On the global magnetic activity of the Sun and solar-type stars

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Magnetic activity is a global property of the Sun:

- The complex processes of solar activity are connected with the solar magnetic fields.
- For solar-type stars and the Sun magnetic activity depends on the physical parameters of the star.
- The very important property of solar irradiance is its cyclical nature. The solar cycle (or solar magnetic activity cycle) is the periodic change in the sun's activity (including changes in the levels of solar radiation and ejection of solar material) and appearance (visible in changes in the number of sunspots, flares, and other visible manifestations).
- At the present time in solar and stellar physics also study multiple and changing cycles with relatively small-amplitude: quasi-biennial, semi centennial and century activity cycles

- We study the relationships between the duration of activity cycle T_{cyc} and effective temperature T_{eff} for solar-type stars and the Sun.
- P.A. Gilman (Ann. Rev. Astron. and Astrophys., 1994) explained the cyclical nature of solar magnetic activity with help of generation of Rossby waves in convective zone. We also assume that Rossby waves which are formed at the bottom of the convective zone of the stars and the Sun can describe the cyclic behavior of solar and solar-type stars activity.
- The Rossby waves conserve vorticity and owes its existence to the variation of the Coriolis force with latitude. The Rossby waves are connected with the primary poloidal magnetic field of a star, which is the source of energy of the complex phenomena of magnetic activity.
- The main our assumption is: the time of generation of Rossby waves t_g corresponds to duration of the activity cycle T_{cyc}. We show that theoretical dependence of the time of generation of Rossby waves t_g versus T_{eff} (the basic parameter of a star) describes well the connection between the star's duration of the activity cycle T_{cyc} (obtained from observations of solar-type stars and the Sun) and their T_{eff} .

• E. Parker (1979, Cosmical Magnetic Fields) proposed the αΩ - dynamo theory which is based on the hypothesis about the generation of the magnetic field due to the differential rotation of the Sun in the turbulent convective shell. This theory can describe the main features of solar magnetic activity.

• Solar cycle models based on what is now called the Babcock-Leighton mechanism: 1) generation of toroidal field from the poloidal field due to the differential rotation of the convective shell (Ω - effect); 2) generation of poloidal field from bipolar magnetic regions of toroidal field due to the differential rotation and the turbulent viscosity (α- effect).

•This theory is simulates well the following phenomena of magnetic activity such as the formation of strong local bipolar magnetic fields (0,1 Tesla), the cyclicity of magnetic activity and Spörer's law. According to the theory of αΩ - dynamo the faster the star rotates, the higher the value of parameter of differential rotation

- The HK Project (Baliunas S.L. et al. , Astrophys. J, 1995) is the longest-running program to monitor stellar activity cycles similar to the 11-year sunspot cycle. Almost 100 stars have been observed continuously since 1966; at present the project is monitoring long-term changes in chromospheric activity for approximately 400 dwarf and giant stars.

- The H-K Project uses a specially-designed instrument to measure the amount of light from active magnetic regions in stars. This light comes from calcium atoms that have lost one electron each. The different wavelengths of light emitted by these atoms were labeled long ago. The "H" and "K" light gave this project its name. This solar "H" and "K" light comes from the upper levels of the Sun near active magnetic regions that we can see, like sunspots.

- Other stars are too far away to see these features on their surfaces. Studying the relative strength of these two wavelengths of calcium light from distant stars similar to our Sun gives an indirect measure of the amount of surface activity on the stars - "starspots". Using this method, astronomers have been able to follow cycles similar to the sunspot cycle that has been observed on the Sun for centuries.

