Finding a second Sun

How can we detect solar-like magnetic cycles with Zeeman-Doppler-Imaging (ZDI)?

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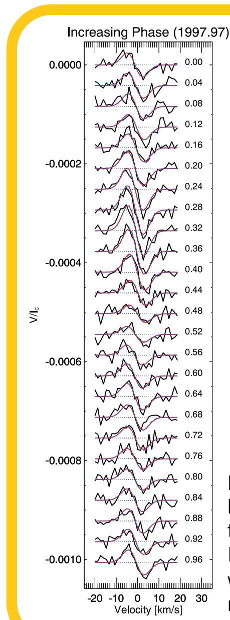


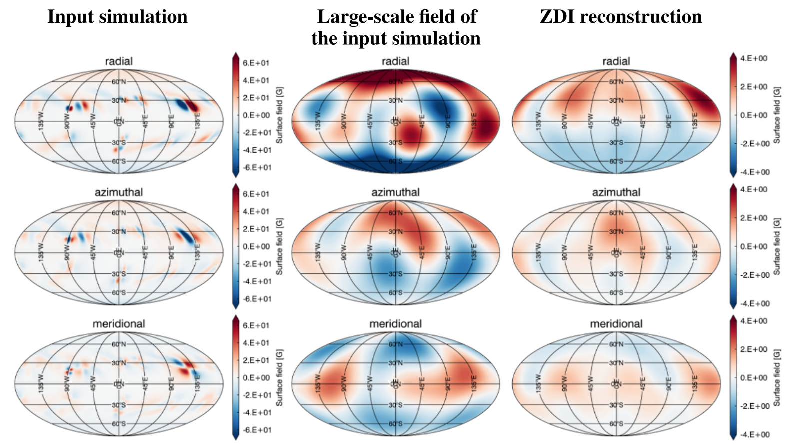


Figure 1. Left panel: The ZDI fit (red solid line) of the noisy Stokes V profiles (black solid line) and for comparison the noise-free Stokes V profiles (dashed blue line). Three panels to the right: The Mollweide projected maps for the map at 1997.97yr (increasing phase). From left to right: The full resolved simulated input map from which the Stokes profiles were modelled, the large-scale field of the input map for $l_\Sigma=3$ and the ZDI reconstructed map. From top to bottom: the radial, azimuthal and meridional surface magnetic field.

Introduction

Spectropolarimetric surveys have now been running for long enough to reveal solar-like magnetic activity cycles, e.g. for 61 Cyg A (Boro Saikia et al. 2018). Our work examines if a solar-like cycle can be observed with ZDI, given that this technique only detects the large-scale field for very slowly-rotating and low-activity stars like our Sun. We aim to determine the best strategy to detect stellar cycles, and which parameters are most sensitive to cycle changes.

Methods

We approach these questions using the 3D non-potential flux transport simulations of Yeates & Mackay (2012) modelling the solar vector magnetic field over 15 years (centred on solar cycle 23). The flux emergence profile was extracted from solar synoptic maps and used as input for a photospheric flux transport model in combination with a non-potential coronal evolution model. We synthesise spectropolarimetric data (Stokes IV) from the simulated maps and reconstruct them using ZDI, see Fig. 1.

How does ZDI see the solar cycle?

To compare the magnetic topologies of the input maps with their ZDI maps, we need to restrict them to the same spherical harmonic mode, e.g., the cumulative $l_\Sigma=3$ mode. We find that ZDI reconstructs most accurately for maps with sunspot numbers SSN < 100, see Fig. 2. At higher SSN, ZDI tends to underestimate the poloidal and axisymmetric fraction up to 20% on average. In general, ZDI recovers approximately one order of magnitude less magnetic energy in the large-scale field, but does recover the relative trends of the input simulations, e.g. with SSN, differential rotation or flux emergence rate, see also Lehmann et al. 2019.

