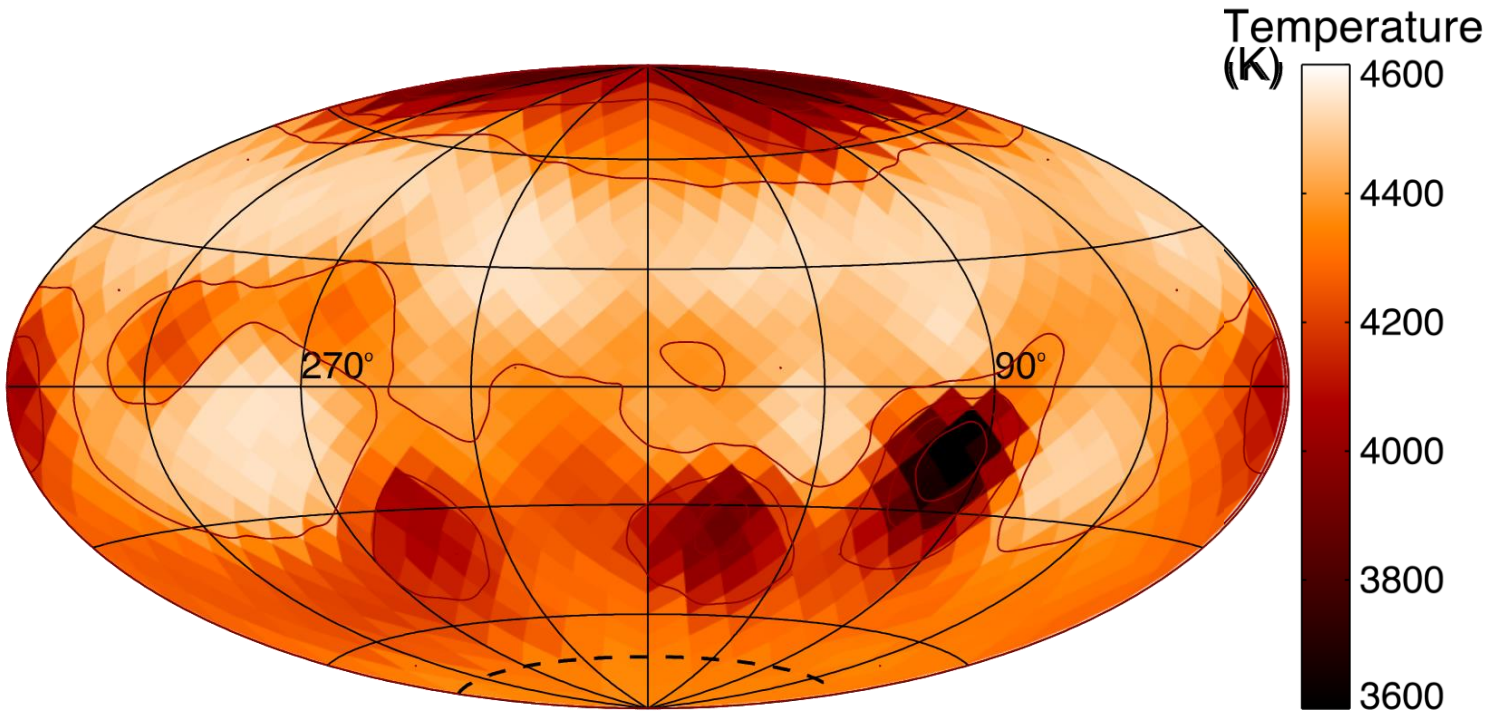
# 2011 ζ And Imaging




P = 17.7 days

Roettenbacher et al. 2016

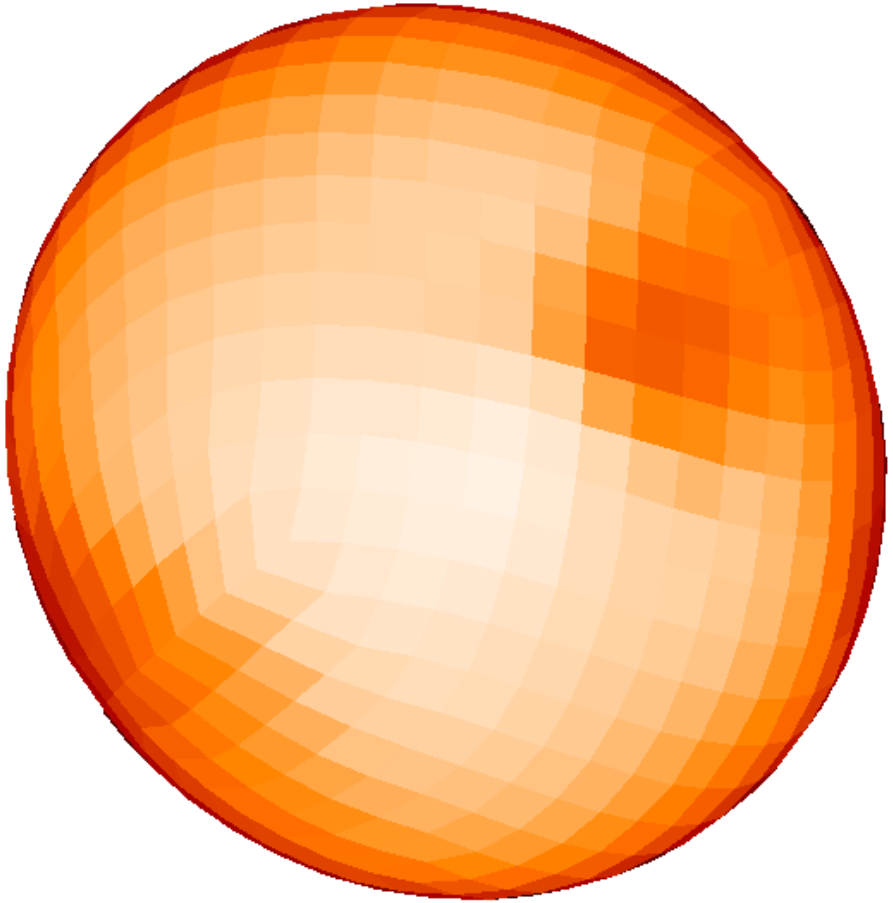
# 2013 ζ And Imaging




P = 17.7 days

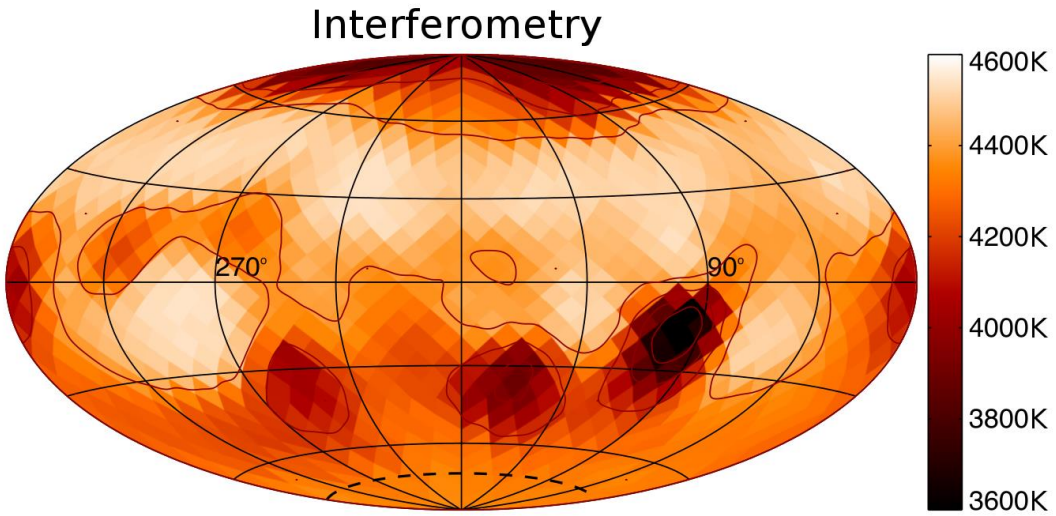
