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Short and long term spot evolution on EI Eri

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Abstract. We investigate flare activity using photometric data obtained with the Transiting Exoplanet Survey Satellite (TESS). Long-term seasonal period analysis was applied on our APT (Automatic Photoelectric Telescopes af Fairborn observatory, Arizona) time series to study changes in the rotational period. We also looked for activity cycle-like changes with short-term Fourier-transform. We also studied the phase and frequency distribution of hand-selected flares on the available TESS data. The MUlti-SIte Continuous Spectroscopy (MUSICOS) campaign was designed in 1998 to achieve high-resolution, multi-wavelength spectroscopic observations from many sites around the globe, which meant that uninterrupted phase coverage of EI Eri became available. We use these data to reconstruct successive surface-temperature maps of the star in order to study the changes of starspots on a very short timescale. We applied our multi-line Doppler imaging code to reconstruct four consecutive Doppler images. These images were also used to measure surface differential rotation with our cross-correlation technique.

Keywords. close binaries, stellar magnetic activity, starspots, Doppler imaging, differential rotation

1. EI Eri: a single lined RS CVn system with an active sub-giant primary

EI Eridani = HD 26337 (G5 IV, $P_{\rm rot} = 1.945$ d, $V = 7.1$) is a well-known, rapidly rotating (v sin i = 51 km/s), active, non-eclipsing, single-lined spectroscopic binary. Table 1 summarizes the astrophysical parameters derived with Spectroscopy Made Easy (Piskunov and Valenti 2017).

It was Fekel et al. (1982) who identified it as an RS CVn type variable. They also detected photometric variability with an amplitude of $V \approx 0.2$. Fekel et al. (1986) derived an orbital period of 1.9472 days, while Hall et al. (1987) detected a photometric period of 1.945 ± 0.005 days from UBV photometry. Oláh and Strassmeier (2002) reported photometric cycles of approximately 2.4 and 12.2 years, which were later confirmed and refined by Oláh et al. (2009) with values of $\approx 2.9 - 3.1$ and ≈ 14 years. They also found a cycle with a length of roughly 4.1–4.9 years. EI Eri is a well-known flaring variable. Pandey and Singh (2012) estimated the flare peak energies in the 0.3–10 keV energy band to be $\approx 10^{31} - 10^{32}$ erg using observations obtained by the XMM-Newton X-ray observatory.

Table 1. Astrophysical parameters for EI Eri derived in this work.

$T_{\rm eff}$	5580 K
$\log g$	3.75
[Fe/H]	-0.27
$v_{\rm mic}$	2 km/s
$v \sin i$	51 km/s

EI Eri has been a prime target for Doppler imaging since the first applications of the technique. Strassmeier (1990), Strassmeier et al. (1991) and Hatzes and Vogt (1992) reported a permanent polar spot with a radically changing appendage. The presence of the polar feature was confirmed by Washuettl et al. (2001) and later, Washuettl et al. (2009) and Kővári et al. (2009). Constantly changing low latitude features were reported as well by these authors. However, since the rotational period of EI Eri is very close to two days, covering a rotation with optimal phase coverage from a singular observing site takes around a month, which introduces serious blurring and renders the Doppler images unable to represent the rapid spot evolution with adequate time resolution. Consequently, EI Eri was selected as a target for the MUSICOS multi-site campaign. Our results are based on these data.

2. Activity cycles and flaring

To look for activity cycles, we used short-term Fourier transform (Kolláth and Oláh 2009) on our 41 years long dataset. The signal of the longest, high-amplitude feature on the upper time-frenquency plot is suppressed, but above about 13.6 years, which is one-third of the length of the data, all signals have the same amplification. Smoothly changing cycles can be seen between 4.5 and 5.5, and between 8.9 and 11.6 years, which are not harmonics, as the speed and the direction of their changes are not the same. A weak cycle-like feature of about 2.5 years is also present at the beginning of the covered time interval. For the STFT plot, see Fig 1.

We identified 41 flares in the two available TESS sectors. To calculate their energies in the TESS band, we followed similar procedures as in Oláh et al. (2022). The flare frequency distribution in the left panel of Fig 2 shows a broken power-law shape. Two-component fits of the FFD yield power-law indices of 1.41 ± 0.02 and 2.26 ± 0.08 (one minus the slope of the fitted line) for the first and second parts, respectively, while a fit for all datapoints gives 1.66 ± 0.04.

To test whether there is a significant increase in the occurrence of flares at given phases, we ran a two-sided Kuiper's test (Kuiper 1960). This test compares the measured data to a given distributiion, but is invariant under cyclic transformation, which makes it well-suited for comparing phase-distributions. The test rejects the null hypothesis of a uniform flare-phase distribution with a p-value of 0.006. The increase in flare rate appears on the side facing the secondary component.

