SOLAR ROTATION AND ACTIVITY IN THE PAST AND THEIR POSSIBLE INFLUENCE UPON THE EVOLUTION OF LIFE*

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Abstract. It is proposed that the rotational angular momentum of the lower Main Sequence stars determines the intensity of their magnetic spot activity. As a consequence of this feedback coupling, the stellar rotation and the activity decay exponentially by magnetic braking of the induced stellar flare- and wind-activity. Therefore, the Sun should have rotated much faster and must have shown a very enhanced activity in its early history. This strong solar activity in the past could have had influenced the evolution of terrestrial life, and may explain the stagnation of maritime life for about 2×10^9 yr, the diversification of species during the Cambrian formation, and the land conquest by life in the upper Silurian system.

1. Stellar Rotation and Activity

There is increasing observational evidence for large-scale magnetic-star spot activity of rapidly rotating stars of the lower Main Sequence. Such stars are exclusively found as *components of close binary systems*, where nearly synchronous rotation of the components with the orbital revolution occurs.

As is well known – and contrary to what is observed for the components of close binary systems – single Main Sequence stars with spectral types later than F5 are generally spinning with low velocities, at least at their surface layers (see, e.g., Brosche, 1962; Kraft, 1969; Smith, 1979). This is especially the case for the Sun, though it may have a hidden fast-spinning core, as was pointed out already by Jeans (1926), and revived by Dicke (1964, 1970a, b). On the other hand, during its pre-Main Sequence evolution, the Sun was nearly convective throughout its interior until it reached the Main Sequence. Due to this deep convection zone equipartition of angular momentum must have taken place. Thus the Sun must have been rotating rigidly during the 'T Tauri'-evolution phase (Fricke and Kippenhahn, 1972).

As was shown from photometric observations within the last 25 years by the author (1975, 1979) the primary component of the eclipsing binary XY UMa, which is a solar-type star, exhibits such enhanced stellar activity. The orbital period of this close double star is only $P_o = 0.479$ day, and the dimensions and mass of its tidally-deformed primary component are also similar to the Sun. There exists a spot cycle of about 3.7 years average length during which the stellar hemisphere pointing towards the terrestrial observer may be covered with up to 20% of subliminous areas of reduced temperature. The mean system brightness shows a standard deviation of ± 0.08 magnitude during the

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time interval covered by observations. This would correspond to an average spot area of about 4% per stellar hemisphere.

The relevant solar activity during 20 cycles of 11.2 years average length since 1755 can be described by a mean solar number $\bar{R} \approx 51 \pm 35$ s.d., which is equivalent to about 0.08% of the solar hemisphere covered with spots.

Due to the tidal-dynamical coupling of the components of XY UMa their angular rotational velocities ω_r will be nearly synchronized with the orbital period amounting to $\omega_r = 1.518 \times 10^{-4}$ rad s^{-1}. This is 52 times that of the Sun which shows an equatorial angular velocity in its surface layers of $\omega_{r\odot} = 2.905 \times 10^{-6}$ rad s^{-1}.

Obviously, the *rotational angular momentum* of a star of the lower Main Sequence *determines its stellar activity.* Thus we can define a *characteristic number* α for such stars later than spectral type F5: It is the ratio of average stellar activity $\bar{A}$ to the angular momentum J as determined from the observable rotational velocity of the stellar surface layers. This characteristic number depends itself on the moment of inertia I of the star. Since for smaller sections of the Main Sequence the stars have a homologous structure and comply with a mass-luminosity relation of the form $LM^{-\beta} = c$, where L is the stellar luminosity and β, c are constants, α depends within certain limits only on the stellar mass M. In this case, and since $J = I\omega_r$; $I = KMR^2$ where K is a constant depending on the stellar model and R the stellar radius, the relation can be written as

$$\bar{A}/\omega_r \approx \alpha(M); \quad \text{or} \quad \frac{\bar{A}}{\alpha(M)\omega_r} = \text{const}; \tag{1}$$

i.e., $\alpha(M)$ is approximately proportional to M^{-1} for stars with homologous structure.

