Zeeman Doppler Imaging

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Abstract. Stellar rotation maps the surface of a star into its line spectrum and gives a dimension to a point on the star - the Doppler dimension. This is of great importance for the detection of Zeeman polarization especially in certain cases. Typically a magnetic configuration will exhibit both polarities, thus the polarization signals of oposite signs may superpose and cancel. The Doppler coordinate will be in general different for parts of the stars having different polarities and therefore the polarization signals will also appear at different wavelengths and will not cancel.

Moreover, the time variations plus the Doppler coordinate constitutes two variables that may allow the reconstruction of two dimensional map of the magnetic field over the star surface.

Attention will be given to the set-up that allows spectropolarimetry with high spectral resolution and high S/N ratio. The use of cross dispersion spectrographs allows one to observe several tens of spectral lines. The method of adding signals to increase S/N ratio will be indicated.

1. Introduction

Zeeman Doppler-Imaging (ZDI) differs from (simple or intensity) Doppler-Imaging by several aspects the main being its use of polarimetry. In the following, we will stress the other aspects as well. The Doppler effect due to stellar rotation yields a resolution of the surface of the star via its broadened spectral lines. Since different parts of the star contribute to the spectrum at different wavelengths, they become "resolved". The star is no more a point, it has an extension described by a Doppler coordinate (see paper I).

Consider the following situation : two spot members of a bipolar group having magnetic fields of opposite polarities will produce Zeeman polarizations of opposite signs. The sum of these signals will generaly cancel. Now, if due to the stellar rotation, the two spots appear at different wavelengths in the spectrum, their Zeeman polarizations may be resolvable. Thus the detection of the polarization signature of a magnetic field represents the *first* objective of ZDI.

In the simple Doppler imaging, the detection of a spot is achieved mainly by the time variation of the profiles of stellar spectral lines. In the case of ZDI , the detection of polarization is direct and does not require observation of time variation. Some singularities in Doppler imaging, like the event of a polar spot needs modeling for the purpose of their observation. However, any Zeeman

polarization is a direct and unique detection of a magnetic field, no modeling is required at this stage.

The second objective of ZDI is the transformation from the two dimensional data -Doppler coordinate and time variation- to the two coordinates of the star's surface. This is achieved by applying maximum entropy technique (Brown et al. 1991). Donati et al. (1992) derived the first magnetic map of HR1099.

The S/N required for ZDI is generaly very high; for solar type stars, the polarization signals are of the order of 1% and therefore one should aim to S/N equal to or better than 10^{-3}.

Spectral resolution for ZDI should also be high. The profile of the net Zeeman polarization has positive and negative peaks. Low spectral resolution may considerably reduce the ZDI signals. From a consideration of the width of the intrinsic line profile one should have a spectral resolution of the order of 100000. However, we have had good results with a resolution of 40000.

In the following we discuss : 1) The needed instrumentation. 2) The observing procedure and data reduction. 3) The technique of co-adding many lines to improve S/N.

2. Instrumentation.

A general description of the instrumentation has been given in paper III. Here we give only the outlines and indicate the progress and evolution needed in order to use ZDI with the cross dispersion spectrograph UCLES at the AAT.

The Polarimeter. Circular analysis is achieved with the combination of $\lambda/4$ retarder plate in front of a linear analyzer. The linear analyzer is a beam splitter which selects the two linear states which now have the encoded intial circular polarization. These too beams may be subjected to further analyses separately. The retarder can be rotated to the two orientations $\pm 45°$ relatively to the beam splitter. This arrangements ensure that the two beams $b_{1,2}$ corespond to circular left and right states respectivly in the first orientation and the reverse states at the second one. With the polarimeter installed at the Cassegrain focus one avoids instrumental polarization.

The fiber link. For the spectral analysis of the two beams, they must be brought to the coude spectrograph. This is done with the help of double optical fibers.

The double image-slicer. At the exit of the fibers we use image-slicers to obtain high spectral resolution and no light loss. The general performance was excellent and magnetic fields were detected on four solar type stars.

Instrumental evolution. The above set-up used at CFHT and described in (Semel et al., 1993) used only three spectral lines. Although not achromatic, it was quite efficient.