In the Table we present the information about the periods of rotation and effective temperatures of stars, about the duration of their "11-year" (T_{11}) and quasi-biennial (T_2) cycles. The periods of cycles of activity are given according to our calculations of cyclic periodicities of HK-project stars with help of Fourier analysis of light curves of stars

1	2	3	4	5	6	7	8
№	Catalog HD	Spectr.class	P_{rot}, days (Soon et al. 1996)	Teff, K (Allen 1977)	T^{HK}_{11} (Baliunas et al. 1995), years	T_{11}, years	T_2, years
1	Sun	G2-G4	25	5780	10.0	10,7	2,7
2	HD 1835	G 2,5	8	5750	9,1	9,5	3,2
3	HD 3229	F2	4	7000	4,1	-	-
4	HD 3651	K0	45	4900	13,8	-	-
5	HD 4628	K4	38,5	4500	8,37	-	-
6	HD20630	G5	9,24	5520	10,2	-	-
7	HD26913	G0	7,15	6030	7,8	-	-
8	HD26965	K1	43	4850	10,1	-	-
9	HD32147	K5	48	4130	12,1	-	-
10	HD 10476	K1	35	5000	9,6	10	2,8
11	HD 13421	G0	17	5920	-	-	–
12	HD 18256	F6	3	6450	6,8	6,7	3,2
13	HD 25998	F7	2	6320	-	7,1	–
14	HD 35296	F8	10	6200	-	10,8	–
15	HD 39587	G0	14	5920	-	10,5	–
16	HD 75332	F7	11	6320	-	9	2,4
17	HD76151	G3	15	5700	-	-	2,52 *
18	HD 76572	F6	4	6450	7,1	8,5	–
19	HD78366	G0	9,67	6030	-	10,2	-
20	HD 81809	G2	41	5780	8,2	8,5	2,0
21	HD 82885	G8	18	5490	7,9	8,6	–
22	HD100180	F7	14	6320	12	8	--
23	HD103095	G8	31	5490	7,3	8	–
24	HD114710	F9.5	12	6000	14,5	11,5	2,0

Table (continuation)

25	HD115383	G0	12	5920	-	10,3	3,5
26	HD115404	K1	18	4850	12,4	11,8	2,7
27	HD120136	F7	4	6320	11,6	11,6	3,3
28	HD124570	F6	26	6450	-	-	2,7
29	HD129333	G0	3	5920	-	9	3,2
30	HD131156	G2	6	5780	-	8,5	4
31	HD143761	G0	17	5920	-	-	–
32	HD 149661	K2	21	4780	14,4	11,5	3,5
33	HD152391	G7	11	5500	10,7	10,8	2,8
34	HD154417	F8	7,78	6100	7,4	-	-
35	HD155875	K1	30	4850	5,7	-	-
36	HD156026	K5	21	4130	21	11	-
37	HD157856	F6	4	6450	-	10,9	2,6
38	HD 158614	G9	34	5300	-	12	2,6
39	HD160346	K3	37	4590	7	8,1	2,3
40	HD166620	K2	42,4	4780	15,8	13,8	-
41	HD182572	G8	41	5490	-	10,5	3,1
42	HD185144	K0	27	5240	-	8,5	2,6
43	HD187691	F8	10	6100	7,4	-	-
44	HD188512	G8	-	5490	-	-	4,1
45	HD190007	K4	29	4500	-	11	2,5
46	HD190406	G1	13,94	5900	8	-	-
47	HD201091	K5	35	4410	-	13,1	3,6
48	HD201092	K7	38	4160	-	11,7	2,5
49	HD203387	G8	–	5490	-	-	2,6
50	HD206860	G0	9	6300	6,2		-
51	HD216385	F7	7	6320	-	7	2,4
52	HD219834	K2	43		10		-
53	HD224930	G3	33	5750	10,2		-

Our data set of the rotation periods and the effective temperatures of stars from the Table shows the following power-law dependence: $P_{rot} \sim T_{eff}^{-3,9}$