For the Sun and the primary component of XY UMa the empirical value of this ratio is

$$\frac{\alpha_\odot}{\alpha_{XY}} \approx 1.04.$$

Such a relation is conform with the present ideas about the origin of solar/stellar spot activity by the dynamo mechanism (e.g., Parker, 1970, 1977; Stix, 1976) which demands *rotation* and *convection* of the outer layers of the relevant star.

2. Braking of Solar Rotation by Magnetic Activity

As was shown long ago by Lüst and Schlüter (1955) the rotational angular momentum of stars can be removed by their magnetic fields. In the case of the Sun with a general magnetic field of about one gauss its present angular momentum could be lost within a few 10^9 yr.

A very potent mechanism for slowing down at least the surface rotation of lower Main Sequence stars was proposed by Schatzman (1962, 1965) and extended by Mestel (1968) for stellar wind braking: By very small mass loss during flare- or prominence-activity in the strong magnetic fields of stellar spots a large amount of angular momentum can be removed from active stars.

Since there is a *coupling* between *angular momentum* and the *magnetic activity* of a star as was outlined, both have to decay exponentially with time. This means especially, that the Sun must have been spinning much faster and, subsequently, must have shown a much enhanced spot activity at the beginning of its Main Sequence phase about 5×10^9 yr ago.

But why do we still observe fast rotation and strong stellar spot activity on the components of close binary systems of the lower Main Sequence? In this case the loss of rotational angular momentum of the component showing spot activity is replenished from the much larger orbital angular momentum by the tidal feedback mechanism. Therefore, nearly synchronous rotation for the components will be maintained, though relevant consequences for the complex evolution of such binary systems exists: As the case may be the total angular momentum of the system may remain constant or decrease. In the latter case the orbital period decreases too, and the components may even come into contact (Huang, 1966). But since the ratio of orbital to rotational angular momentum in close binary systems is $\geqslant 50$, the relevant effect for the change of the orbital period cannot be very large. Actually XY UMa showed a constant period in the last 50 yr (Geyer, 1977).

For getting some ideas about the solar rotation and activity in the past we make the following assumption:

(1) The relation (1) is valid for the Sun for its photospheric layers which rotate differentially at present according to the law

$$\omega_{\odot}(B) = 2.905 \times 10^{-6}(1 - 0.193 \sin^2 B), \text{ in rad s}^{-1}, \tag{2}$$

where B is the heliographic latitude.

(2) The loss of rotational angular momentum by prominences and flares takes place in the same heliographic latitude range $5^\circ \leqslant |B| \leqslant 40^\circ$ where also the maximum of its spot activity occurs. By this way also the differential rotation could be kept alive.

(3) The mass loss of the Sun did not exceed a few per cent of its present mass, and its radius was constant during 5×10^9 yr. Therefore, its moment of inertia was practically constant during this time interval.

With these assumptions the change of rotational angular momentum with time is given according to Equation (1) by

$$-\frac{\mathrm{d}J}{\mathrm{d}t} = A(\omega) = \alpha\omega. \tag{3}$$

Since

$$\frac{\mathrm{d}J}{\mathrm{d}t} = I\frac{\mathrm{d}\omega}{\mathrm{d}t} + \omega\frac{\mathrm{d}I}{\mathrm{d}t}; \quad \text{and} \quad \frac{\mathrm{d}I}{\mathrm{d}t} \equiv 0$$

we obtain

$$-I\frac{\mathrm{d}\omega}{\mathrm{d}t} = \alpha\omega, \tag{4}$$

which admit of the solution

$$\omega(t) = \omega(0)\exp(-\lambda t), \tag{5}$$

with $\alpha/I = \lambda$, and $\omega(0)$ the angular velocity at the beginning of the Sun's Main Sequence phase.

As previously mentioned the angular velocity and the activity decay exponentially with a mean lifetime of $\tau = 1/\lambda$.

