



Multiepoch resolved observations of the Atmosphere of the Betelgeuse in 2019-2020 using differential speckle polarimetry

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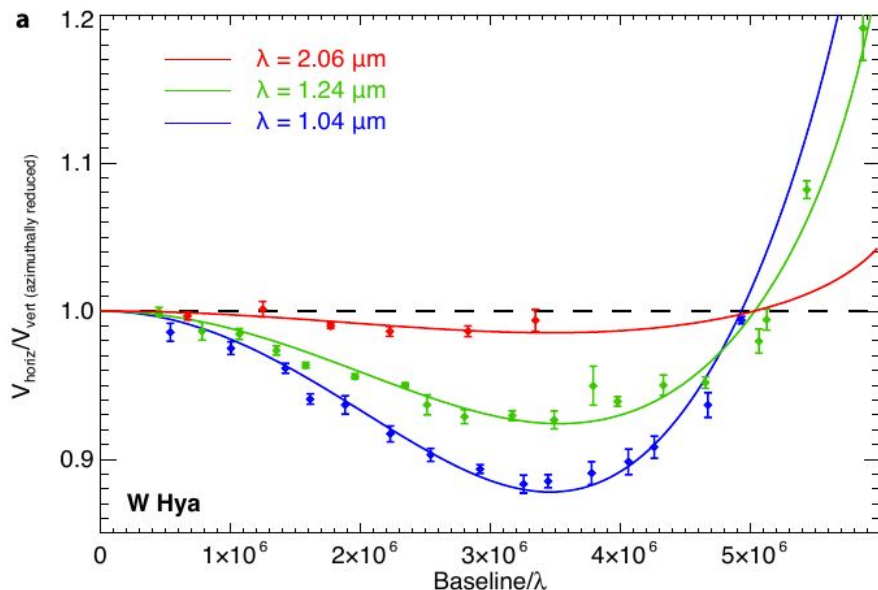
Polarimetric interferometry

Visibility - Fourier transform of object's image I.

Basic observable - differential polarimetric visibility - ratio of visibilities in orthogonal polarizations:

$$\mathcal{R}_Q(\vec{f}) = \frac{\tilde{I}(\vec{f}) + \tilde{Q}(\vec{f})}{\tilde{I}(\vec{f}) - \tilde{Q}(\vec{f})}, \quad \mathcal{R}_U(\vec{f}) = \frac{\tilde{I}(\vec{f}) + \tilde{U}(\vec{f})}{\tilde{I}(\vec{f}) - \tilde{U}(\vec{f})}.$$

$\tilde{I}(\vec{f}), \tilde{Q}(\vec{f}), \tilde{U}(\vec{f})$ - Fourier transforms of Stokes parameters distributions.



$$\mathcal{R}_Q \neq 1$$

$$\mathcal{R}_U \neq 1$$

Polarized flux is resolved

Norris et al 2012Natur.484..220N:
(dual beam polarimetry + aperture masking at VLT/NACO)

Short-exposure images in dual-beam polarimeter

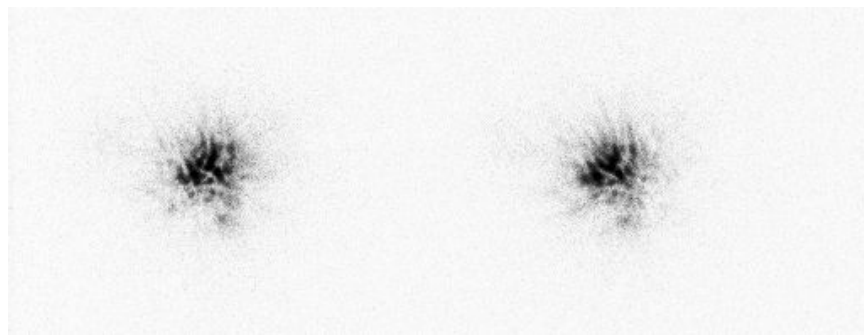
$$F_{\text{horz}}(\vec{\alpha}) = T_{\text{a,horz}}(\vec{\alpha}) \otimes (I(\vec{\alpha}) + Q(\vec{\alpha})) + \mathcal{N}_1(\vec{\alpha}),$$

$$F_{\text{vert}}(\vec{\alpha}) = T_{\text{a,vert}}(\vec{\alpha}) \otimes (I(\vec{\alpha}) - Q(\vec{\alpha})) + \mathcal{N}_2(\vec{\alpha}),$$

