ON THE ROTATION-ACTIVITY CONNECTION

A. Mangeney
Observatoire de Paris-Meudon
92190 Meudon
France

ABSTRACT. New observations of large scale convection on the Sun challenge the currently accepted dynamo theory of the generation of stellar magnetic field. The available evidence of the correlation between stellar activity and rotation teaches us something about the interaction of rotation with large scale convection. The question of what parameter to use to describe this correlation is discussed.

I. INTRODUCTION

It is now established that as a rule the outer atmospheres of stars are far from the simple state of spherical symmetry, hydrostatic and radiative equilibrium

Furthermore, at the Sun's surface the magnetic field appear in a highly concentrated form ; higher up in the atmosphere it structures strongly the plasma with a mixture of closed field lines, the so-called "magnetic loops", and open lines, the "coronal holes".

This poses a lot of fundamental questions : among which

- what is the heating mechanism
- why the surface magnetic field is so highly intermittent
- how is this all related to the internal structure of the Sun, essentially the convective zone structure ?
- What is the source of the magnetic field (what is the operating dynamo mechanism and what are its relations with the stellar convection, large scale convection ?)

The study of other stars may help to solve these questions by allowing to study (without the spatial resolution !) the variation with stellar parameters of the main manifestations of activity.

In this respect the fundamental problems are

- to what extent other stars in the H.R diagram have outer atmospheres similar or strongly different from that of the Sun.
- what are the basic stellar parameters (M, g, Ω, Y, Z,...) which

J.-P. Swings (ed.), Highlights of Astronomy, 399–409.

https://doi.org/10.1017/S1539299600006699 Published online by Cambridge University Press

appear to control the various manifestations of stellar activity.

A number of good reviews have been published recently on these subjects (Baliunas, Vaughan, 1985, Rosner et al, 1985, Linsky 1985, while, Zeldovich et al, 1983). Thus, I have deliberately chosen in this contribution, to address myself to two particular problems connected to the interaction of rotation with convection.

The first one, concerns directly the relevance of the dynamo theory in its present state of development to the understanding of the solar cycle. This theory appears indeed to be able to explain successfully the qualitative features of the solar cycle (see for example Zeldovich et al, 1983) with a proper choice of some free parameter. I will review recent results obtained at Paris Observatory that appear to challenge this claim.

The second part of this paper is concerned with what is called the "activity-rotation connection". Indicators of stellar activity appear, indeed, to be strongly correlated with stellar rotation rate. An interaction between rotation and stellar convection zone, leading to dynamo action is now generally accepted to be the explanation for this empirical fact. What is the physically meaningful parameter which is behind this correlation ? This is the question I discuss in the second part.

II. SOME NEW OBSERVATIONAL EVIDENCE CONCERNING THE SUN

In analysing the long record of spectroheliograms of the Paris Observatory (starting in 1919 and presently continuing) a new and completely unexpected pattern of circulation was discovered by Ribes et al, 1985.

Many attempts have been made to detect, through the observation of spot drifts, large scale motions considered as the photospheric manifestation of the Sun's global convection (see Schröter, 1985 for a review). For example, recently Gilman et al, 1984 found evidence in the Mount Wilson white light plate collections of a significant variation of the azimuthal spot velocity with the solar cycle, the volocity peaking at roughly the time of solar minimum.

What distinguishes Ribes et al's approach is 1) a careful digitalization of the plates, allowing to measure spot velocities with an accuracy of a few m/s for the best seeing in Meudon 2) the selection of newly born spots as tracers of the fluid motion in the subphotospheric layers. 3) the comparison with the large scale, long-lived magnetic structures outlined by the Hα filaments.

The reason for restricting oneself only to the newly born spots comes from the knowledge we have of the history of a typical spot-group.

They usually emerge at the surface as simple dipolar features ; as the corresponding magnetic loop rises the leading and following spot diverge and after a few days the following spot starts to fragment and gradually disperses into the general surrounding magnetic field, leaving only the leading spot as an identifiable feature.