Our next objective was to use UCLES, the cross disperssion spectrograph, which allows one to observe 17 spectral orders simultaneously and thus increase the S/N considerably. For this purpose we had to render the polarimeter achromatic. The double image slicer has been modified so that we could squeeze all the sections of the two beams between the orders (to avoid orders superposition).
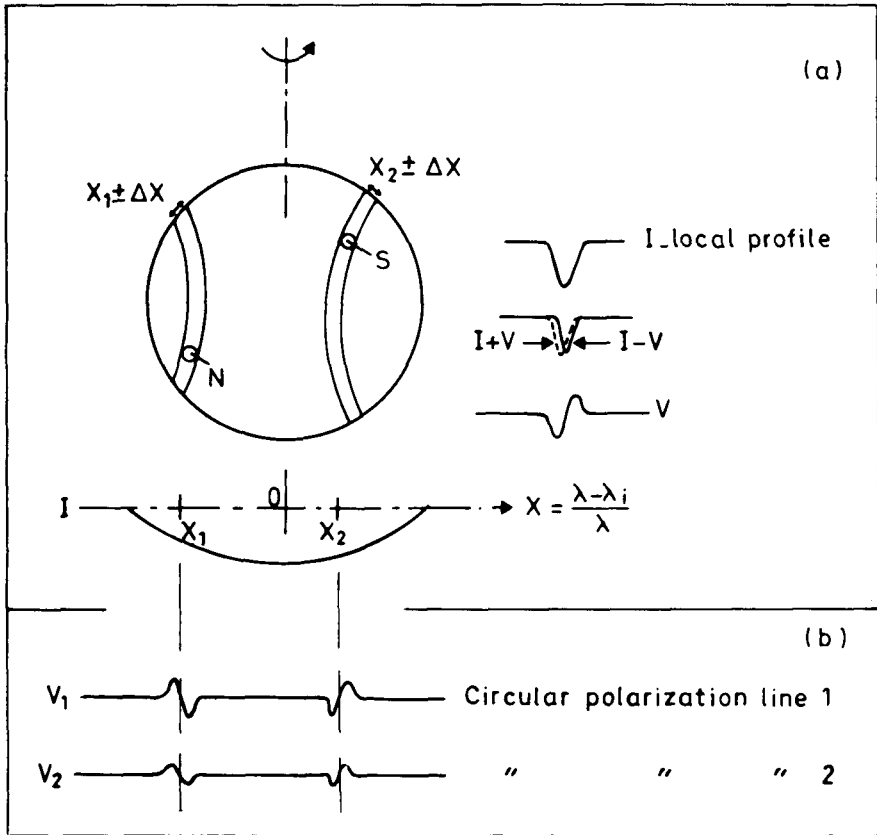
Figure 1.   The principle of ZDI. Let the surface of the star be divided into different velocity zones whose emergent light will have different Doppler shifts. In the spectrum, circular polarization due to the first magnetic spot appears at the "wavelength" X_1, and the second at X_2. The same is true for all spectral lines. (a) On the right, the two profiles $I + V$ and $I - V$ correspond to the two states of circular polarization. Their difference gives the net circular polarization V which has an easily recognizable charcteristic shape. Each stellar spot contributes such a signal to the spectrum at the appropriate wavelength. (b) The observed $V_1(X)$ and $V_2(X)$ correspond to the lines 1 and 2 respectivly. It is obvious why their addition makes sense.
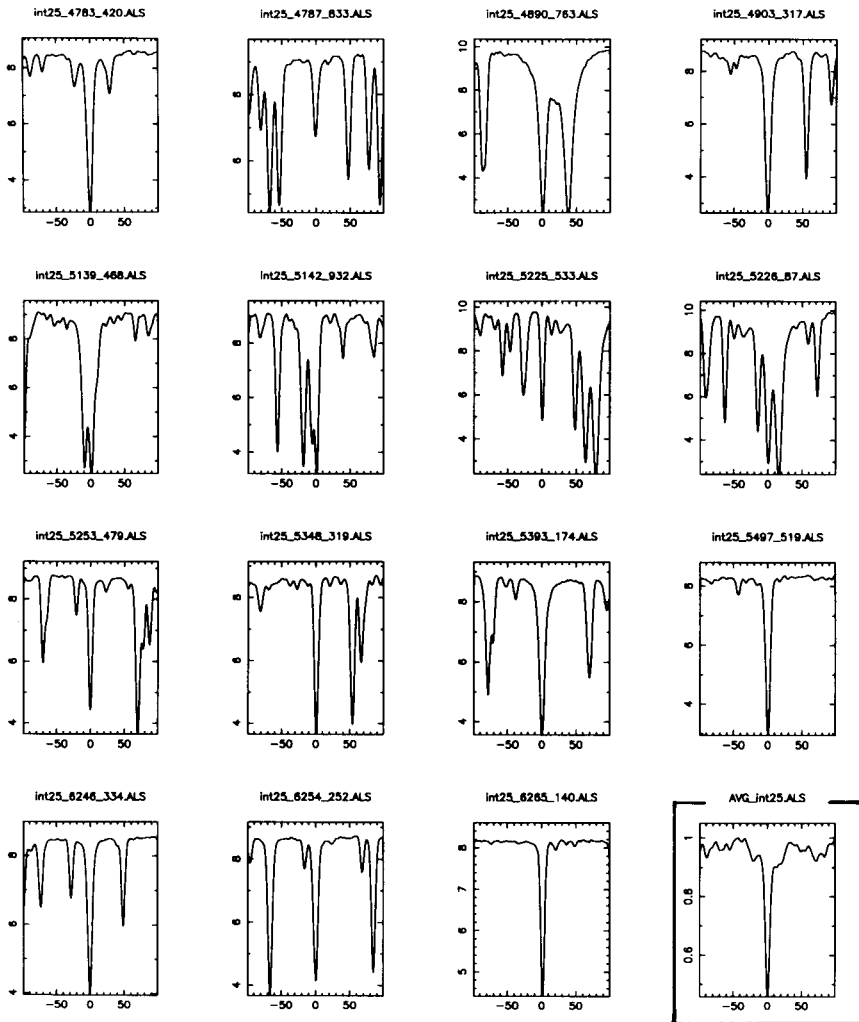
Figure 2. Averaging solar spectral lines as a test. Here 27 lines were added to get the average line profile shown in the frame on the lowest right row. The "wavelength" is in terms of the variable X, in km/sec. Portions of the spectrum around 15 lines are shown. In each frame the line at $X = 0$ adds coherently, all the other neighboring lines add incoherently and contributes to the 'noise' in the continuum of the average line. Above each frame: The laboratory λ_0 in Å, at $X = 0$, is listed after the symbol 'int25_'. For the first frame on top left, $\lambda_0 = 4783.420$Å. For the addition of the circular polarizations, the blending lines will add only to the 'noise'.