PSF of atmosphere
+telescope

convolution


noise



Meanwhile in Fourier space

$$\tilde{F}_{\text{horz}}(\vec{f}) = \tilde{T}_{\text{a,horz}}(\vec{f}) \cdot (\tilde{I}(\vec{f}) + \tilde{Q}(\vec{f})) + \tilde{N}_1(\vec{f}),$$

$$\tilde{F}_{\text{vert}}(\vec{f}) = \tilde{T}_{\text{a,vert}}(\vec{f}) \cdot (\tilde{I}(\vec{f}) - \tilde{Q}(\vec{f})) + \tilde{N}_2(\vec{f}),$$

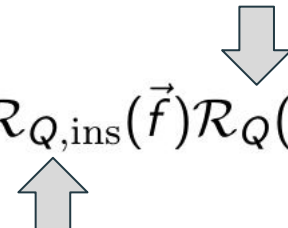


 OTF of atmosphere
+telescope product noise

Safonov 2013AstL...39..237S:

estimator

$$\mathcal{R}_{Q,\text{obs}}(\vec{f}) = \frac{\langle \tilde{F}_{\text{horz}} \tilde{F}_{\text{vert}}^* \rangle}{\langle \tilde{F}_{\text{vert}} \tilde{F}_{\text{vert}}^* \rangle - M_{\text{ph}}} \approx \mathcal{R}_{Q,\text{ins}}(\vec{f}) \mathcal{R}_Q(\vec{f}).$$

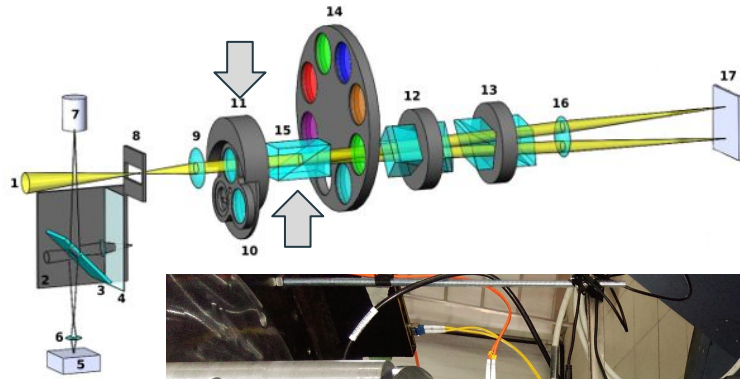


 differential polarimetric visibility Bias due to instrumental polarization (can be removed using measurements of unpolarized stars).

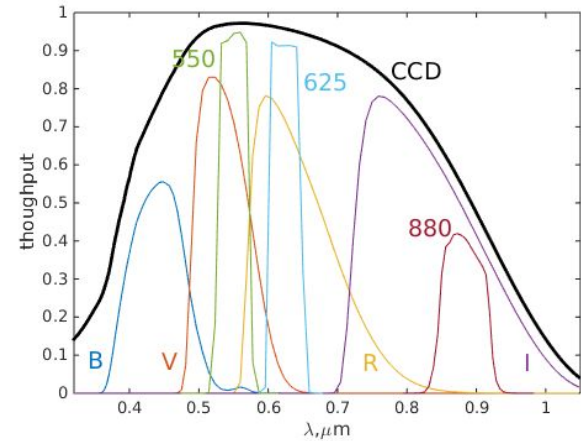
Differential Speckle Polarimetry

Mode details: Safonov, 2013 (2013AstL...39..237S),

Speckle polarimeter of 2.5-m telescope



- EMCCD-based speckle interferometer FOV 5"x10"
- Dual-beam polarimeter: Wollaston prism + rotating HWP
- Atmospheric Dispersion Compensator
- Wavelength range: 0.4-1.0 μm
- Standard mode: HWP rotates at $300^\circ/\text{sec}$, $t_{\text{exp}}=30\text{ms}$, 5000-35000 frames are accumulated

