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THE MAGNETIC EVOLUTION OF YOUNG SUNS

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Abstract. Magnetic fields are one of the main drivers of the evolution of solar-type stars. They affect everything from the rotational evolution of the star through to the habitability of orbiting exoplanets. In this project we are attempting to help understand how the magnetic dynamos of young Suns evolve from chaotic variability to the regular magnetic cycles that we see on our own Sun today. To do this, in 2018 we started a monitoring campaign using the NARVAL, and more recently NEONARVAL, spectropolarimeters on the Téléscope Bernard Lyot to observe five of the brightest young Suns. As of mid-2021 we have so far obtained two to four epochs of spectropolarimetric data on each of our targets and from these have created preliminary maps of the stellar magnetic topologies. So far two of our targets have shown magnetic polarity reversals that could indicate developing cycles, with one of the targets showing a strong link between the differential rotation measured from its brightness features and that measured from its magnetic features.

Keywords: stars: solar-type, stars: pre-main sequence, stars: imaging, stars: magnetic fields, starspots

1 Introduction

Sun-like stars can be broadly defined as having an internal structure similar to that of our own Sun. Such stars would have an inner radiative zone, which in the Sun rotates as a solid body, and an outer convection zone, which in the solar case rotates differentially, with the equator rotating faster than the poles. It is this difference in rotation between the Sun's radiative and convective zones that drives the solar dynamo. This dynamo creates a regular magnetic activity cycle in the Sun with an $\sim$11 year cycle of increasing/decreasing sunspots and magnetic polarity reversals every $\sim$22 years.

But what of young solar-type stars? When young these stars rotated much more rapidly, up to 100 times the current solar rate (i.e. Gallet & Bouvier 2015), which was thought to have driven a powerful magnetic dynamo (Gudel 2007). There is some evidence that the magnetic dynamo in these stars operates differently to that of today's solar dynamo. Unlike today's Sun young solar-type stars appear to have a more chaotic dynamo with measurements of the magnetic activity, taken from Calcium HK observations, showing high levels of variability and no real regular cycles (i.e. Baliunas et al. 1995). Young solar-type stars also show large regions of near-surface azimuthal magnetic field (field wrapped around the star's rotation axis) (i.e. Marsden et al. 2006, 2011a; Waite et al. 2011). This is something not seen on the Sun, with most of the solar azimuthal field confined to the tachocline layer between the solar radiative and convection zones, with this interface layer thought to be the seat of the solar dynamo. This may not be the case for young Suns.

Magnetic fields are directly linked to the rotational evolution of solar-type stars (Gallet & Bouvier 2015). The study of magnetic field generation on young, rapidly-rotating solar-type stars is of importance in understanding not only the history of our own Sun, and its impact on our Earth, but more generally in understanding how the magnetic dynamo operates under different conditions. Thus in 2018 we started a project aimed at studying the magnetic fields on young Suns using the NARVAL, and more recently the NEONARVAL, spectropolarimeters on the Téléscope Bernard Lyot (TBL) at Pic du Midi. We chose to monitor five of the best young Sun candidates to map their magnetic fields and look for evidence of changes in their magnetic fields that may indicate the development of emerging cycles on such stars.

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2 Targets and Observations

The five targets chosen are some of the brightest (V $\sim$ 5.1 to 7.9) young solar-type stars known: AF Lep, 111 Tau, V1358 Ori, EK Dra, and V889 Her. Based on GAIA DR2 data (Gaia Collaboration 2018) and the Baraffe et al. (2015) stellar evolution models, these stars range in age from around 30 to 50 Myrs and have masses from $\sim$1.0 to 1.2 $M_{\odot}$. All the stars are rapid rotators with rotational periods ranging from $\sim$1 to 3.6 days (Marsden et al. 2006; Hackman et al. 2016; Mittag et al. 2018). As part of our project, each star has been observed $\sim$10 to 20 times at nearly yearly epochs in Stokes V using NARVAL or NEONARVAL for (as at mid-2021) two semesters (2018B and 2019B) for AF Lep and V1358 Ori, three for 111 Tau (2018B, 2019B, and 2020B) and four semesters (2018A, 2019A, 2020A, and 2021A) for both EK Dra and V889 Her. For some of the targets previous magnetic maps exist; AF Lep - Millburn et al. (in prep.), V1358 Ori - Hackman et al. (2016), 111 Tau - Waite et al. (2015), EK Dra - Waite et al. (2017), and V889 Her - Marsden et al. (2006); Jeffers & Donati (2008); Jeffers et al. (2011), that will also be used to compare to our observations.

