Zeeman Doppler Imaging of the Surface Activity and Magnetic Fields of Young Solar-Type Stars

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Abstract.

The cyclic magnetic activity of the modern-day Sun is generally considered to be powered by a self-regenerating interface-layer dynamo. However, Zeeman Doppler Imaging of the spots and magnetic fields of active young solar-type stars suggests that a distributed rather than an interface-layer dynamo is present. This paper outlines techniques we have used to map and study the spots and surface magnetic fields of a small sample of young active solar-type stars, the results obtained, and the implications for magnetic field generation in young cool stars.

1. Introduction

Zeeman Doppler Imaging (ZDI) of young solar-type stars offers an empirical way to study the evolution of stellar magnetism and activity, and use stars as proxies for studying early solar evolution. ZDI employs high-resolution spectropolarimetry of rapidly rotating, active stars to map (i.e. 'image') spots and surface magnetic fields, and measure differential rotation, and can provide magnetic (though not spot) maps for slowly rotating stars for which magnetic fields can be definitely detected. The maps resulting from ZDI can be used to inform stellar dynamos models, and provide an empirical basis for modeling stellar coronas and winds.

The telescopes used for ZDI include the Telescope Bernard Lyot and its NARVAL instrument (France, http://www.ast.obs-mip.fr/projets/narval/v1/) and the ESPaDOnS-equipped Canada-France-Hawaii Telescope in the northern hemisphere (http://www.ast.obs-mip.fr/projets/espadons/espadons.html). In the south, the telescopes used for ZDI are the HARPSpol-equipped ESO 3.6m telescope at La Silla (Piskunov et al. 2011), and the Anglo-Australian Telescope at Siding Spring Observatory, Australia (see Carter et al. (1996)

and Figure 1). Here we summarize some results from ongoing studies of young solar-type stars done as part of a larger international cool star magnetism research program called the Bcool project (http://bcool.ast.obs-mip.fr).

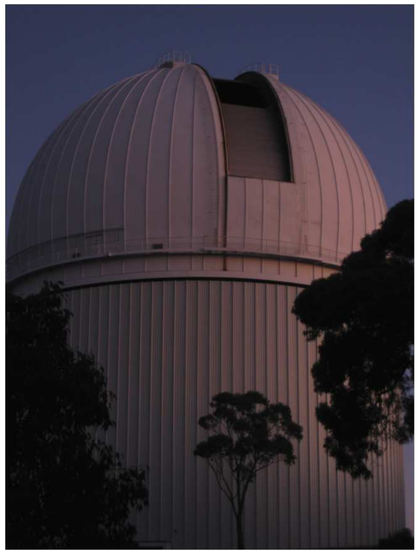

Figure .1: A southern-hemisphere facility for Zeeman Doppler Imaging: The 3.9m Anglo-Australian Telescope at Siding Spring Observatory, Australia.

2. Method

ZDI is based on theory developed by the late Meir Semel (see Semel (1989) and Figure 2). As magnetic fields polarize light due to the Zeeman effect, and as stellar rotation shifts the wavelength of light from different magnetic regions due to the Doppler effect, spectropolarimetry can be used to map stellar magnetic fields in a way analogous to Doppler imaging of starspots. ZDI involves repeated simultaneous measurements of intensity (Stokes I) and polarization (Stokes V) profiles as the target star rotates, to achieve relatively complete phase coverage, and similar approaches are used to reconstruct spot (strictly 'spot occupancy') maps and magnetic maps.

The raw data are reduced and analysed using a collection of dedicated software programs. ESpRIT (Echelle Spectra Reduction: an Interactive Tool) is used to extract wavelength-calibrated spectra and sum the thousands of available photospheric spectral lines observed to increase signal-to-noise ratio in the intensity and polarization profiles by more than an order of magnitude using Least Squares Deconvolution (LSD, Donati et al. (1997)). Maximum entropy reconstruction takes as input the intensity and polarization profiles and creates surface maps (i.e. stellar surface images, Donati & Brown (1997)). Different versions of the imaging code are used to generate the resulting spot and magnetic maps.

The young solar-type stars chosen for our ZDI studies have been selected on the basis of their Ca II H&K emission or other activity indicators. Until recently our focus has been on a small sample of targets identified purely on the basis of stellar properties, using the available literature and survey observations to select single young solar-type stars with the rapid rotation (normally $v\ sini > 20$ km/s) needed for spot mapping, and exhibiting definite magnetic field detections (see for example Waite et al. (2011a,b); Marsden et al. (2011a,b)). Recently however our work has expanded to include the more active planet-hosting solar-type stars, using the fact that a Bcool project study has established that solar-type stars with a chromospheric S-index greater than about 0.2 show a high magnetic field detection rate (Marsden et. al. 2013, http://arxiv.org/abs/1311.337). A list of our targets and other cool stars with magnetic field observations made for the Bcool project has now been published (Vidotto et al. 2014).