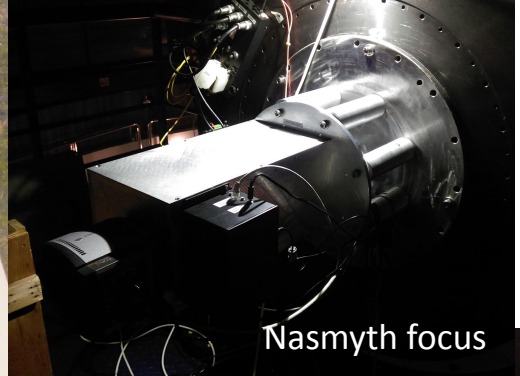
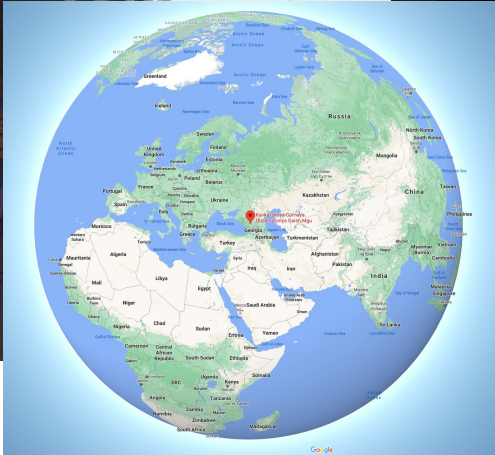


Safonov et al 2017AstL...43..344S

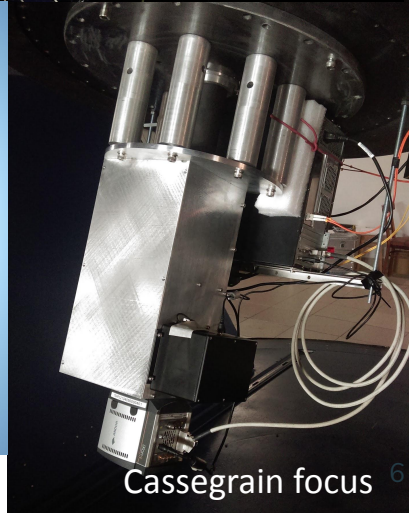
Speckle polarimeter of 2.5-m telescope



Feeding optics: 2.5-m telescope of SAI MSU:
lat= $43^{\circ}44'10''$ N, lon= $42^{\circ}40'03''$ E, altitude 2127 m a.s.l.
Kornilov et al 2010MNRAS.408.1233K