Roettenbacher et al. 2016

# 2013 ζ And in *H*-band



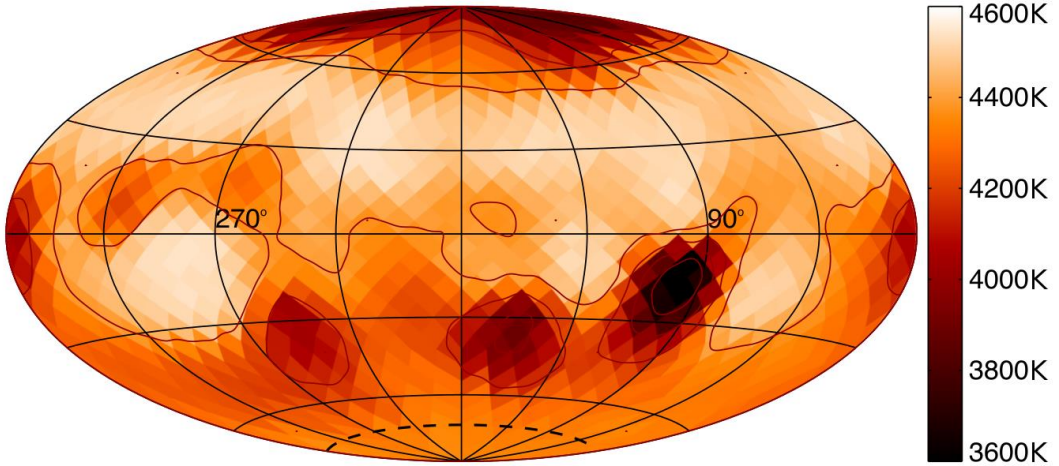
Roettenbacher et al. 2016

# ζ Andromedae

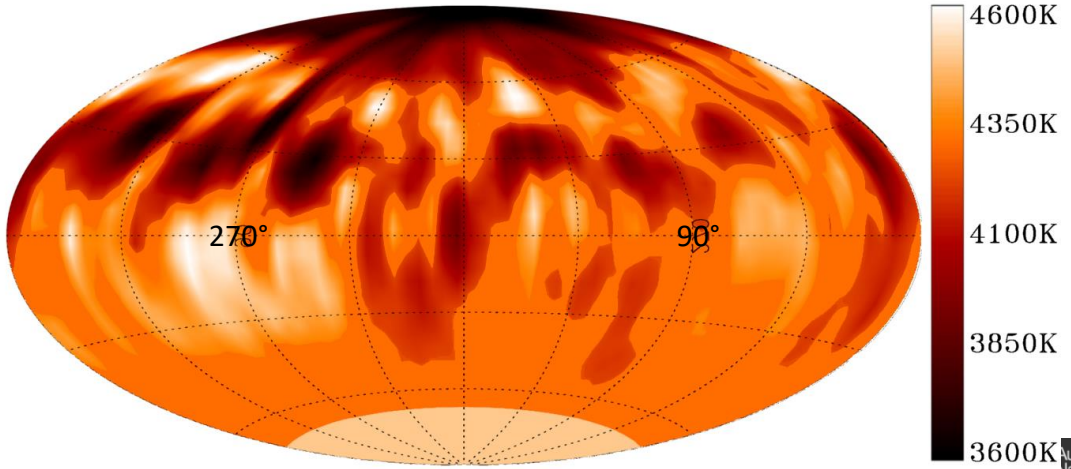


# ζ Andromedae

Interferometry