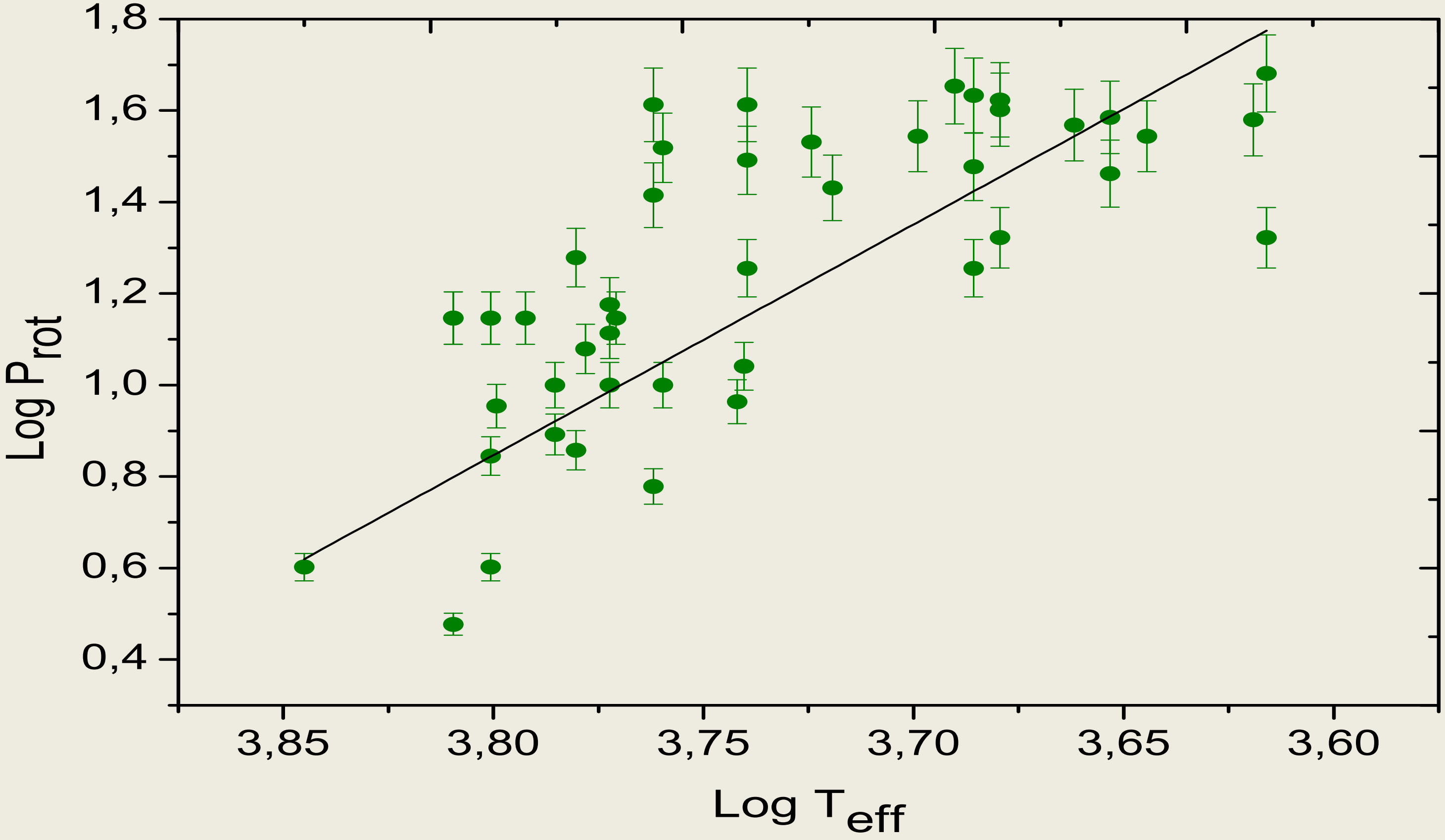

Figure 1. Diagram "the rotation period – the effective temperature" for 52 solar-type stars. Error bars correspond to standard error equal to 1σ.