3 Magnetic Maps of Young Suns

The (NEO)NARVAL spectropolarimetric observations of the targets have been reduced using the standard TBL data reduction pipeline and then using the technique of Zeeman Doppler Imaging (ZDI) using ZDIpy (Folsom et al. 2018) to produce magnetic maps of all the targets. Examples of preliminary maps from our TBL observations produced for one of our targets, the late-F star 111 Tau, are given in Fig. 1.

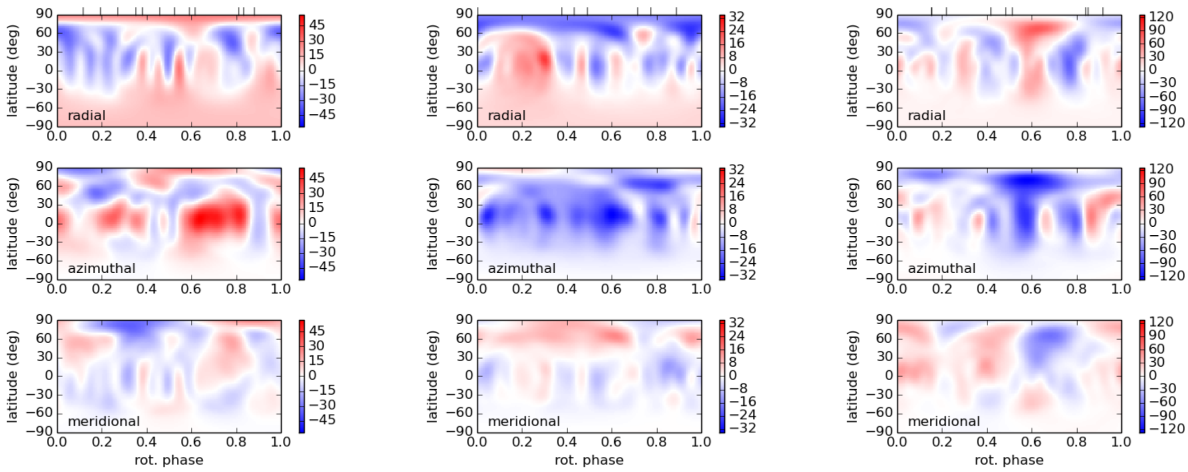

Fig. 1. Preliminary magnetic maps of 111 Tau from Nov/Dec 2018 (left), Dec 2019 (centre), and Dec/Jan 2020/21 (right). The top row shows the radial magnetic field, the middle row the azimuthal field, and the bottom row the meridional magnetic field. The scale bars are in Gauss, with the ticks at the top of the plots showing the phases of observations.

Fig. 1 shows that for 111 Tau the dominant polarity of the radial field around the northern pole has changed from positive in 2018 to negative in 2019 and then to a more mixed polarity in 2020/21. However, the polarity in the southern hemisphere appears to remain unchanged (predominantly positive) at all epochs. At the same time the azimuthal magnetic field changed from a mixed polarity (with possibly dominant positive regions) in 2018 to a more negative polarity field in both 2019 and 2020/21. These could potentially be indications of a nascent cycle starting to form on this young Sun.

Our magnetic maps can also determine the geometry of stellar magnetic fields, e.g. the amount of poloidal or toroidal field, the axisymmetry of the field, and the amount of field contained in the dipolar, quadrupolar, etc., components. These are important indicators that will be used to study the dynamo in our stars.

4 Polarity Reversals

One of the key features of the Sun's 22 years magnetic cycle is the reversal of the dominant magnetic polarity in each hemisphere every $\sim$ 11 years. Thus one of the key observational quantities to measure from our magnetic maps is the location of the magnetic dipole at each epoch. This can more clearly show a magnetic polarity reversal than trying to determine this just from looking at the magnetic maps. An example of the location of the positive dipole on another late-F star, AF Lep, taken from both our (NEO)NARVAL observations and other datasets obtained for the star, is shown in the left-hand side of Fig. 2.