It is thus to be expected that the drag exerted by the photospheric plasma on the complex magnetic structure exhibited by the old spots will be much stronger that the one experienced by the young spots. Indeed old spots tend to follow the general surface differential rotation, while Ribes et al observed that the center of gravity of young spots appear to rotate rigidly, a result consistent with the hypothesis of the anchoring of these young spots deep in the subphotospheric layer, which, as shown recently the helioseismology experiments rotate approximatively rigidly (Duvall and Harvey, 1984).

A relatively short part of the available collection is presently analysed, covering however, now almost a full activity cycle (1965, 1976). Furthermore the removal of plates unfit for analysis, together with the observing holes due to cloudiness, leaves a relatively small sample of spot groups which could be followed, for a sufficiently long time, in order to ascertain their age and measure their drift velocity on the solar disc.

However this admittedly small sample exhibit unambiguously a meridional circulation pattern shown in figure 1, with velocity ~ 100 m/s, significantly larger than any possible experimental error.

This roughly axisymmetric circulation pattern consists of four bands in latitude symmetric with respect to the equator, the sense of the meridional drift changing alternatively from one band to the other.

It has been suggested sometime ago by Mc Intosh that large scale, long lived unpolar magnetic structures were outlined by Hα filaments. How the above mentionned circulation pattern relates to these magnetic structures ?

Ribes et al used a technique similar to Makarov's (1984) to exhibit these structures from the data accumulated in Meudon. This procedure reveals a large scale band pattern shown in figure 1 for the period 1965-1976 which presumably delineates magnetic regions of different polarities.

The important point here is that at a given time, the latitudes at which the spot circulation changes sign coincides with the boundaries of the Hα bands.

This remarkable coïncidence suggests that we are observing a pattern of azimuthal counter rotating rolls. These rolls have a typical life time of a few years, and evolve seemingly through by bifurcation of the most equatorial roll, a new equatorial roll appearig inside the branches of the old roll.

It is easily seen that this bifurcation process appears at a given latitude as a reversal of the circulation pattern.

Note that the velocities are typically those expected for a deep large scale convection (Weiss, 1964). These considerations suggest strongly that this whole pattern is indeed the long searched for global solar convection.

If this true, it raises an interesting fluid dynamical problem. Indeed, for such large scale fluid motions, the Proudman-Taylor theorem should apply and the motions be severely restricted in the directios parallel to the rotation axis.

A consequence of this constraint is to produce convective cells in the form of "bananas" more or less parallel to the rotation axis, as suggested by Busse 1970, and observed int he extensive numerical simulations (see Glatzmaier, 1985, for example).

To relax Proudman Taylor's constraint, several alternatives may be thought of.

