

# The importance of non-photon noise in astronomical spectropolarimetry

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**Abstract.** Stellar spectropolarimetry has become an extremely popular technique during the last decade or two, and has led to major advances in the studies of stellar magnetic fields. Many important discoveries have been made thanks to ultra-precise measurements of very small polarimetric signals, which require very stable instruments and special observing strategies. The so called beam-swapping technique is a well-known polarimetric technique capable of suppressing many spurious signals due to various instrumental effects. However, when one is interested in ultra-high signal-to-noise ratio measurements, observers start to hit various limitations introduced by the instrument, by the atmosphere, and even by the software for data-reduction. These limitations cannot be overcome by the observing strategies, and sources of errors other than photon-noise must be taken into account. Here we discuss the advantages of the beam-swapping technique, and the impact of small instrument and atmospheric instabilities, and how these issues offer an explanation for the origin of the apparently significant observed polarisation signals produced by effects other than those intrinsic to the observed target.

**Keywords.** Polarization, techniques: polarimetric, methods: data analysis, stars: magnetic fields

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## 1. Introduction

Many important astronomical discoveries are based on observations performed at the limit of the instrument capabilities. This is specially true for spectropolarimetric measurements, when the Stokes profiles of spectral lines are often detected by measuring relative differences in signals of the order of  $10^{-3}$  or less. We tend to believe that key to success is increasing photon counts, and that having collected  $10^6$  electrons or more in a spectral bin is sufficient to guarantee the reliability of our measurements. In other words, once an instrument has been successfully commissioned and offered to the community, we all tend to believe that photon-noise is the only source of error, and that error bars scale as  $N^{-1/2}$ . This may not be quite true.

## 2. Sources of non-photon noise

In stellar astronomy, a popular design for polarimeters is the one proposed by Apenzeller (1967). It comprises a retarder waveplate that may rotate at fixed positions in front of a beam splitting device such as a Wollaston prism. For linear polarization measurements, a half-waveplate is employed and rotated through  $22.5^\circ$  steps. For circular polarization measurements, a quarter wave-plate is adopted, and exposures are taken at

position angles separated by  $90^\circ$ . For instance, after crossing the  $\lambda/4$  waveplate (with its position angle set to  $-45^\circ$ ) and the Wollaston prism, the spectrum of a star is split into two beams, one proportional to  $I + V$  (the parallel beam) and one proportional to  $I - V$  (the perpendicular beam), and the reduced Stokes parameter  $P_V = V/I$  can be promptly obtained from the ratio between the difference and the sum of the two fluxes.

When observing at only one position of the waveplate, the accuracy of this kind of measurement is strongly limited by a number of factors: (1) the difference in the transmission function of the two beams may not be perfectly corrected by flat-fielding; (2) the properties of the polarimetric optics may deviate from their nominal values (for instance, the retardation of the waveplate could differ from  $90^\circ$  or  $180^\circ$ , and the position angle of the fast-axis may be wavelength dependent). More important may be wavelength calibration issues: case (a) of Fig. 1 shows how an offset as small as 2% of the FWHM of a spectral line observed in opposite polarization may be responsible for a polarization signal with an amplitude as large as 2%. But how to know if the signal is intrinsic to the source, or if it is an instrumental artifact, due, e.g., to a wrong relative wavelength calibration?