To obtain an approximate value for the initial solar angular velocity $\omega(0)$, we make use of the enigmatic phenomenon of the present solar system: namely, that 99.4% of its total angular momentum is in the orbital motion of the planets, though they contribute only 0.14% to the total mass. This picture would not be altered if the Sun has a faster-spinning core. We can now argue as follows: Suppose the Sun would have reached the Main Sequence as a rigid rotator. The maximum angular velocity which it could have attained is that of the critical angular velocity where centripetal- and gravitational-forces balance: i.e.,

$$\omega_{\text{crit}}^2 = GMR^{-3}.$$

The relevant critical angular momentum is then given by

$$J_{\text{crit}} = KG^{1/2}M^{3/2}R^{1/2},$$

which we now can identify as the total angular momentum of the solar system at its forming phase. Out of this amount most of it went into the orbital angular momentum J_{or} of the planets and the rest

$$\Delta J = J_{\text{crit}} - J_{\text{or}}$$

was at utmost available for the real Sun. From the present data about the solar system we find $\Delta J/J_{\text{crit}} \approx 11.6\%$ with $J_{\text{or}} \approx 3.142 \times 10^{50}\ \text{g cm}^2\ \text{s}^{-1}$. Therefore we may adopt for $\omega(0) = \Delta J/I = 7.245 \times 10^{-5}\ \text{rad s}^{-1}$, and together with the present angular velocity of the Sun we find $\lambda = 6.43 \times 10^{-10}\ \text{yr}^{-1}$ and $\tau = 1.55 \times 10^9$ yr.

In Figure 1 and Table I the presumable history of the solar rotation and activity are given according to these numerical values and Equation (5).

3. Implications for the Evolution of Life

Beside the dynamical influence of a faster spinning Sun with a relevant oblateness of the solar body onto the orbital motion of the inner planets, the much enhanced sunspot activity in the early history of the solar system certainly must have influenced the evolution of life on the Earth. On account of the much stronger solar particle- and extreme ultraviolet (EUV) radiation during pronounced activities, not only the terrestrial magnetic field was strongly disturbed and reduced, but also the original reducing atmosphere must have been influenced by nuclear processes much more strongly than nowadays. Actually there are at least three palaeozoic phases which appear enigmatic:

The first one is the archaeozoic-proterozoic period, lasting about 2×10^9 yr, during

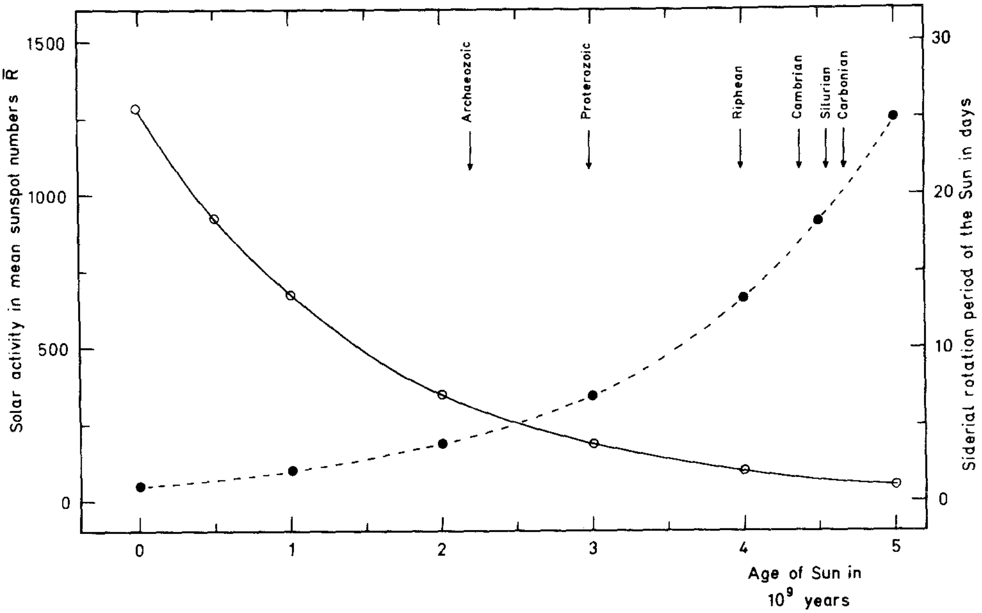

Fig. 1. The presumable increase of the solar rotation (dotted line, right hand ordinate) and the decay of the average solar activity during the Sun's Main Sequence phase. Some essential palaeozoic epochs are marked by arrows.

