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ORIGIN OF THE AXIAL ROTATION OF THE SUN

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Abstract

In earlier papers the solar atmosphere has been shown to rotate rapidly as a result of the electric and magnetic forces which act on the atmospheric ions. At the equator the ionized layers move much faster than the solar surface proper but this relative movement decreases with latitude in the manner required by observation. The fast moving atmospheric layers transfer momentum to the sun proper and its rotation is a necessary consequence of the observed atmospheric motions. The resultant torque is calculated and the angular acceleration shown to be adequate to account for the observed rotation.

THE almost universal prevalence of rapid rotation in celestial objects has been pointed out again and again by astronomers, but the origin of such rotation has been somewhat of a mystery. Celestial mechanics shows how a star may rotate faster and faster as it contracts due to condensation, but gives no clue as to the origin of the initial rotation, which must be comparable to the final value. In an important paper Jeans[1] discussed the relation of the radiation of matter to the rotation of a star and he concluded that the radiation of the star carries off angular momentum in such a way that it "generally lessens the angular momentum per unit mass of the star." He thus pointed out that the common assumption of a constant angular momentum for a radiating star is invalid. We must, therefore, for the most part, attribute the observed high rotational velocities to changes in the mean density together with an initial rotation of the star or else to some phenomena not adequately described by celestial mechanics.

In a series of papers which deal with the electromagnetic effects operating in the solar atmosphere, it has been shown[2] that the anomalies of the sun's apparent rotation arise from an electromagnetic drift of the ionized atmosphere and are not directly dependent on the motion of the surface of the sun proper. It was shown that the solar atmosphere rotates in the same direction as the sun proper but *much faster* and that this superposed drift results from the interaction of the atmospheric ions with the observed solar magnetic field and a radial electric field.

The sun may be thought of as a highly viscous mass of gas bound together by gravitational, radiative and electromagnetic forces in such a manner as to form a semi-rigid system. Radiative viscosity acts in such a manner as to equalize differences of rotation in different layers but Jeans[1] calculations indicate that these forces alone are incapable of equalizing the rotations in a time

[1] Jeans, Monthly Notices R. A. S. **86**, 328, 444 (1926).

[2] Gunn, Phys. Rev. **35**, 635 (1930); **36**, 1251 (1930).

so short as the age of the sun. The sun's observed magnetic field is asymmetric with respect to the axis of rotation and hence shells of highly conducting solar matter rotating about the geographical axis will induce electromotive forces and systems of electrical eddy currents which will strongly oppose motion relative to the magnetic field. A quantitative calculation of the electromagnetic damping forces due to axial slippage is difficult but we have seen that in regions of high electrical conductivity the forces due to radial contraction are tremendous[3] and it seems probable that electrical forces contribute in an important manner to the apparent viscosity of the sun. To be sure that these forces have time to act we must examine whether the electrical time constant of the induced current circuit is sufficiently short compared to the solar age for current systems to build up. It is convenient to note that the largest time constant τ possible is the constant for the whole sun which is given by $\tau = L\Sigma$ where L is the effective inductance and Σ is the total conductivity. On making this calculation it results that τ is of the order of 10^9 years. This is very small compared to the age of the sun and we assume that inductive effects are unimportant.

On account of the high effective viscosity of the interior it seems satisfactory to assume as a first approximation that the sun is a semi-rigid body rotating on its axis at a period corresponding to the observed period of rotation of its magnetic pole. With the solar radius known it is evident that the peripheral velocity of any point on the solar surface proper can be calculated. The difference between this velocity and the velocity of the same point as determined by an earth-bound observer watching the solar atmosphere is evidently the atmospheric drift velocity. This superposed drift velocity $\boldsymbol{U}$ of the ionized atmosphere is readily determined from observation or can be calculated from[2]

$$\boldsymbol{u} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2\left(1 + \left(\frac{R}{\lambda}\right)^2\right)} \tag{1}$$

where E and B are the electric and magnetic field intensities, λ the mean free path of the ions, and R the radius of the helix generated by an ion as it spirals around the impressed magnetic field. This radius is calculated from

$$R = \frac{mV}{Be} = \frac{(2mkT)^{1/2}}{Be} \tag{2}$$

where m is the mass of the ion, V the component of velocity perpendicular to B and e the ionic charge.