For the investigated sample of stars from the **Table** the periods of "11-year" cycles T_{11} and their effective temperatures T_{eff} are connected in power-law dependence: $T_{11} \sim T_{eff}^{-1,1}$

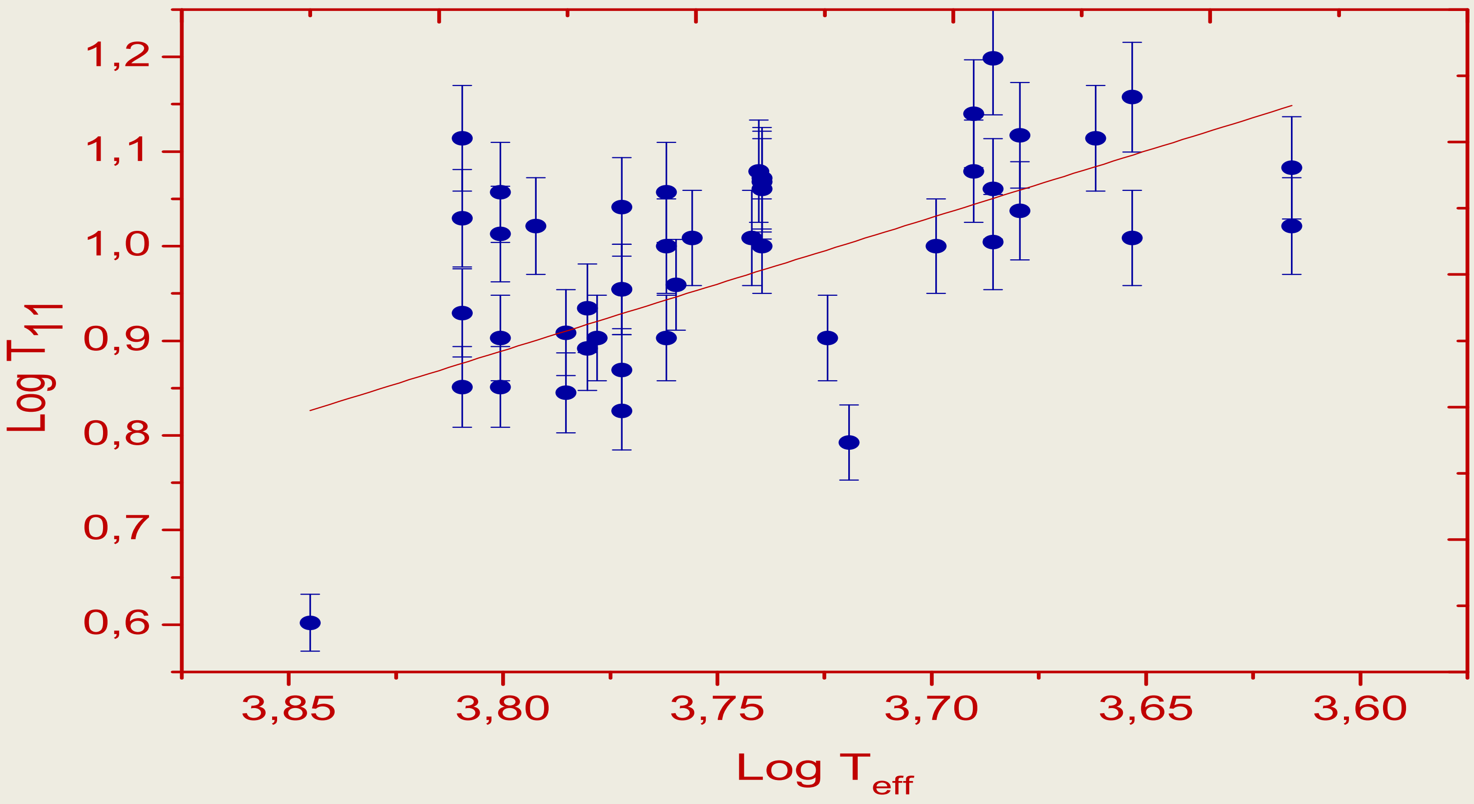

Figure 2. **Diagram "the duration of the cycle T_{11} – the effective temperature T_{eff} ". Error bars correspond to standard error equal to 1σ.**