### 3. The beam-swapping technique

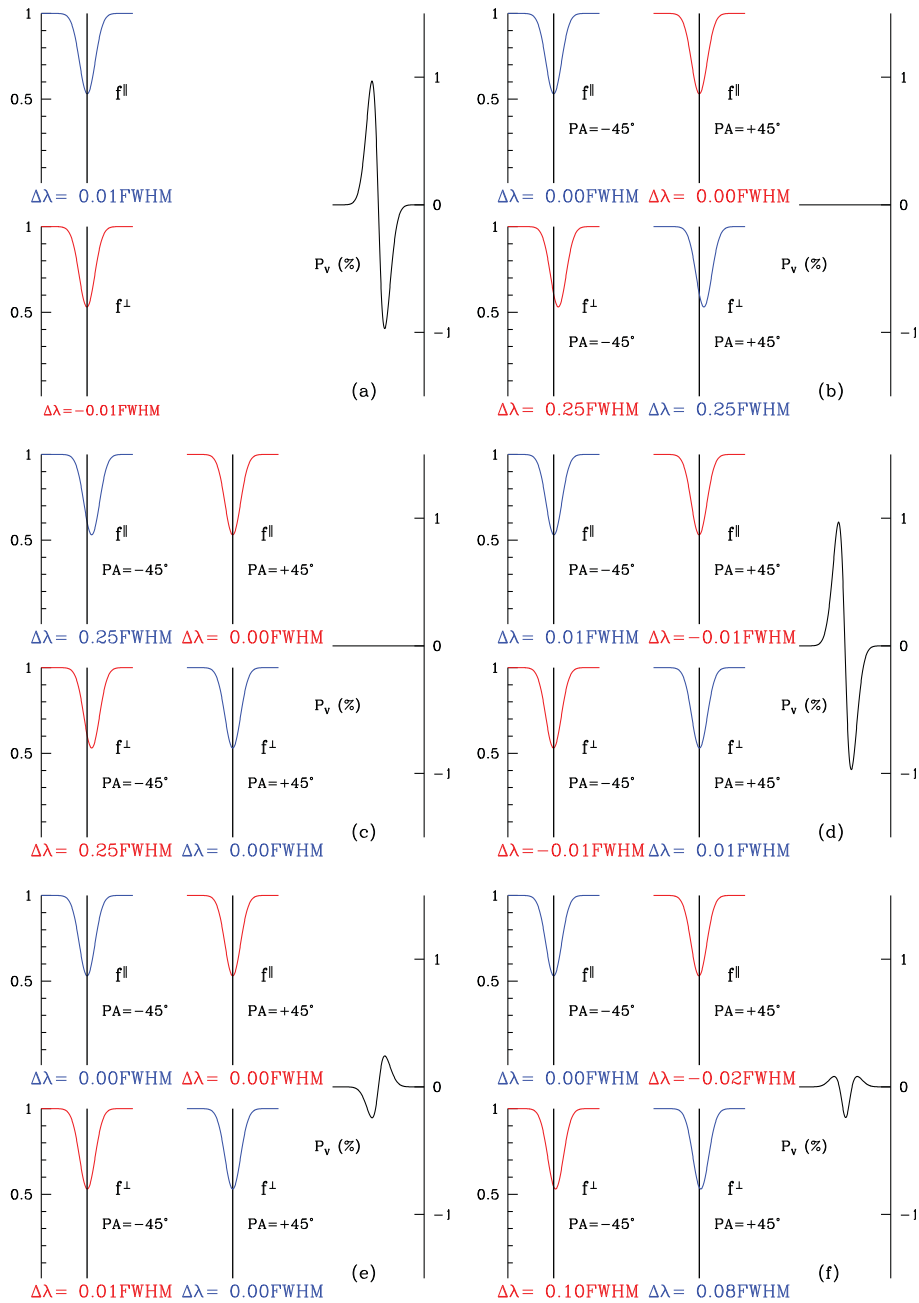
It is well known that most of these problems are largely solved by using a beam-swapping technique. By observing the same target with different position angles (PA) of the retarder waveplate, the polarization in the two beams changes its sign, while most of the instrumental effects remain the same. The so-called double-difference and double-ratio methods take advantage of this property, and permit one to minimize the instrumental effects. For instance, one can measure circular polarization by calculating

$$P_V = \frac{V}{I} = \frac{1}{2} \left\{ \left( \frac{f^{\parallel} - f^{\perp}}{f^{\parallel} + f^{\perp}} \right)_{\text{PA}=-45^\circ} - \left( \frac{f^{\parallel} - f^{\perp}}{f^{\parallel} + f^{\perp}} \right)_{\text{PA}=+45^\circ} \right\},$$

where  $f^{\parallel}$  and  $f^{\perp}$  are the beams split by the Wollaston prism, polarized in the direction parallel and perpendicular to the prism principal plane, respectively (for more details see, e.g., Bagnulo *et al.* 2009). Case (b) in Fig. 1 shows that if the wavelength shift between parallel and perpendicular beams is an instrumental or a calibration artifact which remains constant as the retarder waveplate rotates, its effect is canceled out when the fluxes are combined as prescribed by the double difference method, and the resulting reduced Stokes profile is flat. Similarly, the effect of an offset in both parallel and perpendicular beams only at one position of the retarder waveplate (case c) is canceled out. If the wavelength shift is due to the polarization intrinsic to the spectral line, the offset between top and bottom beam is reversed when the retarder waveplate is rotated by  $90^\circ$  (case d).