3.   Sources of spurious polarimetric signals

Almost everything along the light path from the source to the detector may cause spurious polarimetric signals: temporal variation of the light source due to seeing or instrumental drifts, instrumental polarization, performance of the polarimeter, polarization-dependent fringing, transfer optics, and detector sensitivity. Solutions may be found through careful design of the instrumental setup and of the observing procedure, and experimental tests should be performed to rule out the presence of spurious signals. There is no universal solution for all types of polarization measurement: a specific method has to be devised for each particular case.

4.   Polarimetry, seeing and time variations

A fundamental principle of polarimetry is that it requires comparison of two measurements of the same source of light, that differ *only* in their state of polarization. Any other difference between the two beams to be compared introduces spurious polarization signal. This restrictive condition is discussed in some detail. We can either make the two measurements successively, but otherwise identically, or simultaneously by a double beam setup. In any case, the fundamental principle is not completly satisfied. However, we may increase the required symmetry as will be shown below.

Two types of differences in the measured intensities of the two orthogonal states of polarization should be considered:

i) changes between successive exposures, due to seeing and Doppler effects due to earth-star relative velocity and stellar rotation, or due to instrumental changes;

ii) effects in double-beam comparisons. In the latter case the two intensities are measured on different CCD pixels and with corresponding problems. First, the absolute calibration of detector pixel sensitivity is not known to the required precision of 10^{-3}. Second, aberrations in the optics may make the two spectra slightly different. Third, curvature of the slit image and other characteristics of the spectrograph causes wavelength differences between corresponding pixels.