3. Doppler imaging and differential rotation of EI Eri

The Doppler imaging code iMap (Carroll et al. 2012) used in this work carries out multi-line Doppler inversion on a list of photospheric lines. As the wavelength coverage of our dataset is limited, we used five (Fe I 6400, Fe I 6408, Fe I 6421, Fe I 6430 and Ca I 6439) lines with well-defined continuum, suitable line depth, and temperature sensitivity. The stellar surface was divided into 6x6 deg segments. Since our MUSICOS data comes from six different instruments, spectral resolutions differ, which may introduce artifacts since the profiles and distortions caused by the surface features are sampled differently. We counteract this by decreasing the spectral resolutions to the lowest value with a

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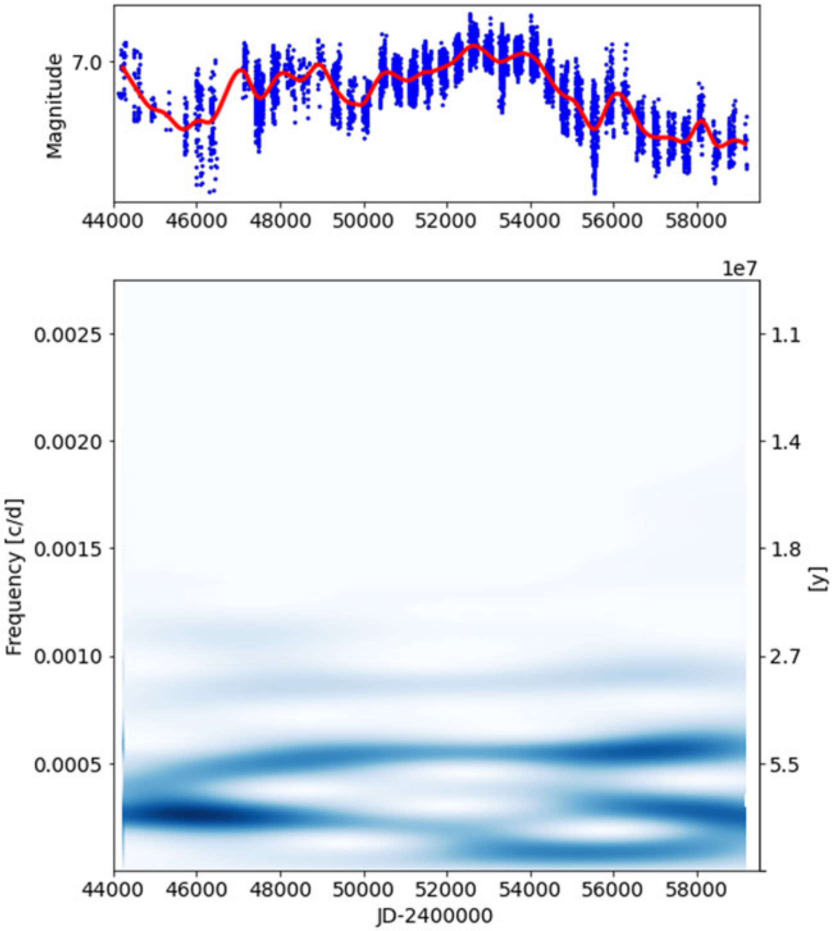

Figure 1. Short term Fourier transform of all the available V band data for EI Eri.

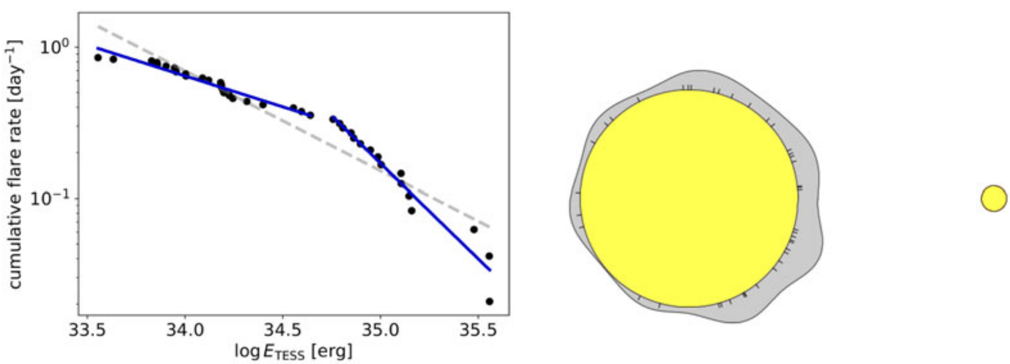

Figure 2. *Left*: Flare-frequency distribution of EI Eri from the two available TESS sectors. *Right*: Flare distribution in the reference frame of the secondary component.

