Meridional flow velocities on solar-like stars with known activity cycles

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Abstract

The direct measurements of the meridional flow velocities on stars are impossible today. To evaluate the meridional flow velocities on solar-like stars with stable activity periods, we supposed that during the stellar Hale cycle the matter on surfaces of stars passes the meridional way equivalent to $2\pi R_\odot$. We present here the dependence of the mean meridional flow velocity on Rossby number, which is an effective parameter of the stellar magnetic dynamo.

Keywords: stars: solar-like; stars: activity; stars: Hale cycle; stars: meridional flow velocity

1. Introduction

Today the physics of the large-scale flows on the Sun and stars are intensively simulated by scientists to determine the detailed mechanisms of activity cycles. Recent results and bibliography are presented, for example, in the papers by Upton and Hathaway (2014), Zhao et al. (2013), Guerrero et al. (2013), Moss et al. (2013), Kitchatinov (2013), Kitchatinov and Olemskov (2012).

The empirical dependence of the mean meridional flow speed on the number of the 22-year Hale cycle (Plachinda et al., 2011) was obtained under the assumption that during the Hale cycle the total length of the reverse track of the poloidal dipole polarity is equivalent to the circumference of the Sun as the magnetic dipole moment does not vanish and migrates between the poles (Livshits and Obridko, 2006; Moss et al., 2013).

The mean velocity $\langle v \rangle = 6.29$ m s$^{-1}$, which gives $P_{Hale} = 22$ years for the Sun, corresponds to the 7.3 years activity period for the solar-like star 61 Cyg A and is well agreed with the observations (Plachinda et al., 2011). Therefore we supposed that the magnetic flux transported by meridional flows on the surfaces of solar-like stars with stable activity period also passes the way equivalent to $2\pi R_\odot$ during the own Hale cycle. We use this approach to draw the dependence of the mean meridional flow velocity on the Rossby number. In other words, in this paper we use the empirical data to see whether the duration of activity cycle on convective stars depends on the effective parameter of dynamo processes.

2. Parameters of stars

We selected stars with well-known activity periods. In the Table 1 and Table 2 we summarized the physical parameters of the stars that we have got from literature.

The names of the stars are listed in the 1st column of the Tables. Columns 2-4 in the Table 1 contain magnitude $V$, spectral type and color index $B-V$. The rotation periods of the stars and the references are given in the 5th and 6th columns, the duration of activity cycles and the references are given in the 7th and 8th columns.

The masses of the stars and the references are listed in the 9th and 10th columns in the Table 1, columns 11 and 12 represent the radii of the stars and the references, columns 13-14 give the logarithm of gravity and the references. Finally, columns 15-16 show the effective temperature and the references.

The 2nd column in the Table 2 shows the parameter $R_{HK}^cyc$ defined as the ratio of the chromospheric emission in the cores of the CaII H and K lines to the total bolometric emission of the star, and the 3rd column contains the references. The logarithm of the convective turnover time, the Rossby number obtained from the dependence of $\tau_c$ from $B-V$ and the mean meridional flow velocity are listed in the last three columns in the Table 2.

The convective turnover time $\tau_c$ and the Rossby number were calculated using the methods described in the Section 3. The mean meridional flow velocity has been calculated using the equation $2\pi R_\odot / \langle v \rangle = P_{Hale}$ (Plachinda et al., 2011), where $R_\odot$ is the radius of a star, $P_{Hale}$ is the stellar magnetic activity period, $P_{Hale} = 2P_{cyc}$, where $P_{cyc}$ is a star-spot activity period. The mean activity period of the Sun calculated by averaging of sunspot numbers for all years of observations from 1755 to 2008 is equals to $P_{cyc\odot} = 11$ years.