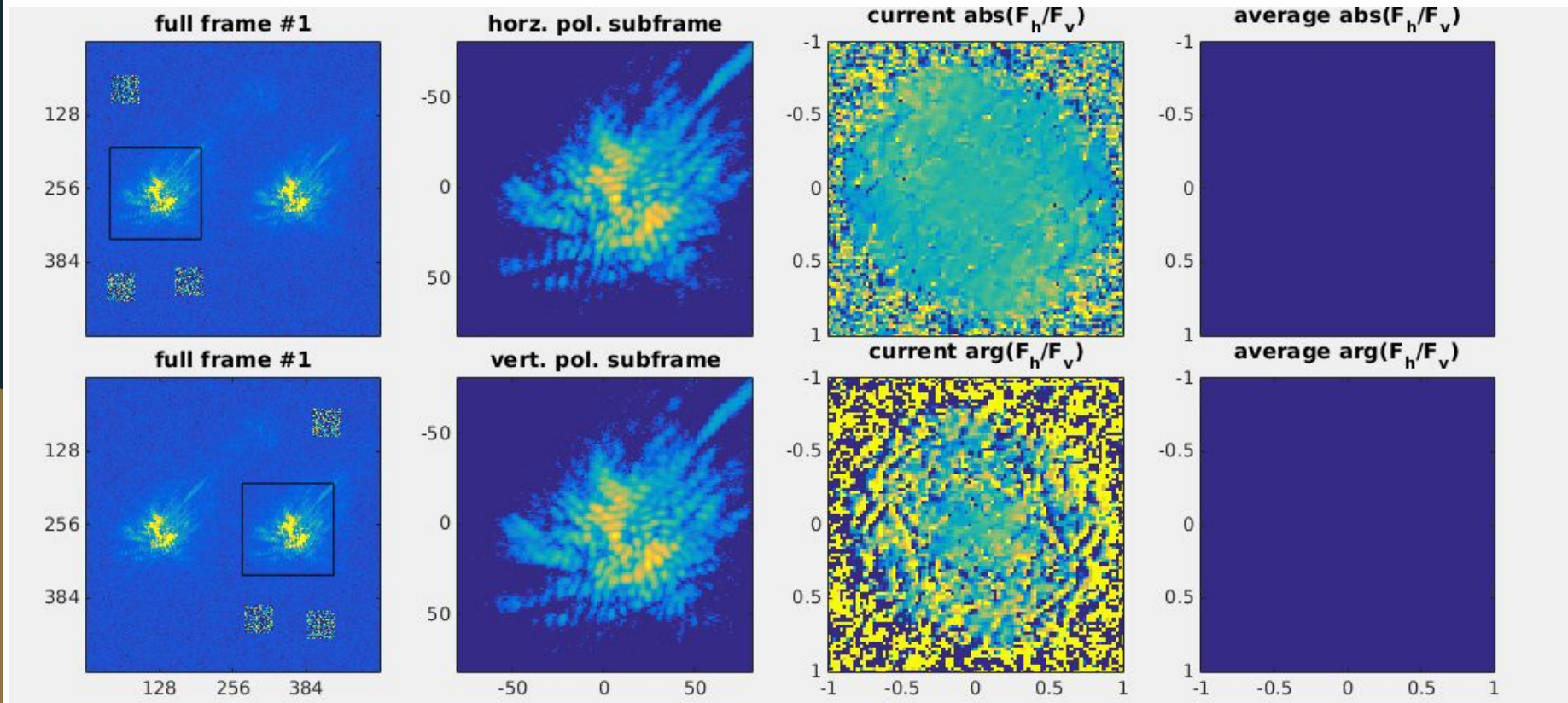


Nasmyth focus

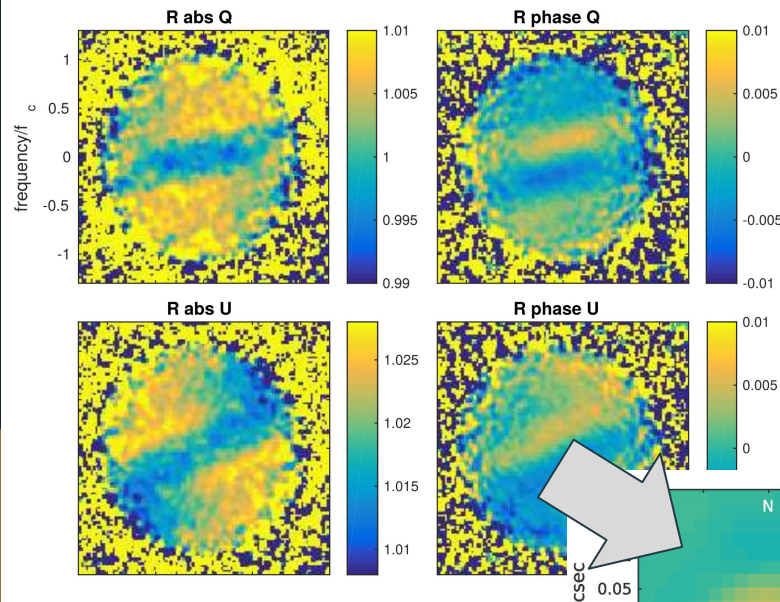


Cassegrain focus

Differential Speckle Polarimetry processing: μ Cep



Interpreting R value: μ Cep



Under assumption that:

1. The polarized flux is small relative to the total flux
2. Star is point-like.

$$\mathcal{R}_Q(\vec{f}) = 1 + 2\tilde{Q}(\vec{f}), \quad \mathcal{R}_U(\vec{f}) = 1 + 2\tilde{U}(\vec{f})$$

