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What counts as a polarity reversal?

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ABSTRACT

Context. IF V889 HER SOFIN DATA COULD BE USED, YOU COULD FIRST DO THE ZDI ANALYSIS OF THAT, THEN USE IT HERE AS WELL, AND PUBLISH BOTH!
Aims.
Methods.
Results.

Key words. Stars: activity – Stars: magnetic field – Stars: solar-type –

1. Introduction

Polarity reversals of the stellar large-scale magnetic field have been observed is the Sun for a century (Hale & Nicholson 1925), and in recent years they have become an observable phenomenon in other stars as well (e.g. Donati et al. 2008; Lehtinen et al. 2022; Willamo et al. 2022). In the Sun, the polarity reversal is most obvious around the poles, above latitudes 60 or so (?). During the solar minimum, the polar magnetic field is at its strongest, and as the solar activity increases, the polar field weakens, until its polarity is reversed close to solar maximum. In more active stars, on the other hand, such as the young solar analogue LQ Hya, the reversal might actually happen at spot minimum (Lehtinen et al. 2022), which might indicate a different type of dynamo driving their magnetic activity. In other stars, the magnetic fields are commonly mapped with the ZDI method (Semel 1989; Brown et al. 1991). When a solar-like polarity reversal occurs, it leaves little place for doubt, if the observations before and after the reversal are good and frequent enough. Thus, no quantitative criterion for a polarity reversal has been formulated. Such clear reversals of the magnetic polarity have been observed in at least χ^1 Ori (Rosén et al. 2016), HD 29615 (Waite et al. 2015; Hackman et al. 2016), τ Boo (Donati et al. 2008; Fares et al. 2009, 2013; Mengel et al. 2016; Jeffers et al. 2018), 61 Cyg A (Boro Saikia et al. 2022) and LQ Hya (Lehtinen et al. 2022). The ZDI maps of V1358 Ori also show a clear polarity reversal in Willamo et al. (2022), although the reliability of this could be questioned, since one of the two maps was constructed from only four observed rotational phases. Still, if these maps are believed, they all display clear reversals of polarity. However, with more complex field configurations, the reversal is not always as clear, as is the case with HD 35296 in Willamo et al. (2022). Here, we raise the question of what kind of criterion could be used in these kind of unclear situations, to decide whether some case should be counted as a true polarity reversal or merely a random reconfiguration of the magnetic field.

2. Observations/Data

We analyse two stars with confirmed or suspected polarity reversals published in the litterature, from which we have access to the magnetic field data both before and after the reversal. This includes V1358 Ori (Willamo et al. 2022) and LQ Hya (Lehtinen et al. 2022), from which we have access to the data from our earlier observations. The data for the magnetic field of V1358 Ori is also available at the CDS. Information of their original observations is summarised in Table 1. In order to get more reliable results, a similar analysis should be done to preferably all stars with published polarity reversals. Here, however, we aim for a quick analysis to raise the question of this definition, instead of a thorough study aiming for a definite answer.

The ZDI for both stars has been done using the code InversLSD (Kochukhov et al. 2014). In InversLSD the stellar surface is split into 1876 elements, with an increasing number of grid elements closer to the equator. Thus, all elements have approximately the same area. The code uses a spherical harmonics decomposition of the magnetic field, but converts the spherical harmonic coefficients also to physical magnetic field, which is our preferred data format due to its direct observational interpretation.

As a control star we use BE Cet. A ZDI map of BE Cet from 2017 was published by Willamo et al. (2022), where the radial magnetic field at polar regions is clearly divided into positive and negative regions. Thus, whatever criterion we use for the confirmation of a polarity reversal, it should not count the map of BE Cet to have any specific polarity to be reversed.

Available solar data? Add the Sun as a star?
https://solis.nso.edu/0/vsm/aboutmaps.html
https://nispdata.nso.edu/ftp/HMI/hmi_integral_vector_maps/

In priciple, these could be used, but that would be a big effort, since their format is fits... It would of course be interesting to see the Sun as a prime example, but since the data available for other stars is so different, how well could they be compared?

Table 1. Observations.

