The relation between stellar magnetic field geometry and chromospheric activity cycles – I. The highly variable field of $\epsilon$ Eridani at activity minimum

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ABSTRACT

The young and magnetically active K dwarf $\epsilon$ Eridani exhibits a chromospheric activity cycle of about 3 yr. Previous reconstructions of its large-scale magnetic field show strong variations at yearly epochs. To understand how $\epsilon$ Eridani’s large-scale magnetic field geometry evolves over its activity cycle, we focus on high-cadence observations spanning 5 months at its activity minimum. Over this time-span, we reconstruct three maps of $\epsilon$ Eridani’s large-scale magnetic field using the tomographic technique of Zeeman–Doppler imaging. The results show that at the minimum of its cycle, $\epsilon$ Eridani’s large-scale field is more complex than the simple dipolar structure of the Sun and 61 Cyg A at minimum. Additionally, we observe a surprisingly rapid regeneration of a strong axisymmetric toroidal field as $\epsilon$ Eridani emerges from its S-index activity minimum. Our results show that all stars do not exhibit the same field geometry as the Sun, and this will be an important constraint for the dynamo models of active solar-type stars.

Key words: techniques: polarimetric – stars: activity – stars: individual: $\epsilon$ Eridani – stars: magnetic field – stars: solar-type.

1 INTRODUCTION

The evolution of the Sun’s large-scale magnetic field ranges from dipolar at activity minimum to complex at activity maximum (DeRosa, Brun & Hoeksema 2012). A solar-like magnetic cycle has also been observed in the K dwarf 61 Cyg A, where its large-scale field is a simple dipole at activity minimum. In this Letter, we investigate the evolution of the large-scale magnetic field of $\epsilon$ Eridani, which is well established to be a magnetically active star (Valenti, Marcy & Basri 1995; Metcalfe et al. 2013). Previously in Jeffers et al. (2014), we reconstructed the large-scale magnetic field geometry of $\epsilon$ Eridani to understand how the photospheric large-scale magnetic field geometry of $\epsilon$ Eridani varies over its S-index cycle. These observations comprise six epochs spanning nearly 7 yr or approximately two S-index cycles. We showed that each map has evolved dramatically from one epoch to the next, and that we clearly reconstruct the weakest magnetic field structures at its Ca II H&K (or S-index) minimum. The motivation for this work is to investigate the evolution of $\epsilon$ Eridani’s large-scale magnetic field with a higher cadence of observations over its S-index minimum to understand how its field evolution differs from the Sun and 61 Cyg A. To achieve this, we obtained spectropolarimetric observations every night, weather permitting, over a period of 5 months.

2 OBSERVATIONS AND DATA ANALYSIS

We observed $\epsilon$ Eridani over a time-span of 5 months from 2014 September to 2015 January using the high-resolution spectropolarimeter NARVAL located at the Telescope Bernard Lyot, France (Aurière 2003). The total data set comprises 40 spectra that were obtained every night with acceptable observational conditions and are summarized in Table 1 (shown later). The data were reduced and processed following an identical procedure already explained in section 3 of Jeffers et al. (2014).

All Stokes $I$ and Stokes $V$ reduced spectra were processed using least-squares deconvolution (LSD; Donati et al. 1997). By extracting the information contained in each spectral line, LSD enables the
of the large-scale magnetic field topology of \( \epsilon \) Eridani are reconstructed by assuming that the field geometry is projected on to a spherical harmonics frame (Donati et al. 2006), where the magnetic energy is decomposed into poloidal and toroidal components. A spherical harmonics expansion with \( \ell_{\text{max}} = 10 \) was used as there was no improvement to the fits using larger values. A reduced \( \chi^2 \) of 1.05 was obtained for all of the maps when differential rotation was included in the image-reconstruction process.

3.1 Magnetic maps

The reconstructed large-scale magnetic field is shown in the central panels of Fig. 1. The observed and the modelled Stokes V LSD profiles are shown on the sides of the magnetic maps. Over the 5 month time-span of the observations, there is a significant evolution of the large-scale magnetic field topology of \( \epsilon \) Eridani. The total observations were divided up into three epochs to avoid the presence of large gaps without observations, resulting from poor weather conditions. The division of the observations into the maps was tested for different combinations of observations (e.g. five maps versus three maps), and the result was comparable to the maps presented in Fig. 1, though a slightly lower \( \chi^2 \) was obtained for the data set divided into three maps. We extensively tested the phase coverage of the maps by assigning random phases to the epochs of observation, which resulted in a very similar configuration of magnetic features.

