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Spectropolarimetry with the DAO 1.8–m Telescope ⋆

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Abstract. The fast–switching DAO spectropolarimeter, mounted on the 1.8–m Plaskett telescope started operation in 2007. Almost 14 000 medium–resolution ($R \approx 15\,000$) polarimetric spectra of 65 O–F type stars have been obtained since then in the course of three ongoing projects: the DAO Magnetic Field Survey, supporting the observations for the CFHT MiMeS survey, and an investigation of the systematic differences between the observed longitudinal field, measured with the Hβ line and metallic lines. The projects are briefly described here. The current status, as well as some results are presented.

Key words: magnetic fields – Ap and Bp stars – Zeeman effect – fast–modulation ferroelectric liquid crystal spectropolarimetry – survey

1 The DAO Spectropolarimeter

The Dominion Astrophysical Observatory (DAO) is located on the Vancouver Island, just north of Victoria, British Columbia. The Observatory is operated by the National Research Council of Canada's Herzberg Institute of Astrophysics, and has two telescopes located on its grounds: the 1.2–m telescope and the 1.8–m Plaskett telescope. The 1.2–m telescope is used exclusively for high–resolution coudé spectroscopy, often in robotic mode. The 1.8–m Plaskett telescope is used for direct imaging, spectroscopy, and spectropolarimetry.

A grating spectrograph that offers a wide variety of spectral resolutions ranging from $R = 200$ to 15 000 is mounted at the Cassegrain focus of the 1.8–m Plaskett telescope. Three years ago an inexpensive polarimetric module for this spectrograph was designed and built by the observatory staff (Monin et al., 2011). The module is installed behind the spectrograph slit. The polarimetric module and the Cassegrain spectrograph together form what is known as the DAO spectropolarimeter. The instrument is optimized to measure circular polarization from stellar sources in a 260 Å–wide spectral window, centered on Hβ with a resolution of about $R = 15\,000$.

The module incorporates a two–beam design. An achromatic quarter–wave plate converts circularly–polarized light into linear. A calcite beam displacer then separates the orthogonal linear polarization components. The two beams travel parallel to each other inside the spectrograph. As a result, two spectra in opposite polarizations are recorded on a CCD. Since both spectra are taken under exactly the same conditions, the polarization signal is independent of sky transparency, seeing or slit losses but not the instrumental systematics. In our spectropolarimeter we use fast modulation to fight the instrumental systematics. A fast–switching ferroelectric liquid crystal (FLC) half–wave plate is installed between the quarter–wave plate and the beam splitter. The FLC half–wave plate interchanges the two beams, so that the beams travel the same path inside of the instrument. The

⋆ Based on the observations acquired at the Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, National Research Council of Canada.

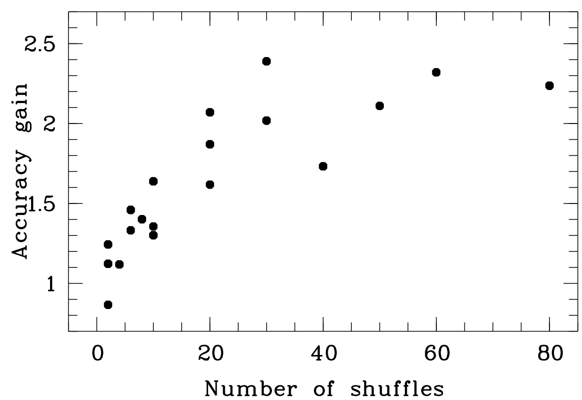

Figure 1: The DAO spectropolarimeter uses fast modulation in order to fight the instrumental effects. The relative increase in positional accuracy versus the number of switch cycles is shown in this figure. With 20 or more switch cycles the accuracy improves by a factor of two or more.

