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# Rotation and Spot Activity of Young Solar-Type Stars

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## Abstract

We report on our study of rotation and spot activity in 21 young solar-type stars, based on period analysis of extended photometric records. Our results reveal activity cycles in nearly all of the stars and active longitudes on the more active members of the sample. The lengths of the activity cycles fall on a sequence of activity branches that have an apparent turnoff point close to the limit separating the stars with active longitudes from those with axisymmetric long-term spot distributions. We find that on many stars the active longitudes do not exactly follow the rotation of the star, which may be explained by a longitudinally propagating non-axisymmetric dynamo mode. The rotation and temperature dependence of differential rotation on the sample stars appears to agree qualitatively with other recent studies.

## 1 Introduction

Understanding the mechanisms of stellar activity is an enterprise that requires knowledge of the types of activity across a wide range of stars with different ages and types. Central observational input parameters required for dynamo models are the rotation periods and differential rotation characteristics of the stars, as well as information about the magnetic field geometries and possible activity cycles. In practice, activity studies often suffer from limitations in their sample size or the parameter range that can be covered, but they can still provide valuable input for piecing together a full picture of activity behaviour across stars of different types and ages.

Here we discuss the results of Lehtinen *et al.* (2016) where we studied the rotation and spot activity of 21 young and single solar-type stars. We used extended time series of ground based photometry from the T3 0.4 m Automatic Photoelectric Telescope at the Fairborn observatory (Henry, 1995) and performed piecewise period analysis for the spot modulated light curves using the Continuous Period Search method (Lehtinen *et al.*, 2011). We drew estimates for the surface differential rotation of the stars from the variability seen in the photometric rotation periods and searched for activity cycles from the varying mean levels and amplitudes of the light curve fits. To investigate the presence of long-lived active longitudes, we studied the rotational phase distribution of the light curve minima.

Finally, in order to relate the photometric results to the activity levels of the stars, we derived the chromospheric $\log R'_{\mathrm{HK}}$ indices from high resolution spectroscopy observed with the FIES spectrograph at the Nordic Optical Telescope (Telting *et al.*, 2014). All the stars in our sample have moderate to high activity levels at $-4.7 < \log R'_{\mathrm{HK}} < -4.0$.

## 2 Differential rotation

For deriving estimates of the the surface differential rotation, we followed Jetsu (1993) and used the $\pm 3\sigma$ ranges of the detected photometric period variations as proxies for the relative differential rotation coefficient $k = \Delta\Omega/\Omega$. Here $\Omega$ is the angular rotation rate at the equator of the star and $\Delta\Omega$ the rotational shear between the equator and pole. The method of looking at period variations has its issues with telling apart differential rotation and active region growth and decay, as well as with the stability of period estimation from low-amplitude light curves. However, for stars with higher activity levels and more stable light curves, it can still be used to probe the general dependence of differential rotation from other stellar parameters in a population of stars.

We found that in our sample the stars rapidly approach rigid rotators as their rotation periods decrease, i.e. $k$ decreases with $P_{\mathrm{rot}}$. On the other hand, the absolute value of the equator to pole shear $\Delta\Omega$ has only a weak relation with the rotation rate. The power law fits that we found for our results are $k \propto P_{\mathrm{rot}}^{1.36\pm0.19}$ and $\Delta\Omega \propto \Omega^{-0.36\pm0.19}$. We did not find any significant temperature dependence for differential rotation within our sample, which covers the effective temperature range $4500\ \mathrm{K} < T_{\mathrm{eff}} < 6000\ \mathrm{K}$. All of these results are more or less in qualitative agreement with those obtained for the Kepler field stars (Reinhold & Gizon, 2015) as well as with the mean field models of Küker & Rüdiger (2011).

Table 1 shows a comparison between the power law fits $k \propto P_{\mathrm{rot}}^{\mu}$ and $\Delta\Omega \propto \Omega^{\nu}$ found in our work and in other past studies that used rotation period ranges for estimating differential rotation. There is a fair amount of scatter between the different results, but they mostly show steeper laws for $k$ and correspondingly shallower ones for $\Delta\Omega$. To some extent part of the variation between the reported power laws has to originate from the limited stellar samples and narrow ranges of rotation periods available for the studies. However, it is also likely that the methodological differences in deriving the differential rotation proxies have had systematic effects on the interpretation of the data, thus causing further discrepancy between the results.

