

Determining the Stellar Spin Axis Orientation

Anna-Lea Lesage¹, Günter Wiedemann²

¹*Leiden Observatory, P.O. Box 9513, Leiden, The Netherlands*

²*Hamburg Observatory, Gojenbergsweg 112, 21029 Hamburg, Germany*

Abstract.

We present an observing method that permits the determination of the absolute stellar spin axis position angle based on spectro-astrometric observations for slowly-rotating late-type stars. This method is complementary to current interferometric observations that determine the orientation of stellar spin axis for early-type fast-rotating stars.

Spectro-astrometry enables us to study phenomena below the diffraction limit, at the milli-arcsecond scale. It relies on the wavelength dependent variations of the centroid position of a structured source in a long-slit spectrum. A rotating star has a slight tilt in its spectral lines, which induces a displacement of the photocentre's position. By monitoring the amplitude of the displacement for varying slit orientations, we can infer the absolute position angle of the stellar spin axis.

Finally, we present first observational results on Aldebaran obtained with the Thüringer Landesternwarte high resolution spectrograph. We were able to retrieve Aldebaran's position angle with less than 10° errors.

1. Motivation

1.1 Introduction

In their earliest variations, stellar formation theory, directly inspired by our own solar system, predicted that during its formation the star conserved its angular momentum, and consequently the spin axis orientation and kept a perfect spin-orbit alignment if the system happened to host planets. Nowadays, the large number of misaligned system discovered in the last decades, be it spin-orbit misalignment in cases of exoplanets (Fabrycky et al 2009), or spin-axis misalignment in cases of binaries (Albrecht et al 2009), imply that stellar for-

mation is more chaotic than imagined before. Finally, recent simulations converge towards a state of random distribution of stellar spin axes (Bate et al 2010) in open clusters.

Recent interferometric observations have managed to determine the spin axis orientation for a handful of early-type fast-rotating stars (Monnier et al (2007) and deSouza et al (2003)). Indeed, fast rotating stars are theorized to present cases of gravitation-darkening, i.e. the equatorial latitude of the star is cooler than the polar latitude. By imaging the oblateness of those stars and the brightness distribution, it is possible to retrieve the absolute orientation of the stellar spin axes.

However, this method would not work for slowly-rotating late-type stars as they neither present gravitational darkening nor oblateness strong enough to be measured. Hence, we propose an alternative method relying on spectro-astrometric observations, to determine the absolute position angle of the stellar spin axis for those late-type slowly rotating stars.

1.2 Spectro-astrometry

Spectro-astrometry is an observing technique relying on long-slit spectra. Taking advantage of the conservation of the spatial information along the slit spatial axis, this technique resolves spatial features in the milli-arcsecond scale, well below the diffraction limit of the telescope. Since each slit orientation delivers only one-dimensional content along that orientation, it is necessary to probe several slit orientations on sky to unravel the full spatial information. Finally, it is common to probe anti-parallel slit orientations. By doing so, instrumental artefacts are identified and can be strongly reduced when subtracting both orientations (Brannigam et al 2006).

In practice, the spatial information is extracted by measuring the wavelength dependence of the photocentre of the spectral order. This is either done via Gaussian fit or arithmetic weighted mean. Both methods are valid and yield similar results, assuming the spectra were properly corrected for bad pixels. As a result, the position of the photocentre is measured with sub-pixel precision, enabling the milli-arcsecond scale information.

Nonetheless the analysis of the position spectrum still requires a proper understanding of the features one wishes to observe. For instance, spectro-astrometry was used successfully for mapping the surfaces of giant stars (Voigt and Wiedemann 2009).

2. The Method

We use in the method the angle conventions defined in the figure .1. The absolute stellar position angle is deduced from: $PA_{\text{star}} = PA_{\text{slit}} + \psi$. Since the orientation of the slit on sky is known, the determination of the stellar position angle is directly linked to the measurement of the angle ψ .