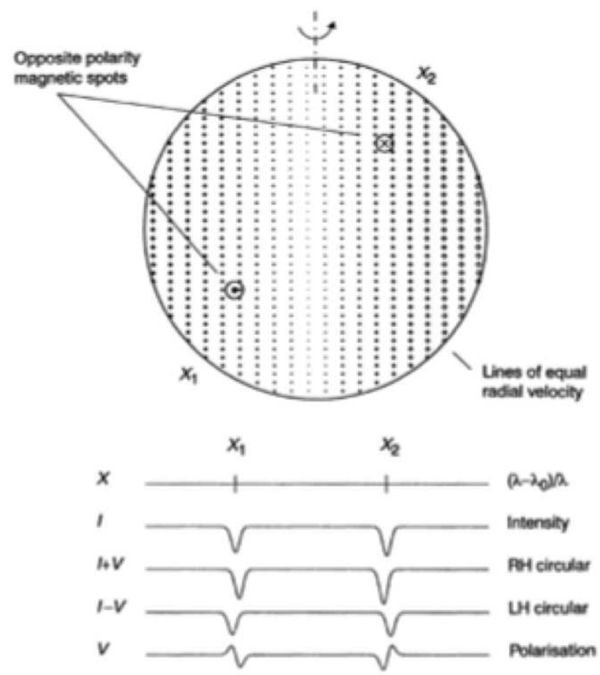

Figure .2: In Zeeman Doppler Imaging the Zeeman polarization signatures from different locations of magnetic field have different Doppler shifts that produce a characteristic polarization signal when left and right circularly polarized measurements are combined. Here the magnetic spots X_1 and X_2 produce an observable Stokes V polarization, detected by combining spectropolarimetric observations alternately switching between left- and right-hand circularly polarized light. From Carter et al. (1996).

3. Results

The key results from our ZDI observations of active young solar-type stars can be summarized as follows:

- SPOT DISTRIBUTIONS The surface distributions of starspots on rapidly rotating F, G and K stars at or near the Zero-Age Main-Sequence are typified by large, dark spot features at or near the stellar rotational pole. In addition lower-latitude spot features are frequently present down to equatorial latitudes, but these features are smaller and at lower contrast to the surrounding photosphere than the polar spots. Given that the darkness of spot features on our maps just measures spot occupancy, and given the prevalence of groups of relatively small spot groups on the Sun today, the observed spot features may either indicate either small numbers of large spots or large numbers of small spots that are spatially unresolved.

- AZIMUTHAL FIELDS A typical characteristic of the observed active young solar-type stars is the presence of persistent large-scale surface azimuthal fields that form a high-latitude, ring-like structure around the stellar rotational pole. Such a field structure is however not observed on the solar surface today.

- DIFFERENTIAL ROTATION The observed differential rotation of both spots and surface magnetic features on young solar-type stars can be measured by fitting a solar-like differential rotation law for the rotation rate Ω as a function of the equatorial rotation rate Ω_{eq}, the differential rotation $d\Omega$ and the latitude θ, namely $\Omega(\theta) = \Omega_{eq} - d\Omega sin^2\theta$. The observed differential rotation for cool stars tends to increase with stellar mass, as shown in Figure 4. For some stars the differential rotation apparent is so small that the star seems almost a solid-body rotator, while other stars exhibit differential rotation much greater than solar.

- GLOBAL FIELD CHANGES For a few young solar-type stars, maps made from observations at different epochs indicate irregular global field changes on time scales of several months to years. The changes so observed include reversal of the radial field polarity with a weakening of the corresponding azimuthal field ring, or major simultaneous changes in both radial field and azimuthal field but without any field reversal (Marsden et al., in preparation). Nevertheless, empirical evidence from ZDI regarding long-term magnetic field changes and the development of magnetic cycles in young solar-type stars remains extremely limited because of the paucity of stars yet regularly observed over multiple epochs.

As an example of recent results obtained from ZDI of young solar-type stars, Figure 3 shows preliminary spot and surface magnetic field maps for the rapidly rotating active young G dwarf star AH Lep (HD 36869; Carter et al., in preparation). This star shows large spot features at high latitudes and large-scale radial, meridional and azimuthal fields on the surface.

