The Solar Internal Rotation and its Implications

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Abstract: The present internal rotation of the Sun as deduced from helioseismological data has many implications which concern the location of the solar cycle dynamo mechanism, core magnetism and history of the angular momentum. These aspects and their mutual connections are briefly discussed.

1. The present internal rotation

Recent measurement of p-mode rotational splittings (Morrow, 1988; Rhodes *et al.*, 1988; Woodard and Libbrecht, 1988) have pointed out that the surface rotation persists through the solar convection zone, at the base of which there is a tendency towards a rigid rotation. The inversion of helioseismological data indicates that the change of the rotational behaviour occurs in a transition layer located between $r = 0.7\,R_\odot$ and $r = 0.5\,R_\odot$. The optimization of data (Morrow, 1988) leads to a rotational behaviour that can approximately be described by the following expressions:

For $r_2 \le r \le R_\odot$ (standard c.z.) $\omega(r,\varphi) = \omega(R_\odot,\varphi) = a + b\sin^2\varphi + c\sin^4\varphi$, (1a)

for $r_1 \le r \le r_2$ (transition layer) $\omega(r,\varphi) = \omega + f(\varphi)[(r - r_1)/(r_2 - r_1)]$, (1b)

for $r \le r_1$ (radiative interior) $\omega(r,\varphi) = \omega_c$, (1c)

where φ is the latitude, $f(\varphi) = \omega(R_\odot,\varphi) - \omega_c$ and a = 2.87μrad s^{-1}, b = $-$ 0.31 μrad s^{-1}, c = $-$ 0.503 μrad s^{-1}, $\omega_c = 2.74$ μrad s^{-1}. The latitude at which $\omega(R_\odot,\varphi) = \omega_c$ is $\varphi_0 = 32.35°$ as deduced from (1a). The radial behaviour of the angular velocity for four latitudes ($\varphi = 0°, 30°, 60°, 90°$) and the isorotation surfaces, as deduced from expressions (1), are shown in Fig. 1 (respectively top and bottom). The inversion of the p-mode rotational splittings gives very uncertain results below $0.3\,R_\odot$.

2. The location of the dynamo

For an $\alpha - \omega$ dynamo it is well known that in order to obtain the correct field migration at the solar surface, since the dynamo wave migrates along the isorotation surfaces and the migration direction is given by the vector $\alpha \nabla \omega \times i_\varphi$ (Yoshimura, 1975), it is necessary that $\partial\omega/\partial r < 0$, as in the solar convection zone $\alpha > 0$ in the north hemisphere and $\alpha < 0$ in the south hemisphere (Steenbeck and Krause, 1969).

However the picture which emerges from the analysis of helioseismological data allows for ω isoplanes displaced almost radially (Fig. 1 bottom) and therefore for $\partial\omega/\partial r \simeq 0$. This situation seems to preclude an $\alpha - \omega$ dynamo from operating in the solar convection zone.

The behaviour of the angular velocity in the transition layer indicates the possibility of a consistent overshooting below the standard convection zone. In this case the sign of α is reversed in both the hemispheres because the convective motions are mainly directed towards the interior. In this region we have $\partial\omega/\partial r > 0$ for $\varphi < \varphi_0$ and $\partial\omega/\partial r < 0$ for $\varphi > \varphi_0$. This picture is consistent with the migration of the sunspots towards the equator at the lower latitudes and migration of other magnetic features towards the poles at the higher latitudes. In the weak buoyancy transition layer it is possible to intensify the magnetic field to exceed greatly the equipartition value over spatial scales comparable with those of the active regions, as it has been shown by an instability analysis of Spruit and Van Ballegooijen (1982). For high order modes, or small spatial scales, the limit field strength is of the order of 1 MGauss (Paternò, 1990).

Attemps to model non linear $\alpha{-}\omega$ dynamos in the transition layer (Belvedere *et al.* these Proceedings) are not yet conclusive about the possibility of a dynamo operating in this layer, as they show that magnetic field is preferentially intensified at high latitudes. This probably depends on the radial shear $\partial\omega/\partial r = f(\varphi)/(r_2 - r_1)$ which is much stronger at high latitudes.