For the investigated sample of stars from the **Table** their periods of quasi-biennial cycles T_2 and their effective temperatures T_{eff} are linked as power-law dependence: $T_2 \sim T_{eff}^{-0,79}$

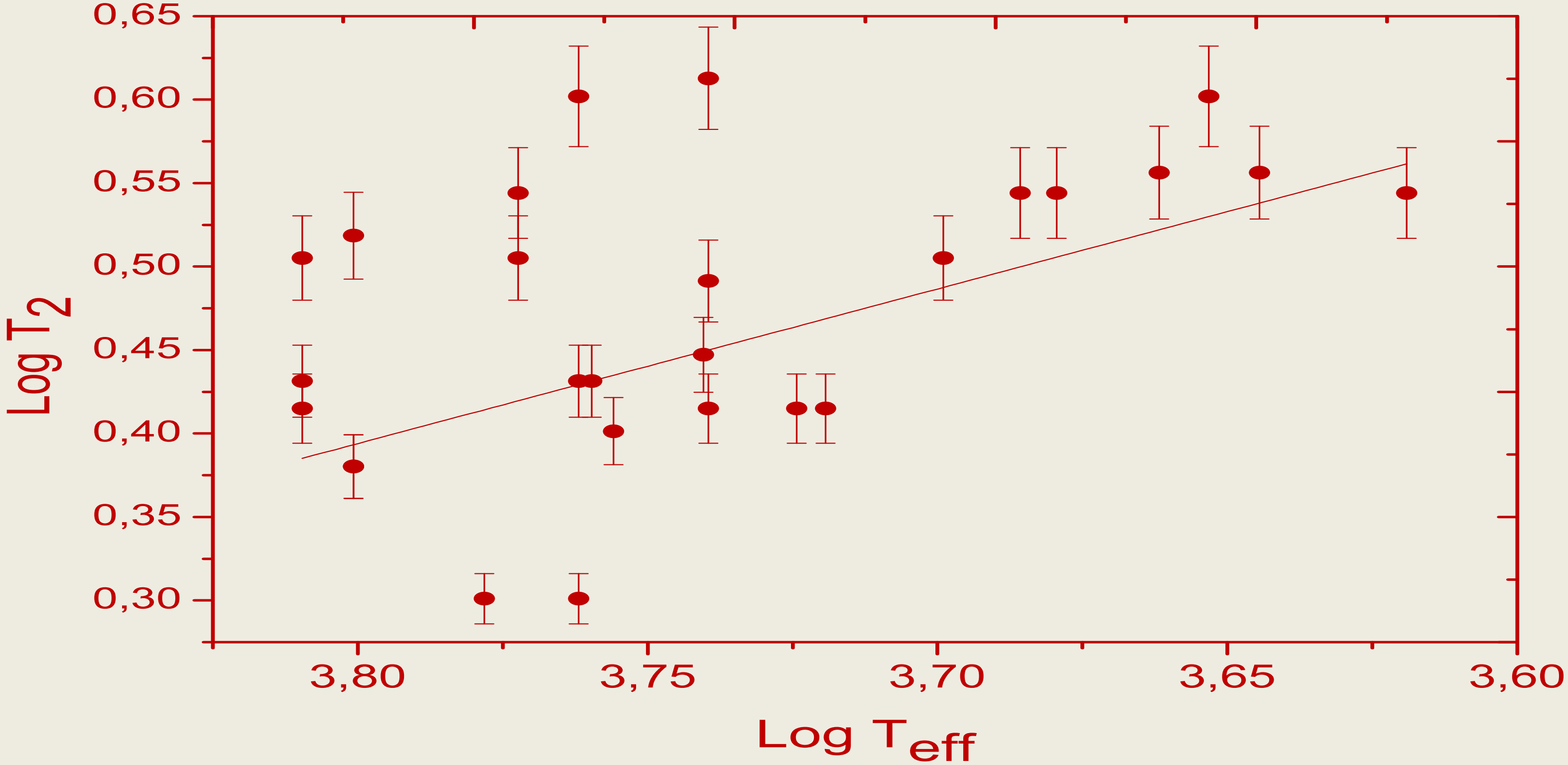

Figure 3. Diagram "the duration of the cycle T_2 – the effective temperature T_{eff} ". Error bars correspond to standard error equal to 1σ.

The estimation of the Sun and solar-type stars magnetic cycles durations.

These properties of the global magnetic activity of the Sun and the exponential dependences of Figures 2, 3 can be understood in the framework of the scheme of generation of magnetic fields: at the bottom of convective zone that are heated plasma with help of photons from radiation zones the giant convection cells are formed.

- The rising element of volume creates a pressure gradient in plasma. The direction depends on the direction of the velocity of an element, the Coriolis acceleration and differential rotation. The pressure gradient will be spread in the spherical shell along the lines of latitudes as Rossby wave.
- The first model with the use of Rossby waves in the theory of hydromagnetic dynamo was proposed by Gillman (1969, Solar Physics; 1994, Ann. Rev. Astron. and Astrophys.) It was analyzed in detail the dynamo action from a typical Rossby wave motion and compares it with the solar cycle. In this model Toroidal fields are dragged up by vertical motions in the Rossby waves to form large-scale vertical fields, whose polarities alternate with longitude roughly like bipolar magnetic regions. Vertical fields of preferentially one polarity are carried toward the pole by the meridional motion in the wave to form an axisymmetric poloidal field. This poloidal field is then stretched out by the differential rotation into a new toroidal field of the opposite sign from the original. The poloidal field changes sign when the toroidal and bipolar regions like fields are maximum, and vice versa