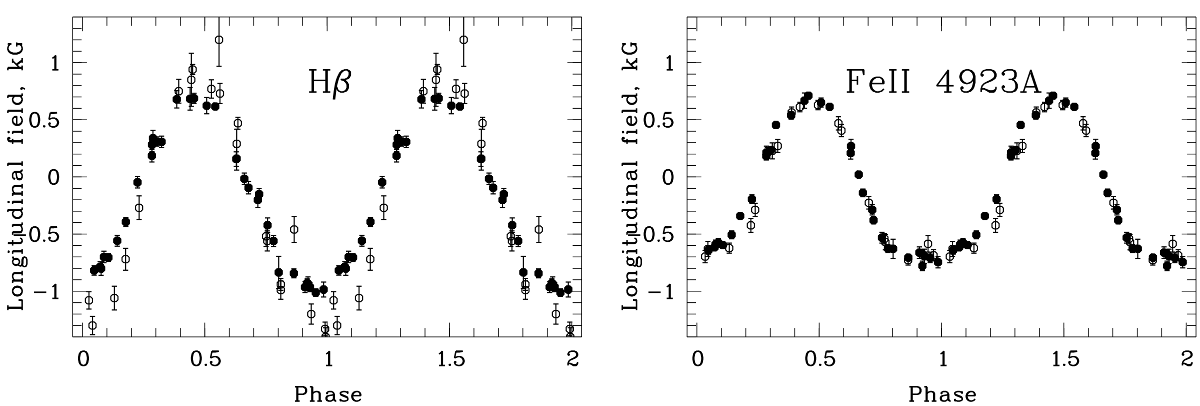

Figure 2: Longitudinal field measurements of the well–known magnetic star α^2 CVn. Left graph: our Hβ line measurements (filled circles) and the Balmer line photoelectric measurements by Borra & Landstreet (1977) (open circles). Right graph: our Fe II λ 4923 line measurements and the metallic line LSD measurements by Wade et al. (2000).

waveplate is synchronized with shuffling of the charge back and forth on the CCD (Chountonov et al., 2000). The DAO spectropolarimeter can be switched up to 100 times per second. In Fig. 1 the gain in positional accuracy is plotted against the number of switch cycles. By executing 20 or more switch cycles (we typically switch 60 times during each exposure) the accuracy can be improved by a factor of two or more. Another advantage of this modulation approach is that no flat–fielding is necessary since the same CCD pixels are used for both polarizations.

The DAO spectropolarimeter was mainly designed to measure the longitudinal magnetic fields in stars through the use of the Zeeman effect. In a magnetic field the spectral lines split into two or more components, and the individual components have different polarizations. The DAO spectropolarimeter can separate components in different polarizations, so that a small magnetic shift can be measured. Magnetic shifts are usually quite small, less than a single CCD pixel. Great care is needed in order to measure such small line displacements. We apply the Fourier cross–correlation technique to measure the shift. The shift is usually measured in the line core, since the polarization signal is strongest there, although other parts of the line profile can be used as well. Magnetic field measurements in the wings of Hβ agree well with the line core measurements if the appropriate correction for Stark effects is applied to the line wing measurements (Mathys et al., 2000). The accuracy of line core measurements is usually higher however. The DAO spectropolarimeter enables us to measure the magnetic shift in both the hydrogen Hβ line, as well as metallic lines. This is a big advantage of our spectropolarimeter over some other instruments. Fig. 2 shows how our measurements compare with previously published data for the bright well–known magnetic star α^2 CVn. Our H β measurements agree with the Balmer line photoelectric measurements obtained by Borra & Landstreet (1977), while our measurements of the Fe II λ 4923 line agree perfectly with the metallic line measurements obtained by Wade et al. (2000).