Doppler imaging

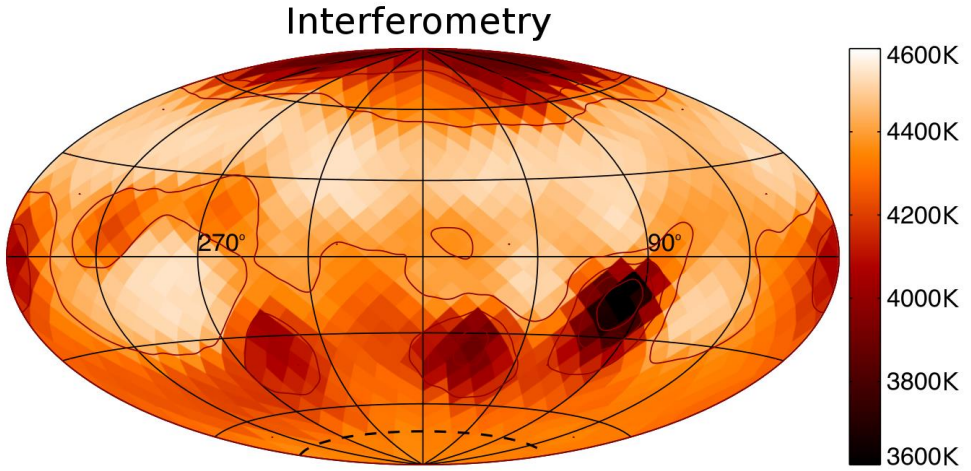


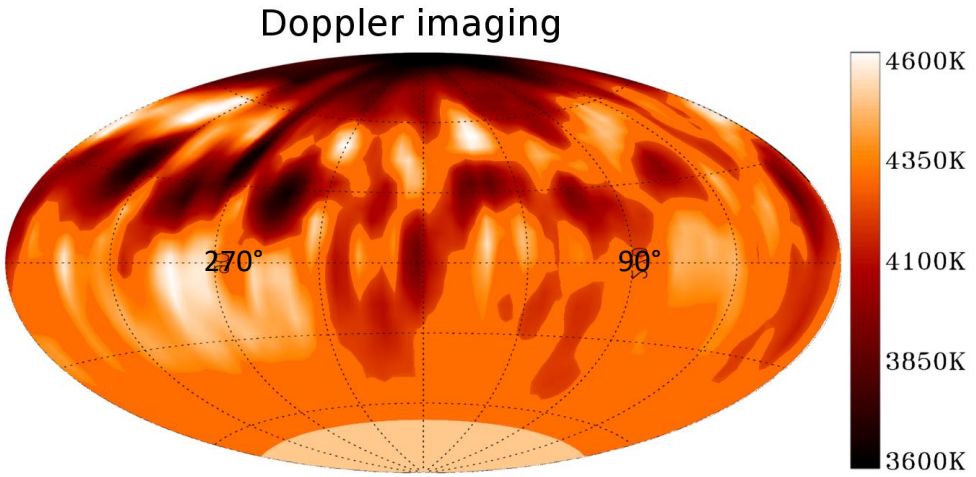

Doppler image provided by Zsolt Kővári

# ζ Andromedae

To Do

- Finalize Doppler image