4.1.   Combining multiple exposures and double beams

Our method uses a two-beam setup and successively interchanges the polarization states of the two beams yielding four observations, i.e. eight spectra. Our working assumptions are that the errors are all small, and that the two classes of effects are uncorrelated, i.e. that the time-dependent effects are the same for the two beams and that the differences between the two beams are constant in time. Then, by combining the 4-observation, all the effects listed above may be reduced or eliminated as described in detail in Semel et al. (1993 paper III). In the present case we improve the approximation to the fundamental principale for polarimetry by taking a cycle of four exposures rather than the earlier two. In the complete cycle the $\lambda/4$ retarder takes successivly the orientations 1,2,2,1.

For sufficiently small V/I we obtain:

$$r(\lambda) - 1 \cong 8\frac{V(\lambda)}{I(\lambda)}, \tag{1}$$

where $I(\lambda)$ is the average intensity of all eight spectra. $V(\lambda)$ is the Stokes V parameter and $r(\lambda)$ is a suiteable ratio of the eight spectra, which represents an extension of the ratio for the case of two exposures as defined in paper III.

5. Reduction of the raw data.

Since we need to detect polarization signals with a noise less than 10^{-3} we must be very careful in treating the data. Since each order occupies about 25 rows on the CCD and since we combine several tens of spectral lines, we are in fact adding or subtracting data for a thousand CCD pixels to get just one wavelength pixel of datum at the end.

    1. **Cleaning**. Any cosmic ray 'spike' may be disaterous. Fortunately, an excellent "cleaning" is possible by comparisation of the four exposures. All the "effects" being small, say , less than a few percents in terms of the normalised intensity, any pixel in a given exposure well beyond this limit is identified as a "wrong" one.

    2. **Inverse rebinning**. In order, to maitain pixel resolution during the process of adding pixels, the spectra are "oversampled" by our software(FIGARO) by a factor of seven and the reduced 'pixels' correspond to exactly 0.5 km/sec. Thus the algebra is done with a precision of one tenth of the original pixel size.

    3. **Flat fielding**. As far as polarization is considered, the procedure of combining the four exposures (8 spectra) as described above and in paper Semel et al. (1993 paper III). is a way to get beyond this problem.

6. The coherent additions of the spectral lines.

In the first ZDI observations, (Donati et al.,1989), three lines were used. Being very similar, i.e., from the same multiplet, of the same strength, and nearly the same g factor, having very close wavelengths and mostly unblended, the three lines could be added with no further considerations. Here, we wish to add lines quite different spectroscopically. Also we want to use all the lines we can and we have to face the fact that most of the spectral lines of rapid rotators are seriously blended because of the stellar rotation.

    Naturally, the best way would be to use radiative transfer but at at the moment this is a formidable task. Even the methods suggested by Semel(1989), based on symmetries that allows one to unblend the Zeeman polarization with no detailed radiative transfer considerations, are at present too difficult. We therefore looked for a rapid and efficient approximate technique.

6.1. The typical shape of V

The weak fields approximation tells us that V is proportional to the first derivative of the intensity profile and this is derived directly from the radiative transfer equations (Semel, 1967). For stronger fields this expansion fails, however for

broad lines and/or for low spectral resolution this symmetry recovers and is a fair approximation. This is practically the situation in our case : magnetic fields are of the order of 1000 gauss and the spectral resolution is 70000. As the signals are very small, this assumption introduces less errors than the noise. We therefore conclude that we can try to add circular polarization of different lines as is suggested by fig 1.

6.2.   Justification for the additions of Zeeman polarizations in presence of blends.

We selected a list of about 27 lines, with no restriction related to their blends. We added their intensity profiles in the same way as indicated by fig. 1. That is, the spectral lines are plotted as function of $X \propto \frac{\lambda - \lambda_0}{\lambda_0}$ where λ_0 is the laboratory wavelength of the line.In other words we replace absolute wavelength by the variable X in units of km/sec. If all shifts are due to Doppler effect, than we require all the profiles to be function of the common variable X.