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Table 1: Parameters of stars

| Name          | V  | Sp | $B - V$ | $P_{rot}$, days | $P_{rot, yr}$ Ref | $M_*$, $M_\odot$ | Ref | $R_*$, $R_\odot$ Ref | $\log g$ | $R_{eff}$, K | Ref |
|---------------|----|----|---------|-----------------|-------------------|-----------------|-----|----------------------|---------|-------------|-----|
| Sun           | 6.39 | G2 V | 0.65 | 25.4 | 11.0 | 1.00 | 1.00 | 4.44 | 5780 |
| BE Cet        | 5.87 | K0 V | 0.85 | 48.0 | 13.8 | 1.04 | 0.94 | 4.51 | 5250 |
| HD4628        | 5.75 | K2 V | 0.88 | 38.5 | 7.83 | 0.77 | 0.69 | 4.64 | 5004 |
| 107 Psc       | 5.24 | K1 V | 0.84 | 35.2 | 9.6 | 0.816 | 0.82 | 4.54 | 5098 |
| HD16160       | 5.82 | K3 V | 0.98 | 48.0 | 13.2 | 0.809 | 0.76 | 4.62 | 5262 |
| $\kappa^1$ Cet | 4.80 | G5 V | 0.68 | 9.214 | 2 | 1.02 | 0.877 | 4.5 | 5630 |
| 40a$^2$ Eri   | 4.43 | K1 V | 0.82 | 43.0 | 8 | 0.81 | 0.82 | 4.51 | 5090 |
| HD32147       | 6.22 | K3 V | 1.06 | 47.4 | 9 | 0.838 | 0.78 | 4.48 | 4945 |
| HD78366       | 5.93 | F9 V | 0.585 | 9.67 | 12.2 | 1.13 | 1.075 | 23 | 4.46 | 5938 |
| HD81809       | 5.38 | G2 V | 0.64 | 18.0 | 8.17 | 1.33 | 2.24 | 14 | 3.86 | 5884 |
| DX Leo        | 7.01 | K0 V | 0.78 | 5.377 | 10 | 3.21 | 0.93 | 4.4 | 5121 |
| CFUMa         | 6.45 | K1 V | 0.75 | 31.0 | 8 | 0.661 | 0.681 | 4.63 | 4759 |
| $\beta$ Com   | 4.26 | F9.5 V | 0.57 | 12.35 | 7 | 1.17 | 1.1 | 4.4 | 5060 |
| HD115404      | 6.66 | K2 V | 0.93 | 18.47 | 11 | 12.4 | 0.86 | 4.77 | 4582 |
| 18 Sco        | 5.49 | G2 V | 0.652 | 23.7 | 9 | 0.1 | 0.103 | 24 | 4.47 | 5334 |
| V2133 Oph     | 5.75 | K2 V | 0.827 | 21.07 | 17.4 | 1 | 0.91 | 0.85 | 4.5 | 5924 |
| V2292 Oph     | 6.64 | G7 V | 0.76 | 11.43 | 11 | 10.9 | 0.97 | 0.87 | 4.58 | 5266 |
| V2215 Oph     | 6.34 | K5 V | 1.16 | 18.0 | 21 | 0.72 | 0.63 | 4.67 | 4319 |
| HD160546      | 6.52 | K3 V | 0.96 | 36.4 | 11 | 7 | 0.86 | 0.77 | 4.5 | 4562 |
| HD166620      | 6.40 | K2 V | 0.87 | 42.4 | 7 | 15.8 | 0.89 | 0.791 | 4.0 | 5035 |
| 61 Cyg A      | 5.21 | K5 V | 1.18 | 35.37 | 7 | 7.3 | 0.69 | 0.665 | 4.63 | 4400 |
| 61 Cyg B      | 6.03 | K7 V | 1.37 | 38.74 | 7.17 | 8.05 | 0.605 | 20 | 4.71 | 4040 |
| HN Peg        | 5.94 | G0 V | 0.587 | 4.86 | 7 | 5.2 | 1.1 | 2 | 4.48 | 5567 |
| 94 Aqr A      | 5.29 | G8.5 IV | 0.79 | 42.0 | 8 | 21.0 | 1.04 | 1.99 | 4.36 | 5370 |
| 94 Aqr B      | 8.88 | K2 V | 0.88 | 43.0 | 8 | 10 | 0.96 | 0.93 | 4.54 | 5136 |
| BY Dra        | 8.07 | K6 V | 1.2 | 3.83 | 4 | 13.74 | 0.58 | 0.71 | 4.65 | 4622 |
| V833 Taur     | 8.42 | K5 V | 1.19 | 1.7936 | 4 | 6.4 | 0.93 | 0.77 | 4.5 | 4450 |