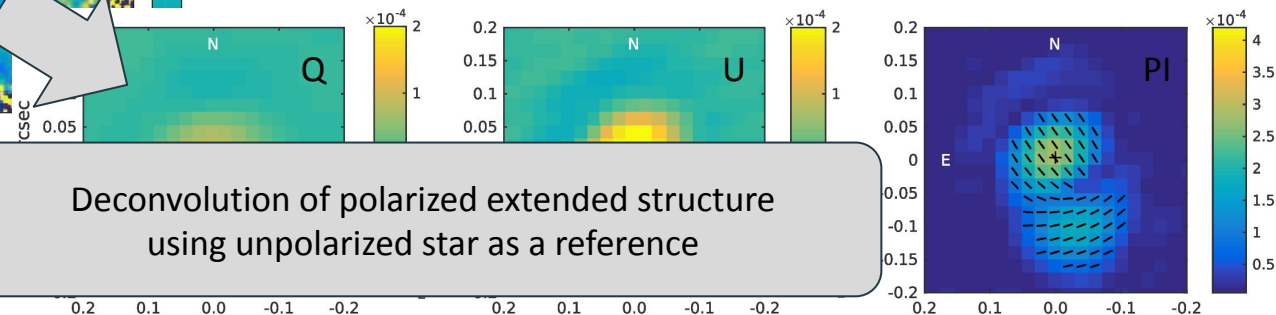
Stokes parameters distributions can be found by applying inverse Fourier transform to R .

Polarized intensity and the angle of polarization:

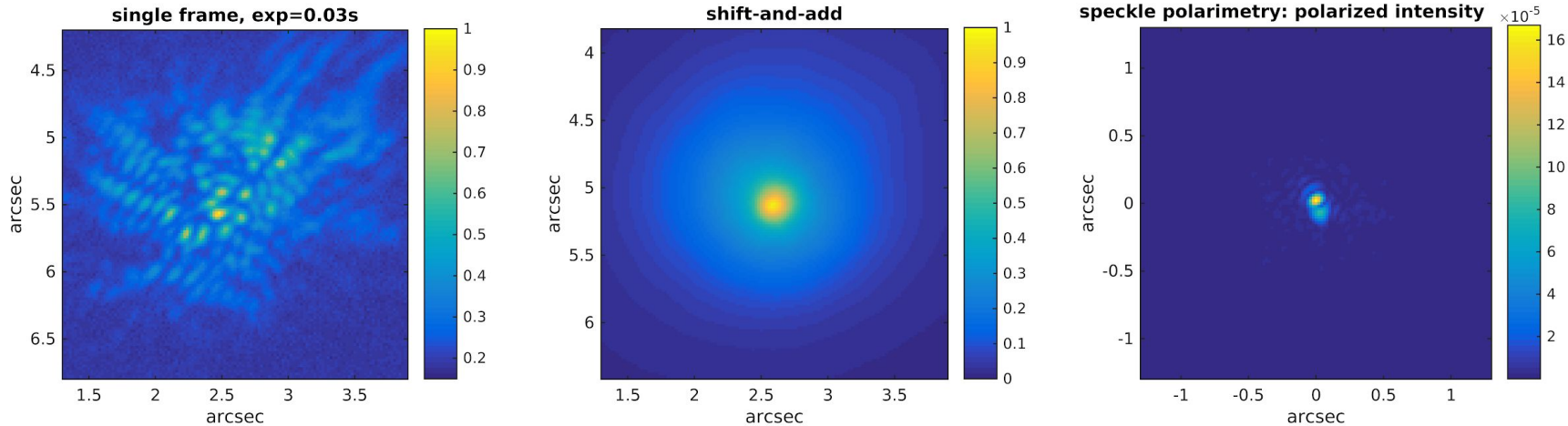
$$PI(\vec{\alpha}) = \sqrt{Q^2(\vec{\alpha}) + U^2(\vec{\alpha})}, \quad \chi(\vec{\alpha}) = \frac{1}{2} \text{atan} \frac{U(\vec{\alpha})}{Q(\vec{\alpha})}$$

Directly by comparison with n

Deconvolution of polarized extended structure
using unpolarized star as a reference



