Stellar Spectropolarimetry

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Abstract. Stellar spectropolarimetry involves the study of magnetic fields on stars through the collection of high-resolution polarised spectra. This field has grown rapidly in recent years with the advent of two new high-resolution echelle spectropolarimeters available to the astronomical community, ESPaDOnS on the 3.6-m Canada France Hawaii telescope and NARVAL on the 2-m Telescope Bernard Lyot. In addition, several groups are now developing new magnetic imaging codes as well as new techniques to recover information from polarised spectra. In light of this a splinter session at *Cool Stars XV* was organised to present and discuss some of the latest techniques and results in this field. In this paper I attempt to summarise the ideas and results presented at the session.

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INTRODUCTION

On cool stars the generation of magnetic fields is probably the most important process occurring in the star, affecting not only the multitude of activity phenomena observed on such stars but also such things as the star's angular momentum evolution. On the Sun, magnetic field is generated through an $\alpha - \Omega$ dynamo process, but what of other stars? What effect do basic stellar parameters such as rotation rate, age, mass, convection zone depth, etc., have on the operation of stellar dynamos? One of the key windows we have onto stellar dynamos is through the mapping of magnetic field topologies on stellar surfaces.

The technique of Zeeman Doppler imaging (ZDI) was first introduced by Meir Semel in the late 1980s [18] as a way to determine the magnetic topologies of rapidly rotating cool stars. This method has since been developed by people such as Steve Brown and Jean-Francois Donati [3, 9] and was put into practice using the SEMPOL visitor instrument on the Canada France Hawaii and Anglo-Australian telescopes. As the polarisation signatures in each spectral line are extremely small (of the order of 0.1% of the contiuum level), the technique of Least-Squares Deconvolution, LSD [10], was developed to "sum" the Stokes V signature in each of the several thousand atomic lines in an echelle spectra into a single, high signal-to-noise LSD profile. Magnetic topologies are then recovered through the inversion of a time series of these Stokes V LSD profiles.

Although limited to recovering large-scale magnetic fields from stellar surfaces, due to cancellation effects from mixed polarity regions, ZDI has been remarkably successful, detecting and mapping magnetic fields on a range of cool stars from pre-main sequence objects through to evolved giants. With the recent development of two new spectropolarimeters, and more in the pipeline, the field of spectropolarimetry is currently experiencing a boom. Along with new instruments a number of groups have developed new

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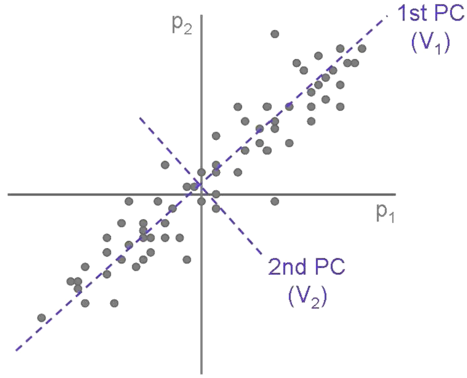

FIGURE 1. Plot showing the first (V_1) and second (V_2) principle components of a dataset depending on two physical parameters (p_1 and p_2).

codes for magnetic imaging which overcome some of the limitations of LSD and ZDI. A number of new techniques and results were presented at the "Stellar Spectropolarimetry" splinter session of *Cool Stars XV*. Below I present summaries of the talks presented.

NEW TECHNIQUES

Detection and denoising of Zeeman signatures in stellar polarised spectra (speaker: M. J. Martinez-Gonzalez)

Although LSD is very powerful, one of the drawbacks is that the "mean" profile created is difficult to associate with a standard spectral line. Using the technique of Principle Component Analysis (PCA [13]) a new method has been developed [14] that takes advantage of multi-line observations to increase the signal-to-noise of individual spectral lines, and in doing so preserve the information in the individual line. Given some dataset (say an echelle spectrum) which depends on **p** parameters (physical stellar parameters) and plotting the dataset in **p**-dimensional space, the resultant cloud of points will be elongated in some directions. These directions are the principle components of the data set with the first principle component containing most of the correlation, see Figure 1.

In this technique, each spectral line is converted to a velocity scale and as noise should have negligible correlation, PCA is used to detect correlation between the velocity points of the numerous spectral lines in each spectrum. Thus this technique uses information contained within all spectral lines observed to "denoise" an individual spectral line. This denoising has been applied to simulated Stokes Q and V data and was shown to increase signal-to-noise up to an order of magnitude over individual lines and has been applied to real data from II Peg (see section on talk by M. Kopf below).

