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ON THE MAGNETOHYDRODYNAMICS MECHANISM
OF SOLAR ACTIVITY

by

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SUMMARY

The author shows how the differential rotation could be sustained by coupling, at resonance, an oscillation of the photosphere with the rotation period using the effect of planetary tides, and how the latter modulate the activity within the 11-year period. He shows also how the toroidal field is concentrated and expulsed from the photosphere by vortices due to the Coriolis forces, and how, finally, this field is sustained by the disruptive discharges constituting the granulation.

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According to accretion theories, all celestial bodies should be strongly magnetic, since the interstellar medium includes weak and frozen-in fields. But the stellar magnetism is far from constituting a rule and is, to the contrary, an exception. We should like to show that this magnetism, as well as the differential rotation, of which it is inseparable, are very superficial phenomena due to an external cause, say, the tides exerted by the planets in the case of the Sun and the companions in the case of magnetic stars.

1. The Differential Rotation. According to theories of relationship, the Sun had, after the placement of planets in orbits, a very strong differential rotation, since, indeed, it passed from the ellipsoidal to the spherical shape, of which a feeble reminder still subsists. The current theories of solar magnetism wish to find in this mechanical energy the source of magnetism. However, Babcock [1], estimating it at $6 \cdot 10^{38}$ ergs, acknowledges that

it could not assure this magnetism for a period in excess of a few millenia. If, as will be shown below, this source ought to be even ascribed not to the rotation, but to radiation, the frictions would have hardly permitted its persistance for $4 \cdot 10^9$ years. Thus it requires a sustaining mechanism. Though very weak, the tides, exerted upon the Sun by the planets, could have prolonged a feeble residual rotation to our contemporary epoch.

While the Moon to Earth ratio is $^1/_{81}$ that of planets to Sun is only $^1/_{743}$. But, while the lunar action imparts to the center of gravity of the system Earth-Moon the description of a circumference, of 0.73 R_E radius, included in our Globe, the only action of Jupiter makes the center of gravity of the System Sun-Jupiter describe a circumference of a radius already exceeding that of the Sun. Jupiter and Saturn are in conjunction every 20 years, periodically extending that distance to nearly two solar radii. The curve described by the point of that solar system's center of gravity, was traced by C. H. Cleminshaw [2]: It is a loop, of which the period is about 22 years, Uranus and Neptune having mostly for effect a shift the elongation maximum by a few years. During the activity maximum of 1957, the lag was of two years. The current maximum (1968) lags by 3 years. In calculating this curve for the preceding century it would be interesting to find out, whether or not this curve accounts for the inequalities of the 11-year period (8 to 17 years, according to Turner's rule).

The average tide exerted by the Sun on the Earth, corresponds to energy expenditure of $1.4 \cdot 10^{19}/3$ ergs/s. The mass of the Earth being $3 \cdot 10^5$ times smaller than that of the Sun and the sum of tide actions $\sum(m/a^3)$ being for the seven other planets 5.5 times greater, planetary tides exerted upon the Sun could not exceed 10^{14} ergs/sec. But, instead of affecting a thickness of 3km of ocean water, they are being exerted upon a light and mobile gas (H + He), which is rarefied, at high temperature, and they can affect several million kilometers of the photosphere. We shall see that the thickness of the latter, in state of differential rotation, is of the order of 5000 km. With an average density of $2 \cdot 10^{-5}$ g/cm^3, its mass is $6 \cdot 10^{26}$ g and its kinetic energy is of 10^{36} ergs for a 0.5 km/sec velocity excess.

The effect of planetary tides is to make the solar atmosphere oscillate with a period of 33/2 days, in resonance with the internal rotation period of 33 days. The slightest friction retarding the "cotidal" ellipsoid will produce an equatorial acceleration adding up to the differential rotation. This is an effect analogous to the one foreseen by E. Holmberg [3] for producing a differential rotation of the terrestrial atmosphere by the resonant gravitational and thermal oscillation of solar tides. But, while this effect is considerable in the case of Venus [4], it remains very feeble in the case of the Sun.