This technique means that we add all of the central lines of interest *coherently* and all the, undesirable neighboring, blending lines *incoherently*. It is easy to understand that incoherent addition of many blending lines will reduce 'the continuum' around the average line resultant from the coherent addition. In figure 2 we show the result of the application of this procedure to the observation of the moon. It is a remarkable and surprising result that one gets an average line which has "no wavelength" and still allows one to measure Doppler dimensions. When this approach was applied to the circular polarisation in the moon spectra, we found no signal above noise. Next, this method was applied to the spectropolarimetric data of the binary system HR1099. 28 lines were used and the results are shown in figures 3 and 4. It is easy to see that the circular polarisation occur at the primary star and almost nowhere else (there is a residual signal in the secondary star, but hardly above the noise level).

7.   Conclusions

1) Spectropolarimetry at the AAT with UCLES allows one to obtain very high S/N and high spectral resolution data by the coherent co-additions of many lines. A further developement of this technique is anticipated including eventually the modeling of the atmosphere in correlation with the magnetic fields.

2) The inspection of the polarization of the primary star of HR1099, shows that at least three patchs of magnetic fields are present on this star. This is evident by three maxima and three minima. This detailed signatures of magnetic fields are due to the actual performance of ZDI. Improving spectral resolution and S/N may disclose more magnetic details.

3) It is likely that HR1099 undergoes variability in its activity from year to year. Magnetic (and brightness) mapping , the next objective of ZDI and continous observation of solar type stars may be a clue for the understanding of solar and stellar dynamos.
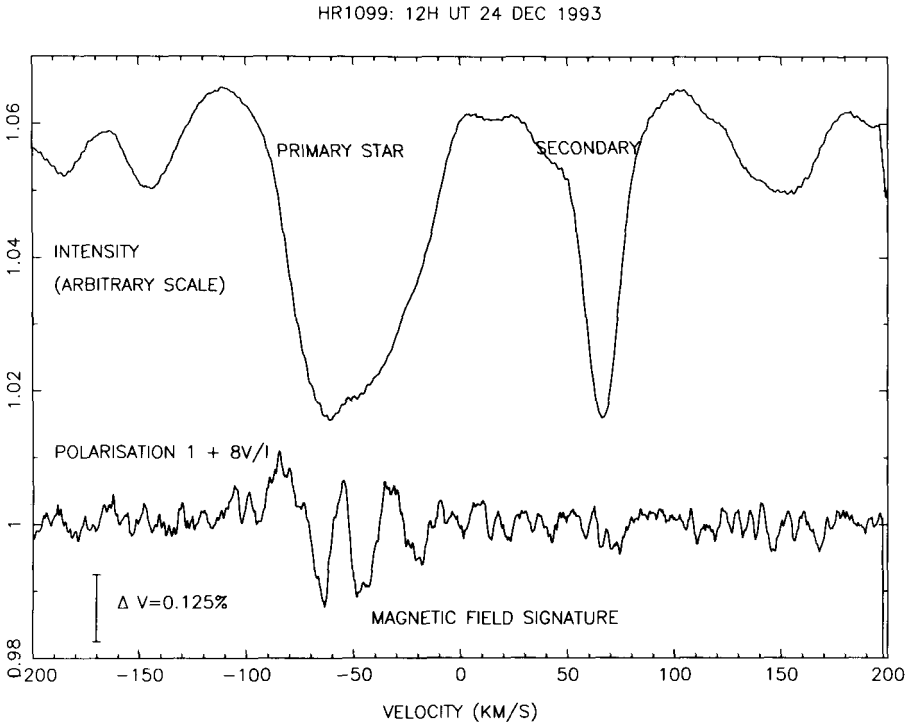
HR1099: 12H UT 24 DEC 1993