LSD - a nonlinear approach
(speaker: C. Sennhauser)

With normal LSD it is assumed that any Stokes profile can be written as a set of linear equations **I = M • Z** where **I** is the observed Stokes profiles, **M** is the line mask and **Z** is the sought after "mean" profile produced by LSD. LSD transforms each line into the corresponding velocity scale and looks for a least-squares solution for each element of **Z** independently. LSD does not account for the fact that most of the line profiles are blended.

A new "nonlinear" LSD technique has been developed that does not treat the lines independently but accounts for many lines which contribute to the profile. This is done by setting up a single over-determined system of equations including the whole vector of **Z** which are solved simultaneously. In addition, rather than just linearly adding the line depths "nonlinear" LSD uses the interpolation formula of [15] to account for different line depths. This enables the more accurate recovery of the line profile. Simulations of both atomic and molecular spectra have shown that the "nonlinear" LSD technique can retrieve an accurate stellar profile from even heavily blended molecular lines.

Spectropolarimetric multiline analysis of magnetic fields
(speaker: J. C. Ramirez Velez)

PCA can also be used to recover the Zeeman signature in polarised echelle spectra using another method. This alternative method, uses the information from all atomic lines contained in the observed spectra, but contrary to the PCA "denoising" method presented above, it is model dependent. A synthetic database of spectra for different combinations of the stellar parameters, magnetic field intensities, orientations, etc., is created. This database can be extremely large depending on the number of free parameters. However, the dataset can be compressed using PCA, resulting that only a few principle components are required for the analysis of the spectra. The principal components of the theoretical dataset can then be cross-correlated with the observed stellar spectra to obtain "mean" Zeeman signatures with dramatically increased signal-to-noise which can show the presence of magnetic fields on the stellar surface. This technique has been dubbed PCA-ZDI.

As a test of the procedure, a set of 500 synthetic "multi-Zeeman" signatures were created and inverted to recover their initial stellar parameters. After inversion, the results show that the multi-Zeeman signatures properly encode the information of all the physical parameters, in particular the magnetic field. PCA-ZDI has been successfully used to recover the first detection of linear polarisation profiles in a cool star [19].

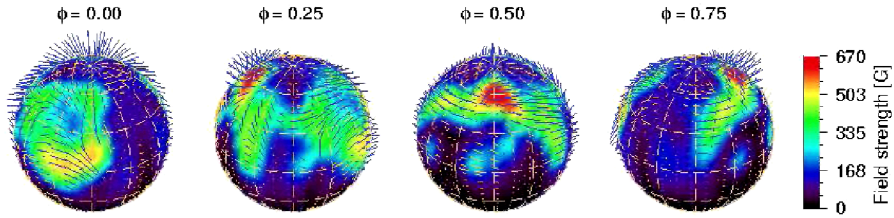

FIGURE 2. Magnetic field reconstruction for II Peg in 2004 at four different rotational phases.

Magnetic surface field evolution on II Pegasi (2004 to 2007) (speaker: M. Kopf)

Due to the complexities of calculating disk integrated line profiles in all 4 Stokes parameters in the presence of a magnetic field, many ZDI applications rely either on approximations or ignore polarised radiative transfer completely. iMap is a new Zeeman Doppler imaging code [4] incorporating polarised radiative transfer using artificial neural networks to do the calculations. The artificial neural network was trained on the basis of a synthetic database of Stokes profiles to obtain approximate models for the non-linear mapping between the atmospheric parameters and Stokes spectra. The technique is called "PCA-MLP synthesis" as PCA is again used to reduce the dimensionality of the database. In addition, as explained previously, PCA is used to "denoise" the individual spectra lines allowing for inversions from single lines.

iMap has been used to reconstruct the magnetic and temperature maps of the early-K RS CVn star II Pegasi at 2 epochs (2004 and 2007). Figure 2 shows the magnetic reconstruction for the 2004 epoch. iMap uses an iterative optimisation process which uses the temperature map created from Stokes *I* profiles in the inversion of the Stokes *V* profiles. Previously Stokes *I* and *V* maps were created independently. The resultant maps show regions of magnetic field at high latitudes with the position of cool spots and magnetic regions partly over lapping. The images also revealed a polarity switch occurring on the star as well as migration of the dominant magnetic surface structure between the two epochs.