The star is no longer considered as an unresolved point source on the slit, which means that Doppler effects due to the star's rotation can no longer be neglected. The part of the star coming towards us is blue shifted, and the portion of the star moving away from the observer is red shifted. While the spatial axis of the slit conserves the spatial information, the dispersion axis translates these Doppler shifts into wavelength displacements. Once the two informations are combined, it is possible to model the star in the wavelength-spatial referential proper to the spectrograph. As seen on the figure .2, in the wavelength-spatial referential, the star is no longer a round object, but a slanted ellipse whose inclination is linked to the angle ψ . As a result, the stellar lines, which are the result of the convolution of

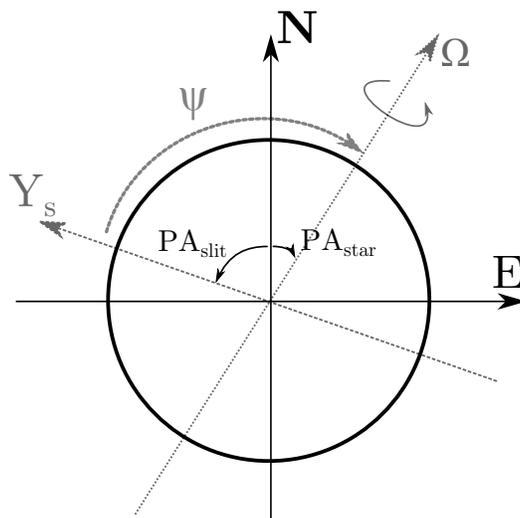


Figure .1: Angle conventions used for the method.

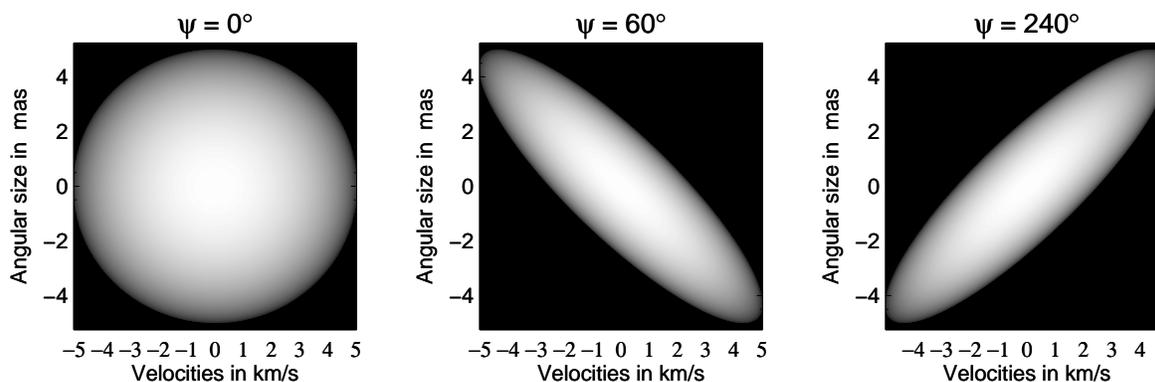


Figure .2: Stellar profile in the wavelength-spatial referential taking into account the Doppler shifts cause by the stellar rotation, and the angle between slit and spin axis.

the intrinsic stellar spectrum with the two-dimensional model of the star in the spectrograph's referential, are tilted with the angle ψ .

The tilt of the stellar lines follows a sine function of the form : $\sin(\psi - PA_{\text{star}})$. It is measured as a displacement in the position spectrum at the position of the stellar lines, i.e. the photocentre of the spectral order is displaced from the continuum. By monitoring the amplitude of this displacement as a function of the slit orientation, it is possible to retrieve the absolute position angle of the star, as illustrated step-by-step in figure .3.

2.1 Retrieving the signal in the position spectrum

In some cases, e.g. when the seeing and the spectrograph plate scale are small, the displacement of the photocentre in the position spectrum at the line position is visible with the naked eye, and can be directly measured. However, in most cases, we expect the signal to be drown

