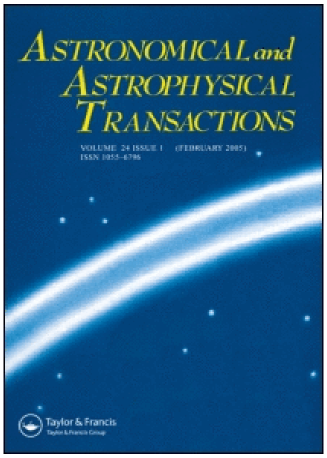

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MAGNETIC FIELD GENERATION ON THE SUN

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We consider the contradiction between the minimum entropy production theorem and the conception of the solar differential rotation being maintained by viscous forces. This difficulty can be overcome if the condition that the highest possible part of the total energy entering the convection zone from below is transformed into the magnetic field energy is fulfilled (Vandakurov, 1999c). We expect that this condition is satisfied if a change in the magnetic field distribution is not followed by a significant change in the rotation structure. Here we use this condition to study allowed rotation laws. In the case of the lower half of the solar convection zone, the rotation latitude dependence obtained appears to be in agreement with that observed on the Sun.

KEY WORDS Solar convection zone, differential rotation, turbulent viscosity

It is known that a great turbulent viscous force should be present in the differentially rotating solar convection zone to compensate the Coriolis force. Since the viscosity is a source of entropy production, the latter is high. On the other hand, we are dealing with a near equilibrium system for which, according to Prigogine (1980), a state with minimum entropy production is expected to form. Hence, rigid rotation seems to be the most probable.

To solve this paradox, we consider the convection zone rotation problem by invoking an additional condition, which can facilitate the heat flux transport. In the case of the Sun, the huge convection zone dimensions seem to have importance; therefore, we assume that it can be preferable to transform the thermal energy entering the convection zone from below into magnetic energy, instead of performing convective transportation of this energy over the whole depth of the convection zone (Vandakurov, 1999c). In other words, we suggest that an equilibrium structure is realized which requires the smallest energy for its maintenance.

As far as the general problem of stellar magnetized rotating structures is concerned, the following circumstances should be taken into account. Observations show that in the presence of a magnetic field in a radiative zone chemical inhomogenities (spots) are often formed (see, e.g., Borra *et al.*, 1982), whereas complex rotating structures can be present in stellar or atmospheric convection zones. As examples of the latter structures, the solar differential rotation or the superrotation of Venus's convective atmosphere (see, e.g., Schubert *et al.*, 1977; Young and

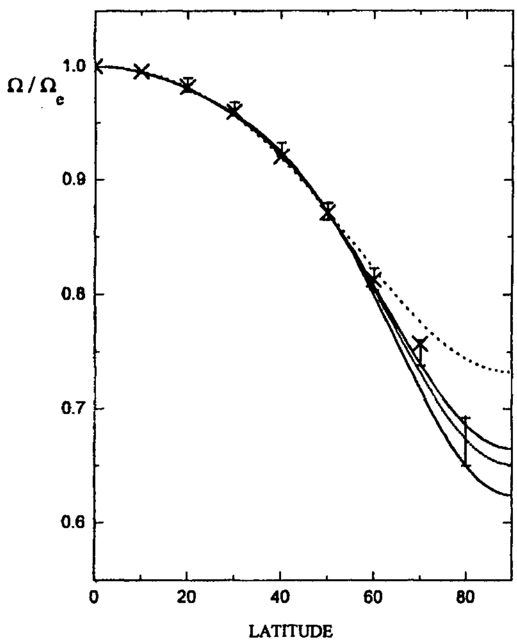
Pollack, 1977; Marov, 1981; Kondrat'ev *et al.*, 1987) can be presented. We consider the phenomena listed as a manifestation of the insolubility effect discussed by Vandakurov (1999a, b).