2 Spectropolarimetry with the DAO 1.8-m Telescope

The DAO spectropolarimeter was commissioned in October 2007. Since then, it has been used extensively for several different projects. The spectropolarimeter is typically scheduled for two to three weeks of observing time each quarter. In three years of operation 519 magnetic field measurements have been obtained for 65 O–F type stars as faint as the 9th magnitude. The instrument archive now contains 13 728 individual polarization spectra. Both slowly and rapidly rotating stars have been successfully observed, with the fastest object rotating at about 400 km/s. An accuracy of about 20 to 100 G in Hβ can be achieved with the DAO spectropolarimeter; this depends mostly on the object's brightness and its $v \sin i$.

The DAO spectropolarimeter is used in three major ongoing projects:

- MiMeS support program;
- DAO Magnetic Field Survey;
- Hydrogen versus metallic line magnetic field measurements.

The first project is support observations for the CFHT Large Program called Magnetism in Massive Stars (MiMeS). The MiMeS program is aimed at significantly improving our knowledge of how magnetic fields in massive stars influence massive star evolution and also how the fields modify mass loss in these stars (see Gregg Wade's article in these Proceedings). Part of this program consists of a large survey of stars more massive than 8 solar masses. At the DAO we have been doing the follow up spectropolarimetric observations of some objects from the MiMeS survey.

The DAO Magnetic Field Survey is an extension to the MiMeS survey to less massive upper main sequence stars. Many of these stars, especially fainter ones, have not been examined for the presence of a magnetic field. Most well–known magnetic B–type stars with magnetospheres are non–thermal radio sources. In the early stages of the DAO Magnetic Field Survey we therefore were concentrating our efforts on observing peculiar B–type stars known to be radio sources. As a result we have discovered four new magnetic stars: HD 135679, HD 164429, HD 176582, and HD 189775. HD 176582 (B5 IV, $V = 6.4$, $v \sin i = 100$ km/s) was the first magnetic star, discovered at the DAO (Bohlender & Monin, 2011). Since then we have broadened our target list considerably to now include non–radio sources. The list also includes many cooler Ap–type stars.

Our third program aims to investigate the long–standing puzzle of differences, observed between the magnetic field measurements obtained using Balmer lines versus those, acquired with metallic lines. These differences are commonly attributed to inhomogeneous distribution of metals over the stellar surface. However, differences in observational techniques and/or interpretation of data may also play a role, since, due to a big difference in line widths, hydrogen lines and metallic lines are usually observed with different instruments. The DAO spectropolarimeter is capable of measuring both hydrogen and metallic lines simultaneously, and we have therefore observed several stars with well–established magnetic fields and well–known periods throughout their rotation cycles. For some