Magnetic Doppler imaging of active stars (speaker: O. Kochukhov)

Although LSD/ZDI has been a spectacular success there are a few limitations. One of these is the fact that LSD/ZDI reconstructs the temperature and magnetic field maps independently and as such often fails to recover magnetic fields inside cool spots. A new magnetic imaging code (Invers13) for mapping magnetic fields on cool active stars has been developed to overcome this problem. The main attractions of the code are (i) direct modelling of 2 (*I* & *V*) or 4 (*I*, *Q*, *U*, & *V*) Stokes parameters in individual spectral lines using polarised spectrum synthesis, (ii) self-consistent mapping of temperature and

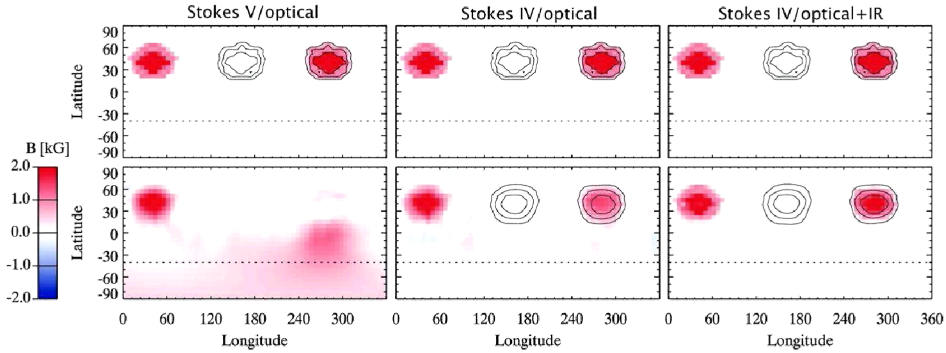

FIGURE 3. Top images show the true magnetic (colours) and temperature (contours) distributions. Bottom images show the reconstructed images (left) using Stokes *V* profiles alone (without simultaneous Stokes *I* mapping), (centre) simultaneous Stokes *I* and *V* mapping, and (right) simultaneous Stokes *I* and *V* mapping using both optical and infrared lines.

magnetic field (the temperature and magnetic field maps are recovered simultaneously), (iii) ability to probe into starspot interiors using molecular and/or infrared lines.

By creating the temperature and magnetic field maps simultaneously, as well as including molecular and/or infrared lines in the imaging process, Invers13 has the ability to more accurately recover the magnetic field strength inside cool spot regions. Simulations using Invers13 (see Figure 3) show that although the simultaneous creation of both the temperature and magnetic maps can recover the temperature distribution accurately, the strength of magnetic fields inside cool spots is still somewhat underestimated (although more accurately recovered than using Stokes *V* information alone). The inclusion of infrared lines in the imaging process is able to more accurately reproduce the field strength inside cool spots.

NEW RESULTS

Observational evidence for a non-solar-type dynamo operating in late-type stars (speaker: S. V. Jeffers)

Long term spectropolarimetric observations of stars is one of the key ways we have of understanding how the dynamo works in stars other than the Sun. HD 171488 is a active zero-age main-sequence early-G star with a rotation rate approximately 20 times faster than the current Sun. Magnetic topologies, using LSD/ZDI, of this star have been taken over 4 epochs (2004 to 2007). This is the first long term analysis of the spot/magnetic field distribution and differential rotation on an early-G dwarf (other than the Sun).

The spot maps showed a persistent polar spot with lower latitude features, however no evidence for “active longitudes” or “flip-flops” [2] is seen. For all epochs the radial magnetic field shows mixed polarity at all latitudes with the negative field tending to dominate. In contrast the azimuthal field shows a persistent ring of positive field around the pole, with mixed polarity at lower latitudes. These results are similar to that found for lower mass solar-type stars [6]. No cyclic evolution in the magnetic field of HD 171488 was observed.

Using the sheared imaged method of [8, 17] the differential rotation from both the brightness and magnetic features was determined at all possible epochs. The differential rotation measured was extremely high at almost an order of magnitude greater than that shown on the Sun. Unlike lower mass stars [7] there was no evidence of temporal evolution in the differential rotation measurements and no evidence of a difference in differential rotation measurements from the brightness and magnetic features. Due to this difference in differential rotation between brightness and magnetic features seen on lower mass stars it has been hypothesised that the brightness and magnetic features of these stars are anchored at different depths in the stellar convection zone [7]. Could the thinner convection zone of HD 171488 mean that they are anchored at similar levels?

Zeeman Doppler imaging of a pre-main sequence binary system (speaker: N. J. Dunstone)

Another interesting system that has recently been observed using LSD/ZDI is HD 155555. This is a pre-main sequence binary (G5IV + K0IV) in which both stars show evidence of magnetic fields in their Stokes *V* profiles. HD 155555 was observed at two epochs (2004 and 2007). In order to correctly disentangle the Zeeman signatures of the two stars when they are overlapping, a new binary ZDI code was developed (ZDots, [11]).