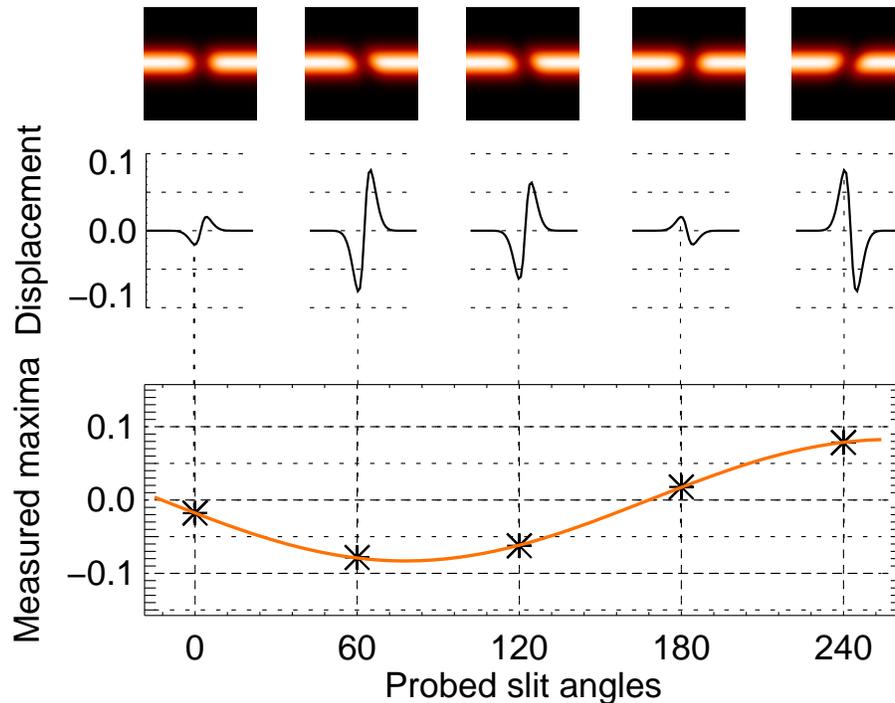


Figure .3: Working principle of the method: The stellar rotation induces a line tilt whose inclination is correlated to the angle ψ as seen in the upper row. The line tilt is translated in the position spectrum as a displacement from the continuum as shown in the middle row. The amplitude of the displacement with probed slit orientation follow a sine curve whose phase yields the absolute stellar position angle.

in a sea of noise. Then retrieving the displacement amplitude becomes a challenge. As a solution, we propose to proceed to a cross-correlation analysis between position spectrum and the derivative of the intensity spectrum, i.e. a function of the contrast of the spectrum. By doing so, we combine the information of multiple stellar lines to enhance the signal. We then monitor the amplitude of the cross-correlation function as a function of slit orientation.

2.2 Seeing and instrumental oise

Seeing and instrumental profile are the two main error sources in this method. The instrumental profile can induce a distortion of the stellar wavelength-spatial profile, causing a tilt which is no longer correlated to the slit orientation. Furthermore, seeing acts similarly on a shorter timescale. While the instrumental profile may change over an hour, seeing profile fluctuate in less than a second.

The influence of profile distortions caused by seeing can be kept minimal by choosing relatively large exposure times. As a result the effects of seeing are smeared over the spectrum without influencing the stellar profile over that time scale. On the other hand, disentangling