This permanent tide is modulated with an 11-year period by the action of planetary revolutions. It must therefore be manifest in a superficial solar oscillation of same period. Now, the homogenous measurements of the equatorial and polar diameters performed by Monte Mario between 1870 and 1937, have indicated to M. Cimino [5] an oscillation of 22 years with ±0.2" amplitude, the Sun passing through the spherical shape during the periods of activity maximum. An 11-year solar diameter variation was also recognized by B. Meyermann [6], while other authors failed to confirm it.

This very feeble planetary tide action would be incapable of engendering itself a differential rotation, or even of compensating entirely the slowing up. It could only have prolonged it till our contemporary times before its total disappearance. Then the Sun should no longer show any activity. It has, however, been proved by the fact that the equatorial velocity of the Sun varies with the 11-year cycle. This is the way the spectroscopic measurements made at Mount-Wilson of the lines of the reversing layer have shown an equatorial velocity of 2.06 km/sec in 1906-1908, epoch of activity maximum, and of 1.90 km/sec in 1919-1924, epoch of activity minimum. We therefore have to do with a major effect, reaching 8 percent.

2. Solar Magnetism. All the magnetohydrodynamic theories proposed for the interpretation of solar magnetism since the works by G. Gouy (1912) and Sir J. Larmor (1919) had involved a hypothetical internal field, assumed at times to be very intense. However, H. Lamb [7] had shown as early as in 1883, how the celestial bodies behaved, on account of their dimension, as media of quasi-infinite conduction, in which the magnetic field lines remained fixed.

The duration of such a field persistance in a sphere of radius R, of permeability μ and of conductivity σ, for an intensity reduction equal to 1/e, that is, 37 percent, would be equal to $4\mu\sigma R^2/\pi$. If we postulate $\mu = 1$, $\sigma = 10^{-5}$ (*), $R = 7.10^{10}$ cm, this duration would attain $2 \cdot 10^9$ years. Thus, the Sun's interior behaves as if it were magnetically empty, and this is due to the presence under the photosphere of a convective gas layer impenetrable to the lines of force. However, the only thing to be retained from C. Walén works [8], is that gas currents can induce a toroidal field, capable of emerging locally and producing bipolar spots satisfying the Hale law. It was shown by T. G. Gowling [9], that this result could be simply realized by the differential rotation. Interpreting the magnetograph data of W. H. Babcock and H. D. Babcock of Mount-Wilson [10], the first author proposed an attractive theory of solar activity, in which the field, always remaining superficial, is transformed from poloidal to toroidal and then into spot fields that disperse into chromospheric and coronal archs and irregular plages, restoring every 11 years a new poloidal field of opposite direction. Nevertheless, the magnetic energy is borrowed from the mechanical energy of the differential rotation, and we have shown above that it could not be so. Thus, we must search for mechanisms assuring field regeneration, making it emerge from the photosphere and concentrating a weak poloidal field of the order of the unity into a spot field capable of attaining up to 4500 gauss. This amplification will take place in three stages.

1. The equatorial differential rotation allows it to make up for some 20 rounds per 11-year cycle, that is, an initial polar field of one unity may engender in each hemisphere a toroidal field of 20 gauss, both field being opposed.

2. The pull of the cotidal wave into tune on the rotating Sun will induce at middle latitudes very flat superficial vortices due to Coriolis forces. These vortices, called upon as early as of 1865 by H. Faye, appear to be the only ones capable of concentrating the toroidal field up to some hundred units and make it emerge at the photosphere level. The magnetic field symmetry of a spot is that of such a vortex. Their gyratory direction will be immaterial. They will be concealed by the Evershed effect and will not carry the granulation, which has the character of a quasi-instantaneous disruptive discharge.

(*) [the French abbreviation's "u. é. m."English equivalent could not be determined]

When the emergent field becomes intense enough to set the granulation aside, they will be able to give rise by its magnetic pressure to either the guiding or the guided spot.