Star	Instrument(s)	Maps around reversal	Reference
LQ Hya	HARPS	2010^{-},2011^{-},2016^{-},2017^{+}	Lehtinen et al. (2022)
V1358 Ori	HARPS	2013^{+},2017^{-}	Hackman et al. (2016); Willamo et al. (2022)

Notes. The years for the maps around the polarity reversal are shown, with a + or - indicating whether the radial field around the pole was positive or negative in that map.

3. Possible definitions

When thinking of a general definition of a reversal of the polarity of a star's magnetic field, a natural place to start is to look at the Sun. The solar magnetic field is reversed around the polar regions during each solar maximum. The lower latitude magnetic field is not seen as clearly, since here the magnetic field is mostly seen around randomly appearing sunspots, and the quiet Sun regions are missing a similar, strong magnetic field. In the Sun, polar regions above perhaps latitude 60 could be used for the definition. **ANY EXPLICIT DEFINITION FOR THE SUN? I think not...**

But, keeping in mind that the dynamo mechanisms in more active stars, which are the typical targets of ZDI, might be different than the solar dynamo, is the Sun as a star representative enough to be used as a general definition? The definition could easily be modified to include different latitudes around the visible pole. An easy approach is to set some limit for the average polar magnetic field, which the field strength needs to exceed, and have different signs in the consecutive ZDI maps, to be counted as a true polarity reversal. Then the two parameters that can be modified, would be the limiting latitude, and the required average field strength.

We define the quantity $B_{\mathrm{rad},>\mathrm{lat}}$ as the mean value of the signed radial magnetic field, when taking into account all grid elements above some limiting latitude lat. The strength of the magnetic field is also normalised according to the size of each grid point, since, although the grid points are of approximately equal area, especially around the poles (at the pole there are only four grid points) the size of each surface element is not exactly the same.

Then we have tried limiting latitude values of lat=60, lat=70 and lat=80 degrees. This means that the average radial component of the magnetic field has been calculated above these latitudes, and the resulting value has been compared to a limit field strength. As this limit field strength we have tried several different statistical values: the global average value of the total magnetic field $B_{\mathrm{tot}} = \sqrt{B^2_{\mathrm{rad}} + B^2_{\mathrm{mer}} + B^2_{\mathrm{azi}}}$ weighted with the size of the grid element (with rad, mer and azi referring to the radial, meridional and azimuthal components of the magnetic field, respectively), the root mean square (rms) of the global total magnetic field or just the radial component, and the absolute value of the mode of the total or the radial magnetic field.

The rms total magnetic field is calculated as

$$\mathrm{rms}(B_{\mathrm{tot}}) = \sqrt{\frac{1}{n}\sum_{i}^{n} w_i B^2_{\mathrm{tot},i}}, \tag{1}$$

where n is the number of data points i and $B_{\mathrm{tot},i} = \sqrt{B^2_{\mathrm{rad},i} + B^2_{\mathrm{mer},i} + B^2_{\mathrm{azi},i}}$. w_i is the weight of each data point, which is proportional to the solid angle of the grid point and normalised around unity. The radial rms magnetic field is calculated similarly, except replacing B_{tot} with B_{rad}. Since the rms is always a positive value, we do not need to take its absolute value, in contrast to the mode. The mode has not been weighted with the size of the surface element.

Another possible approach could be to use the spherical harmonics, and define some criterion based on them. The individual spherical harmonic coefficients are, however, quite uncertain, and we believe the magnetic field to be a more reliable measure of the magnetic polarity. This approach also has the advantage, that its physical interpretation is very straight forward, since the magnetic field is a physical quantity, in contrast to spherical harmonics.

4. Results

These different considered criteria are compared in Table 4, which shows whether the polarity reversals for the two stars would be counted as real or not, according to each criterion. **MAYBE SHOW SOME OF THE ZDI MAPS AGAIN HERE?**

First, we check if $B_{\mathrm{rad,lat}}$ for our control star BE Cet is below the statistical values for the different criteria. The average radial magnetic field on polar regions for BE Cet is very low, below all global statistical values concidered as a criterion, for every tried limiting latitude. Thus, none of the criteria fail this control, and can be accepted for further concideration.