4. Discussion

The results of ZDI observations of active young solar-type stars can be interpreted in terms of a dynamo model for cool young stars that has key differences to the modern-day Sun due to an order-of-magnitude more rapid rotation. In particular, we can use the results from ZDI to make some inferences that the Zero-Age Main-Sequence Sun's early rapid rotation:

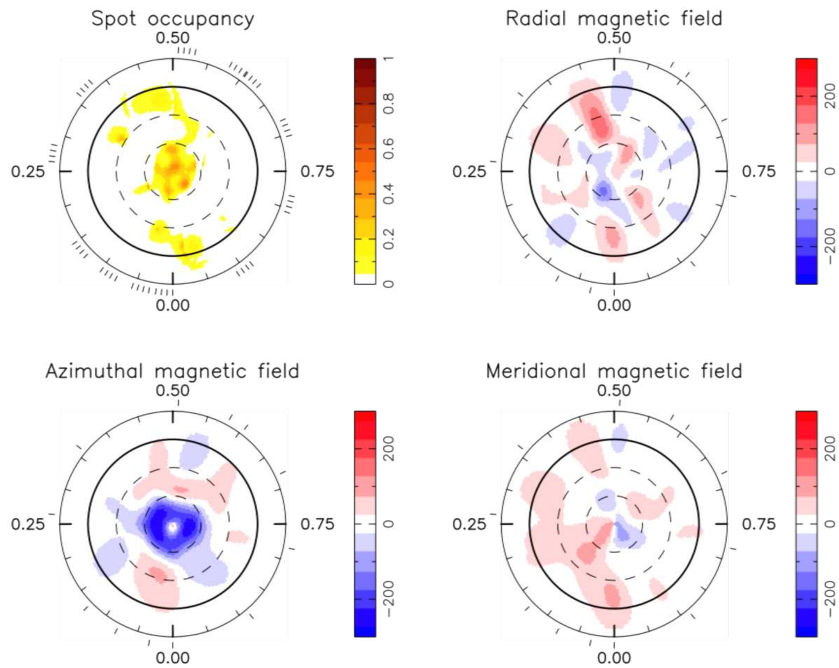

Figure .3: Preliminary spot and magnetic maps for the young solar- type star AH Lep (HD 36869) viewed as squashed polar projections showing the pole at center and the equator as the bold circle. At top left is the spot occupancy map, and the other three maps show the three different components of the observed large-scale surface magnetic fields. Ticks indicate the phases of observation and the magnetic scale is in Gauss. From Carter et al., in preparation.

- Caused flux tubes generated by an internal dynamo to emerge preferentially towards the poles, and so leading to spot features predominating at much higher latitudes than the modern-day Sun

- Distributed the dynamo action close to the surface, so that the azimuthal field component that is hidden today in the Sun's subsurface layers just above its self-regenerating, interface-layer dynamo is instead raised enough to be made visible at the surface

- Exhibited solar-like differential rotation described by the same type of differential rotation law used for the Sun today

- Caused an irregular precursor to the magnetic cycle, with perhaps incomplete 'attempted' field reversals rather the regular magnetic cycles observed on the Sun today.

The results summarized here suggest that ZDI of young solar-type stars provides a useful proxy for probing the early solar dynamo and its significant qualitative and quantitative