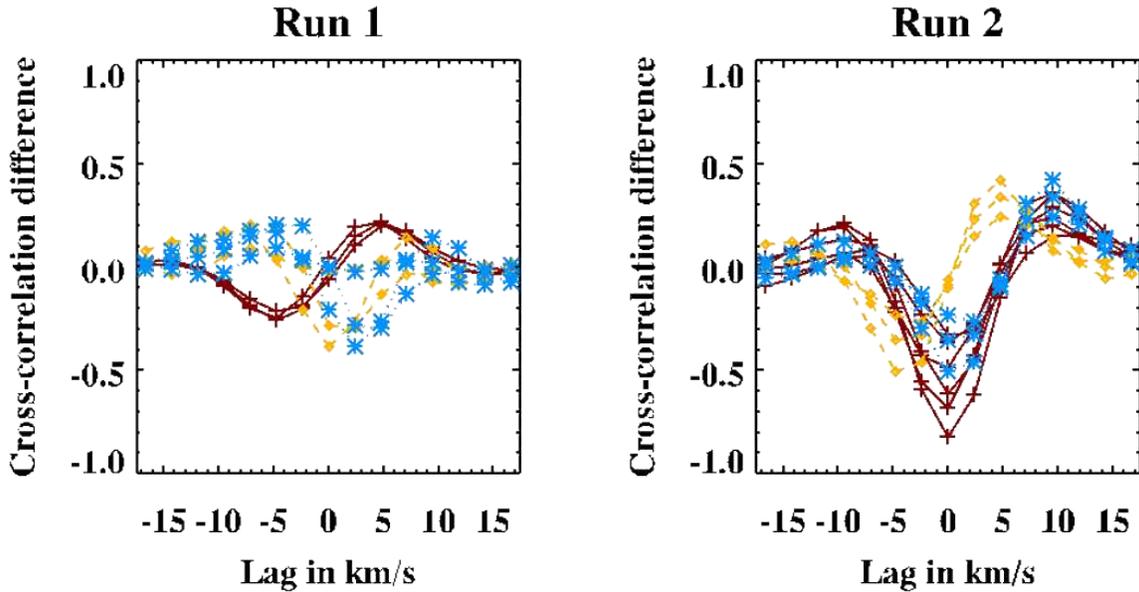


Figure .4: Two observing runs of Aldebaran for two different orientations. In red, the cross-correlation signal from the target star Aldebaran. In blue and yellow, the cross-correlation signal measured before and after respectively of the telluric lines in a reference star. Run 1 and 2 probed respectively slit orientations 202° and 130° .

the displacement caused by the instrumental profile from the one generated by the stellar rotation requires a special observing technique and additional instrument.

We have developed a differential image rotator, a small instrument to be inserted between the telescope output and the slit, which splits the input beam along two polarisations, rotates both beams to anti-parallel orientations, and projects them both on the slit (Lesage et al 2012). The resulting spectrum features the same orders twice, one for each beam orientation. As such, the anti-parallel orientations are taken simultaneously and have seen same seeing and instrumental profile. With this instrument, it becomes possible to compare directly the two anti-parallel orientation and be seeing independent.

Additionally we recommend to observe an early-type star before and after the observing run, while keeping the latter short. By measuring the line tilt displacement along the telluric lines and comparing it to the line tilt displacement of the target star, we disentangle the stellar signal from the instrumental profile. As illustrated in figure .4, when the stellar signal is the strongest, i.e. when the angle ψ is close to 90° or 270° , the stellar signal (here is continuous red) diverges from the signal measured in the telluric lines (in blue and yellow stars). However, if the stellar signal is minimal, i.e. when the angle ψ is either 0° or 180° , then the signal measured in the telluric lines dominates.