When looking at the ZDI maps published in Willamo et al. (2022) and Lehtinen et al. (2022), the radial magnetic field at the polar regions is quite clearly reversed in both stars. Thus, we deem the polarity reversals of both LQ Hya and V1358 Ori to be definitely true ones, and require the adopted criterion to count them as such. It should be noted, though, that the reliability of the 2013 map of V1358 Ori could be questioned, since it was calculated from only four observed rotational phases. However, since this unreliability is in the map itself, and not in its interpretion, we can here assume the map to be reliable, since we are interested in the question how clear polarity reversals with a straight forward interpretation are treated by our criterion.

With this requirement, we can accept those criteria which have a 'yes' in the last column in Table 4 for both stars. This includes $|\mathrm{mode}(B_{\mathrm{tot}})|$ for all latitude limits, $|\mathrm{mode}(B_{\mathrm{rad}})|$ for latitudes >80, and $\mathrm{rms}(B_{\mathrm{rad}})$ for latitudes >80. The statistically simplest value, $\langle|B_{\mathrm{tot}}|\rangle$, is clearly not a suitable criterion, since it would only count the reversal of V1358 Ori a true one, if including only latitudes >80, and not count LQ Hya as having a true reversal with any limiting latitudes.

In the case of LQ Hya, with four ZDI maps (where the first three have a similar polarity, which is reversed in the last one) we can also look if the first three maps all have $B_{\mathrm{rad},>\mathrm{lat}}$ exceeding the limit magnetic field. As we can see, with $\mathrm{rms}(B_{\mathrm{rad}})$ and lat=70, and with $|\mathrm{mode}(B_{\mathrm{rad}})|$ and lat=70, the strength of the polar magnetic field for the 2016 map does not exceed the limit, and thus this map would have to be overlooked for a smooth reversal. Thus, these combinations of limiting magnetic fields and latitudes, do not seem to be as good as the preferred ones listed earlier.

Table 2. Summary of the different statistical values of the global magnetic field of each ZDI map.

Map	rms($B_{\rm rad}$)	rms($B_{\rm tot}$)	mode($B_{\rm rad}$)	mode($B_{\rm tot}$)	$\langle\lvert B_{\rm tot}\rvert\rangle$
LQ Hya 2010	0.19777	0.31849	0.00881	0.02179	0.25593
LQ Hya 2011	0.09108	0.20324	0.06016	0.01202	0.16880
LQ Hya 2016	0.11590	0.19467	0.08435	0.01072	0.16286
LQ Hya 2017	0.08636	0.18208	-0.0529	0.00828	0.15685
V1358 Ori 2013	0.03086	0.06058	-0.03493	0.00305	0.04997
V1358 Ori 2017	0.03214	0.07131	0.01360	0.00173	0.05807
BE Cet 2017	0.01331	0.01927	-0.00965	0.01044	0.01653

Table 3. The mean radial magnetic field above the limiting latitude $B_{\rm rad,>lat}$ for each ZDI map.

Map	lat	$B_{\rm rad,>lat}$ [kG]
LQ Hya 2010	60	-0.17317
LQ Hya 2010	70	-0.05122
LQ Hya 2010	80	-0.03036
LQ Hya 2011	60	-0.09351
LQ Hya 2011	70	-0.09201
LQ Hya 2011	80	-0.14546
LQ Hya 2016	60	-0.01360
LQ Hya 2016	70	-0.05429
LQ Hya 2016	80	-0.12211
LQ Hya 2017	60	0.04631
LQ Hya 2017	70	0.08747
LQ Hya 2017	80	0.14661
V1358 Ori 2013	60	0.02237
V1358 Ori 2013	70	0.03746
V1358 Ori 2013	80	0.05331
V1358 Ori 2017	60	-0.06742
V1358 Ori 2017	70	-0.08425
V1358 Ori 2017	80	-0.09795
BE Cet 2017	60	0.00010
BE Cet 2017	70	0.00069
BE Cet 2017	80	0.00041

Suitable simulated ZDI maps?