Gain in resolution: μ Cep



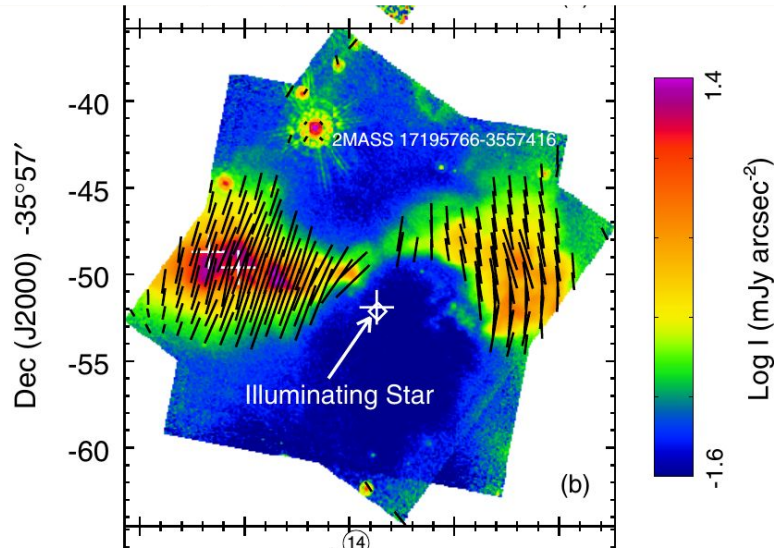
We know Fourier transforms of object Stokes parameters distribution up to frequencies $D/\lambda \rightarrow$ the characteristic angular resolution of resulting image is λ/D .

In case of 2.5-m telescope working in visual resolution is 50 mas.

Evolved stars

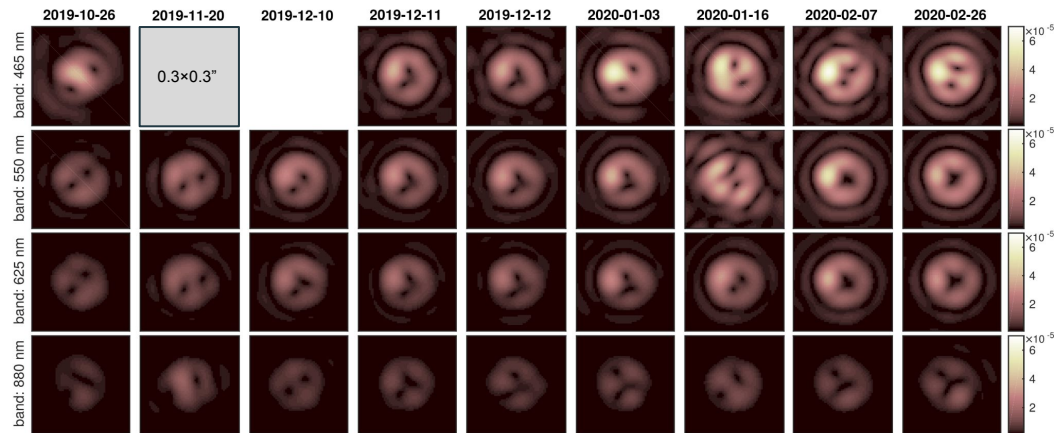
Red supergiant, asymptotic giant branch, post-AGB stars

- Have cold extended atmospheres,
- Conditions for dust condensation.
- Dust particles are accelerated by radiation pressure, shockwaves.
- Dust envelope envelope is formed, which scatters the stellar radiation. The scattered radiation is polarized.



