A New Zeeman-Doppler Imaging Code for Active Late Type-stars. An Application to II Peg

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Abstract. The fact, that late-type stars exhibit complex and small scale surface magnetic fields, imposes special requirements on their observation as well as on their modeling and reconstruction. Our new Zeeman-Doppler imaging code iMap, which we present here, was particularly designed for the application to late type stars. It does full radiative transfer calculations and utilizes a regularization scheme which is based on local maximum entropy. Furthermore a new multi-line cross-correlation technique by means of a Principal Component Analysis is used to enhance the quality of individual observed polarized line profiles.

In a first application we present Zeeman-Doppler images of II Pegasi, which reveal a surprisingly large scale surface structure with one predominant magnetic longitude, containing a mainly radially oriented field.

1. Introduction

Zeeman-Doppler imaging (ZDI) is a method to achieve spatial information about the surface magnetic field distribution of stars. It was introduced by Semel (1989) and successfully applied since, to a number of stars, mainly early-type stars (Cp stars, Wade et al. 2000; Kochukhov et al. 2004). However there is only a small number of Zeeman-Doppler images of late-type stars (Donati 1999; Petit 2006). This is due to the complex magnetic field surface distribution, which may lead to a severe reduction or even the complete mutual cancellation of the circular polarization profiles by different magnetic polarities. The linear polarization profiles are typically more than one order of magnitude smaller than the circular polarization profiles and therefore even more difficult to detect. The multi-line techniques, such as the one introduced by Semel & Li (1996) or the more elaborated Least-Square Deconvolution, developed by Donati et al. (1997), are used to enhance the polarization signal to a level, where a detailed diagnostic of the surface magnetic field becomes feasible. A drawback of this method is the involvement of the weak field approximation and the reduced interpretability of the retrieved mean line profile.

We have developed a Zeeman-Doppler imaging code (iMap), particularly with regard to the forthcoming spectropolarimeter PEPSI (Potsdam Echelle Polarimetric and Spectroscopic Instrument), which will be installed at the 8.4 m Large Binocular Telescope (LBT; Strassmeier et al. 2003, 2007). It will allow the observation of late-type stars in full Stokes with a high enough signal-to-noise ratio. Faint objects however, will still require an enhancement of the signal-to-noise ratio. To boost the polarization signal, we also have developed a new
multi-line technique. In the following we present the basic internals of the ZDI code as well as the new multi-line technique. In a first application we present magnetic surface maps of II Pegasi.

2. Basic Principles of the Zeeman-Doppler Imaging Code

Zeeman-Doppler imaging is an inverse problem, where an error function between the rotationally modulated observed and the synthesized Stokes spectra is minimized. The synthetic spectra are fitted, by adjusting the free parameters, namely temperature and vector components of the magnetic field, of the underlying surface model. The forward module of our code, which synthesizes the Stokes profiles, incorporates the full numerical solution of the polarized radiative transfer equation (RTE) by means of the Diagonal Element Lambda Operator (DELO) method (Rees et al. 1989). It uses Kurucz model atmospheres (Kurucz 1993) and atomic line parameters from the Vienna Atomic Line Database (VALD) (Piskunov et al. 1995).

The stellar surface is parametrized on a variable equal-area or equal degree partition with a minimum size of $1^\circ \times 1^\circ$ in longitude and latitude. For each surface segment the local Stokes profiles are calculated with respect to its position in the observer coordinate frame.

The contribution of each zone to the disk integrated spectra is weighted by its projected area and the corresponding local profiles are Doppler shifted according to its radial velocity. Temperature and magnetic field distribution can be described by an individual segment based or by a global spherical harmonics setting. The center to limb variation is taken into account by adjusting the depth stratification of atmospheric parameters for each surface element.

The inversion module of our ZDI code incorporates an entropy regularized conjugated gradient method or optionally a Levenberg-Marquard method and is able to make use of all four Stokes components. We used a regularization function, similar to that formulated by Brown et al. (1991), which is:

\[
S = -\sum_i (|P_i| + \alpha) \log \frac{|P_i| + \alpha}{|m_k| + \alpha} - 1 ,
\]  

where $m_i$ is the default value of the surface segment $i$. To ensure, that the entropy is also defined for zero values of the surface distribution $P$ the value of $\alpha$ is set to a small positive number.

Not much details about the default image can be found in the ZDI literature, even though effects can be rather drastic, depending on its definition. The default values are usually set all to an equal value, which is in most cases the global average of the parameter under consideration. Having small scale variations with great local differences, this can be a problem. We therefore propose an adaptive local entropy function where the default values $m_i$ are retrieved by the actual mean values of the neighboring segments:

\[
S = -\sum_i (|P_i| + \alpha) \log \frac{|P_i| + \alpha}{\frac{1}{k} \sum_{j=0}^{k} \beta(j)|m_j| + \alpha} - 1 .
\]
Here the sum in the logarithm runs over the $k$ neighboring elements of segment $i$ and $\beta(j)$ is an extra term which includes a particular weighting.

Our ZDI code can retrieve consecutively or simultaneously the temperature (Doppler imaging) and the magnetic field distribution (Zeeman-Doppler imaging), by using all four Stokes components or only Stokes I and V.