5. Discussion

With only two stars, our results can be seen only as a guide line for a general definition for a polarity reversal of a global stellar magnetic field. Thus, our aim is not to present a definite definition for such reversals, but rather to bring this question into discussion, and describe some difficulties in deciding a suitable definition. One thing which complicates this kind of detailed analysis of the stellar magnetic fields, is that when the ZDI maps are published, commonly only a figure of the map is published, and not the data itself. Thus, the data is commonly available only by a personal request of the authors. Therefore, we encourage authors to publish also the numerical data of the magnetic fields in databases such as the CDS. Furthermore, the common format of the data is not as the magnetic field itself, but as spherical harmonic coefficients, which are used to calculate the magnetic field. This transformation from spherical harmonics to magnetic field is rather complex, so publishing both the perhaps mathematically more useful spherical harmonics, and the physically more intuitive magnetic field could be helpful. Thus, for more reliable results, and a more definite answer to our question, our analysis should be repeated to preferably all stars with published polarity reversals. This would require receiving the ZDI data from all corresponding authors, and transferring the spherical harmonic data into the magnetic field components, when necessary.

6. Conclusions

Based on our analysis, we suggest a suitable criterion for the polarity reversal of the magnetic field retrieved from ZDI observations: the criterion could be to require the absolute mean radial magnetic field above latitude lat to exceed either,

a) $|B_{\rm rad,>lat}| > |\mathrm{mode}(B_{\rm tot})|$, where lat=60, 70 or 80,
b) $|B_{\rm rad,>lat}| > |\mathrm{mode}(B_{\rm rad})|$, where lat=80, or
c) $|B_{\rm rad,>lat}| > \mathrm{rms}(B_{\rm rad})$, where lat=80,

and be reversed between two consecutive observations. At this point, we do not have a strong preference between these alternatives. In any case, these criteria need to be tested on more stars, in order to decide, what would truly be a suitable rule. In order for this, it would be important for the community to publish magnetic field data or the spherical harmonic coefficients used to derive that, so that data for this kind of analysis would be publicly available, in addition to the ZDI maps themselves.

Acknowledgements.

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Table 4. Different criteria for the polarity reversals.

Star	Latitude limit	Limit for $|\langle \mathrm{Brad} \rangle|$	Reversal (yes/no)
V1358 Ori	80	rms(B_{tot})	no
V1358 Ori	70	rms(B_{tot})	no
V1358 Ori	60	rms(B_{tot})	no
LQ Hya	80	rms(B_{tot})	no
LQ Hya	70	rms(B_{tot})	no
LQ Hya	60	rms(B_{tot})	no
V1358 Ori	80	rms(B_{rad})	yes
V1358 Ori	70	rms(B_{rad})	yes
V1358 Ori	60	rms(B_{rad})	no
LQ Hya	80	rms(B_{rad})	yes
LQ Hya	70	rms(B_{rad})	*
LQ Hya	60	rms(B_{rad})	no
V1358 Ori	80	$|\mathrm{mode}(B_{\mathrm{tot}})|$	yes
V1358 Ori	70	$|\mathrm{mode}(B_{\mathrm{tot}})|$	yes
V1358 Ori	60	$|\mathrm{mode}(B_{\mathrm{tot}})|$	yes
LQ Hya	80	$|\mathrm{mode}(B_{\mathrm{tot}})|$	yes
LQ Hya	70	$|\mathrm{mode}(B_{\mathrm{tot}})|$	yes
LQ Hya	60	$|\mathrm{mode}(B_{\mathrm{tot}})|$	yes
V1358 Ori	80	$|\mathrm{mode}(B_{\mathrm{rad}})|$	yes
V1358 Ori	70	$|\mathrm{mode}(B_{\mathrm{rad}})|$	yes
V1358 Ori	60	$|\mathrm{mode}(B_{\mathrm{rad}})|$	no
LQ Hya	80	$|\mathrm{mode}(B_{\mathrm{rad}})|$	yes
LQ Hya	70	$|\mathrm{mode}(B_{\mathrm{rad}})|$	*
LQ Hya	60	$|\mathrm{mode}(B_{\mathrm{rad}})|$	no
V1358 Ori	80	$\langle |B_{\mathrm{tot}}| \rangle$	yes
V1358 Ori	70	$\langle |B_{\mathrm{tot}}| \rangle$	no
V1358 Ori	60	$\langle |B_{\mathrm{tot}}| \rangle$	no
LQ Hya	80	$\langle |B_{\mathrm{tot}}| \rangle$	no
LQ Hya	70	$\langle |B_{\mathrm{tot}}| \rangle$	no
LQ Hya	60	$\langle |B_{\mathrm{tot}}| \rangle$	no

Notes. *Only yes if overlooking the 2016 map

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