*References for rotation periods; †References for periods of the activity cycles; ‡References for stellar masses; §References for radii of stars; 
References for log g; ‡References for effective temperatures $T_{eff}$

(1) Balisumas et al. (1995); (2) Messina and Guinan (2002); (3) Hall et al. (2007); (4) Olah et al. (2000); (5) Noyes et al. (1984); (6) Cranmer and Saar (2011); (7) Donahue and Saar (1996); (8) Balisumas et al. (1996); (9) Cincunegui et al. (2007); (10) Messina et al. (1999); (11) Wright et al. (2011); (12) Santos et al. (2004); (13) Isaacson and Fischer (2010); (14) Allende Prieto and Lambert (1999); (15) Fuhrmann (2008); (16) Chmielewski (2000); (17) Boyajian et al. (2012); (18) Mishenina et al. (2012); (20) Kervella et al. (2008); (21) Takeda et al. (2007); (22) Eker et al. (2008); (23) Masana et al. (2006); (24) Lammer et al. (2012); (25) Soubiran et al. (2010); (26) Roser et al. (2011); (27) Mishenina et al. (2003); (28) Hillen et al. (2012); (29) van Belle and von Braun (2009)

3. The dependence of the Rossby number on the mean chromospheric emission ratio $\langle R'_{HK} \rangle$

![Figure 1: log $\langle R'_{HK} \rangle$ versus log Ro](image1)

Figure 1: log $\langle R'_{HK} \rangle$ versus logRo.

![Figure 2: $\log \langle R'_{HK} \rangle$ versus log Ro (mass)](image2)

Figure 2: log $\langle R'_{HK} \rangle$ versus logRo (mass). The solid line represents the linear fit to all data points.

The Rossby number, $Ro = P_{rot}/\tau_c$, is the ratio of the stellar rotation period $P_{rot}$ to the convective turnover time $\tau_c$. To find the convective turnover time $Noyes$ et al. (1984, eq. 4) used the empirical dependence of $\tau_c$ on color index $B - V$, and Wright et al. (2011) chose the empirical dep-
dependence of $\tau_c$ on stellar masses.

The dependence of $\log (R'_{HK})$ on $\log Ro$ for $\tau_c = f(B-V)$ according to Noyes et al. (1984) is shown in Figure 1 by dashed curve. The dependence of $\log (R'_{HK})$ on $\log Ro$, where $\tau_c = f(M_*)$, is plotted in Figure 2.

The relation between $\log (R'_{HK})$ and $\log Ro$ is more accurate in the case of using of the dependence of $\tau_c$ on color index $B-V$. The significance level of the difference between the scatterings is more than 99.99%. Therefore we used the relation $\tau_c = f(B-V)$ to evaluate the Rossby number.

We have supplemented the list of stars of Noyes et al. (1984) using, in particular, the stars with higher level of the chromospheric activity. The relation between $\log (R'_{HK})$ and $\log Ro$ in this case may be presented as $\log R'_{HK} = -4.63 - 0.83 \log Ro$ (solid line in Figure 1).