It is clear from Eq. (1) that the drift motion of the atmosphere drops abruptly as the ion pressure increases to such a value that the free path becomes of the order of R. Thus a more or less sharply defined transition layer exists between the atmosphere and the solar surface proper. In this critical transition region between the sun and its atmosphere there is a constant

[3] Gunn, Phys. Rev. **35**, 107 (1930).

interchange of momentum, and the faster moving layers transfer their momentum to the slower. At the surface of the sun the temperature is low and the radiative and electromagnetic viscosities are small compared to the molecular viscosity, so that we need only consider the forces due to the latter. The tangential force applied to the periphery of the sun by the more rapidly rotating atmosphere is

$$F = \eta u \frac{A}{S} \tag{3}$$

where η is the mean coefficient of viscosity of the transition layer, u the mean difference in velocity of the layers, A the effective area in contact and S their separation. To a sufficient approximation we may assume that in the transition layer the coefficient of viscosity is independent of the magnetic field and write

$$\eta = \frac{(3ZmkT)^{1/2}}{2(2)^{1/2}\pi\sigma^2} \tag{4}$$

where m is the mass of the hydrogen atom, Z the mean atomic weight of the ions composing the layer, k the Boltzmann constant, T the absolute temperature, and σ the kinetic theory diameter of the ions. To a sufficient approximation we may assume that the effective contact area A is a ring around the equator of width R where R is the radius of the sun and that the mean velocity difference is not appreciably different from the equatorial value. The torque Q applied to the solar mass is

$$Q = I\alpha = \frac{(3ZmkT)^{1/2}}{(2)^{1/2}\sigma^2} \frac{u}{S} R^3 \tag{5}$$

where I is the effective moment of inertia and α is the angular acceleration. Assuming that the solar density is uniform we get from Eq. (5)

$$\alpha = \frac{5(3ZmkT)^{1/2}}{2(2)^{1/2}\sigma^2} \frac{uR}{SM} \tag{6}$$

where M is the mass of the sun. Taking from earlier work $Z = 3.3$, $m = 1.66 \times 10^{-24}$ gm, $k = 1.37 \times 10^{-16}$, $T = 6{,}000$, $\sigma = 10^{-8}$ cm, $R = 7 \times 10^{10}$ cm, $M = 2 \times 10^{33}$ gm, $u = 5 \times 10^{4}$ cm/sec and $S = 5 \times 10^{6}$ cm we find $\alpha = 2.3 \times 10^{-26}$ rad/sec.^{2}

We have seen in an earlier paper[4] that the solar magnetic field is maintained by a system of electrical currents which flow in rings about the sun's axis and that this system of currents is not primarily related to the rotation, but to the sun's radial and axial symmetry. This circumstance suggests that the magnetic field and hence motions of the solar atmosphere have not changed in order of magnitude for a considerable portion of the sun's life, which various estimates put at 7×10^{12} years or 2×10^{20} seconds. By multiply-

[4] Gunn, Phys. Rev. **34**, 335, 1621 (1929).

ing the angular acceleration α by the life time we find to a crude approximation that the final angular velocity of the sun should be 4.6×10^{-6} radians per second, if its initial rotation was negligibly small. The observed angular velocity, as computed from the motion of the magnetic pole is 2.3×10^{-6} radians per second. The agreement is rather better than one might expect from a calculation based on steady states.

Were allowance made for the increased radiation during the youthful period and a smaller moment of inertia used, due to the concentration of mass toward the center, then the elapsed time necessary to account for the observed rotation would be considerably reduced. This suggests that in the earlier stages of development the sun was unmagnetized and was a typical pulsating star.[3] It is clear that the solar rotation can be accounted for by the mechanical drag of the solar atmosphere on the sun proper if the velocity of the atmosphere exceeds that at the surface by 0.5 km/sec. This is the precise value required to explain the anomalous rotation of the sun; this having been adequately accounted for in an earlier paper by the author. The mechanism of rotation which we have considered doubtless has universal application in all stars having a magnetic field. It seems probable that this mechanism, which constantly supplies angular momentum to stellar systems, may assist in explaining certain puzzling facts in connection with spiral nebulae and binary systems. Numerical application to other star systems seems meaningless at the present time due to lack of data, and we can only point out that most other stars will behave like the sun. Ordinary mechanics has been found inadequate to explain the rapid rotation of heavenly bodies. The present investigation shows that the rotations can be accounted for by the momentum transferred to the body proper by its own highly ionized atmosphere. We have shown previously that the motion of the solar atmosphere is controlled by the magnetic and electric fields existing in the atmospheric layers and that these fields are probably controlled by the rate of radiation of matter. We may then conclude that the rotation of all heavenly bodies is intimately related to the dissolution of matter and in a static, non-radiating universe rotating systems would not exist.