3. The angular momentum evolution

The possibility of tracing back the rotation of the Sun is offered by the observations of the stars with about the same mass of the Sun in earlier evolutionary stages. In Fig. 2 (top) typical rotation rates of a sample of younger suns are shown as functions of the age.

The spinup phase from T Tau ($t \simeq 10^6$ ys, $\Omega \simeq 3\Omega_\odot$) to α Per ($t \simeq 5 \cdot 10^7$ ys, $\Omega \simeq 26\Omega_\odot$) is consistent with the conservation of angular momentum and rigid body rotation. The hypothesis of rigid rotation for almost fully convective stars is consistent with a rapid redistribution of angular momentum due to the convective motions. On taking into account the slight contraction which affects the mass distribution inside, we obtain:

$$\Omega_2/\Omega_1 = (h_1 R_1/h_2 R_2)^2 \simeq 10, \tag{2}$$

where the suffices 1 and 2 refer respectively to the initial and final conditions and $h_1^2 \simeq 0.2$, $h_2^2 \simeq 0.1$ are the radii of gyration, in units of R^2, of the two configurations, assuming two polytropic structures respectively with $n = 1.5$ and $n = 2.5$.

The spin-down phase from α Per through Pleiades and Hyades to the present Sun can be discussed in terms of magnetic wind torques considering the field to be a potential field inside the Alfvénic surface and radial thereafter (Schatzman, 1962; Mestel, 1968). In this situation it is possible to have a strong braking with a small mass loss provided that the Alfvén radius is sufficiently large. In the absence of strong mass loss, which on the other hand is not observed during these evolutionary phases, the rate of braking is given by

$$\frac{\partial \Omega}{\partial t} \simeq \frac{2}{3h^2} \frac{dm/dt}{M} \left[\frac{r_A}{R}\right]^2 \Omega, \tag{3}$$

where dm/dt is the rate of mass loss, r_A the Alfvénic radius, M the mass of the layers in which the braking occurs, and expression (3) has been deduced from the relevant equations (Castellani and Paternò, 1984). The slow spin-down phase (Pleiades-Sun) is quite consistent with the slowing down of the whole Sun (Paternò, 1984), while the fast spin-down phase (α Per - Pleiades) can only be explained if the convection zone spins-down independently of the radiative interior.

This picture is not consistent with helioseismological data which suggest for rigid rotation at least until to a depth of $0.3\,R_\odot$. A very effective transport mechanism must have been active during the fast spin-down phase for transferring the internal angular momentum to the outer layers.

In Fig. 2 (bottom) we compare the marginal gradient of Ω for the two hydrodynamical instabilities GSF and ABCD, as calculated by Dziembowski *et al.* (1986), with the mean equatorial velocity of the Sun as deduced by Libbrecht and Woodard (1990) analyzing the 1986 and 1988 helioseismological data. Since the ABCD instability, which has the lowest threshold among the hydrodynamical instabilities, does not explain the observed behaviour of Ω, we are induced to think that some hydromagnetic mechanism is at work in the Sun's core (Dziembowski *et al.*, 1985).