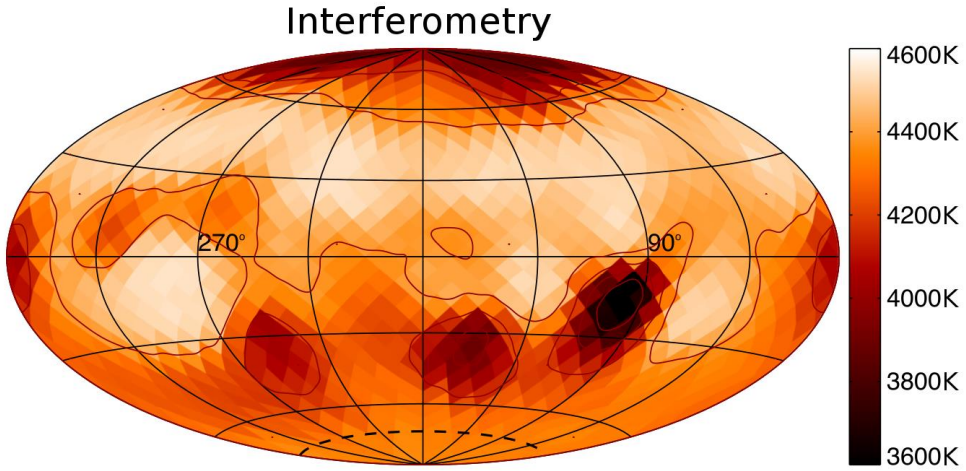



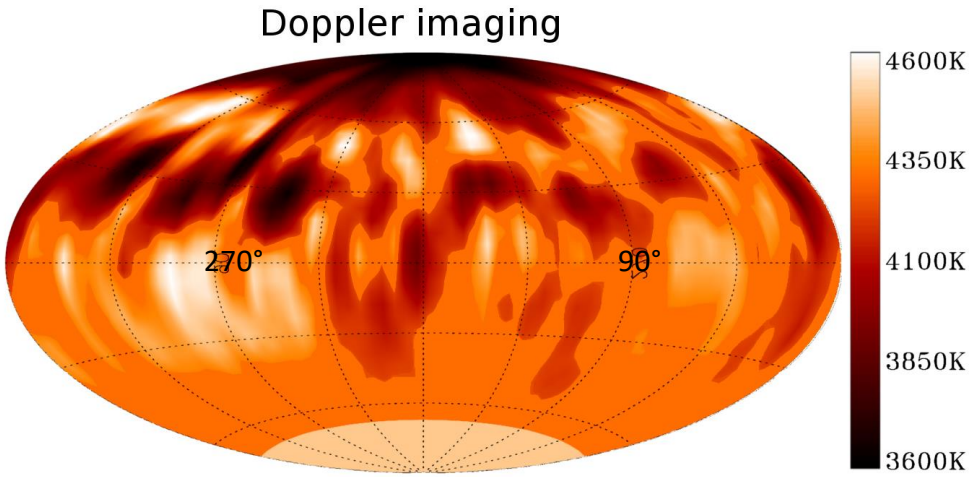

Doppler image provided by Zsolt Kővári

# ζ Andromedae

To Do

- Finalize Doppler image
- Surfaces converted to light curves