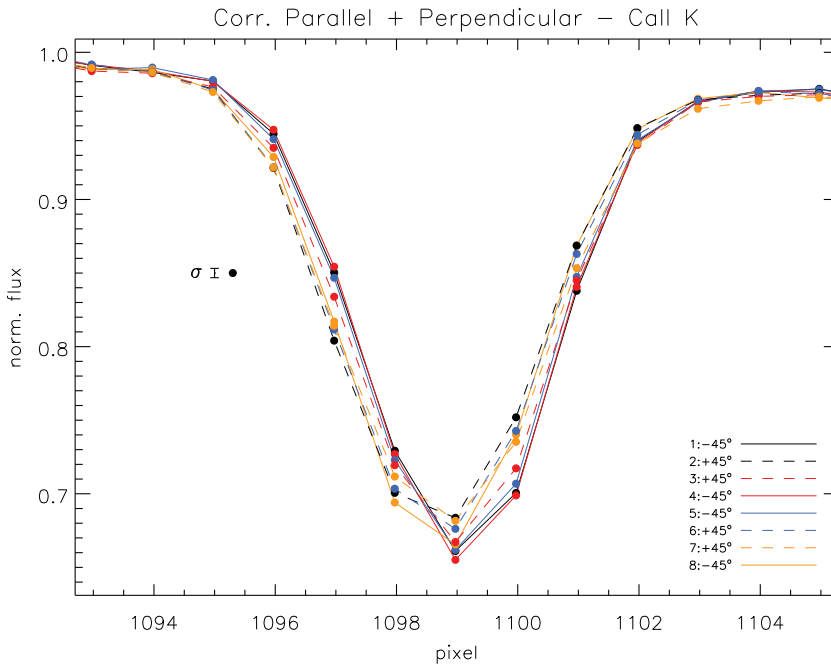
The beam swapping technique works under the assumption of perfectly stable observing conditions. Any change between one exposure and the next will produce a spurious instrumental effect. For instance, cases (e) and (f) of Fig. 1 show that an artificial offset between spectral lines in opposite polarizations which affects only one beam may be responsible for a spurious polarization signal.

These considerations are particularly relevant to the case of Cassegrain mounted instruments, for instance the FORS instrument of the ESO VLT. The telescope has an



**Figure 1.** Combinations of gaussian profiles to simulate polarimetric observations of a spectral line. The Figure is explained in the text. From Bagnulo *et al.* (2013)

alt-az mounting, hence the instrument rotates during observations, potentially making it subject to (small) differential flexures. These flexures (of the order of a fraction of a pixel) are negligible in normal spectroscopy, but may have a large impact when trying for instance to measure weak magnetic fields.



**Figure 2.** The profiles of spectral line Ca II K of the supergiant star HD 92207 observed with FORS during a polarimetric series at various positions of the retarder waveplate. The offsets, due to instrument flexures or seeing effects, may lead to the detection of a spurious signal of polarization in spectral lines. From Bagnulo *et al.* (2013). See the on-line edition of this book for a color version of this figure.

#### 4. The case of FORS at the ESO Very Large Telescope

During the last 15 years, the FORS instrument of the ESO Very Large Telescope has been extensively used to study stellar magnetism. A number of interesting discoveries of magnetic fields in several classes of stars have been announced, many of which obtained just at a  $3\sigma$  level; some of the discoveries were confirmed by measurements obtained with other instruments, some were not.

In light of the comments above about instrument flexures and seeing instability, some of the FORS magnetic field detections are a natural subject for a deeper investigation. As an example, Fig. 2 shows the profile of the Ca II K of the supergiant star HD 92207 observed with FORS at various positions of the retarder waveplate. In the ideal case, even if the star were strongly magnetic, we would expect all profiles obtained at various positions of the retarder waveplate to be superposed on each other, within photon-noise error bars. The observed offsets (due either to instrument flexures or seeing) are responsible for a noisier than expected profile. Combined with a less than optimal wavelength calibration, this led to a spurious field detection (for details see Bagnulo *et al.* 2013).

#### 5. Impact on scientific results

There is a growing recognition that magnetic fields can play a significant role in many stages of stellar evolution. For example, fields mediate angular momentum loss during star formation; they strongly affect internal transport of angular momentum during later evolution and can affect the results of vertical chemical transport; and they are a fundamental ingredient of many kinds of stellar surface and environmental activity and mass

loss. Thus it is becoming increasingly important to know what kinds of magnetic fields are present in individual stars and in particular evolutionary situations. Fields are increasingly being found that are only a little above the current thresholds for reliable detection.

In order to know whether to trust any particular field detection, it is essential to understand the problems that can lead to spurious detections, and to be confident that these problems are well understood and can be managed. This is particularly a problem in Cassegrain-mounted spectropolarimeters, which can be subject to flexure. Instruments such as FORS of the ESO VLT and ISIS of the William Hershell Telescope are particularly important in discovery of fields, especially in faint stars and those with very broad lines, such as white dwarfs and rapidly rotating main sequence stars.

Our revision of FORS1 data (Bagnulo *et al.* 2012) shows that a non-negligible fraction of the field detections obtained in the last few years is actually spurious. It is thus essential to understand all important sources of noise in such instruments, and to have tests that can make it possible to estimate realistic measurement uncertainties. Only in this way can a really useful census of magnetic fields in stars be achieved.

Lesson learnt should be applied also to high-resolution spectropolarimeters, even though they are generally much more stable.

## References

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