We determine the differential rotation of the magnetic features, as described in Jeffers et al. (2014), using the first two epochs, which was calculated to be \( \Omega_{\text{eq}} = 0.593 \text{ rad d}^{-1}, \delta \Omega_{\text{eq}} = 0.151 \text{ rad d}^{-1}, \) which is equivalent to \( P_{\text{eq}} = 10.58 \text{ d} \) and \( P_{\text{mic}} = 14.21 \text{ d}. \) This is in agreement with our previous measurements of differential rotation for \( \epsilon \) Eridani using magnetic features (Jeffers et al. 2014). Other

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### Table 1. Journal of observations. Phase = 0 is defined as Julian Date = 245 4101.5 and is used for all epochs, with subsequent epochs taking phase = 0 as an integer number of rotational periods from this value. The exposure time of all observations is 400 s.

<table>
<thead>
<tr>
<th>Date</th>
<th>Julian Date (+245 4000)</th>
<th>UT</th>
<th>Phase</th>
<th>LSD</th>
<th>S-index</th>
</tr>
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<tbody>
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<td>2902.67</td>
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<tr>
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<td>-0.2362</td>
<td>38 801</td>
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</tr>
<tr>
<td>2014 September 13</td>
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<tr>
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<td>0.10469</td>
<td>35 976</td>
<td>0.391</td>
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### Table 2. Stellar parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
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</thead>
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<tr>
<td>Magnitude</td>
<td>( V = 3.7 )</td>
<td></td>
</tr>
<tr>
<td>Spectral type</td>
<td>K2V</td>
<td>Valenti &amp; Fischer (2005)</td>
</tr>
<tr>
<td>Distance</td>
<td>3.2 pc</td>
<td>van Leeuwen (2007)</td>
</tr>
<tr>
<td>Effective temperature</td>
<td>5146 ± 31 K</td>
<td>Valenti &amp; Fischer (2005)</td>
</tr>
<tr>
<td>Mass (( M_\odot ))</td>
<td>0.856 ± 0.008</td>
<td>Valenti &amp; Fischer (2005)</td>
</tr>
<tr>
<td>Radius (( R_\odot ))</td>
<td>0.74 ± 0.01</td>
<td>Baines &amp; Armstrong (2012)</td>
</tr>
<tr>
<td>( v \sin i ) (km s(^{-1}))</td>
<td>2.2 ± 0.04</td>
<td>Brewer et al. (2016)</td>
</tr>
<tr>
<td>( P_{\text{mic}} ) (d)</td>
<td>11.68</td>
<td>Donahue, Saar &amp; Baliunas (1996)</td>
</tr>
<tr>
<td>Inclination</td>
<td>46° ± 2</td>
<td>Jeffers et al. (2014)</td>
</tr>
<tr>
<td>Age</td>
<td>440 Myr</td>
<td>Barnes (2007)</td>
</tr>
</tbody>
</table>
differential rotation measurements for \( \epsilon \) Eridani have been measured using photometric data taken with the MOST satellite, where values of 11.35 and 11.55 d are measured for two different spots (Croll et al. 2006), or \( P_{\text{min}} = 11.04 \) d and \( P_{\text{max}} = 12.18 \) d by Donahue et al. (1996). While all of these values broadly agree, the differences can be explained by each method measuring different features, for example, plage regions, photometry and magnetic features, which do not necessarily probe the same depth in the stellar atmosphere or stellar latitudes. Since there are a range of \( \sin i \) values in the literature, we also reconstructed the ZDI maps for an inclination of \( 30^\circ \) or stellar latitudes. Since there are a range of \( \sin i \) values, which do not necessarily probe the same depth in the stellar atmosphere or stellar latitudes. 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Figure 1. Magnetic field maps of ϵ Eridani reconstructed for 2014.71, 2014.84 and 2014.98, shown with the Stokes V fits to the sides (ordered from the left-to-right hand panel and top to bottom panel). For each image, the magnetic field projection is shown in terms of radial (upper panel), azimuthal (middle panel) and meridional (lower panel) field components, where red indicates positive polarity and blue indicates negative polarity. The magnetic field strength is in Gauss, where for each map the scale is identical ($B_{\text{max}} = 25$ G). The tick marks at the top of each radial field map indicate the observational phases used to reconstruct the large-scale magnetic field geometry. The Stokes V profiles are plotted separated by a constant value for clarity.