In this case, we are dealing with equations derived from the *exact* nonlinear equilibrium equation by separation of variables. It turns out that during any transition from a lower to higher approximation, the number of higher order terms which appear in the expansions of nonlinear forces is larger than the number of similar terms in the expansions of the hydrodynamic velocity or magnetic field; and the higher the order of approximation in question, the larger is this difference in numbers. Therefore in the absence of the truncation effect, the number of variables turns out to be smaller than the number of equations, and the whole system of equations is insoluble. We suggest that this effect accounts for the formation of spots in magnetic stars (Vandakurov, 1999b). The concentration of a part of the solar magnetic flux in a kG state (see Stenflo, 1989a) might also be produced by the effect in question. Note that the above-mentioned truncation effect takes place if the rotation is rigid and/or the magnetic field is dipolar (see also Vandakurov, 2001).

Thus, the formation of complex rotating structures in convective zones is possible only through an effect produced by turbulent viscosity. Since the direct maintenance of nonrigid rotation is at variance with the laws of irreversible thermodynamics, we are forced to conclude that the turbulent convective viscous force acts so as to suppress the high-order rotational and magnetic modes producing the truncation effect. We think that a similar suppressing effect is realized in Young and Pollack's (1977) numerical model of Venus's convective atmosphere rotation. This model is characterized by a high superrotation of upper layers, close to that observed, however the justification of dropping the high-order terms performed in the model has led to a discussion (see Rossow *et al.*, 1980, and Young and Pollack, 1980).

In the solar case, the realization of the transformation of thermal to magnetic energy seems preferable; then differential rotation, under the influence of turbulent viscosity, adjusts itself to create the most favorable conditions for magnetic-field generation. In particular, the fulfillment of the minimum entropy production condition will be equivalent to realization of a nearly inviscid field-generation process. But the suppression of high- order rotational and magnetic modes is certainly necessary. It seems most likely that to fulfil the above favorable conditions for field generation, the requirement must also be satisfied that any change in the magnetic-field distribution should not be accompanied by a noticeable change of the equilibrium rotation-field structure. This requirement is apparently confirmed by observations (see, e.g., Howard, 1984; Schou *et al.*, 1998). It is obvious that the conditions cited are not satisfied if the zone rotation is rigid.

We perform a preliminary study of the solar rotation models for which the largest possible part of the total energy entering the convection zone from below is transformed into magnetic energy, assuming that the minimum entropy production condition is also satisfied in the case of the principal modes (these modes are assumed not to be suppressed by turbulent viscosity). We define the magnetic-field generation zone as that in which replacement of the magnetic field by some



Figure

other field would not essentially change the equilibrium distribution of the rotation field. Our earlier studies dealt only with axisymmetric magnetic fields (Vandakurov 1999c). This work uses the same approximations to investigate any axisymmetric or nonaxisymmetric toroidal magnetic fields.

The figure shows the latitude distributions of relative angular rotation rates obtained in several equilibrium models with nonaxisymmetric toroidal magnetic fields. The model parameters were chosen so that replacement of a nonaxisymmetric by an axisymmetric magnetic field of the same (toroidal) type would not bring about a noticeable change in the rotation rate distribution. The lower and the upper solid curves relate, respectively, to the lowest layer in the convective zone and a layer in its central part. The upper dotted curve corresponds to a layer with a relative radius of 0.92. The crosses and dashes identify the experimental data of Howard (1984) and Birch and Kosovichev (1998).

We readily see that within the lower half of the convective zone or even in a somewhat extended region the condition of a weak interrelation between the variations of the field and rotation is met, the latitude distribution of the rotation rate obtained being fairly close to that observed on the Sun. These results provide support for the conclusions of Vandakurov (1999c) that the formation of complex rotational structures in the approximately adiabatic convective zone is possible only if (a) there exists an additional condition based on energy considerations, which is not satisfied under rigid rotation of the medium, and (b) convective motions suppress the rotational and magnetic modes inhibiting formation of the complex rotational structures discussed here. In this case, the condition of minimum entropy production reduces to realization of the above-mentioned approximately inviscid rotational structures. We note in this connection that a conclusion of the approximately inviscid nature of the solar differential rotation was also recently drawn by Elliot *et al.* (2000).

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