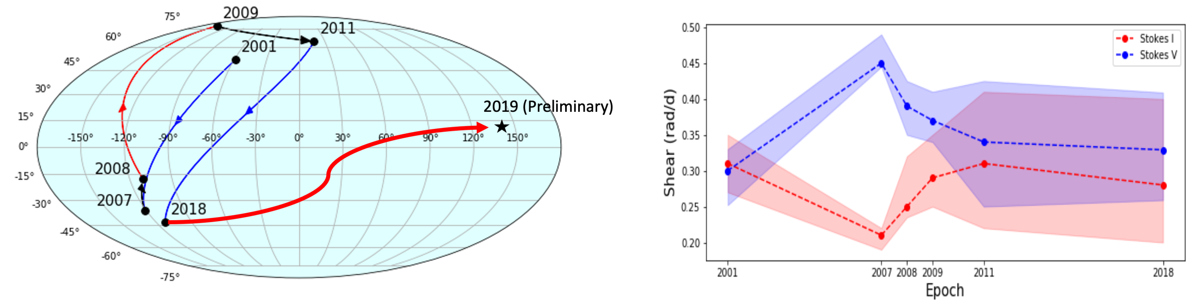

Fig. 2. Preliminary location of the positive dipole for AF Lep (left) and the preliminary variations in the level of surface differential rotation from both the brightness features (Stokes I) and the magnetic features (Stokes V) for the same star (right). These are from both our TBL observations and previously obtained datasets (Millburn et al. in prep.).

Fig. 2 (left) shows that AF Lep has undergone at least three (and potentially four) polarity reversals during the $\sim$20 years of observations. If this is a regular cycle (yet to be determined) it would indicate a magnetic cycle approximately half the length of the Sun's 22 year magnetic cycle, or possibly even shorter.

5 Spot Maps of Young Suns

As our targets are mostly fast rotators with $v\sin i$ values of $\sim$20 km/s or more (with the exception of 111 Tau with a $v\sin i$ of 16 km/s), we can also use the observations to map the location of the spot/brightness features on the stellar surface. Again we use the ZDIpy mapping code and map both dark and bright features. An example of the preliminary spot maps for AF Lep for three epochs (one from the TBL and two from previous observations) are given in Fig. 3.

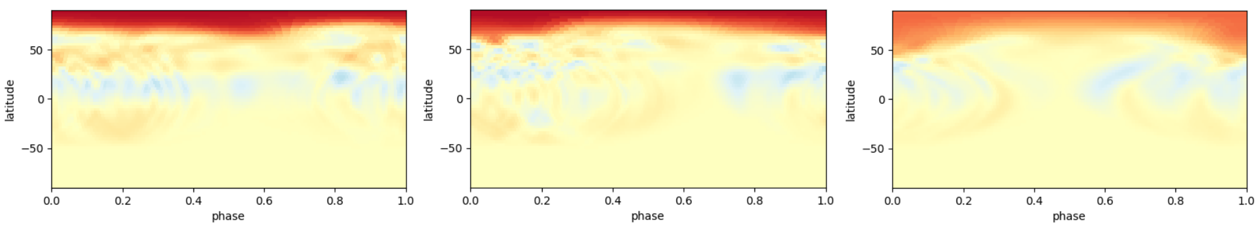

Fig. 3. Preliminary spot maps of AF Lep from 2001 (left), 2008 (centre), and our 2018 TBL observations (right), with brown features indicating dark spots, yellow the photosphere and blue features being bright spots (Millburn et al. in prep.).

Fig. 3 shows that AF Lep always maintains a polar spot feature (with possibly varying intensity), similar to other young, rapidly-rotating stars, but the amount and location of lower latitude features potentially varies. We plan to investigate if the location of lower latitude features is linked to the magnetic features on the star.

6 Surface Differential Rotation

Differential rotation (DR), where the equatorial regions of a star rotate faster than the polar regions, is thought to be a key driver of the magnetic dynamo. Thus measuring the level of DR on our stars, and any variability of the values such as that seen on other young solar-type stars (i.e. Collier Cameron & Donati 2002; Donati et al. 2003), can provide another window into the operation of the stellar dynamo. Through the imaging process, for both magnetic and spot maps, we can measure the level of surface DR on our star by incorporating a solar-like DR law into the imaging process. We use a simplified solar-like law:

$$\Omega(\theta) = \Omega_{\text{eq}} - d\Omega \sin^2(\theta)$$

where $\Omega(\theta)$ is the rotation rate at latitude θ, Ω_{eq} is the equatorial rotation, and $d\Omega$ is the shear between the equator and the poles (the differential rotation). The values of Ω_{eq} and $d\Omega$ are treated as free parameters and varied to find the best fit to the data as described in Petit et al. (2002). This is done for both the brightness (Stokes I) and magnetic (Stokes V) features with preliminary results for AF Lep being shown in the right panel of Fig. 2.