Gaussian-kernel. The viability of this approach is thoroughly tested in Kriskovics et al. (2023). The resulting four consecutive Doppler images in equirectangular projection are shown in Fig 3 (clockwise, from the upper left). The four maps show a persistent polar feature with a temperature of roughly 1100 K below the temperature of the unspotted

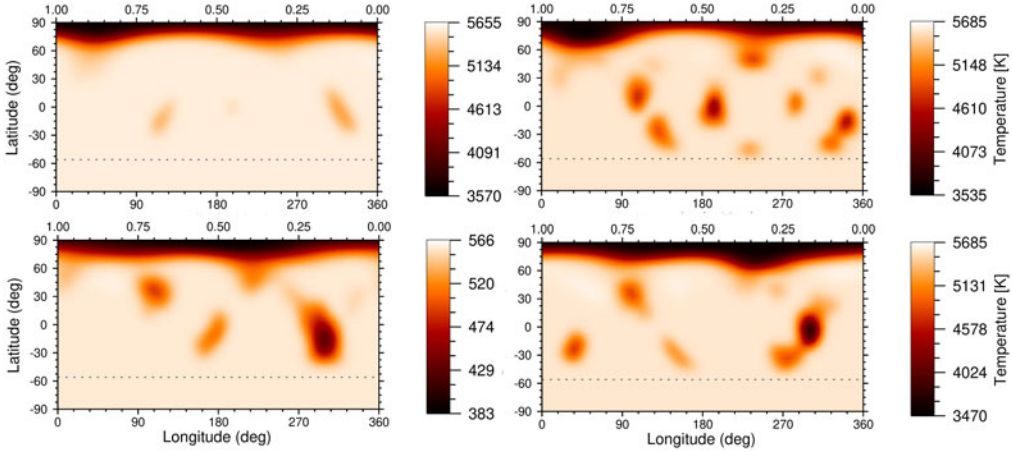

Figure 3. Doppler images of EI Eri in chronological order, clockwise from the upper left.

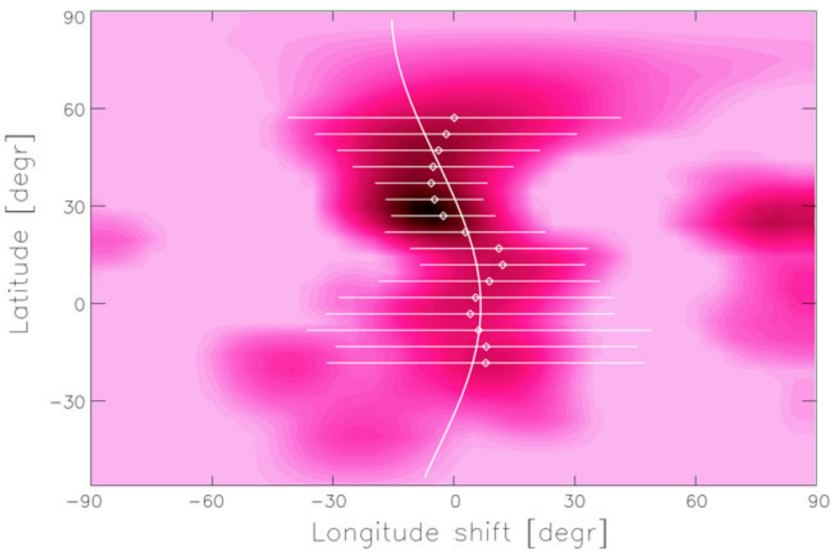

Figure 4. Average cross-correlation map for EI Eri.

surface. Associated with the dominant polar spot, a less prominent appendage appears on the second image around 120 deg longitude. This feature is further strengthened on the third image. On the fourth inversion, the appendage starts to fade, but is still present. The overall contrast of the polar feature seems to increase in time. In addi tion, several low-latitude features show rapid evolution as well, e.g. around 270 deg longitude, a spot starts to appear and strenghthens from the first image to the fourth. For more discussion, see Kriskovics et al. (2023).

We measured the surface differential rotation of EI Eri by the means of cross-correlation of consecutive Doppler images (Donati and Collier–Cameron 1997). In Fig 4, the average correlation pattern is fitted with a quadratic DR law, which yields $\alpha = 0.036 \pm 0.007$ ($\Omega_{\rm eq} = 186.922 \pm 0.384$ deg/day, $\Delta\Omega = 6.768 \pm 1.349$ deg/day). This fits well with previous measurements on rapidly rotating subgiants, as well as with the empirical relation of $|\alpha| \approx 0.013\, P_{\rm rot}$ for binaries originally suggested by Kővári et al. (2017). For more details

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on the surface differential rotation of different active stars, see Kővári et al. (2017), and their Fig 1.

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