As with HD 171488 above, the radial field of both stars in HD 155555 shows mixed polarities at all latitudes and rings of azimuthal field present on both stars, with the secondary showing a simpler field geometry to that of the primary.

The differential rotation of the two components was measured (for the 2007 epoch only) using the same method as HD 171488 above, and the differential rotation levels were found to be similar to that shown by single stars of similar spectral types [1]. This is in contrast to previous work on evolved binary systems which often shows low rates of differential rotation [16]. As HD 155555 is tidally locked, it is believed that the low differential rotation seen in evolved binary systems is likely due to their internal structure (i.e. their large convection zones) rather than tidal locking. As with other stars of similar masses, the magnetic signatures give stronger differential rotation measurements than the brightness features, in contrast to HD 171488 above.

A preliminary binary star field extrapolation of the coronal magnetic field was done using [12] showing interaction of the coronal magnetic field of the two components for the facing hemispheres (see Figure 4). In addition, the secondary star appears to show a significantly tilted magnetic axis ($\sim 75^\circ$) compared to its rotation axis.

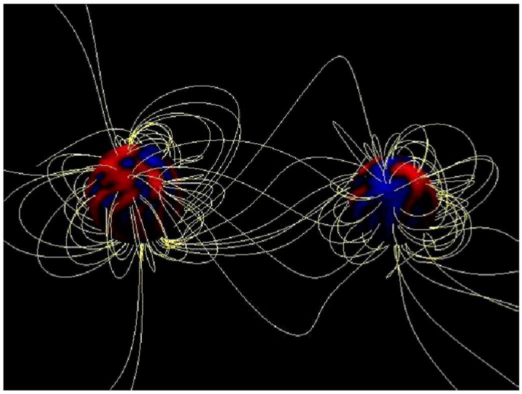

FIGURE 4. Preliminary binary field extrapolation with the primary on the left and the secondary on the right, using the code of [12].

Correlating magnetic field strength and starspots on FK Com (speaker: H. Korhonen)

This final presentation is slightly different as it uses low-resolution spectropolarimetry (from FORS1 on the VLT) and high-resolution spectroscopy (from the robotic STELLA observatory [20]) observations of FK Com to determine a relationship between magnetic field strength and the location of surface spot features. FK Com is a single, extremely rapidly rotating (vsini $\sim$ 160 km/s), evolved, mid-G giant.

The FORS1 observations were used to measure the circular polarisation in the hydrogen balmer and strong metal lines to obtain measurements of the mean longitudinal field ($<B_Z>$) at 9 different rotational phases of the star. The high-resolution spectroscopy was used to do traditional Doppler imaging on the star to recover the location of spot groups on the surface. The reconstructed temperature map showed two main spot groups located around 0.2 phase apart.

Surprisingly, both the maximum and minimum values of $<B_Z>$ were found to occur within the broad photometric minimum of FK Com's light curve. However, this can be explained if the two main active regions on the star have opposite polarity as their magnetic field strength would then cancel out to produce a minimum in $<B_Z>$ when both spots are visible. FK Com would make at excellent target for Zeeman Doppler imaging to recover the global magnetic topology of the star.

CONCLUSIONS

Our understanding of the processes by which stars produce magnetic fields is still in the development stage. However, thanks largely to the technique of stellar spectropolarimetry we are starting to gain an understanding of how basic stellar parameters do/don't influence the magnetic field topology and differential rotation of stars. The picture is more complicated than might have first been imagined but recent results have shown intriguing differences in the differential rotation of higher and lower mass stars and between evolved and pre-main sequence binaries. In addition, evidence for magnetic cycles on some stars [5] but not others (yet?) has been seen.

With recent instruments such as ESPaDOnS and NARVAL coming online producing new results for previously unobtainable stars (see results on M-stars and slowly rotating G-stars by Donati and Morin in these proceedings) our parameter space has expanded markedly. As well, there are forthcoming polarimeters for the Large Binocular Telescope and HARPS. With the development of new magnetic imaging codes such as those presented above we should soon have an unprecedented observational dataset from which to (indirectly) observe the underlying stellar dynamo. As with many areas of astronomy, more observations are required. Monitoring of stellar magnetic fields on different stellar spectral types over long periods of time will provide key data to better understand the generation and evolution of magnetic fields in cool stars.

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