TABLE I

Presumable history of solar surface rotation and activity since the begin of its Main Sequences phase

Age (10^9 yr)	Angular vel. ω_r (rad s^{-1})	Sid. rot. period P (days)	Spot area $\bar{A}$ (%)	Sunspot No. $\bar{R}$	Remarks
0.00	7.25×10^{-5}	1.0	2.13	1275	Sun on the Main Sequence
2.00	2.00×10^{-5}	3.6	0.60	350	First traces of terrestrial life; begin of atmospheric transformation from a reducing to an oxidizing
4.40	4.28×10^{-6}	17.0	0.13	75	Cambrian diversification of maritime life.
4.55	3.88×10^{-6}	18.7	0.11	68	Begin of land conquest by plants in upper Silurian system.
4.65	3.64×10^{-6}	20.0	0.10	64	Carboniferous phase of land life.
5.00	2.91×10^{-6}	25.03	0.08	51 ± 35 s.d.	Present

which an obvious stagnation in the evolution to higher organized life took place.

The second one is mainly the Cambrian phase where a more or less sudden diversification of the maritime primitive life to highly organized species occurred, though metazoan biota can be traced back far into the riphean period (see, e.g. Durham, 1978).

Finally, the third decisive phase was the conquest of land by the life in upper Silurian and lower Devonian times.

After life has formed about 3.2×10^9 yr ago in aquatic medium it was of course well protected against EUV-radiation in the water, though the original terrestrial atmosphere was a reducing one. Therefore, no ozoniferous atmospheric layers did exist and the EUV-radiation could penetrate to the ground. Yet the main problem for early life was certainly the much higher production of carbon 14 and tritium by the solar component of cosmic radiation according to the well-known neutron reaction with atmospheric nitrogen, represented by the relations

$$N^{14} + n \rightarrow C^{14} + H^1 ; \qquad N^{14} + n \rightarrow C^{12} + H^3 \rightarrow He^3 .$$

Though the mutation rate was also much enhanced by this way, early life had to *combat* against *too much radioactive carbon* and *water* in its cellular tissues in a radioactive surrounding. This must have restricted the organisms to uniformity, and forced them not to exceed a certain maximum size, as is observed in the proterozoic times.

At the beginning of the Cambrian system, when the transmutation of the terrestrial atmosphere from a reducing to an oxidizing one was nearly completed, the solar activity had dropped to about 50% above the present value. Therefore, the C^{14} and H^3 restriction onto life were much relaxed, and due to the still high mutation rate the diversification of the maritime species could take place.

Finally in the Silurian period only 150 million years later the sunspot activity was only $\frac{1}{3}$ higher than nowadays, and also the ozone layers in the upper atmosphere were fully developed; so that the organisms could leave the protecting water with impunity and conquer the land.

The presented views for an about ten times higher average solar activity at the original phase of life can be reconciled with the findings about the ancient solar particle wind traced in lunar soil and rocks (e.g., Geiss, 1980). For example, the isotopic ratio of He^4/He^3 is higher in lunar soil probes in comparison to the Apollo solar wind sail experiments. On the other hand, terrestrial water enclosures or crystalline water of archaeozoic sediments and minerals or also proterozoic organic minerals like Shungit should show a smaller He^4/He^3 ratio on account of the atmospheric He^3 enrichment in early times.

Furthermore, the lunar palaeomagnetism which was discovered in Apollo 11 lavas, and which must have existed at least for about 4×10^9 yr, is also very much in favour of enhanced solar wind activity in the far past (Runcorn, 1978).

Finally recent EUV-observations of XY UMa with the International Ultraviolet Explorer show very strong chromospheric ultraviolet line- and continuum-emissions whenever larger spotted areas of the stellar sphere are pointing towards the observer (Geyer, 1980). Similar effects, though less prominent, are also known for the spot-active Sun.

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