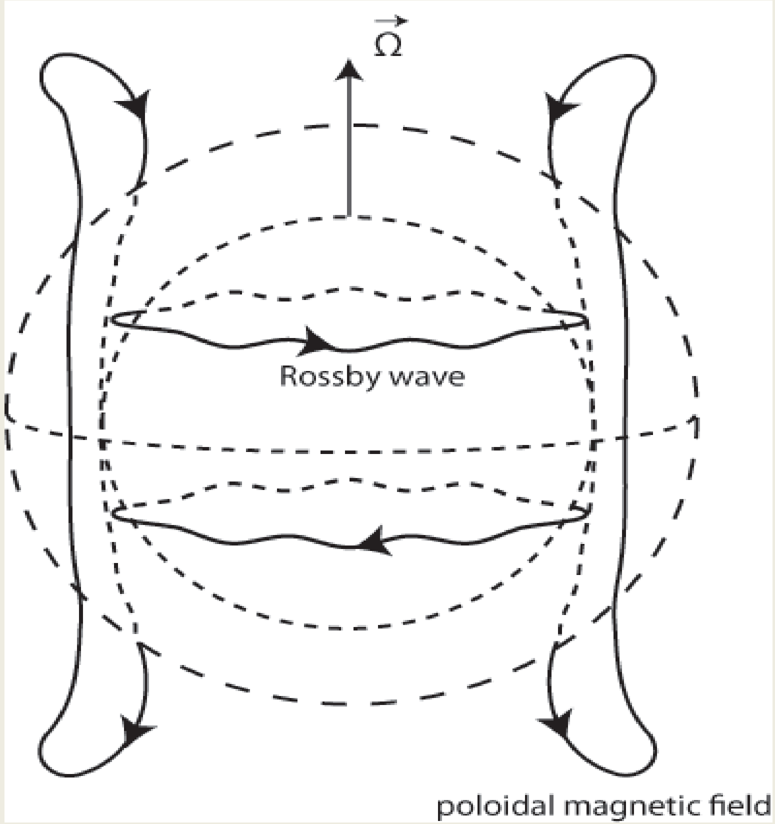

Figure 4. The scheme of the Rossby waves and the poloidal magnetic field

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- On the length of the latitude the whole number of Rossby waves is packed.
- Therefore, the length of these waves should be of the order of $\lambda \approx (1/m)2\pi R_1 cos\varphi$, where φ is the helio-latitude of parallels, $R_l \approx 0{,}7R_{Sun}$ is the radius of the base of the convective envelope, *m* is the integer number of Rossby waves.
- For giant cells which are observed in photosphere the wave number is of order *m=6*.
- At different latitudes the various Rossby waves and different poloidal magnetic fields are generated. The ordered geometric structure of the spicules indicates the regularity of poloidal field.
- Therefore, the lines of force of poloidal fields, created by Rossby waves, must be regular and not be entangled due to the large-scale convection. So the convection around the base of convective envelope must be laminar. The length of the Rossby wave is approximately equal to the thickness of the shell of laminar convection.

The characteristic time t of the convective ascent of the plasma element which is heated by photons from the radiation zone is equal to

$$t \approx \frac{v}{gh\left(\frac{1}{\rho}\frac{\partial\rho}{\partial T}\right)\Delta T} \sim const$$

where ν- is the coefficient of viscosity of the plasma, *g* is the free fall acceleration, *h* is the thickness of the shell of laminar convection

$\left(\frac{1}{\rho}\frac{\partial\rho}{\partial T}\right)$ is coefficient of thermal expansion of the plasma, *ΔT* is the *gradient in the layer.*

The average Archimedean acceleration of a plasma element is approximately equal to $a \approx g\left(\frac{1}{\rho}\frac{\partial\rho}{\partial T}\right)\Delta T$

- Then the average Archimedean speed of a plasma element is $V = at \approx \frac{v}{h}$