4. The dependence of the mean meridional flow velocity on the Rossby number and the activity cycle period

The Figure 3 shows that the mean meridional flow velocities $\langle \nu \rangle$ for solar-type stars located near $5.4 \pm 1.5$ m s$^{-1}$ that is in good agreement with the mean value of the meridional flow velocity of the Sun $6.29$ m s$^{-1}$, obtained in the same manner. We could suggest that the mean meridional flow velocity does not depend on the Rossby number. The only five stars out of 28 show higher values which significantly (more than $3 \sigma$) deviates from the mean value of the meridional flow velocity. So, we can suppose that in the case of 80% stars with the stable activity period the meridional flow determines the duration of the Hale’s cycle.

![Figure 3: Mean meridional flow velocity versus Rossby number. The dotted line is a fit to all data excluding 5 points (stars symbols) which lie out of 10 m s$^{-1}$.](image)

On the other hand, Figure 4 demonstrates that the observed cycle period shows the exponential decay when the velocity of the flow increases. The relation between $P_{\text{cyc}}$ and $\langle \nu \rangle$ may be presented as $P_{\text{cyc}} = 5.74 + 35 \exp (-((\nu - 2.1)/1.66))$ (dashed line in Figure 4).

The dynamo models show qualitatively similar but much slower decay (see Bonanno et al., 2002, Figure 8). Therefore, we can not eliminate another way to interpret the detected velocity as the phase velocity of the dynamo wave drift (e.g., Kit chatinov, 2002).

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References

Allende Prieto, C., Lambert, D.L., 1999. Fundamental parameters of nearby stars from the comparison with evolutionary calculations: masses, radii and effective temperatures. Astronomy and Astrophysics 352, 555–562.

Balucinska-Churchill, C., Diaz, R.F., Mauas, P.J.D., 2007. 

Cranmer, S.R., Saar, S.H., 2011. Testing a Predictive Theoretical Model for the Mass Loss Rates of Cool Stars. The Astrophysical Journal 741, 54.

Donahue, R.A., Saar, S.H., 1996. A relationship between mean rotational velocities and the lithium line emission from late-type stars. The Astrophysical Journal 457, 101.

Chmielowski, Y., 2000. The infrared triplet lines of ionized calcium as a diagnostic tool for F, G, K-type stellar atmospheres. Astronomy and Astrophysics 353, 666–690.

Cincunegui, C., Diaz, R.F., Mauas, P.J.D., 2007. 

Fuhrmann, K., 2008. Nearby stars of the Galactic disc and halo IV. Monthly Notices of the Royal Astronomical Society 384, 173–224.

Guerrero, G., Smolarkiewicz, P.K., Kosovichev, A.G., Mansour, N.N., 2013. Differential rotation in solar-like stars from global simulations. The Astrophysical Journal 779, 176.

Hall, J.C., Lockwood, G.W., Skiff, B.A., 2007. The Activity and Variability of the Sun and Sun-like stars. I. Synoptic Ca II H and K Observations. The Astronomical Journal 133, 862–881.

Hillen, M., Verhoelst, T., Degrucce, P., Acke, B., van Winckel, H., 2012. The dynamic atmospheres of Mira stars: comparing the CODEX models to PTTI time series of T U Andromedae. Astronomy & Astrophysics 538, L6.

Isaacson, H., Fischer, D., 2010. Chromospheric Activity and Jitter Measurements for 2630 Stars on the California Planet Search. The Astrophysical Journal 725, 875–885.

Kervella, P., Merand, A., Pichon, B., 2008. The radii of the nearby K5V and K7V stars 61 Cyg A & B-CHARA/FLUOR interferometry and CESAM2k modeling. Astronomy & Astrophysics 488, 667–674.

Kitchatinov, L., Olofsson, H., 2012. Differential rotation of main-sequence dwarfs: predicting the dependence on surface temperature and rotation rate. Monthly Notices of the Royal Astronomical Society 423, 344–351.

Kitchatinov, L.L., 2002. The direction of propagation of the solar dynamo wave. Astronomy Letters 28, 626–631.

