THE STABILITY OF THE ATMOSPHERE OF A ROTATING STAR

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Abstract

It is shown that electromagnetic forces acting on the gaseous ions of a rotating magnetized star can account for its atmospheric stability even when the star proper approaches a condition of rotational instability. Milne's theory of the chromospheric stability is shown to be inconsistent with observation if electromagnetic forces are taken into account. Because the ions are entrapped by the magnetic field the loss of atmosphere by a rapidly rotating star is small and therefore its angular velocity may increase until rotational instability of the entire mass sets in. The considerations of the paper lend considerable theoretical support to the fission theory of multiple stars.

DUE to the opacity of the sun's atmosphere observations thereof are necessarily confined to a relatively thin superficial layer. In this layer the material is highly ionized and the pressure so low that all the ions describe long free paths. The outer layers of this ionized region cannot be in gravitational equilibrium with a supporting gaseous pressure, for eclipse spectra show that surprisingly large amounts of calcium and hydrogen exist several thousands of kilometers above the photosphere. The forces responsible for this departure from the expected equilibrium distribution have not been understood although it has been long recognized that an acceptable mechanism must account for the observed fact that stars which rotate on their axes so fast that their equatorial acceleration approaches zero, do not perceptibly lose their atmospheres. The fission theory of binary stars seems entirely too well founded on observation to deny that rotational break up does not take place, and indeed, Struve[1] has shown that many stars are in a condition of rotation favorable to a shedding of their atmospheric material if an outward supporting force, such as has hitherto been assumed, actually exists.

Effect of a Magnetic Field

The sun is known to possess a general magnetic field which we have shown to have an important influence on solar atmospheric motions. It seems probable that most dwarf stars possess magnetic and electric fields not unlike that of the sun[2] and that theories of electromagnetic solar effects and mechanisms will have direct application to the general case of a rotating star. The magnitude and distribution of the solar magnetic fields are known from direct observation[3] so that the magnetic force on an ion moving as a result of a ther-

[1] O. Struve, Astrophys. J. **72**, 1 (1930); **73**, 94 (1931).

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

[3] Hale, Astrophys. J. **38**, 31 (1913); Hale, Sears, Van Maanen and Ellerman, Astrophys. J. **47**, 1 (1918).

mal collision is readily calculable. The magnetic forces are, in general, much larger than gravitational forces and therefore might be expected to determine the stability and motions of the ions that constitute the solar atmosphere.

Page[4] and others have shown that a constant force F acting on ions carrying a charge e immersed in a magnetic field of strength B and executing long free paths *does not cause the ions to move in the direction of the impressed force* but gives rise to a motion with constant velocity $\boldsymbol{u}$ specified by

$$\boldsymbol{u} = \boldsymbol{F} \times \boldsymbol{B}/eB^2 \quad (1)$$

where e and B are in e.m.u. This modifies in an important manner earlier conclusions in regard to the stability of the solar atmosphere. At the solar equator B is northerly and tangential to the surface and any radial force which might arise from gravitational, electric or radiation effects, does not produce a radial motion but superposes a uniform velocity on the ions toward the east or west. We have seen that an electrical force on the ions combined with the known magnetic field will account for the anomalous rotation of the sun[5] if the ions describe mean free paths longer than the radius r of the helix generated by the moving ions. This radius is defined by

$$r = mv/Be = (2mkT)^{1/2}/Be \quad (2)$$

where mv is the ionic momentum in a plane perpendicular to the magnetic field B, e the ionic charge, k the Boltzmann constant and T the absolute temperature. The free paths of the ions are all greater than r at all observable levels of the reversing layer and chromosphere but as B decreases to very small values at the outer boundary of the chromosphere, r probably becomes very large and comparable to the total depth of the chromosphere. In such a circumstance we might expect electromagnetic effects to be unimportant in coronal regions although sufficient data are not yet available to make a definite decision. Except for this outer region of the sun's atmosphere the mean free path is larger than r defined by Eq. (2), and therefore electromagnetic forces and interactions play an important part in determining its equilibrium.

Stability of the Chromosphere

Milne has constructed a theory of the chromospheric stability[6] which depends on the selective absorption of light, emitted at the photosphere, by the ions of the chromosphere. In order to attain even approximate stability and prevent the chromospheric material from being blown completely away by radiation pressure it was necessary for Milne to assume, further, that the motion of the ions away from the sun produced a Doppler displacement of the absorption line and thus modified the incident force. This subsidiary assumption appears to be fatal to Milne's theory, for we have seen that at the equator an outward force does not result in an outward motion of the ion but will produce a tangential drift of the positive ions. Thus the radiation pressure cannot be modified appreciably by Doppler effects and if it actually

[4] Page, Phys. Rev. **33,** 553 (1929).
[5] R. Gunn, Phys. Rev. **35,** 635 (1930); **37,** 1129 (1931).
[6] E. A. Milne, Monthly Notices **84,** 354 (1924).

exists it should produce a *westward* drift of the chromosphere which is not observed. There appears to be no way by which a radiation pressure theory can be brought into agreement with observation when the magnetic forces on an ion are taken into account, and thus Milne's theory could be valid only if there is no magnetic field in the chromosphere. Several lines of evidence show that an appreciable chromospheric magnetic field exists and indeed its value, near the base of the layer, has been measured.[3]

