

## Stellar Magnetic Fields in Swollen Convection Zones

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**Abstract.** Solar magnetic activity is generated through dynamo action operating at the base of the solar convection zone. However, for rapidly rotating solar-type stars this might not be the case with magnetic images showing regions of near-surface azimuthal field indicating that the operation of dynamo may in fact be distributed throughout the entire convection zone. Here we present the first magnetic images of a pre-main sequence star with both components having swollen outer convection zones. These results are part of an international study to understand how the generation of magnetic fields is affected by basic stellar parameters such as mass, rotation rate, the depth of the stellar convection zone, and binarity. The magnetic images were obtained by observing the star in circularly polarised light and using the technique of Zeeman Doppler imaging.

### 1. Introduction

For young, rapidly rotating solar-type stars the generation of magnetic fields is an important process, affecting everything from stellar activity to angular momentum loss. Large regions of near-surface azimuthal magnetic field found on these young stars (e.g. Donati et al. 2003) indicate distributed dynamos operate throughout the convection zone.

HD 155555 is a young pre-main sequence binary with both components showing magnetic activity. The star's youth means that both components have swollen convection zones and thus provides an interesting case to study the effect of convection zone depth and binarity on the generation of magnetic fields. The stellar parameters of the system are given in Table 1.

### 2. Observations and Data Analysis

HD 155555 was observed over eight nights in September 2004 at the Anglo-Australian Telescope using the high resolution SEMPOL spectropolarimeter (Donati et al. 2003). The observations were taken in circularly polarised light.

Table 1. Stellar parameters for HD 155555. Except for the  $v \sin i$  values, the data is taken from Strassmeier & Rice (2000).

Sp. type	Age (Myr)	Mass ( $M_{\odot}$ )	Radius ( $R_{\odot}$ )	Orbital period (d)	$v \sin i$ (km/s)	Inclination angle, $i$
G5IV	$\sim 18$	$\sim 1.1$	$\sim 1.55$	$\sim 1.68$	$35.0 \pm 0.5$	used $52^{\circ}$
K0IV		$\sim 1.0$	$\sim 1.42$		$31.0 \pm 0.5$	

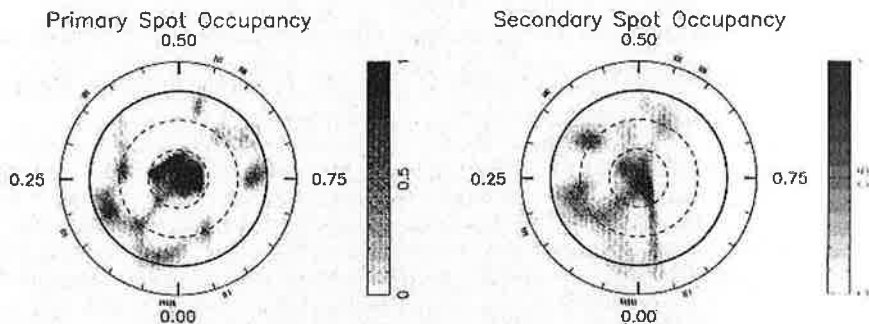


Figure 1. Maximum entropy brightness images for the primary (*left*) and secondary (*right*) of HD 155555. The images are flattened polar projections extending down to  $-30^{\circ}$  latitude. The bold circles represent the equator and the radial ticks outside each image indicate the phases at which the star was observed. For the primary, phase 0.75 faces the secondary and for the secondary, phase 0.25 faces the primary.

The ephemeris of (Strassmeier & Rice 2000) was used to determine the phase of the observations, with the phase of conjunction found to be shifted by 0.002.

The technique of Least-Squares Deconvolution (LSD, Donati et al. 1997) was used to combine the signal in over 3500 photospheric lines in each celestial spectrum into a single high S/N LSD profile, with the same line set used for the simultaneously obtained Stokes I and V data. LSD works better on Stokes V profiles so the average S/N of all LSD profiles is  $\sim 1,100$  for Stokes I and  $\sim 10,000$  for Stokes V.

Zeeman Doppler imaging (ZDI, Donati et al. 1997) was then used to recreate photospheric brightness and magnetic field maps of HD 155555 from the Stokes I and V LSD profiles respectively. Those phases where the profiles of the stars overlapped (around 0.25 and 0.75) were ignored. The resultant maps are shown in Figs. 1 and 2.