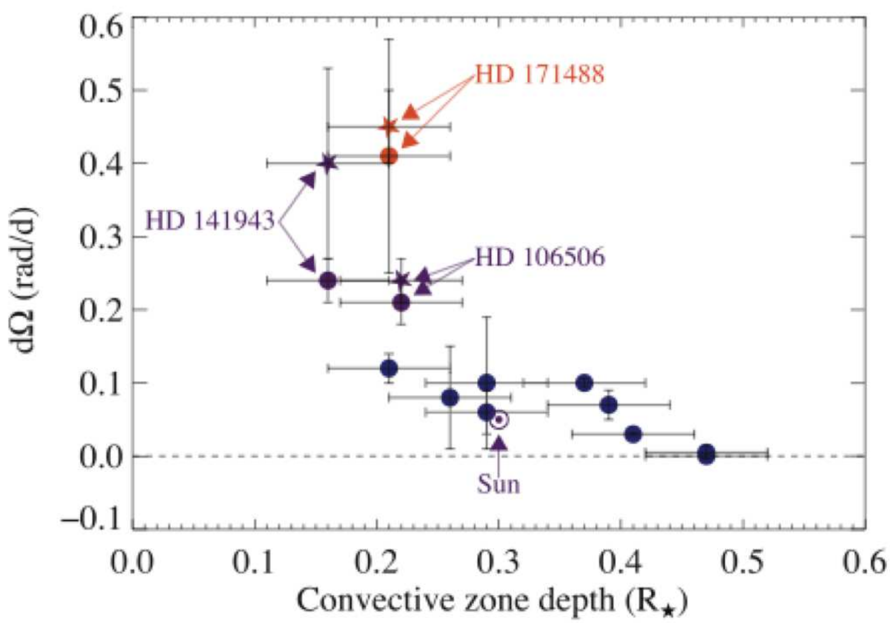

Figure .4: An increase in differential rotation with stellar mass (i.e. towards shallower convective zones) is observed using spots (filled circles) and magnetic features (stars). Adapted from Marsden et al. (2011b)

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differences to the Sun today. More generally, ZDI of cool young stars implies that major dynamo evolution occurs during their early to mid main-sequence evolution. Detailed 3D MHD modeling of the dynamos of solar-type stars using an anelastic spherical harmonic code (e.g. Brown et al. (2011) and Nelson et al. (2013)) can complement ZDI observations to help trace the onset of magnetic cycles in young solar-type stars, and it is notable that the azimuthal field wreaths arising from the dynamo models are similar to the ring-like surface field structures observed using ZDI.

The radial magnetic field maps of the stellar surface produced from ZDI can be extrapolated into magnetic and temperature models of stellar coronas by using relevant physical constraints (see for example Marsden et al. (2007), and Figure 5). In addition, these same magnetic maps can be used to model stellar winds, by adapting the Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme (BATS-R-US) solar space weather modeling code (see `http://ccmc.gsfc.nasa.gov/models/modelinfo.php?model=BATS-R-US` and Vidotto 2014, `http://arxiv.org/pdf/1405.5986v1.pdf`). ZDI maps of the radial fields of planet-hosting stars can thus provide a useful scientific tool for studying stellar space weather impacts on planetary systems.

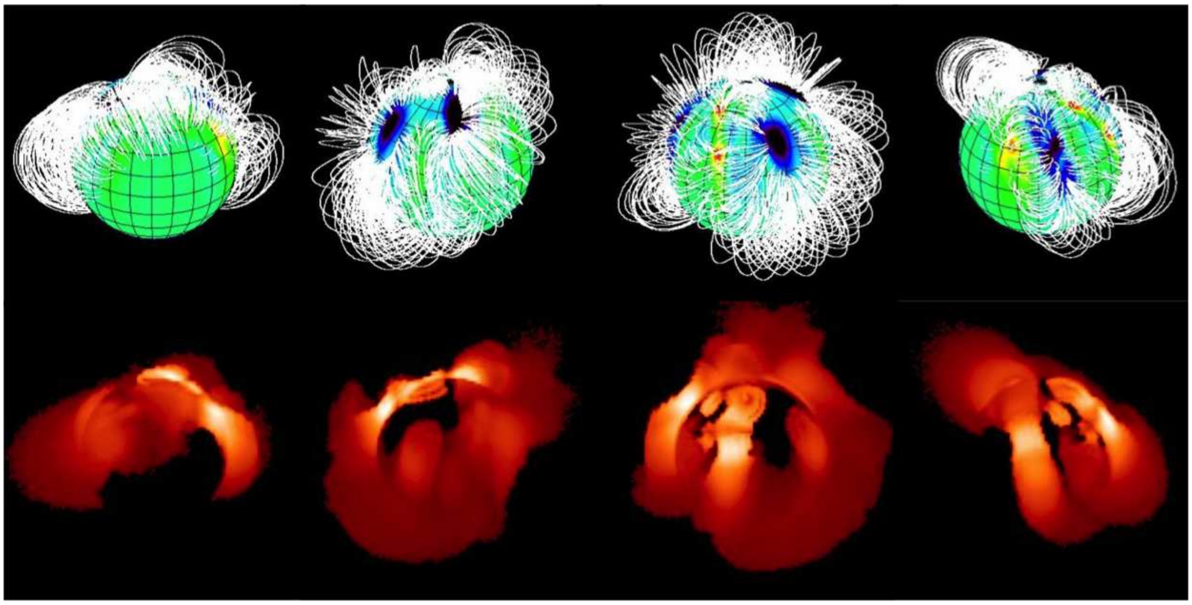

Figure .5: Models of the closed field lines (top row) and coronal emission (bottom row) for the star HD 171488, as derived from surface magnetic maps. Adapted from Marsden et al. (2007).

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Hoofing it over to Prochnow Auditorium for a morning plenary session.