Table 1: Power law indices $\mu$ and $\nu$ and their errors $\sigma_{\{\mu,\nu\}}$ for the differential rotation relations $k \propto P_{\mathrm{rot}}^{\mu}$ and $\Delta\Omega \propto \Omega^{\nu}$.

| $\mu$ | $\nu$ | $\sigma_{\{\mu,\nu\}}$ | Reference |
|---|---|---|---|
| 0.76 | 0.24 | 0.06 | Henry *et al.* (1995) |
| 0.3 | 0.7 | 0.1 | Donahue *et al.* (1996) |
| 0.85 | 0.15 | 0.10 | Barnes *et al.* (2005) |
| 0.71 | 0.29 | … | Reinhold & Gizon (2015) |
| 1.36 | −0.36 | 0.19 | Lehtinen *et al.* (2016) |

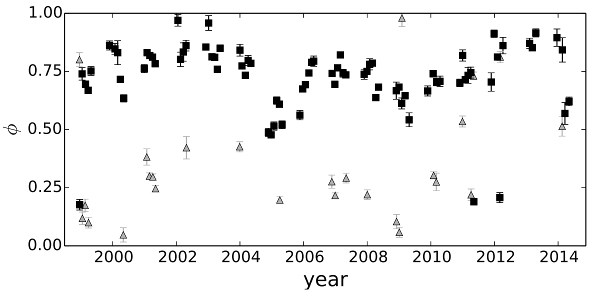

Figure 1: The active longitudes of NQ UMa. Black squares show the rotation phases of the primary light curve minima and grey triangles the secondary light curve minima.

## 3 Active longitudes

Another rotation effect that is often seen on active stars is the confinement of activity into long-lived narrow longitude areas or active longitudes. We investigated the presence of active longitudes in the spot activity of our sample stars by using the Kuiper method to check if any periodicities could be seen in the light curve minimum epochs (Jetsu & Pelt, 1996). We found significant periodicity in 11 out of the 21 studied stars. Phasing the light curve minima with the recovered periods reveals a variety of active longitude structures on these stars. These structures stay intact, with possible migration and jumps, from three or four years up to decades. Particularly well developed active longitudes are shown in Fig. 1 for the star NQ UMa.

The occurrence of active longitudes on the stars is not a random phenomenon. We could find evidence for them only on stars having activity levels above a certain cutoff, or correspondingly having high enough rotation rates. Based on our sample, the cutoff lies roughly at $\log R'_{\mathrm{HK}} = -4.46$. Stars on the less active side of the cutoff also have limited longitudinal activity concentrations, but these do not survive for many years before being disrupted, likely by differential rotation. Thus, the longitude distribution of activity could be explained on the less active stars by the presence of activity complexes similar to those observed on the Sun (Bumba & Howard, 1965), while the longer lived active longitudes on the more active stars require an explanation by non-axisymmetric dynamo modes.

The separate period analyses for the full photometry and the light curve minima enabled us to compare the mean rotation periods of the stars with the periods found for the active longitudes. In seven out of the 11 stars with active longitudes, the active longitude period $P_{\mathrm{al}}$ is significantly different than the mean photometric rotation period $P_{\mathrm{rot}}$. On all of these stars, the active longitudes appear to have shorter rotation periods than the stellar photospheres. This is illustrated graphically in Fig. 2, which displays the active longitude and photometric periods $P_{\mathrm{al}}$ and $P_{\mathrm{rot}}$ and their $1\sigma$ uncertainties, normalized by the $P_{\mathrm{rot}}$ of each star.

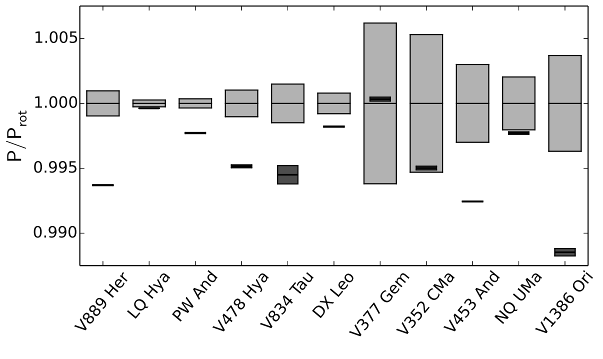

Figure 2: Comparison of the active longitude periods $P_{\mathrm{al}}$ (dark boxes) and mean photometric rotation periods $P_{\mathrm{rot}}$ (light boxes) with their $1\sigma$ uncertainties. Each of the periods are normalized by the photometric period $P_{\mathrm{rot}}$ of the star in question.

A possible explanation for the $P_{\mathrm{al}} < P_{\mathrm{rot}}$ disparity is that the active longitudes are connected to longitudinally propagating non-axisymmetric dynamo modes (Cole *et al.*, 2014). Most new spots would arise near the strongest mean dynamo field, rotating at $P_{\mathrm{al}}$, but would eventually decouple from it and start to follow a rotation period closer to the surface bulk rotation. Alternatively it may be that the active longitudes are simply anchored at a deeper level in the stellar interior than aged individual spots so that the difference between $P_{\mathrm{al}}$ and $P_{\mathrm{rot}}$ relates to radial differential rotation.

## 4 Activity cycles

To search for activity cycles from the photometry, we computed Lomb-Scargle periodograms using the Horne-Baliunas statistic (Horne & Baliunas, 1986) for the evolving light curve means and amplitudes. Only in the case of three stars were we unable to find even poor evidence for cycles. For one of these (V383 Lac), this was simply because of an incomplete observing record that prevented the computation of a reasonable periodogram, while the photometry itself shows strong variability in the mean brightness of the star.