3. Multi-line Technique Based on Principle Component Analysis

In the past there have been several approaches to enhance the signal-to-noise ratio of spectropolarimetric data, mainly circular polarization so far. One of the first was the multi-line technique introduced by Semel & Li (1996), where a few tens or hundreds of magnetic sensitive lines are co-added. This cancels the noise due to its random distribution and coherently adds up the polarization signature. The probably most common technique is the powerful Least-Square-Deconvolution (LSD), developed by Donati et al. (1997). It uses a pre-computed line mask of several thousand lines for cross-correlating the signals and assumes weak field approximation, to retrieve a mean line profile.

In order to avoid simplified a-priori assumptions and to extract single spectral line profiles, but benefit at the same time from a multi-line cross-correlation technique we propose a multi-line principal component reconstruction technique. The use of the well known decomposition and dimensionality reduction capabilities of the Principal Component Analysis (PCA; Bishop 1995) is ideal for this purpose.

We use the PCA method to decompose the entire set of observed Stokes spectra, expressed in velocity space, into a new coordinate system, which accounts for the redundancy and the variance in the data. This procedure will project the most coherent and systematic features, the Zeeman signatures in the observed Stokes profiles, into the first few eigenvectors with the largest eigenvalues, while the incoherent features, such as noise, will be mapped to the less significant eigenvectors with low eigenvalues. By using only the first few eigenvectors to reconstruct the original spectra, we can reproduce the individual Stokes profiles of one particular spectral line, to an extent that the majority of the characteristic features of this line is well reproduced with a minimum of uncorrelated effects.
Figure 2. Left: Surface magnetic field of II Peg. Bright thin lines represent magnetic field vectors pointing outwards, while dark lines represent those pointing inwards. The underlying color gives the absolute field strength. Right: PCA reconstructed Stokes V profiles (straight) for the Fe I 5497 line and fits (dashed). Numbers on the right y-axis represent rotation phases.

The number of the most significant eigenvectors used for the reconstruction is chosen in such a way, that the discrepancy equals the SNR of the original profile.

Since this method allows the reconstruction of individual line profiles, all the known line parameters can be used in the following DI and ZDI process. Figure 1 shows such a reconstruction of the Fe I 5497 line which was present in II Peg data, taken with the SOFIN spectrograph at the Nordic Optical Telescope (NOT) (Tuominen et al. 1999). For the reconstruction of this line, we have used 18 magnetic sensitive spectral lines (Fe I, Ca I, C I) in a wavelength range between 4600 Å and 6000 Å and the three largest principal components of the decomposition.

Although only 18 lines were used in the described multi-line approach, the Stokes V line profile exhibits a much smoother and less noisy behavior and is due to the PCA analysis more reliable in terms of interpretability. A closer look on the eigenvectors, shows that the first eigenvector resembles the mean profile we get, when we simply co-add the spectra. The following few contain mainly individual features of the lines, while the remaining contain mainly the noise. This method will be fully described and statistically analyzed in a forthcoming paper.

4. Zeeman-Doppler Imaging of II Peg

The Observation of II Peg was carried out in August 2004 with the SOFIN spectrograph at the Nordic Optical Telescope (NOT). The data (Stokes I and V) covered 7 rotation phases and showed a signal-to-noise ratio of about 200.
Figure 3. Mercator plots of the magnetic field components of II Peg; top: radial magnetic field; middle: azimuthal magnetic field; bottom: meridional magnetic field.

Principle stellar parameters were taken from Berdyugina et al. (1998). An initial Doppler imaging with the Ca I 6439 line, using our code in DI mode, determined the temperature distribution. The subsequent Zeeman-Doppler imaging, using the PCA-reconstructed Stokes V profile of the spectral line Fe I 5497, was then carried out with the entropy regularized conjugated gradient method. The final magnetic field distribution is shown in Fig. 2, together with PCA reconstructed and fitted Stokes V profiles. Despite the fact we have only used Stokes V profiles, the surface exhibits a rich magnetic structure as can be seen in Fig. 3. Resulting maps show, that the magnetic field is mainly located at high latitude around 60° and in one active longitude where the magnetic field is predominantly radially oriented.

As it has been already observed by e.g. Donati (1999), we also notice only a small correlation between the DI and ZDI map, concerning the concurrence of cool spots and magnetic active regions. This however seems to be plausible, because of the strong suppression of the photon flux in regions, which are between 700K and 1000K cooler than the quiet and hot areas of the surface.

Furthermore, there is a strong imbalance in the polarity of the magnetic field. We believe, that this is due to the smaller contribution from spots to the Zeeman signature as a result of their lower temperature. The complementary use of molecular lines might help, to further constrain the magnetic field in cool spots (Berdyugina et al. 2003; Afram et al. 2006).
5. Conclusion

We have presented a new Zeeman-Doppler imaging code, especially designed for the application to late-type stars, with the ability to use all four Stokes components and recover an arbitrary field configuration (not restricted to spherical harmonics). Furthermore, we showed the ability of a Principal Component Analysis driven multi-line technique that allows an inversion on the basis of individual spectral line profiles. In a first application we could demonstrate the potential of the ZDI code and the multi-line technique. However it should be noted, that the reconstruction of surface magnetic fields having only Stokes V and a rather small number of rotation phases available is far from a well posed problem. Small changes in the regularization function, or the temperature distribution or the optimization strategy can lead to rather drastic effects in the reconstructed magnetic field distribution. Therefore it is important to retrieve Stokes V profiles with the best possible accuracy and signal-to-noise ratio and to make also Stokes Q and U profiles available for ZDI. Although the incorporation of Zeeman sensitive molecular lines (under development for iMap) will help to further constrain the solution of the inversion.

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