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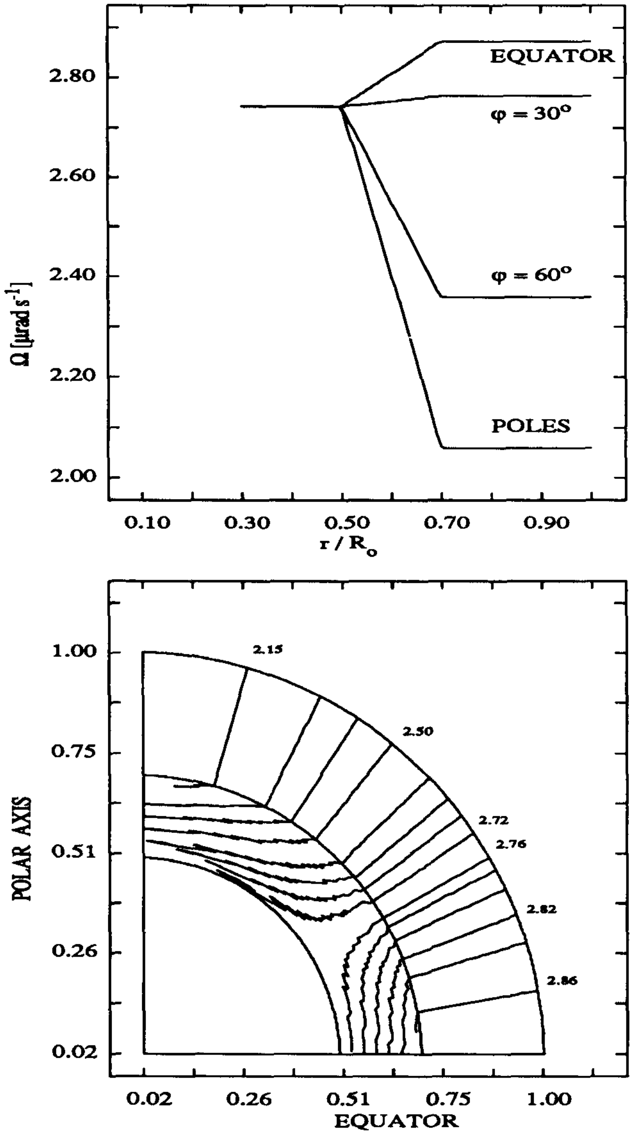

Fig. 1. The radial behaviour of the solar angular velocity at four latitudes (top) and the corresponding isorotation surfaces (bottom) as deduced form a best fit with helioseismological data (Morrow, 1988).

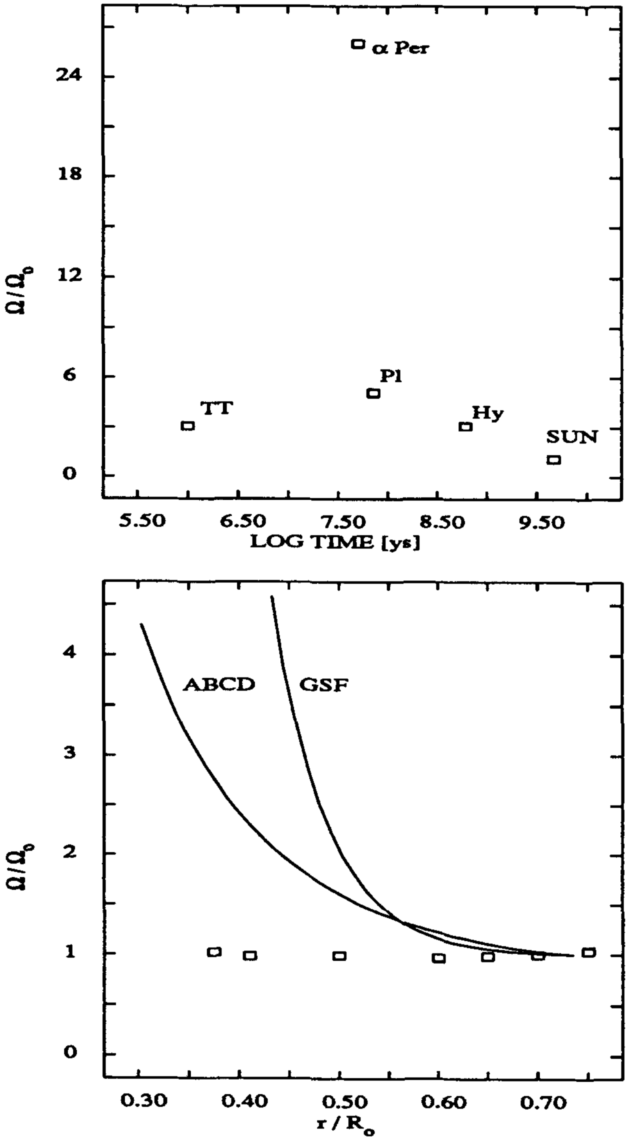

Fig. 2. Observed mean rotation rates of a sample of stars of about 1 $M_\odot$ in earlier evolutionary stages than the Sun as functions of the time (top) and the marginal gradient of the solar angular velocity for the GSF and ABCD instabilities compared with the mean equatorial angular velocity, as deduced from the 1986 and 1988 helioseismological data (Libbrecht and Woodard, 1990), (bottom).