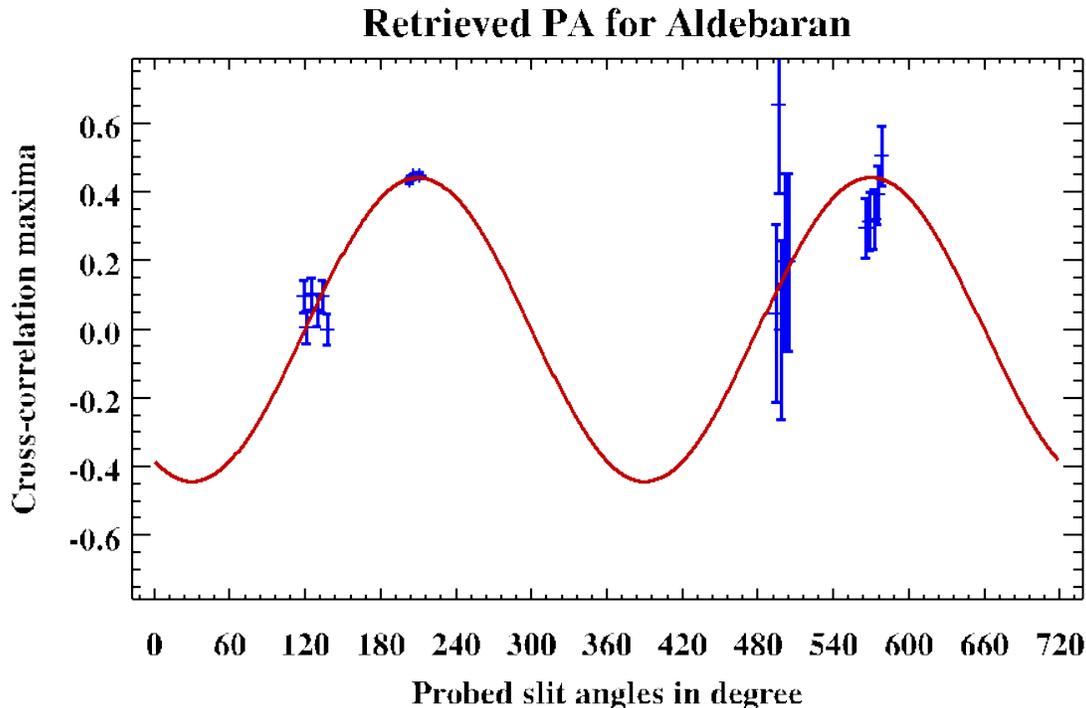


Figure .5: The amplitude of the photocentre displacement as measured from the cross-correlation functions for the four slit orientations probed during the 2 nights observation of Aldebaran. In red, the best sine fit. The second night was characterised by degrading seeing conditions which are reflected by the important scatter of the points compared to the previous night.

3. Observations of Aldebaran

Aldebaran is one of the very few cool giants whose position angle has already been measured by [Lagarde et al \(1995\)](#). As such it is an ideal candidate to test the validity of the method and the instrument. We observed Aldebaran during a 2 nights observing runs on the Coudé high resolution ($R = 60\,000$) Spectrograph of the Thüringer Landessternwarte Tautenburg. We used the natural field rotation of the Coudé spectrograph to probe four different slit orientations on sky during the two nights. With a pixel scale of 0.51 arcseconds, we expected a photocentre displacement of the order of 2 to 5% of a pixel for Aldebaran. From each observing run, spanning about 5° on sky, we extracted 10 independent displacement measurements.

We applied the method described earlier to disentangle the signal from Aldebaran from the instrumental induced signal. In addition, the exposure time was kept relatively high, around 200 seconds, considering that Aldebaran is a $Vmag = 0.8$ star. Figure .5 shows the final step of the analysis, where we fitted a sine curve to the measured displacements. We retrieved a position angle of $115^\circ \pm 4^\circ$ which is in agreement with the angle of $110^\circ \pm 5^\circ$ measured by [Lagarde et al \(1995\)](#).

4. Conclusion

To conclude, we have presented here a method which enables the determination of the position angle of the stellar spin axis. The method was successfully tested on Aldebaran, despite non-optimal seeing and instrumental conditions. Applied to a larger sample of stars, this method would provide a first step in confirming the chaotic aspects of stellar formation which cannot be measured yet.

Acknowledgements. A.-L. Lesage would like to acknowledge the precious help to the instrumental team of the Thüringer Landessternwarte Tautenburg, and the possibility to test the method on their telescope.

References

- Bate, M. R., Lodato, G. and Pringle, J. E., 2010, MNRAS, 401, 1505
- Fabrycky, D. C. and Winn, J. N. 2009, ApJ, 696, 1230
- Albrecht, S., Reffert, S., Snellen, I. A. G. and Winn, J. N. 2009, Nature, 461, 373
- Monnier, J., Zhao, M., Pedretti, E., Thureau, N., Ireland, M., Muirhead, P., Berger, J.-P., Millan-Gabet, R., Van Belle, G., ten Brummelaar, T., McAlister, H., Ridgway, S., Turner, N., Sturmman, L., Sturmman, J. and Berger, D. 2007, Science, 317, 342
- Domiciano de Souza, A., Kervella, P., Jankov, S., Abe, L., Vakili, F., di Folco, E. and Paresce, F. 2003, A&A, 407, L47
- Brannigan, E., Takami, M., Chrysostomou, A. and Bailey, J. 2006, MNRAS, 367, 315-
- Voigt, B., and Wiedemann, G., 2009, 15th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, 1094, 896
- Lesage, A.-L., Schneide, M., and Wiedemann, G., 2012, SPIE Proceedings, 8446
- Lagarde, S., Sanchez, L. J. and Petrov, R. G., 1995, IAU Colloq. 149: Tridimensional Optical Spectroscopic Methods in Astrophysics, 71, 360