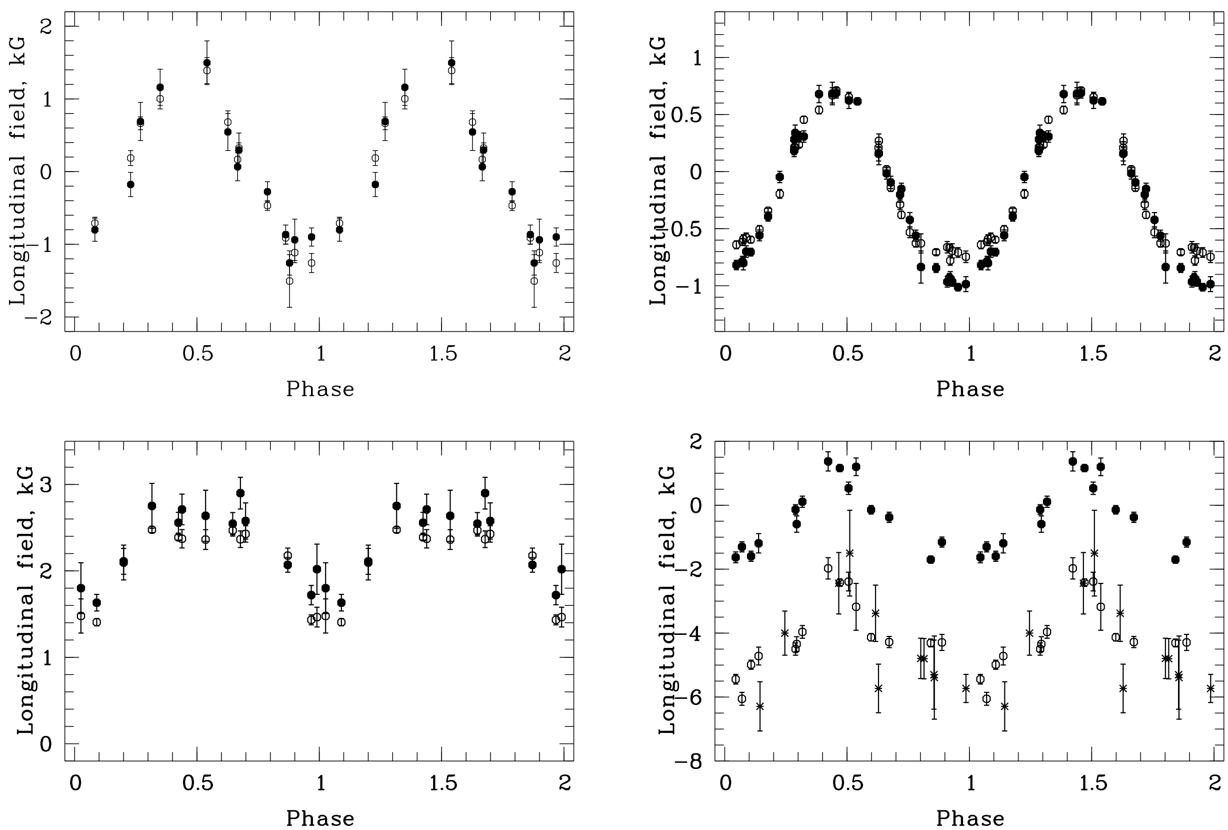

Figure 3: Hydrogen and metallic line longitudinal magnetic field curves obtained with the DAO spectropolarimeter for four known magnetic stars. Filled circles: hydrogen Hβ; open circles: Fe II λ 4923; asterisk: metallic line measurements by Elkin (1994).

stars we see no difference between the Hβ and Fe II λ 4923 line measurements (see upper left panel of Fig. 3). For other stars there is a noticeable difference only at certain phases (Fig. 3, upper right), while some stars show an offset between the hydrogen line and iron line curves (Fig. 3, bottom left). One star, HD 217833, shows a huge offset of about 4 kG (Fig. 3, bottom right). Our iron line measurements for this star are in a good agreement with previously published metallic line measurements (Elkin, 1994). A simple model of these metallic line measurements suggests that the magnetic dipole is almost aligned with the rotation axis and that the polar magnetic field is one of the strongest among the upper main sequence stars. Our hydrogen line measurements, however, suggest a totally different picture. The dipole is tilted almost 90° to the rotation axis and the polar field strength is four times smaller than what is derived from the metallic lines. The most likely reason for the large difference in the two curves is that iron is concentrated in a small spot over the negative magnetic pole. A paper outlining our findings is now in preparation. What is obvious is that hydrogen line measurements are needed for proper characterization of a star's magnetic field geometry and that the DAO polarimeter can provide this kind of information.

3 Summary

The DAO spectropolarimeter, mounted on the 1.8–m Plaskett telescope is capable of measuring longitudinal magnetic fields in both hydrogen Hβ and metallic lines. Both slowly and rapidly rotating stars can be studied with this instrument. The data gathered will allow us to look into the systematic differences between the Balmer and metallic line magnetic field measurements.

Nearly 14 000 spectra of 65 O–F stars have been obtained since the instrument was commissioned in 2007. Four new magnetic stars have been discovered. Periods have been obtained or revised for a number of observed stars.

The MiMeS support program as well as the DAO Magnetic Field Survey of upper main sequence peculiar stars are well underway. Coordination of observations with astronomers, conducting similar surveys at the SAO RAS or other locations would be highly beneficial.

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