- The Coriolis forces turn and stretch the convective cell along a parallel, so that the length of the path of element of the plasma is comparable with the length $l = 2\pi R_I \cos\varphi$
- Average acceleration of the Coriolis force on this parallels is in the order of magnitude is equal to parallels
- The time interval t_g which is necessary for the generation of Rossby waves and poloidal magnetic field is equal to $a_c = 2V\Omega_{Sun}\sin\varphi \approx 2\frac{v}{h}\Omega_{Sun}\sin\varphi$
- where Ω_{Sun} is the angular velocity of rotation of the Sun around the base of convective shell, $R_I \approx 0,7R_{Sun}$.

$$t_g \approx \sqrt{\frac{2l}{a_c}} \approx \sqrt{\frac{\pi R_I \cos\varphi}{\frac{v}{h}\Omega_{sun}\sin\varphi}} \qquad (1)$$

• The time of generation of Rossby waves t_g according (1) depends on the thickness of the layer of laminar convection and plasma viscosity.

• The generation time increases with decreasing of helio-latitude. Therefore, the first waves appear at high latitudes. We'll consider that the poloidal field, connected with Rossby waves have to be the primary for the magnetic activity. **Ω** - effect generates a toroidal field with help of the primary poloidal in average turbulent layer of the convective shell. Magnetic loops of toroidal fields are generated because of the turbulence. Rossby wave compresses these loops and stimulates the formation of spots.

• So Rossby waves lead to the formation of ”active latitudes”.

• Kichadinov (UFN, 2005) showed that meridional fluxes around the base of convective zone are directed from the poles to the equator and they move Rossby waves closer to the equator. The consequence of this will be the slope of the lines of force of poloidal field in the direction to the equator (the axis of symmetry of the field turns). A toroidal field moves too, so in the photosphere there is Spörer's law. The α - effect generates the poloidal field from the toroidal field with the opposite polarity in relation to the primary poloidal field.