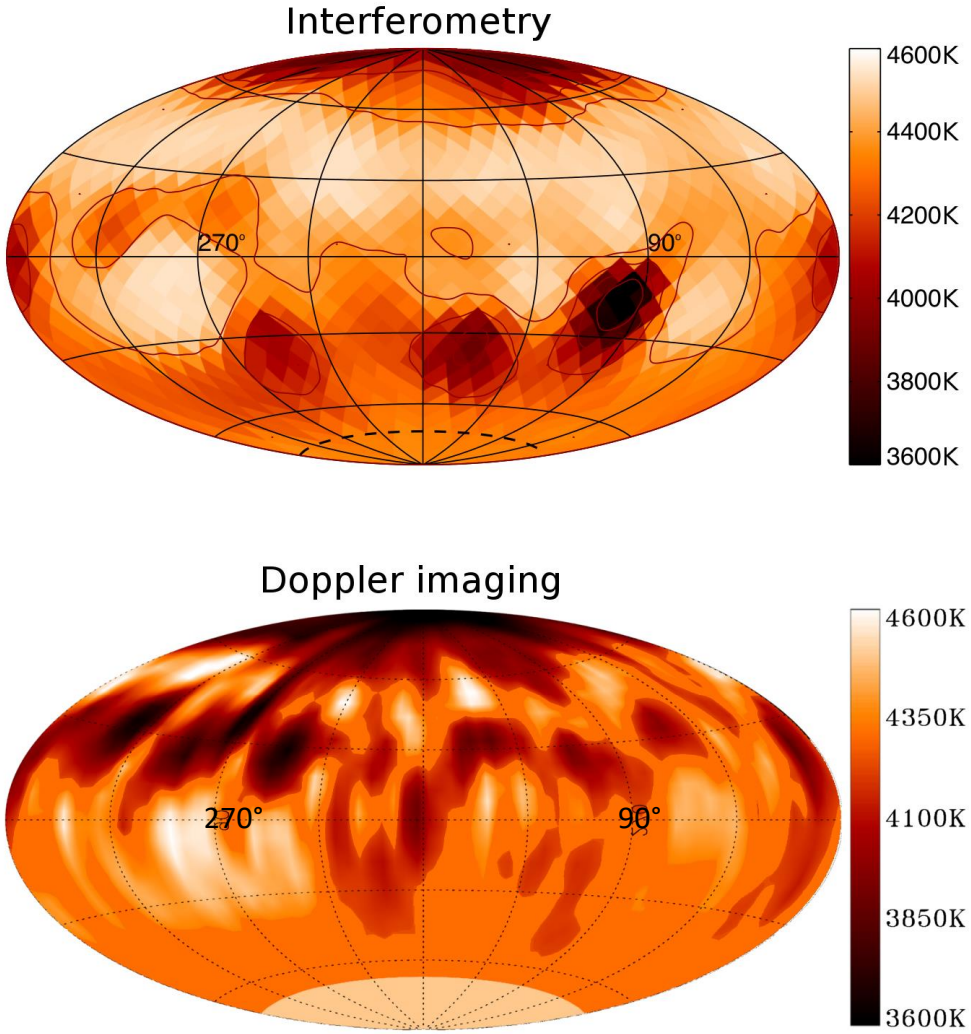




Doppler image provided by Zsolt Kővári

# ζ Andromedae

To Do

- Finalize Doppler image
- Surfaces converted to light curves
- NEW! MIRC surface converted to spectra and compared to observed