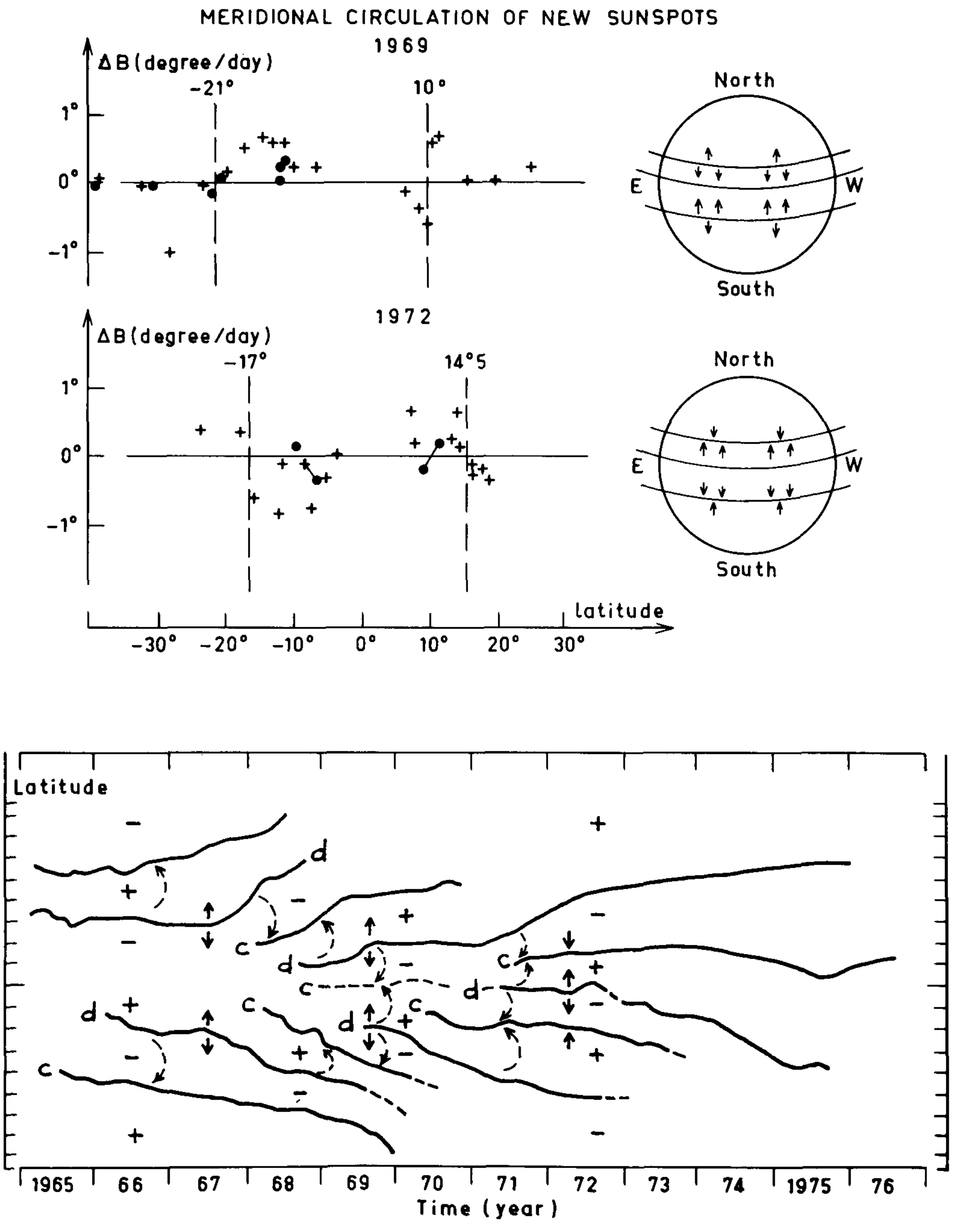

Figure 1. Latitude drift of newly born spots in degrees/day for years 1969, 1972, is shown in the upper part. The direction of these drifts is plotted on the Hα filament pattern for 1965–1976.

The radial rotational shear, as inferred from helioseismology is probably too small to affect the rotation.

Another way is to take into account the presence of the magnetic field.

Recent work by Geiger (1982) may be invoked to throw some light on the problem. He considers the linear theory of the convective instability in a spherical shell of Boussinesq fluid of depth d, permeated by a toroïdal magnetic field, heated from below, with fixed temperatures at the two boundaries. Furthermore the Rayleigh number is chosen to be close to the critical one for the onset of the instability, the rotation and the magnetic field being small in the sense that both the Coriolis force and the Lorentz force are small with respect to the buoyancy.

His results show that the magnetic field tends to favor axisymmetric mode. For a given shell depth the transition between situations where axisymmetric mode are preferred and those where non axysymmetric mode are preferred depend on the rotation rate, the magnetic field, the thermal Prandth number and the magnetic Prandth number, as shown in figure 2.