Kitchatinov, L.L., 2013. Theory of differential rotation and meridional circulation, in: Kosovichev, A.G., de Gouveia Dal Pino, E.M., Y., Y. (Eds.), Solar and Astrophysical Dynamos and Magnetic Activity, Proceedings of the International Astronomical Union, IAU Symposium, volume 294, pp. 399–410.

Lammer, H., et al., 2012. Variability of solar/stellar activity and magnetic field and its influence on planetary atmosphere evolution. Earth, Planets and Space 64, 179–199.

Livshits, I.M., Obridko, V.N., 2006. Variations of the dipole magnetic moment of the sun during the solar activity cycle. Astronomy Reports 50, 926–935.

Masana, E., Jordi, C., Ribas, I., 2006. Effective temperature scale and bolometric corrections from 2MASS photometry. Astronomy and Astrophysics 450, 735–746.

Messina, S., Guinan, E.F., 2002. Astrophysics Magnetic activity of six young solar analogues I. Starspot cycles from long-term photometry. Astronomy & Astrophysics 393, 225–237.

Mishenina, T.V., Kovyukh, V.V., Korotin, S.A., Souffran, C., 2003. Sodium Abundances in Stellar Atmospheres with Differing Metallicities. Astronomy Reports 47, 422–429.

Mishenina, T.V., Soufiani, C., Kovyukh, V.V., Katsova, M.M., Livshits, M.A., 2012. Activity and the Li abundances in the FGK dwarfs. Astronomy & Astrophysics 547, A106.

Moss, D., Kitchatinov, L.L., Sokoloff, D., 2013. Reversals of the solar dipole. Astronomy and Astrophysics 550, L9.

Noyes, R.W., Hartmann, L.W., Baliunas, S.L., Duncan, D.K., Vaughan, A.H., 1984. Rotation, convection, and magnetic activity in lower main-sequence stars. The Astrophysical Journal 279, 763–777.

Olah, K., Kollath, Z., Strassmeier, K.G., 2000. Multi-periodic light variations of active stars. Astronomy and Astrophysics 356, 643–653.

Pachindu, S., Pankon, N., Baklanova, D., 2011. General Magnetic Field of the Sun as a star (GMF): Variability of the frequency spectrum from cycle to cycle. Astronomische Nachrichten 332, 918–924.

Raghavan, D. et al., 2010. A Survey of Stellar Families: Multiplicity of Solar-Type Stars. The Astrophysical Journal Supplement Series 190, 1–42.

Roser, S., Schilbach, E., Piskunov, A.E., Kharchenko, N.V., Scholz, R.D., 2011. A deep all-sky census of the Hyades. Astronomy & Astrophysics 531, A92.

Santos, N.C., Israelian, G., Mayor, M., 2004. Spectroscopic [Fe/H] for 98 extra-solar planet-host stars. Exploring the probability of planet formation. Astronomy and Astrophysics 415, 1153–1166.

Souffran, C., Le Campion, J.F., Cayrel de Strobel, G., Caillol, A., 2010. The PASTEL catalogue of stellar parameters. Astronomy and Astrophysics 515, A111.

Takeda, G., Ford, E.B., Sasaki, A., Rasio, F.A., Fischer, D.A., Valenti, J.A., 2007. Structure and Evolution of Nearby Stars with Planets. II. Physical Properties of 1000 Cool Stars from the SPOCS Catalog. The Astrophysical Journal Supplement Series 168, 297–318.

Upton, L., Hathaway, D.H., 2014. Predicting the Suns Polar Magnetic Fields with a Surface Flux Transport Model. The Astrophysical Journal 780, 1–5.

Wright, N.J., Drake, J.J., Mamajek, E.E., Henry, G.W., 2011. The Stellar-activity-Rotation Relationship and the Evolution of Stellar Dynamos. The Astrophysical Journal 743, 48.

Zhao, J., Bogart, R.S., Kosovichev, A.G., Duvall, T. L., J., Hartlep, T., 2013. Detection of equatorward meridional flow and evidence of double-cell meridional circulation inside the Sun. The Astrophysical Journal 774, L29.