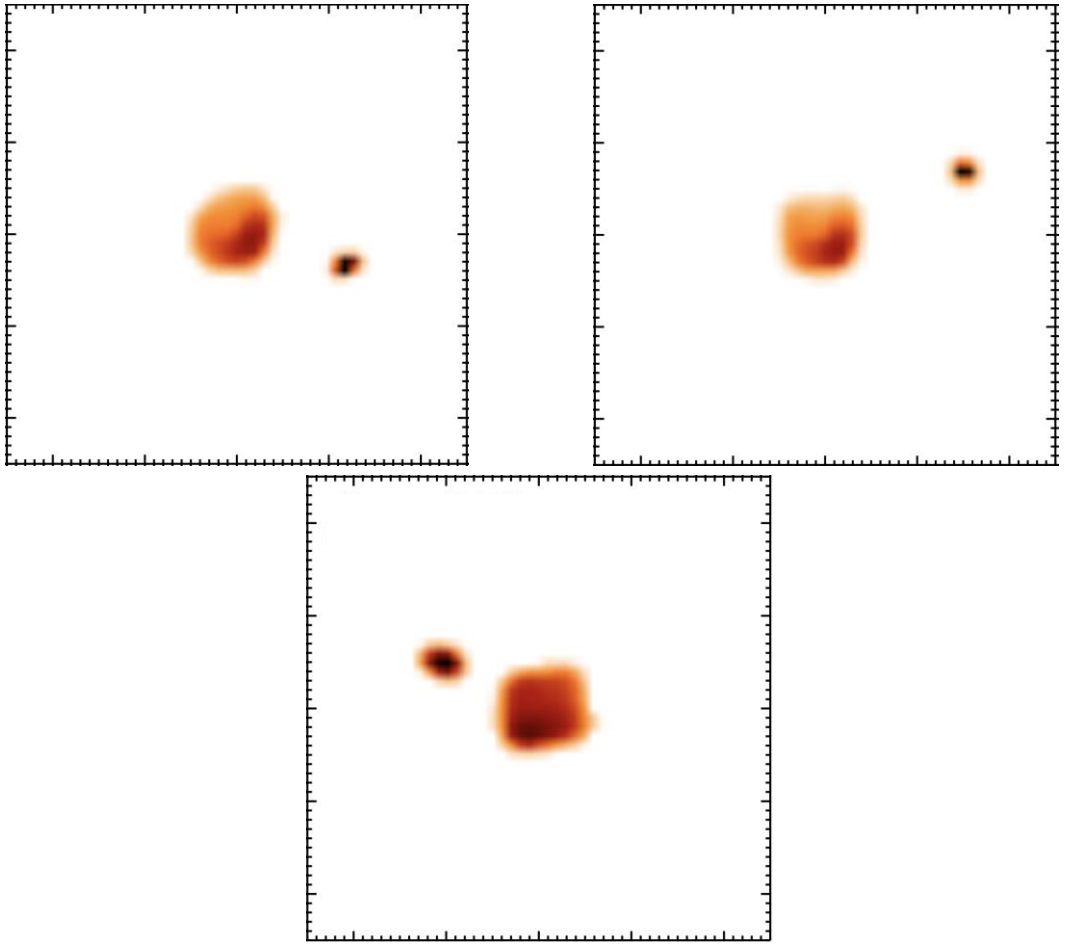



Doppler image provided by Zsolt Kővári

# Next: UX Ari

- Simultaneous MIRCX, VLT UVES spectra, SMARTS 1.3m photometry
- Waiting on the MIRCX pipeline!

2012 MIRC Images



Hummel et al. 2017