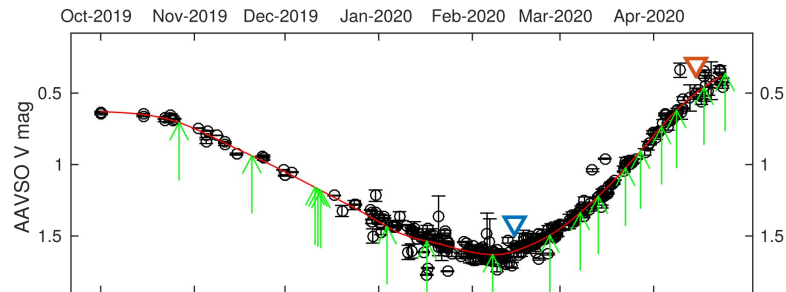
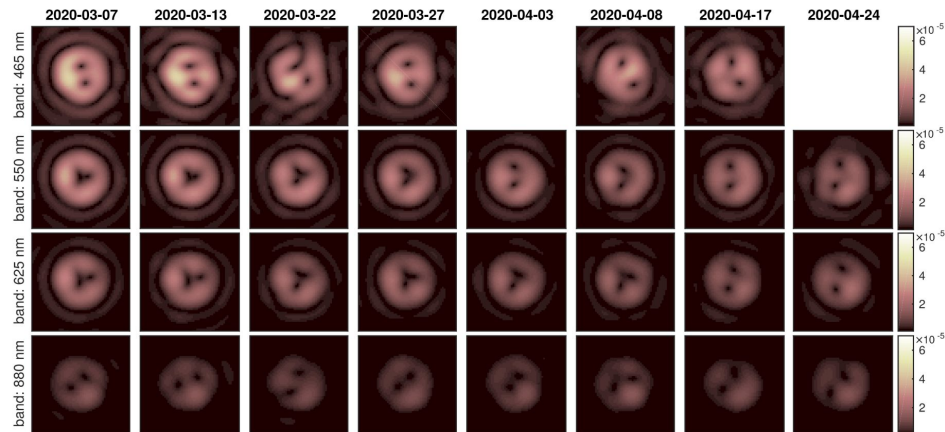
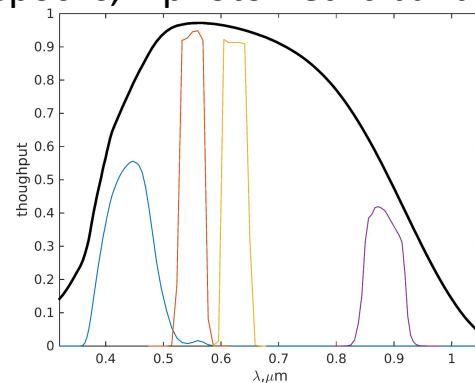
Azimuthal polarization pattern
- > resolution is important

Betelgeuse: DSP observations

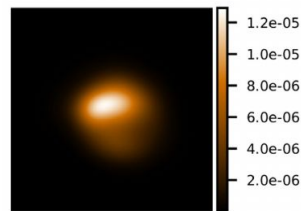
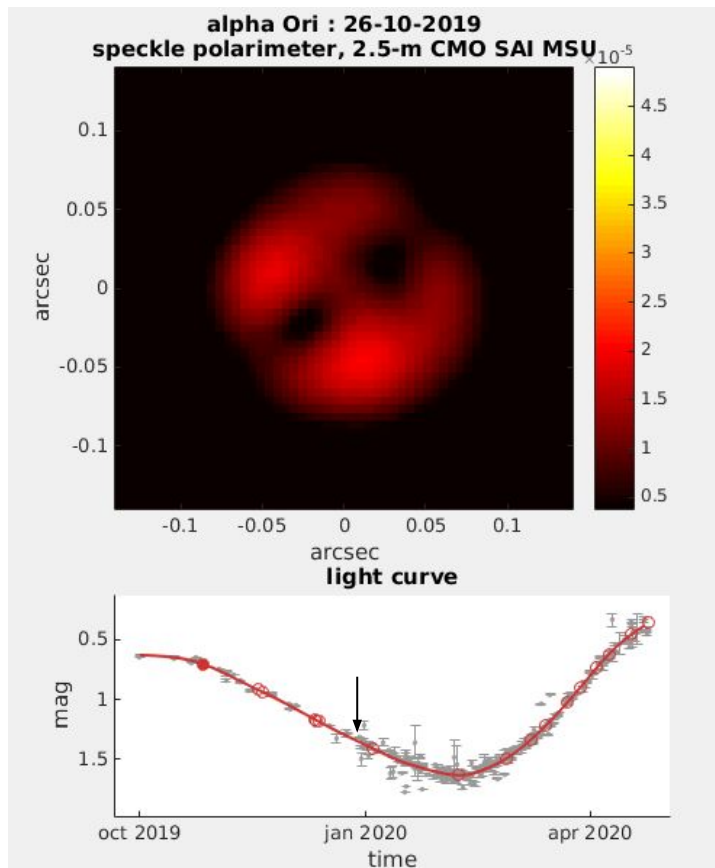


Polarized intensity:

14 epochs, 4 photometric bands.