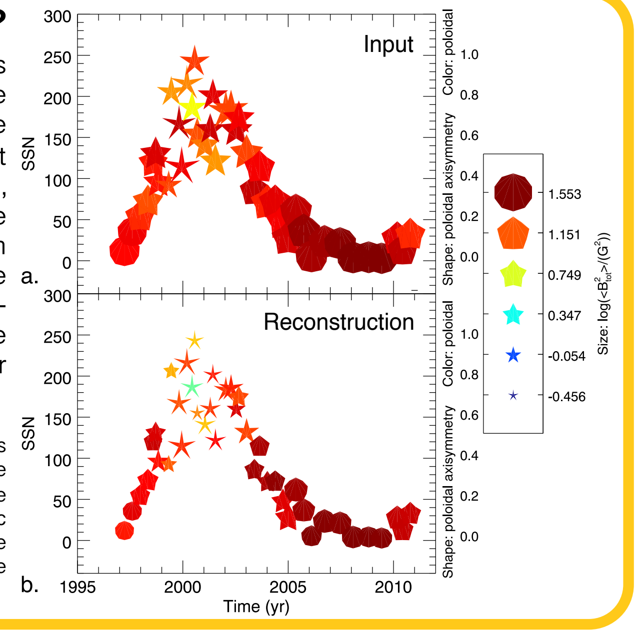
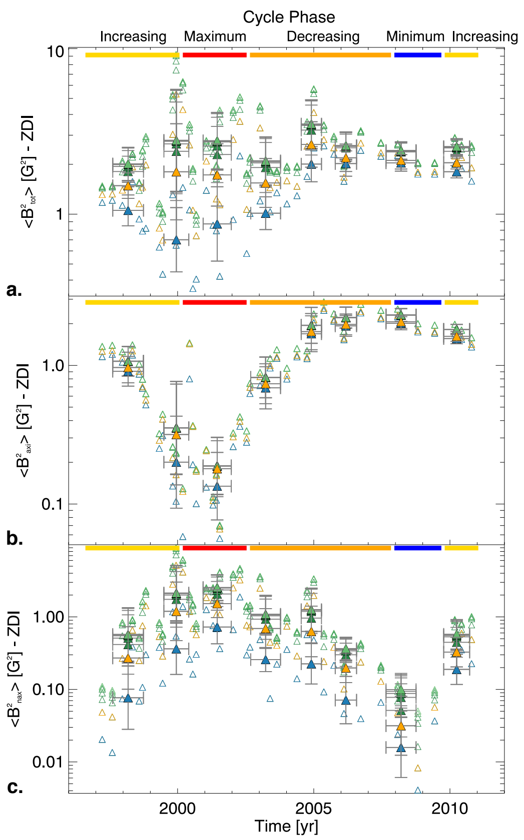


Figure 2. The large-scale magnetic field topology for the input maps (a.) and their ZDI-reconstructed maps (b.) presenting the cumulative $l_\Sigma=3$ mode. The y-axis indicates the sunspot number (SSN) and the x-axis the time in years. The symbol size displays the logarithmic total magnetic energy $<B^2>$. The symbol colour represents the fraction of the poloidal field f_{pol} and the symbol shape shows the fraction of the axisymmetric poloidal field $f_{axi;pol}$.

How to detect a solar-like cycle with ZDI?