In earlier papers it was shown that the anomalous eastward motion of the solar reversing layer and chromosphere arose from the interaction of ions with the solar electric and magnetic fields. The mechanism is such, that although the electrical force on a positive ion is vertically downward and hence in the direction of the gravitational acceleration, the ions move, not downward, but to the eastward with a definite velocity and are thus "supported." The support of the material evidently depends on its being ionized most of the time and this accounts for the predominance in the chromosphere of spectra arising from ions as well as from the next lower state of excitation, for a captured neutralizing electron does not necessarily occupy the lowest orbit initially but may move down in steps and emit the radiation characteristic of a neutral atom. Ions having high recombination coefficients and high ionizing potentials would be expected to remain neutral most of the time and would therefore be caused to diffuse to lower levels by gravitational forces. If the higher levels are constantly replenished by neutral atoms shot undeviated by the magnetic field to high levels by thermal effects and there become ionized, then, after equilibrium is established, the elements of the solar atmosphere should be arranged into more or less definite layers according to their mass and the fraction of the total time the atoms spend in an ionized condition. The ions having a low recombination coefficient and a low ionizing potential should be found highest in the atmosphere while ions with large coefficients and high ionizing potential will sink deep in the reversing layer or photosphere. The combination of a moderately low ionizing potential coupled with slow recombination is believed to account for the presence of large amounts of calcium and hydrogen in the chromosphere. A suggestion that the ionizing potentials of the elements bears some definite relation to the position of the element in the sun's atmosphere has been made by Nicholson and Perrakis[7] who have pointed out that almost all the elements absent from the solar spectrum have high ionization potentials.

In polar regions the magnetic and gravitational fields are parallel, so that support of the type we have considered above is probably not important and the polar distribution of material in the chromosphere might be expected to differ from that at lower latitudes. A complication enters, however, for unionized matter shot to high levels by thermal processes in lower latitudes becomes ionized and will diffuse along the magnetic field and hence set up an atmospheric circulation toward both poles. The transport of material to the poles and its deposition there at high levels appears to make a prediction of the expected change in distribution quite impossible.

[7] Nicholson and Perrakis, Comptes Rendus **186**, 492 (1928).

Loss of Stellar Atmosphere

The thermal energy of a particle in a typical star's atmosphere is small compared to its negative gravitational potential energy and many writers have shown that the loss of atmosphere by a nonrotating star is quite negligible.[8] Certain stars are known, however, to rotate so rapidly on their axes that they are on the verge of break-up[1,9] and therefore have very small equatorial accelerations. Such stars might be expected to lose their equatorial material and yet retain the atmosphere over the poles because rotation alone would not affect the polar acceleration.

In a criticism of the fission theory of binary star systems, Chamberlin[10] has expressed the opinion that rapidly rotating stars "must shed portions of their matter molecule by molecule" and pointed out that the lost molecules would carry off angular momentum and thus reduce the incipient instability of the system. Chamberlin's position has not been without support, for if Milne's analysis of the chromospheric stability is accepted, then material would be expected to be blown away more rapidly as the surface acceleration of a star approached zero. This is contrary to observation for in an important paper Russel brought forward excellent evidence which showed that the loss of stellar atmospheres by high rotation was quite negligible.[9] Clearly, then, a simple outward radial force on each particle arising from the absorption of radiation cannot support the atmosphere, for that outward force must always just balance a variable surface acceleration which is a function of the rotational velocity of the star. Such a balance seems improbable.

Electromagnetic forces readily account for the observed stability in all cases. In lower latitudes any radial force is at right angles to the star's magnetic field and no matter what the magnitude of the force the ionized atmosphere will be constrained to move to the east or west rather than outward or inward. On account of the spherical symmetry it appears that radial forces acting on the ions are the only ones which could be of importance and it is therefore clear that rapid rotation will not directly disturb the radial equilibrium[5]. However, high speed rotation might affect the equilibrium positions of the neutral material, and the abundance of the elements at various levels of the atmosphere might be expected to change slightly with changes in rotation. This readjustment is not believed to be of great importance.

The presence of a magnetic field in the atmosphere of a star effectively prevents the rapid loss of ionized material at its periphery even if the mass of the star is greatly concentrated toward the center. The ways by which a magnetic star might conceivably lose material are:

(a) by loss of large massive units.

(b) by loss of neutral molecules.

(c) by loss of particles, normally ionized, which succeed by a series of favorable collisions in working their way well clear of the star's magnetic field.

[8] Jeans, Dynamical Theory of Gases (1925).

[9] H. N. Russell, Astrophys. J. **31,** 185 (1910).

[10] Chamberlin, Carnegie Inst. Pub. No. 107, p. 169 (1909).

Loss by method (a) requires no discussion, while the loss of neutral molecules is probably not important except in very cool stars, for it is difficult to see how a single atom could pass through the low pressure regions of a star's atmosphere without becoming ionized and hence subject to magnetic forces. The rate of loss by method (c) is believed to be small but it probably takes place slowly in very hot stars and results in an outer atmosphere whose ions describe individual gravitational orbits about the star.

The evolutionary processes in a star, hitherto assumed to depend only on its physical constitution, are now seen to depend in a large measure on electromagnetic processes. In a preceding paper it was shown that the precise mechanism which prevents the loss of atmosphere adds angular momentum to the star until (if the star has sufficient energy) it breaks up forming a binary pair. It seems clear that evolutionary processes of the type considered by Laplace in his nebular hypothesis has no existence in a magnetized star.