Fig. 2 (right) shows that, as seen on other young solar-type stars (i.e. Donati et al. 2003; Marsden et al. 2011b; Waite et al. 2015), the level of DR measured from the magnetic features is usually higher than that from the brightness features. This has been interpreted as being due to the brightness and magnetic features being anchored at different depths in the stellar convection zone (Donati et al. 2003) and would show that unlike the Sun, the level of DR varies with depth in the convection zone. This could indicate that the dynamo in young stars is operating throughout the convection zone rather than being confined to the interface layer, as in the solar case. Also, although these results are preliminary it appears that changes in AF Lep's DR from the brightness features is mirrored by changes in the DR measured from the magnetic features. These could give insights into the dynamics of the stellar convection zone and hence the stellar dynamo.

7 Conclusions

One of the key questions in understanding the generation of stellar magnetic fields in how stars like the Sun go from chaotic variability to the regular cycle seen on our Sun today. One of the main windows we have on the operation of stellar dynamos is through the mapping of stellar magnetic fields. Thus our TBL project has set out to study the magnetic fields of five of the brightest young Suns to look for evidence of emerging dynamos in these stars. So far we have obtained two to four epochs of spectropolarimetric observations on the stars. Our preliminary analysis shows at least two of our stars (AF Lep and 111 Tau) have magnetic polarity changes reminiscent of magnetic cycles, with AF Lep showing multiple polarity reversals when combined with previous data. Also, preliminary analysis of the DR of AF Lep shows an intriguing relationship between the level of DR measured from the magnetic features compared to that from the brightness features. Further observations and study of these young stars will enable us to provide new insights into the operation of the powerful stellar dynamo at this important phase of stellar evolution as well as improving our understanding of the impact the infant Sun may have had on the developing Solar system.

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References

Baliunas, S. L., Donahue, R. A., Soon, W. H., et al. 1995, ApJ, 438, 269
Baraffe, I., Homeier, D., Allard, F., & Chabrier, G. 2015, A&A, 577, A42
Collier Cameron, A. & Donati, J.-F. 2002, MNRAS, 329, L23
Donati, J.-F., Collier Cameron, A., & Petit, P. 2003, MNRAS, 345, 1187
Folsom, C. P., Bouvier, J., Petit, P., et al. 2018, MNRAS, 474, 4956
Gaia Collaboration. 2018, A&A, 616, A1
Gallet, F. & Bouvier, J. 2015, A&A, 577, A98
Gudel, M. 2007, Living Reviews of Solar Physics, 4, 3
Hackman, T., Lehtinen, J., Rosén, L., Kochukhov, O., & Käpylä, M. J. 2016, A&A, 587, A28
Jeffers, S. V. & Donati, J.-F. 2008, MNRAS, 390, 635
Jeffers, S. V., Donati, J.-F., Alecian, E., & Marsden, S. C. 2011, MNRAS, 411, 1301
Marsden, S. C., Donati, J.-F., Semel, M., Petit, P., & Carter, B. D. 2006, MNRAS, 370, 468
Marsden, S. C., Jardine, M. M., Ramírez Vélez, J. C., et al. 2011a, MNRAS, 413, 1922
Marsden, S. C., Jardine, M. M., Ramírez Vélez, J. C., et al. 2011b, MNRAS, 413, 1939
Mittag, M., Schmitt, J. H. M. M., & Schröder, K.-P. 2018, A&A, 618, A48
Petit, P., Donati, J.-F., & Collier Cameron, A. 2002, MNRAS, 334, 374
Waite, I. A., Marsden, S. C., Carter, B. D., et al. 2011, MNRAS, 413, 1949
Waite, I. A., Marsden, S. C., Carter, B. D., et al. 2015, MNRAS, 449, 8
Waite, I. A., Marsden, S. C., Carter, B. D., et al. 2017, MNRAS, 465, 2076