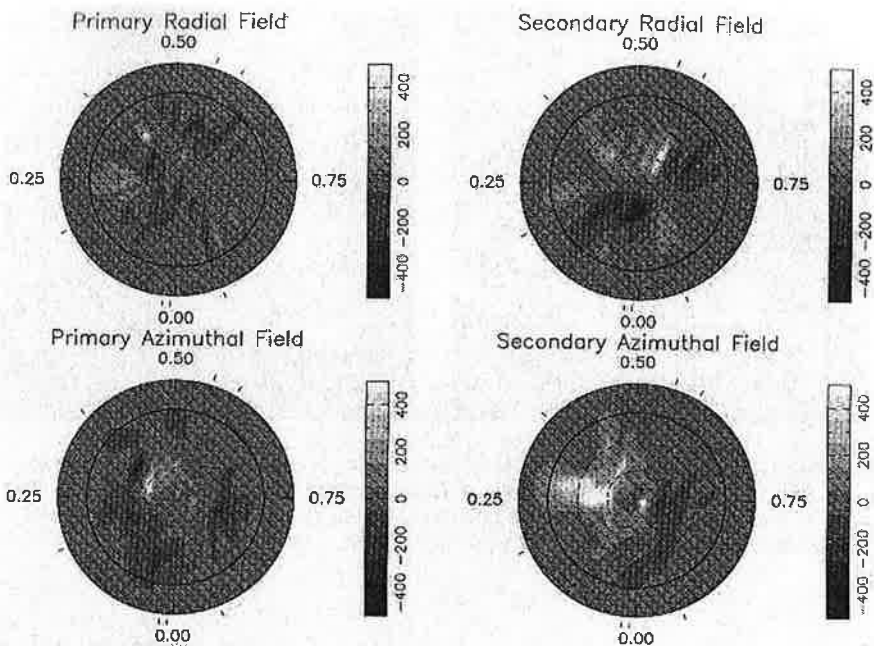


Figure 2. Maximum entropy magnetic images for the primary (*left*) and secondary (*right*) of HD 155555. The images are flattened polar projections as described in Fig. 1. The top images show the surface radial magnetic field, and those at the bottom the azimuthal magnetic field. The scale for the magnetic field is in Gauss.

### 3. Results and Discussion

#### 3.1. Spot Maps

The spot maps for HD 155555 in Fig. 1 show that both stars have polar spots and have a number of low latitude spots mainly located between  $\sim 0^\circ$  and  $\sim 30^\circ$  latitude. For the primary the low latitude spots appear to be similar to those seen on the map of Strassmeier & Rice (2000). This appears to indicate that these spots are long-lived on the timescale of years. This is different to what we see on single stars where spots have lifetimes of weeks or months. For the secondary, the Strassmeier & Rice (2000) map shows lower latitude spots at around a latitude of  $30^\circ$ , similar to what we see here, but at different longitudes.

#### 3.2. Magnetic Field Maps

The magnetic field maps for HD 155555 are given in Fig. 2. The maps for the primary show patterns similar to that seen on young single stars with a rather scattered radial magnetic field image and more of a latitudinal dependence for the azimuthal field with almost a ring of negative azimuthal field around the star. However, the magnetic field maps of the secondary are somewhat different. The radial field appears to show mirrored polarity about a line pointing to the

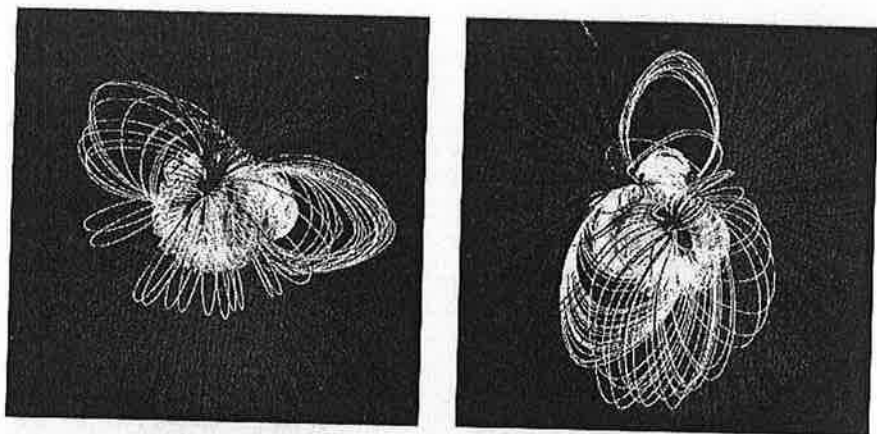


Figure 3. Coronal magnetic field lines of the primary (*left*) and secondary (*right*) of HD 155555 based on the radial magnetic field maps given in Fig. 2. The images show HD 155555 at phases 0.00 (primary) and 0.25 (secondary) and show closed field lines (*in white*) and open field lines (*in grey*).

primary and the azimuthal field shows a large region of positive field facing the primary.

### 3.3. Coronal Field Lines

Using the coronal X-ray modeling technique of Jardine et al. (2002) we have been able to reconstruct the coronal field lines of both the primary and secondary of HD 155555 from the ZDI images of the radial magnetic field (treating the stars as single with no magnetic field interaction). The technique extrapolates the coronal field from the surface map by using a potential field-source surface method which assumes that the magnetic field is forced open by the outward pressure of the coronal gas at the source surface radius (taken here as 3.4 stellar radii). The coronal field maps are given in Fig. 3. Of note is the heavily inclined coronal magnetic field of the secondary with respect to its rotation axis.

The unusual magnetic field of the secondary is a puzzle, especially as mostly closed rather than open field lines face the primary. What is needed is a simultaneous modeling of the two stars' coronal fields and their interaction.

### References

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