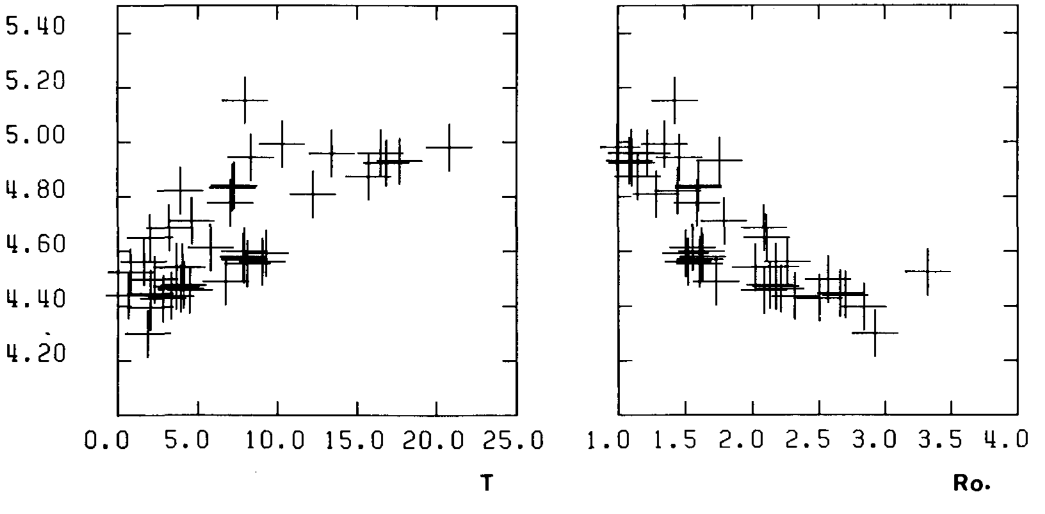

Figure 2 : Regions in the plane ε, η where axysymmetric modes are prefered. The parameters used are $\varepsilon = T^{1/2}(t_D/t_A)\sqrt{\nu/\lambda}$ and $\eta = 1 - \frac{d}{R_0}$ where R_0 is the outer radius of the shell, Ω the rotation rate, T : Taylor Number = $(\frac{2\Omega R_o}{\nu})^2$, ν : viscosity, λ : magnetic diffusivity, $t_D = R_0^2/\nu$, $t_A = R_0/V_A$, V_A being the Alfen velocity in the imposed toroïdal field.

Geiger's calculation are done for parameters far from any astrophysically relevant situation. However they show that the relative amplitude of the rotation rate, of the large scale magnetic field, and the depth of convective layer may have very profound influences on the convective flow. Furthermore it shows that for sufficiently shallow convective zone, and not too large value of the parameter ε, axisymmetric modes with ℓ 1 may be the most unstable ones.

Why numerical simulations of a global solar convection (Glatzmaier, 1984) do not reveal such an axisymmetric pattern ? A possible answer is that the very procedure used probably prevents its occurrence. Indeed, the magnetic field is initially set to zero and the field free convection is allowed to settle down to a quasi stationary state, which will almost inevitably exhibit the typical "banna" pattern. Then a weak seed magnetic field is switched on and one looks how it is amplified by the fluid motions, and how it reacts back on these motions. It may thus happen that this somewhat artificial procedure produces results which are qualitatively different of those which one would have got, had one started initially with a non zero magnetic field.

Although the statistics is poor, it does appear that the spots do not appear at random with respect to the roll patern. But preferentially in the vicinities of the boundaries especially in the regions of presumed upward flow, suggesting that subsurface photospheric field is expelled by the convective updrafts.

After each bifurcation of an equatorial roll, a new one appears and the regions of updraft moves closer to the equator, together with the region of preferential appearance of spots.

This provides a completely new picture of the so called butterfly diagram of sunspots. It is probably not due to the propagation of a dynamo wave but directly to the time evolution of the large scale convective pattern, thereby eliminating the long standing problem related to the shape of the radial differential velocity profile, in relation with the interpretation of the equatorial propagation of the dynamo wave.

Many points remain still to be studied, by looking at the complete collection, and also, to increase the statistics, to apply the same treatment to other collections of spot records.

More and more evidence is accumulating in favor of spot-activity on rapidly rotating late type stars, as shown by the rotational modulation of their visible luminosity (see Baliunas et al 1985 for a review). The interpretation of the photometric modulation is generally interpreted in terms of quasi-single spots. It may also well be that these "spots" are actually sufficiently well defined "active longitudes" like on the Sun. It is noteworthy that during their life these "spots" generaly drifts towards the equator much like what happens on the Sun.

If we accept the above picture for the Sun's activity cycle, a possible suggestion for the occurence of the rather "large spots" observed on active stars is the following. Most of these stars have relatively large rotational velocities leading to a high value of the Taylor number and presumably they lie above the critical line in figure 2, where non axisymmetric modes are favored.