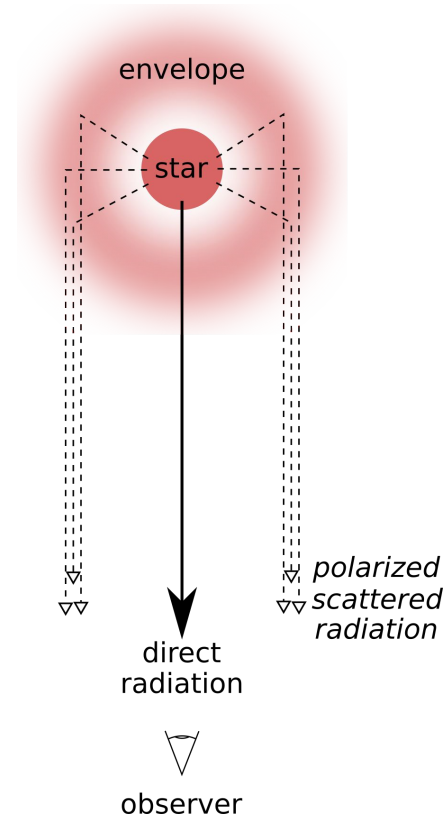
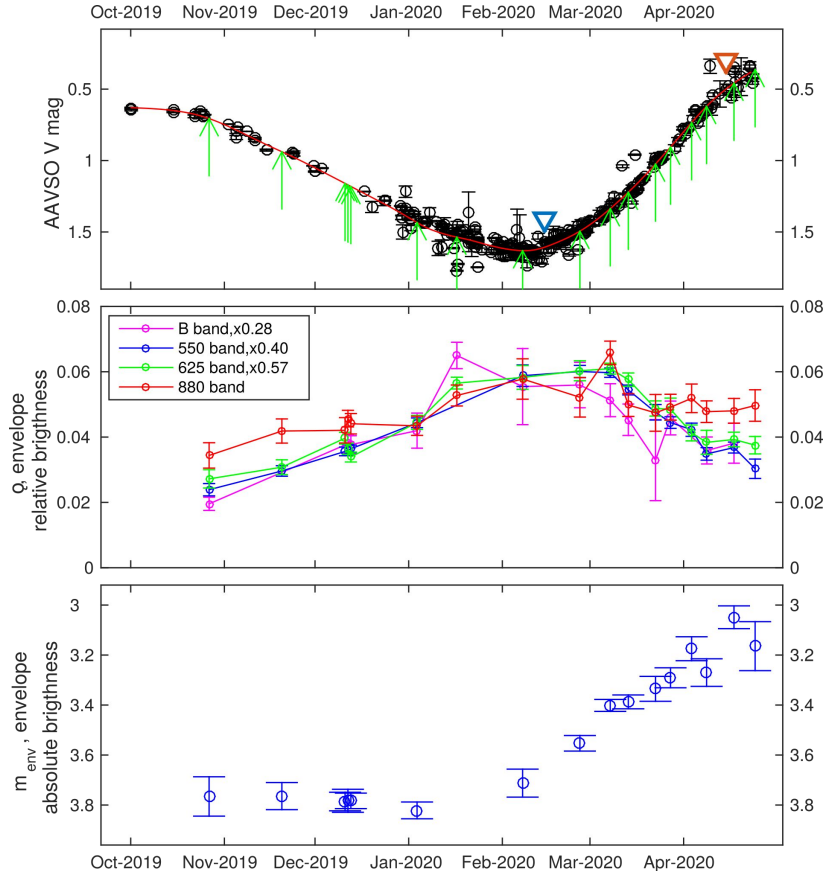
Evolution through the great dimming



VLT/ZIMPOL 644 nm total
intensity (photosphere),
same scale
Montarges et al, 2021

- DSP observations for 14 dates interpolated on equidistant temporal grid
- DSP reveal changing details in the envelope
- The coincidence of the circumstellar envelope appearance (DSP) and photosphere appearance (ZIMPOL) is reasonable

Total resolved polarized flux change



Conclusions

1. Polarized scattered radiation of the dust envelope of the Betelgeuse is resolved in 4 visual bands, on 14 epochs.
 2. The morphology of the envelope was changing, the appearance is correlated between adjacent epochs.
 3. Darkening and subsequent brightening of southern hemisphere was detected.
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- Differential Speckle Polarimetry is a method for polarization imaging of astrophysical objects at diffraction limited resolution.
 - DSP could be useful for resolved, multiepoch observations of dynamic RSG atmospheres.

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Thank you!

2020arXiv200505215S

The effect of finite angular size of photosphere