3. But, in order to give rise to spot fields of several million units, it is necessary to resort to a fundamental phenomenon, capable of inducing the magnetic energy at the expense of radiation. Faye believed the photosphere to be in a convective state. Yet this state requires a partially ionized gas. The atomic hydrogen is neutral in the photosphere and its ionization is completely achieved only at its base, say, at several thousand kilometers, where the temperature exceeds 20,000° K. The convective sheet exists only between the levels of ionization of atomic hydrogen (13.5 ev) and of helium (24.5 ev). In other words, the photosphere of neutral hydrogen and helium appears to be the dielectric of a spherical condenser (analogous to the Earth's troposphere) of minimum conductivity, at the base of which prevails a high electronic pressure.

We have suggested in 1932 [11] that the granulation represents a disruptive discharge in the form of fugacious arcs across the photosphere, whose thickness would be measured by the length of filaments seen lying in the penumbra, say, some 5000 km as an average. The best Janssen and P. Chevalier's negatives show at times granules provided with a long root, widening at the surface by decomposition into bulbs with a shape of tulips. These unstable arcs are indeed quenched at once by magnetic pinching. These are generators of electric current at the expense of thermal energy, as, for example, the G. Medicus' and G. Wehner's arc.[12]. These authors had obtained a direct current of 0.5 a under an electromotive force of 0.8 v with 0.3% efficiency starting from the heat consumed to heat up a cathode covered by barium in a rarefied atmosphere of xenon.

The P. Willard's works [13] have shown as early as in 1906 how light or (*) a positive column was a plasma having the properties of the arc, that is, those of an elastic conductor, which is flexible and extensible, capable of vibrating and winding up in a transverse magnetic field by amplifying the exciting field. Each of the equatorial granulation filaments is wrapped up in the transverse toroidal field and gives rise to a local field, which is

(*) [This sentence is confused and hardly intelligible in the original text] proportional to its intensity and remains fixed in the gaseous current. A field of 3000 gauss intensity is produced by a filament, run through by a current of 10^{12} a and wound up pursuant to a 2000 km curvature radius. The number of granules in the period of activity maximum being $4 \cdot 10^6$, the electronic emission of the Sun attains $4 \cdot 10^{18}$ a, which yields a density of 10^7 thermal electrons per cm^3 at the base of the corona. This emission supplies for its heating and the Roentgen emission $10^7 \times 6 \cdot 10^7 \times 1.6 \cdot 10^{-12}$, say, 10^3 ergs$\cdot cm^{-2} \cdot s^{-1}$/ev. It is necessarily neutralized by an expulsion of slow protons constituting the equatorial solar wind which would attain $7 \cdot 10^{13}$ g/s. These values are in sensible agreement with the experimental data.

Should the activity become very strong, spot pairs, disposed on either side of the equator at the same longitude, could split, on account of locally increased electronic pressure and by their magnetic junction, the two toroidal fields into unstable bipolar equatorial fields, capable of triggering solar outbursts [14].

This is how the thermal energy of the Sun can give rise to electric energy, transforming itself into magnetic energy recurring constantly. The Medicus' and Wehner's experiments, just as those of Villard, are of paramount importance for the understanding of solar activity.

As of 1932, we had shown [32] that the corona necessarily represented that Sun's electronic emission, rendered visible by the photospheric light it diffuses. If, indeed, one wished to consider it as a plasma, the preceding expression $4\mu\sigma R^2/\pi$ with R equal to 10 solar radii, would imply that it could not be deformed in less than 10^{11} years, while in reality it changes from day to day. The fact is that it is run through by electronic jets in a time of the order of the minute, these electronic jets extending by the zodiacal light beyond the orbit of Mars.

This very simple solar activity mechanism, which rests only on well known facts, could not, however, be extended to Babcock's magnetic stars. The latter are very likely subject to much more powerful tide effects by known or unknown companions, and their rotation velocity is much higher. But they have a surface temperature of at least 10^4 °K, for which the superficial hydrogen is highly ionized. The internal convective state extends to the surface and these stars could have neither photosphere nor granulation.

This is how Sirius A, of type A0, actually has a companion exerting strong tides, but its temperature reaches 10^4°K and it is effectively not magnetic. The intense fields of magnetic stars remain external with respect to the convective sheet at chromosphere level, where the magnetic pressure $H^2/8\pi$ balances the gaseous pressure, and they are engendered by an entirely different mechanism from that suggested to us by the Sun.

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