Figure 2. The evolution of ϵ Eridani’s large-scale field during S-index minimum. The symbol shape indicates the axisymmetry of the field (non-axisymmetric by pointed star shape and axisymmetric by decagon), the colour of the symbol indicates the proportion of poloidal (red) and toroidal (blue) components of the field, and the symbol size indicates the magnetic field strength. Additionally, S-index points before and after the activity minimum are included (from Jeffers et al. 2014 and unpublished data). The black line indicates the sinusoidal period of 2.95 d and epoch of S-index minimum using the values of Metcalfe et al. (2013). activity minimum and shows a strong axisymmetry, just like the Sun’s poloidal field. Currently, there is limited information on the long-term evolution of the Sun’s toroidal field as only a few years of vector data are available (Gosain et al. 2013; Vidotto 2016). Within this small time window, however, the solar toroidal field was much weaker than on ϵ Eridani. A longer term comparison of the variation of the toroidal field over the stellar magnetic cycle may shed some light on the nature of the magnetic cycle.

Another star that has been monitored as part of the BCool survey and that has stellar parameters very similar to ϵ Eridani is 61 Cyg A (Boro Saikia et al. 2016), which also exhibits a solar-like magnetic cycle. At activity minimum, the large-scale field of 61 Cyg A is also a simple dipole like the solar case, showing that it is not a limitation of ZDI that we do not see a similar behaviour for ϵ Eridani. The poloidal field of ϵ Eridani is more complex at activity minimum compared to 61 Cyg A and the Sun. The S-index cycle of 61 Cyg A is 7.2 ± 1.3 yr long (Boro Saikia et al. 2016), and its stellar parameters are more similar to ϵ Eridani than the Sun’s. The mass of 61 Cyg A is 0.66 $M_\odot$ (Kervella et al. 2008), which is slightly smaller than ϵ Eridani’s mass of 0.7 $M_\odot$, and given their low $v \sin i$ values, the ZDI technique has a similar resolving power for both stars. The evolutionary state of the two stars is similar to ϵ Eridani having an age that is approximately 7 per cent of its main-sequence
lifetime compared to 14 per cent for 61 Cyg A (calculated using the stellar evolution models of Pols et al. 1998). The main difference is the rotation periods of the two stars, with 61 Cyg A having a rotation period that is approximately three times as long, 35.4 d compared to 11.68 d.

The strength of the mean magnetic field remains constant, despite the changing field geometry. In contrast to this, the maximum strength varies from 20 to 33 G. Since this is the strength in the large-scale component, there are likely to be additional contributions from the small-scale component that remains undetected with techniques such as ZDI. Evidence for additional small-scale field contributions from the small-scale component that remains undetected with techniques such as ZDI. Evidence for additional small-scale field contributions from the small-scale component that remains undetected with techniques such as ZDI. Evidence for additional small-scale field contributions from the small-scale component that remains undetected with techniques such as ZDI. Evidence for additional small-scale field contributions from the small-scale component that remains undetected with techniques such as ZDI. 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The high-cadence observations of \( \varepsilon \) Eridani’s large-scale magnetic field geometry show that the large-scale magnetic field geometry evolves on a time-scale of months with a dramatic increase in the toroidal component of the axisymmetric field at the emergence from its activity minimum. The large-scale field also shows a predominantly poloidal component that is surprisingly complex when compared to the Sun at activity minimum. Our results show that the magnetic field of solar-type stars can be quite different from the Sun’s even when they exhibit clear chromospheric activity cycles.

## 5 Conclusions

The high-cadence observations of \( \varepsilon \) Eridani’s large-scale magnetic field geometry show that the large-scale magnetic field geometry evolves on a time-scale of months with a dramatic increase in the toroidal component of the axisymmetric field at the emergence from its activity minimum. The large-scale field also shows a predominantly poloidal component that is surprisingly complex when compared to the Sun at activity minimum. Our results show that the magnetic field of solar-type stars can be quite different from the Sun’s even when they exhibit clear chromospheric activity cycles.

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## References


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