It is not unexpected then, as argued by Knobloch et al, 1981, that for rapidly rotating stars, the Proudman-Taylor constraint will come into play.

However, the fact that ten to twelve years activity cycles are found exclusively in stars with long rotation periods (rotational periods larger than 20 days, Vaughan et al 1981) probably do not reflect a change in the mean helicity spectrum (and the related dynamo efficiency) but more directly to the stability property of the convective cells.

III. THE ROTATION ACTIVITY CONNECTION

In quite large domains of the HR diagram, the activity seems to be related to the stellar angular rotation rate. Many empirical relations have been proposed to express this observed correlation, in the form of a least square fit through the cloud of points obtained in a two dimensional plane with one coordinate being a measure of the rotation rate and the other coordinate a measure of the activity, i.e. a measure of the radiative loss in some typical temperature range.

In their pioneering exploration of stellar X ray emissionin the HR diagram Pallavicini et al, 1981, proposed

$$L_X = 10^{27}(v_{eq}\sin i)^2 \qquad \text{for stellar type F7-M5}$$
$$\propto L_{Bol} \qquad \text{for earlier types}$$

where v_{eq} is the stellar equatorial velocity.

However, a physically meaningful parameter describing the influence of rotation on the structure of the stellar envelope should be a non dimensional number describing the ratio of the Coriolis force to some other important force.

Durney and Latour, 1978, used a Rossby number $R_0 = t_{NL}\ \Omega$ which is the ratio of the convective turnover time, t_{NL} evaluated within the mixing length theory at depth in the convective zone where dynamo action is expected, to the rotation frequency of the star. This number can be evaluated from a model of a non rotating star and describe the influence of Coriolis forces on the flow at least as long t the rotation is not too strong.

Noyes et al, used such a Rossby number to correlate chromospheric emission in the Ca II H-K lines, with rotation.

A number of reasons suggest that for the dynamo process to be efficient it should be located at the bottom of the convectionzone. In particular this is the place where the Rossby number will be smaller for a given Ω, due to small convective velocity and large cell dimensions and rotational effects most important. Thus the relevant R_0 number should be calculated at the bottom of the convection, say one scaleheight above, to allow for significant velocities.

This was what Noyes et al, 1984 did : they were able to show that chromospheric emission in the Ca II H-K line, was, to a good approximation, a function of this Rossby number, for late type stars located on the main sequence.

The relation is even so tight, that one can obtain from the chromospheric emission, a fairly precise estimation of the rotation rate Ω (Soderblom 1985).

One may however question the physical relevance of this Rossby number for the following reasons.

First, it is based on Mixing length theory, which assumes that the scale length of the motions at a given level is determined by the local scale height. This does not appear to create serious problems for situations where the details of the flow are unimportant such as in internal structure calculations.

But for the problem we are considering, i.e. the action of Coriolis forces on the convection, a correct determination of the relevant scales and velocities is of basic importance. It should be mentionned that almost all numerical calculations of convection, which relax the Boussinesq approximation (Graham, 1975 ; Harburt et al., 1984, Deupree 1976, Chan et al, 1982, Glatzmaier, 1982, Sophia et al 1982, Chan et al, 1983) and predict convective motions which extend throughout the whole convective layer. These calculations have a limited spatial resolution and are performed for still too low a Rayleigh number. Thus it is hard to draw a definite coclusion, but there is at least some doubt that R_0 such as determined above has a direct dynamical signification.

There is some evidence from the lower end of the main sequence (Giampapa, 1983) that the depth of the convection zone may have some influence on the activity level. Indeed these stars become fully convective, while their activity level drops abruptly. Thus it seems that the relevant number measuring the influence of the rotation should include the depth of the convection zone.

