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MUST THE MAGNETIC FIELD SATURATE ON RAPIDLY ROTATING STARS?

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ABSTRACT It is not necessary to invoke a saturation of (unsigned) magnetic flux on the most active stars in order to satisfy observational constraints (saturation of transition region emission and of rotational spin-down of young stars). Thus, observations of saturation effects cannot set limits on the dynamo. There is also no obvious physical reason for such a saturation to occur when the surface filling factor becomes unity. The limit to the surface flux set by the storage capacity of the overshoot layer easily allows a star to fill its surface with a very strong field.

ARGUMENTS FOR SATURATION

Observational arguments:

1. For very rapid rotators the emission from the upper atmosphere does not continue to increase with rotational frequency Ω, but saturates at a maximum value (Vilhu & Rucinski 1983), which is interpreted as a saturation of the surface area coverage by active regions, i.e. of the magnetic field (Vilhu 1983).
2. For very rapidly rotating young stars magnetic braking of rotation appears to saturate (Soderblom et al. 1993).

Theoretical arguments:

It has been argued that magnetic flux is proportional to Ω, but saturates when the filling factor approaches unity at the largest rotation frequencies (e.g. Linsky & Saar 1987). The following 2-component model of the field can explain this behaviour. 1st component: Field strength B, filling factor $0 \leq f \leq 1$. 2nd component: no field, fractional area coverage: $1 - f$. To first order B is determined by horizontal pressure balance:

$$B^2/8\pi = p_2 - p_1, \tag{1}$$

where $p_{1,2}$ are the gas pressures in the 1st and 2nd components, respectively. Consequently, at a given height z, B cannot exceed

$$B(z) \leq B_e(z) = \sqrt{8\pi p_2(z)}. \tag{2}$$

B_e is often called the (thermal) equipartition field.

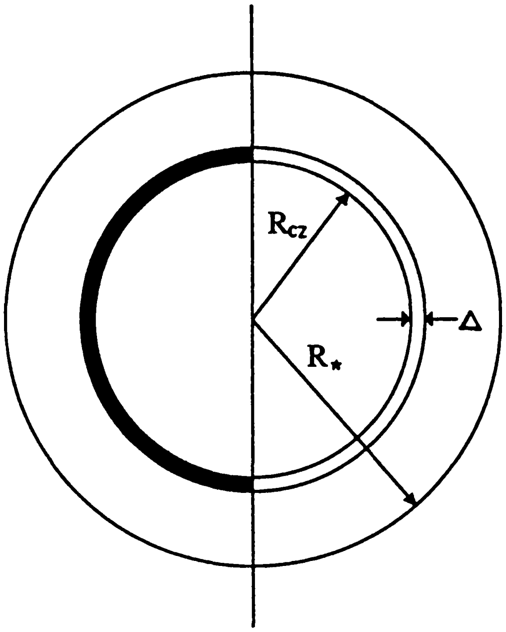

FIGURE I Illustration of the geometry assumed for the storage of the magnetic flux in the overshoot layer below the convection zone.

A MORE CAREFUL LOOK

Relations (1) and (2) are only valid for $f < 1$. For $f = 1$, i.e. for a star completely covered with field, there is no external (non-magnetic gas) to confine the field. B can become arbitrarily large at a height at which $f = 1$.

As an example consider the sun. Magnetic features expand with height, z, since p_e decreases with z, so that above some height z_m neighbouring features merge. $f = 1$ above z_m and in general $B > B_e$ for $z > z_m$. Now, the height z_m depends on the total flux. If the flux is sufficiently large, then z_m can lie below the stellar surface $z = 0$, so that $B(z = 0) > B_e(z = 0)$.

HOW MUCH FLUX CAN A STAR STORE?

All the evidence suggests that the dynamo acts and stores the magnetic flux in the overshoot layer below the convection zone. Here I estimate the amount of flux which may be stored in a toroidal flux system filling the overshoot layer and determine the equivalent surface flux and field strength. The geometry and the meanings of some of the symbols are illustrated in Fig. I.

The maximum amount of flux F_{CZ} (at a field strength B_{CZ}) stored in the overshoot layer below the convection zone is:

$$F_{CZ} \approx B_{CZ} \frac{2\pi}{2} R_{CZ} \Delta. \qquad (3)$$

The equivalent field strength B_S at the surface is given by

$$F_S = 4\pi R_*^2 B_S. \qquad (4)$$

Equating F_S with $2mF_{CZ}$ (where m is the number of loops, with 2 footpoints each, which each toroidal flux ring can produce) we get

$$B_S = B_{CZ}\frac{R_{CZ}}{R_\star^2}2m\Delta. \tag{5}$$

Numerical example: The sun. Take $R_{CZ} = 0.75R_\odot$. This gives for $\Delta = 10^4$ km and $R_\odot = 7 \times 10^5$ km

$$B_S = B_{CZ}\frac{3}{2}\frac{m\Delta}{R_\star} \approx \frac{B_{CZ}m}{45}. \tag{6}$$

For the sun $B_{CZ} \approx 10^5$ G, which gives $B_S \approx 2000m$ G. As Caligari et al. (these proceedings) show, increasingly larger B_{CZ} can be stably stored at R_{CZ} with increasing Ω. For a star with $\Omega = 10\Omega_\odot$, $B_{CZ} \approx 2.5 \times 10^5$, so that $B_S = 5000m$ G $> B_e \approx 1800$ G. The rotation period of such a star is 3 days, which is the longest period to show saturated UV emission (Vilhu & Rucinski 1983).

WHAT ABOUT THE OBSERVATIONAL EVIDENCE?

Saturation of transition-region emission:

Although solar transition region emission increases steadily with $\langle B\rangle$ for quiet sun and active region plage, it does not increase further as $\langle B\rangle$ increases from plage to sunspots (e.g. Gurman 1993). Now, plage $f(z = 0)$ values rarely exceed 20% when averaging over, say, 10″. Thus transition region emission saturates already at rather low f values and saturation of stellar emission may simply stem from a larger concentration of the field into spots with increasing Ω (Radick et al. 1989).

Saturation of rotational spin-down:

Caligari et al. (this volume) demonstrate that as Ω increases the magnetic field is increasingly concentrated at high latitudes, i.e. near the rotation poles of the star. Thus the Alfvén radius is largest near the stellar poles, where little angular momentum loss can take place (since the angular momentum of particles travelling along the axis is zero). This effect by itself could lead to the saturation of angular momentum loss for rapid rotators, without the need for a saturation of the surface field.

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