Dynamics of Solar and Stellar Convection Zones and Atmospheres
Proceedings IAU Symposium No. 365, 2024
A. V. Getling & L. L. Kitchatinov, eds.
doi:10.1017/S174392132300529X

Imaging stellar surface features with optical interferometry

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Abstract. In this contribution, I present a selected overview of optical interferometry imaging results that brought insights on stellar activity and mass loss in evolved stars. I briefly introduce the STELLIM project that aims to characterize stellar surfaces and circumstellar environments by producing fast and reliable interferometric images.

Keywords. Convection, techniques: interferometric, stars: fundamental parameters

1. Introduction on optical interferometers

Optical interferometers like VLTI (Cerro Paranal, Chile) or CHARA (Mount Wilson, US), measure the coherence of the light collected with different telescopes. As such, they do not directly produce images like a standard single telescope would do. However, they deliver information at the very high spatial resolution that is given by the on-sky projected distance between telescopes. For a 200m distance in the near-infrared domain, the achieved spatial resolution is about 1 milli arcsecond (1 mas), which represents a $\sim 1/20$ fraction of the radius of the angularly largest stellar surfaces like Betelgeuse's.

2. Signatures of surface features with optical interferometry

Interferometric observables can be of great help to detect and characterize surface features on a variety of objects. An early example of this type of works can be found in Wilson et al. (1997) with aperture masking observations of Betelgeuse performed on the Herschel Telescope. A modelling with less than 15 parameters allowed to fit a stellar disk and spots. Spots account for 20% of the total flux of the stellar surface and up to a third of the stellar surface. This is in line with theoretical prediction from Schwarzschild (1975) that "convective elements are so large that only a modest number of them exists at any one time on the entire surface of the star ". They were also able to detect variability in the spots flux and positions between the 2 epochs separated by 8 weeks which is compatible with convective activity.

Optical interferometers are sensitive to asymmetric brightness distribution via an observable called the closure phase that is not biased by atmospheric errors. Various estimators can be based on this quantity to probe for asymmetries. Cruzalèbes et al. (2015) studied the degree of asymmetries in 16 evolved stars as a function of spectral types using the VLTI instrument AMBER. Asymmetries were found to be located in the upper right corner of the Hertzsprung–Russell Diagram, and associated with an increase of atmospheric-pressure scale-height, which is compatible with 3D hydro-radiative simulations.

Combined with a relatively high (∼10,000) resolution in spectral dispersion, optical interferometry is then a powerful tool to probe dynamics at high spatial resolution. On the AGB star R Dor, Ohnaka et al. (2019) produced images in spectral lines, exhibiting a bright central region. In the CO first overtone lines: outward motion of $7-15 km/s$ were detected at ∼1.8 Rs The origin of this outflow is open: radiation pressure on dust grains, motion due to convection and/or pulsation?

3. Regularized imaging

Parametric imaging is limited when modelling complex stellar surfaces and environments. It is then possible to produce images that fit interferometric observables by using regularization algorithms This technique has the big advantage of rendering structures that are hard to intuit and model with a parametric approach. In general, the spatial frequencies that are not constrained by observations are filled with *a priori* information on the object. In the reconstruction process, a criteria is minimized to both fit the data and get close to the regularization. The image can be reconstructed with different types of norms, to favor sharp edges for example.

These images can be used as a sort of a guide to orient the parametric modelling. But they must be taken with caution as the reconstruction process can lead to artefacts. Fitting parameters directly on a reconstructed image can lead to biases. A common practice is to make images with various regularization algorithms and parameters and analyse the common features.

This technique has been frequently used to image stellar surfaces on evolved stars (e.g. Haubois et al. 2009; Climent et al. 2020; Montargès et al. 2018; Paladini et al. 2018) but also on solar-type stars (e.g. Roettenbacher et al. 2016). They can be repeated overtime to follow the morphology evolution and determine spots evolution timescales (Norris et al. 2021). Roettenbacher et al. (2017) presents an interesting comparison between photometric imaging, Doppler imaging and interferometric imaging in the detection of spots. They differ in particular in the estimation of the spot latitudes.

Blind imaging contests based on optical interferometry data allow to compare the images reconstructed with various regularized approaches. In Monnier et al. (2014), one can appreciate the variety of reconstructed morphologies that are based on the same dataset obtained from the AGB star R Car observed with the VLTI/PIONIER instrument. They show significant differences up to the highest levels of relative intensity, which points out the necessity to improve the reliability of this technique.

Operational constraints and low number of telescopes imposes to use super-synthesis (uv plane filling with earth rotation) and to move telescopes as quickly as possible. It is currently very difficult to reach a low-artefact image in a short amount of time to allow less than a ∼2 week temporal resolution, which is probably key to determine the nature of surface features on many objects. Trying to go beyond the current status of interferometric imaging, we introduce the STELLIM project (Haubois et al. 2022) that aims to characterize stellar surfaces and circumstellar environments by producing fast and reliable interferometric images. Using a new array of 10+ small apertures optimized for imaging, we want to achieve low-artefact, model-independent, milli-arcsecond imaging at the timescale of the hour.

4. Summary

Optical interferometry is a powerful technique to observe convection and stellar surface dynamics at high spatial resolution. Combined with asteroseismology, it can be used to derive fundamental parameters like mass and effective temperature. Optical interferometric Imaging has boomed in the last decade. However some limits remain due to the small number of telescopes that are currently recombined. In particular, it stops us from reliably imaging phenomena with variability shorter than a few weeks. The STELLIM concept aims at delivering fast and reliable interferometric imaging in the visible, using VLTI as a testbed. It also represents a technological and operational precursor of a kilometric array with more and larger apertures. A 2-telescope demonstrator is being assembled and should soon demonstrate the critical functions of this new type of interferometers. This should push the limits of our current understanding of stellar surfaces and atmospheres, which is at the heart of many central topics in stellar physics.

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