We found that our cycle lengths fall on top of the activity branches described by Saar & Brandenburg (1999), when comparing the rotation to cycle period ratios $P_{\mathrm{rot}}/P_{\mathrm{cyc}}$ with the semi-empirical Rossby numbers and the chromospheric activity levels of the stars. This is shown in Fig. 3 for the period ratios against $\log R'_{\mathrm{HK}}$. In particular, our stars populate the region around the turnoff point between the suggested "Active" and "Transitional/Superactive" branches and show opposite trends of $P_{\mathrm{rot}}/P_{\mathrm{cyc}}$ at the opposite sides of the turnoff. This turnoff lies close to the activity limit that divides the stars into those that have active longitudes and those that do not have them. It is possible that the transition between axisymmetric and non-axisymmetric activity distributions and the change in the trends of $P_{\mathrm{rot}}/P_{\mathrm{cyc}}$ between the "Active" and "Transitional/Superactive" branches

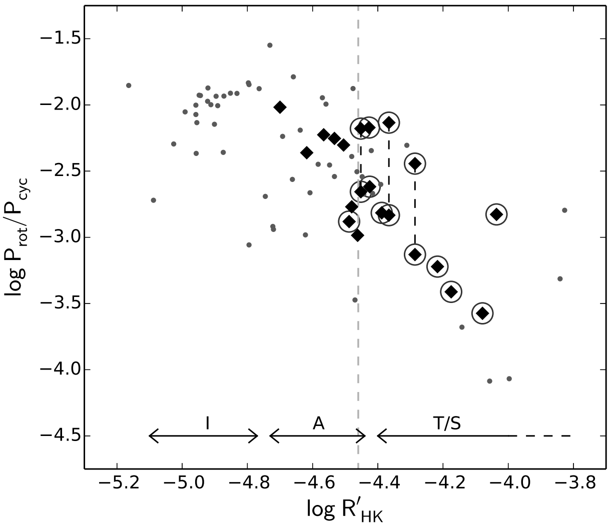

Figure 3: Logarithmic rotation to cycle period ratios $\log P_{\rm rot}/P_{\rm cyc}$ shown against the chromospheric activity indices $\log R'_{\rm HK}$ for the stars in our sample (black diamonds) and reference stars from Saar & Brandenburg (1999) (grey points). Stars with two cycles have their period ratios connected with dashed lines and stars where we find active longitudes have their symbols circled. The approximate limit between stars with and without active longitudes is marked by the grey vertical dashed line. Approximate ranges of the "Inactive", "Active", and "Transitional/Superactive" activity branches are marked with the arrows and labeled "I", "A", and "T/S".

are related. They may both be connected to a fundamental transition in how the dynamo operates in solar-type stars at different rotation rates.

As a further detail, the cycle lengths form two parallel sub-branches along the previously defined branches. On three stars we found two cycles present simultaneously and in all of these cases the two cycle periods fall directly on the two sub-branches. The sub-branches still need more stars with accurately determined cycle periods on them to be well defined, but they do indicate that there should exist systematic relations between the lengths of the multiple cycles that have been found on many active stars, e.g. by Oláh *et al.* (2016).

## References

Barnes, J. R., Collier Cameron, A., Donati, J.-F., James, D. J., Marsden, S. C., *et al.* 2005, MNRAS, 357, L1.

Bumba, V. & Howard, R. 1965, ApJ, 141, 1492.

Cole, E., Käpylä, P. J., Mantere, M. J., & Brandenburg, A. 2014, ApJL, 780, L22.

Donahue, R. A., Saar, S. H., & Baliunas, S. L. 1996, ApJ, 466, 384.

Henry, G. W. 1995, In *Robotic Telescopes. Current Capabilities, Present Developments, and Future Prospects for Automated Astronomy*, edited by G. W. Henry & J. A. Eaton, *Astronomical Society of the Pacific Conference Series*, vol. 79, p. 44.

Henry, G. W., Eaton, J. A., Hamer, J., & Hall, D. S. 1995, ApJS, 97, 513.

Horne, J. H. & Baliunas, S. L. 1986, ApJ, 302, 757.

Jetsu, L. 1993, A&A, 276, 345.

Jetsu, L. & Pelt, J. 1996, A&AS, 118, 587.

Küker, M. & Rüdiger, G. 2011, Astronomische Nachrichten, 332, 933.

Lehtinen, J., Jetsu, L., Hackman, T., Kajatkari, P., & Henry, G. W. 2011, A&A, 527, A136.

Lehtinen, J., Jetsu, L., Hackman, T., Kajatkari, P., & Henry, G. W. 2016, A&A, 588, A38.

Oláh, K., Kővári, Z., Petrovay, K., Soon, W., Baliunas, S., *et al.* 2016, A&A, 590, A133.

Reinhold, T. & Gizon, L. 2015, A&A, 583, A65.

Saar, S. H. & Brandenburg, A. 1999, ApJ, 524, 295.

Telting, J. H., Avila, G., Buchhave, L., Frandsen, S., Gandolfi, D., *et al.* 2014, Astronomische Nachrichten, 335, 41.