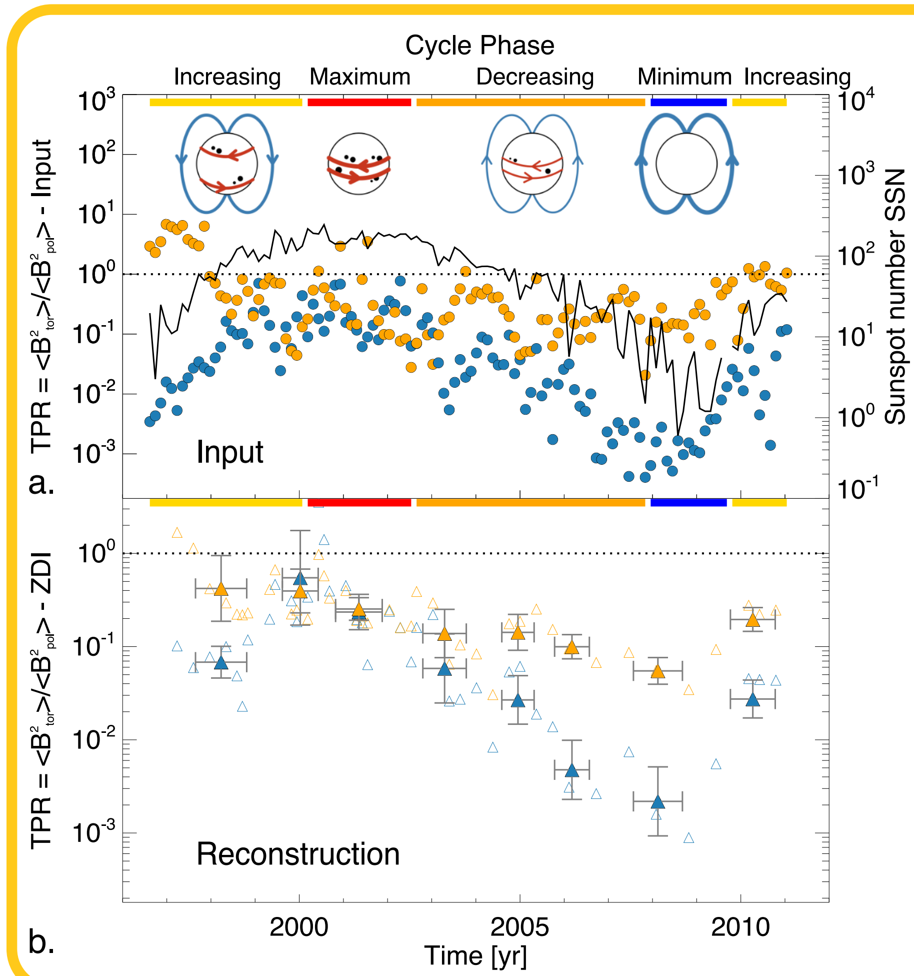


We find, that the total magnetic energy recovered by ZDI, see Fig. 3a, is inappropriate to trace a solar-like cycle. Far better is to use the axisymmetric (axisy.) and non-axisy. energy, see Fig. 3b,c. Both show clear trends well recovered with ZDI. An even better detection is possible by using the energy fraction of the axisy. or axisy. poloidal field, as they show less spread and are more robust to the overall trend. The solar toroidal field is too low to be a reliable tracer but its maximum can be used to confirm the solar-like activity maximum, as they should appear simultaneously.

The best cycle tracers are:

$$<B^2_{axi}>,\ <B^2_{nax}>,\ f_{axi}$$

Figure 3. The total (a), the axisy. (b) and non-axisy. energy (c) over time for the cumulative l-modes ($l_\Sigma=1$: blue, $l_\Sigma=2$: orange, $l_\Sigma=3$-7: greenish). The corresponding cycle phases are indicated by the coloured thick lines at the top of each plot. All 41 ZDI reconstructed maps (open triangles) are shown and their binned mean (filled triangles) and standard derivation (error bars).



Finding hints of solar dynamo modes and active latitudes with ZDI

We find that ZDI can very well recover the global solar dipole in the poloidal axisy. dipole mode. Surprisingly, the toroidal quadrupolar mode captures the sunspot population of the active latitudes, responding to the global properties of the small-scale flux emergence.

Figure 4. The ratio of the toroidal and poloidal magnetic energy $TPR=<B^2_{tor}>/<B^2_{pol}>$ for the dipolar $l=1$ and quadrupolar $l=2$ mode, same format as Fig. 3 but presenting only the first two l-modes, while (a) shows the trend of the input maps (circles) and (b) the trend of their ZDI reconstructions. The four little inserts at the top illustrate how the poloidal dipole (blue), toroidal quadrupole modes (red) and sunspots (black dots) vary along the solar cycle.

ZDI recovers trends with S-index

We also check how the ZDI recovered magnetic properties behave with S-index, which is a widely observed indicator for the chromospheric activity. The ZDI reconstructed surface averaged magnetic field shows only a flat distribution, see Fig. 5a, so that the averaged field can not be used as cycle tracer. We find that ZDI recovers the increase of the toroidal energy with S-index > 0.167 (≈ SSN = 50), while for lower S-index the toroidal energy decreases rapidly indicating the activity minimum, see Fig. 5b. Most prominent is the strong decreasing trend of the axisy. fraction with S-index. ZDI recovers this slope very well. This highlights once more that fractions are better recovered with ZDI and that the axisymmetry is the key tracer to uncover solar-like cycles in other stars than the Sun.

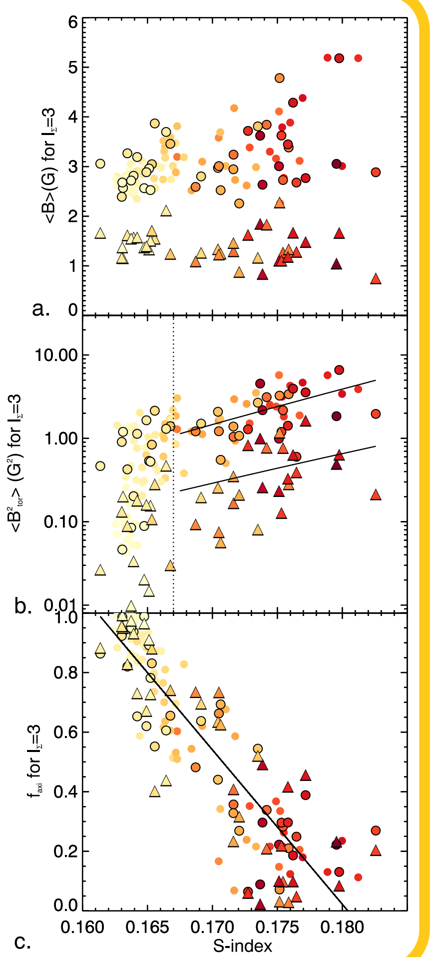


Figure 5. The surface averaged large-scale magnetic field $<B>$ (a), the toroidal energy (b) and the axisy. energy fraction (c) plotted against S-index for $l_\Sigma=3$. The simulated input maps are displayed as circles, where the 41 maps that have a ZDI reconstructed map are ringed with a black border. The ZDI reconstructed maps are plotted as triangles.

References: **Boro Saikia S., et al.**, 2018, A&A, 620, L11; **Lehmann L. T., et al.**, 2019, MNRAS, 483, 5246
Yeates A. R., Mackay D. H., 2012, ApJ, 753, L34

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Read the full paper: arXiv:2010.10214 or ADS