Figure 3.   Results for the binary star HR1099.(AAT-24/12/1993 12H UT) Averaging 28 stellar lines results in two lines, broad and narrow, that represent the primary and secondary stars of the binary system HR1099. The fluctuations in the 'continum' are due to the residuals of the non coherent addition of the blending lines and are 5 times weaker than the 'true' lines. We may expect that the contributions to the averaged polarisation is still much smaller, since 1) on the average the g factor for the blending lines is smaller than those selected, and 2) the polarisation signal has fluctuations which reduce coherence further more for the undesired blends. The average of $r(\lambda) \cong 1 + 8V(\lambda)/I(\lambda)$ shows the quite convincing signature of the magnetic fields in the primary star, three maxima and three minima with the amplitude of about $2.5\ 10^{-3}$.
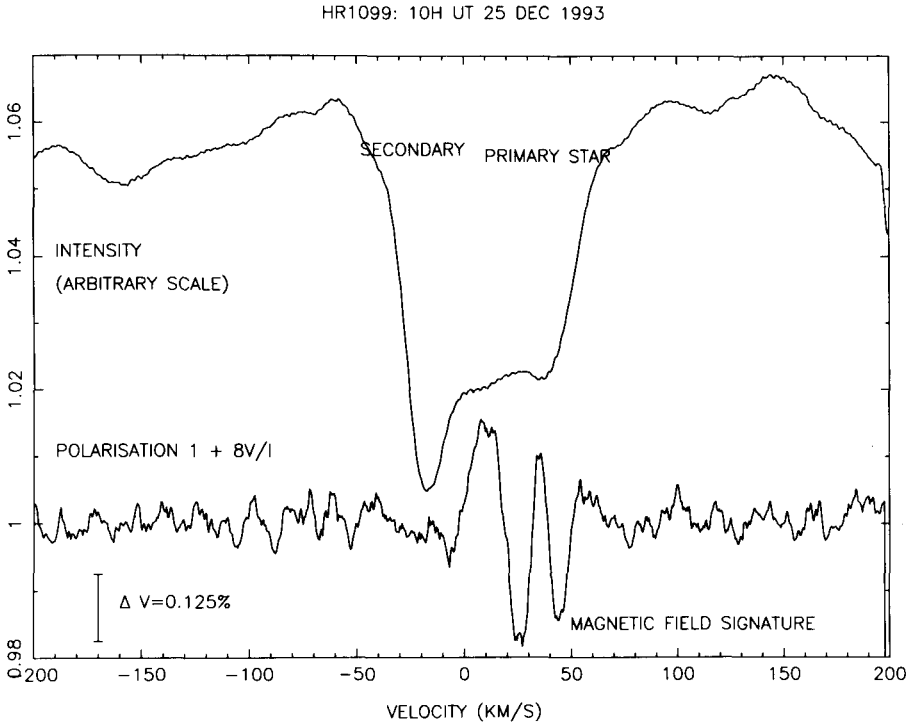
HR1099: 10H UT 25 DEC 1993

Figure 4.   Results for the binary star HR1099.(AAT-25/12/1993 10H UT) The same as figure 3., but 22 hours later. Note the change in the relative positions of the primary and secondary stars and the possible sign and amplitude change for the field.

and participating in the realization of the reduction package. K. Shortridge fixed some of the most important problems in application of "FIGARO" to ZDI. J.-F.Donati, D.Rees, B. Carter, K. Taylor, K.Shortridge, J. Spyromilo and O. Durand were observers during these runs.

It is a pleasure to thank Andy Skumanich for instructive discussion, careful reading the paper and improving it substantially.

Discussion

Ph. Stee: Can you do the same work with slow rotators, because it seems that you need a fast rotation to separate different spots contributions in your line profile ?

M. Semel: This depends on the scales, say in km/sec, of the spot's size, the separation between spots of *opposite* polarities on the one hand and the spectral resolution and the width of the 'local' spectral line on the other hand. If the first two are much bigger than the last two, their contributions are clear in the polarization in the spectral lines. In the opposite case, these contributions may be diluted and cancel.

Ph. Stee: Can you distinguish between Non Radial Pulsations (which produce a local variation of the (effective) photospheric temperature of the star) and spots which are appearing and disappearing on the star surface.
This can be very helpful because for instance with early type stars (as B or Be stars), we don't know if the variation of the photospheric profiles (fast variations in hours) are due to spots or to Non Radial Pulsation.

M. Semel: In the context of ZDI, we deal with magnetic spots that gives rise to Zemman polarization. I doubt whether the magnetic field may appear and disappear in short periods. However, by spectropolarimetry the presence of magnetic field may be disclosed.

References

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