The time interval t_g which is necessary for the generation of **Rossby** waves (see formulae (1)) is equal to **2** years approximately when we use the suitable values of the coefficient of

viscosity, $\nu_r \approx 3 \cdot 10^{12} \frac{[cm^2]}{[s]}$ $h \approx \lambda \approx \frac{l}{m} \approx \frac{2\pi R_l \cos\varphi}{m} \approx \frac{1{,}4\pi}{m} P_{Sun} \cos\varphi$

Where **m** (the **Rossby** wave order) is equal to **6**.

According to estimates from Gillman (1969, Solar Physics; 1994, Ann. Rev. Astron. and Astrophys.) the Rossby waves of 6 order (corresponding to convective scales of supergiant cells) period is equal to **2** years.

The evaluations of period of solar magnetic cycle **is too simplified according to formulae (1)** and our estimation is too approximate,
but **we may suppose** that the value of the coefficient of viscosity at the bottom of convective zone is equal to

$$\nu_r \approx (1{,}5 - 2) \cdot 10^{12} \frac{[cm^2]}{[s]}$$

(this value is not impossible, see Krivodubskij (2010, Izvestiya. KrAO)

So we get the period of the **Rossby** waves generation is equal to **8 -10** years.

We estimate the relationship between the duration of the cycle of activity T_{cyc} and the effective temperature of the stars T_{eff}.

The angular velocity of rotation of the star, and its effective temperature are related by the ratio $\Omega \sim T^4_{eff}$, see Figure 1.

In fully ionized hydrogen plasma concentration depends on the temperature

as $n \sim T^{-3/2}$.

Using radiant viscosity (3) $\nu \sim \nu_r \sim T^{-3/2} \sim T_{eff}^{-3/2}$,
from the formula (1) we obtain the following connection between the star's duration of the activity cycle T_{cyc}

and its effective temperature T_{eff}. : $T_{cyc} \approx tg \sim T_{eff}^{-5/4}$ (2)

Thus we show that theoretical dependence of the time of generation of Rossby waves t_g versus T_{eff} (the basic parameter of a star) describes well the connection between the star's duration of the activity cycle T_{cyc} (obtained from observations of solar-type stars and the Sun, see Table) and their T_{eff}.

Conclusions

- Our study of the relationships between the duration of activity cycle and effective temperature for solar-type stars and the Sun show the existence of the power-law dependences: $P_{rot} \sim T_{eff}^{-3,9}$, $T_{11} \sim T_{eff}^{-1,1}$ and $T_2 \sim T_{eff}^{-0,79}$.
- Under the assumption that the time of generation of Rossby waves t_g corresponds to duration of the activity cycle T_{cyc} it was shown that empirical dependences $T_{11} \sim T_{eff}^{-1,1}$ and $T_2 \sim T_{eff}^{-0,79}$ describes well the dependences between the star's duration of the activity cycle T_{cyc} and their T_{eff} estimated by our model .
- Also it was shown that when we use the different estimations of the value of the coefficient of viscosity at the bottom of convective zone of the Sun, the time of generation of Rossby waves t_g corresponds to duration of the activity cycle T_{cyc} may have the duration of **2 – 10** years.
- Thus we emphasized the significant contribution of Rossby waves in formation of magnetic cycles of stars and the Sun.

References

- Gillman P. A. Solar Physics, 1969, Vol. 8, pp. 316 - 330; Ann. Rev. Astron. and Astrophys. 1994, Vol. 12, pp. 47-70.
- Kichadinov L.L. Physics-Uspekhi (Advances in Physical Sciences) (UFN), Vol. 175, N5, 2005, pp. 475-494.
- Baliunas S.L. et al. Astrophys. J, Vol. 438, 1995, pp. 269-280.

Thank You