As Mangeney and Praderie, 1984, pointed out, as long as the sample of stars is limited to the main sequence, various non dimensional measures of the rotation may be used, each differing from the other by a function of the stellar mass. For example they used a "pseudo Rossby" number R_{0*} including the depth of the convection zone.

$$R_{0*} = \frac{1}{2} \frac{v_{c\,max}}{\Omega \quad d}$$

where v_{cmax} is the maximum convective velocity and d the total depth of the convection zone. The argument for utilising this number, the physical relevance of which is not clear either, is that is calculated from quantities which depend hopefully only weakly of the detailed convective motions

Probably the best number to use is the Taylor number which measures the ratio of the Coriolis force to the viscous force

$$T \simeq \left(\frac{\Omega\ d^2}{\nu}\right)^{1/2}$$

Since we are interested only in the large scale convective modes, the relevant viscosity is the turbulent one, representing the effects of the smaller scales $\nu \simeq v\ell$ where v and ℓ are the velocity and mixing length of a small scale turbulent eddy. For an estimation of ν_t, use of mixing length theory should gives at least a correct order of magnitude. In particular, it has been used with success by Zahn, 1977, to calculate the tidal coupling in close binaries.

His expression for the turbulent viscosity scales as

$$\nu_t \sim 10^{14} \left(\frac{L^* R^{*4}}{M^*} \right)^{1/3} \ cm^2/s$$

the stellar luminosity L*, the radius R* and mass M* being expressed in solar units.

To illustrate this discussion, I have plotted on figure 3, the estimate of the Ca II H and K emission obtained by Noyes et al, for a sample of late type main sequence stars against R_{0*} and T, calculated for each of them on the basis of zero age main sequence stellar model provided by Maeder.

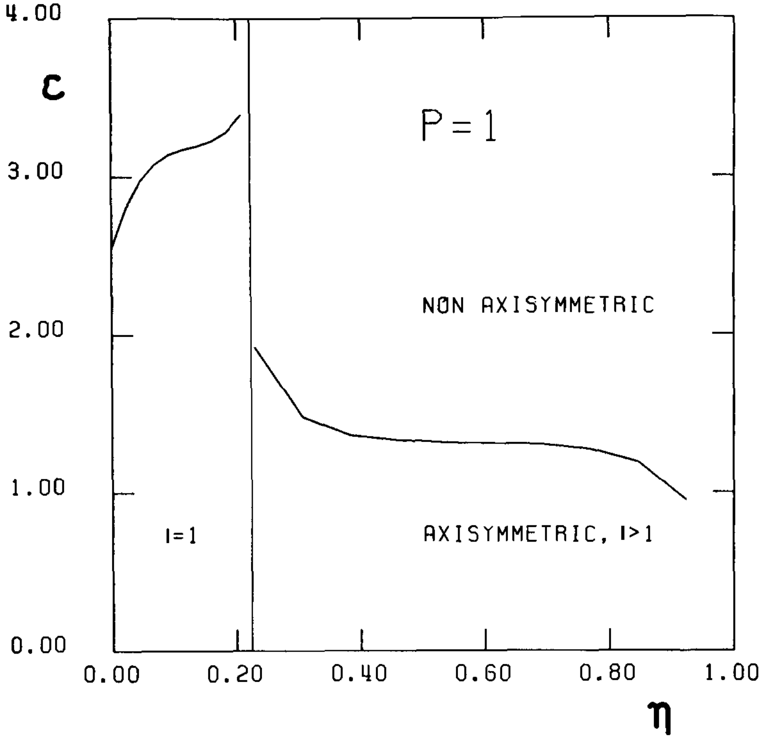

Figure 3. Ca II H-K measures (R'_{HK}) from Noyes et al 1984, plotted against R_{0*}, T

Is it possible to remove this ambiguity inherent to the analysis of star samples limited to the main sequence ?

The obvious answer is to look at stars belonging to clusters of different ages and, evolutionary stages and different rotational velocities. This is very active field of research now. However it is seriously complicated by the existence of empirical relations between what would be thought of a priori as independant variables.

For example Gray (1982), Benz et al, 1984, Duncan et al, 1984, argue that solar type stars exhibit a rotation rate which does depend only on their mass and their age.

In this context the choice of the activity indicator is quite important : it may indeed contain by construction a function of some of the particular parameters with which we want to correlate it.

For example, the computation of surface fluxes, includes a division by the stellar radius squared. Since the radius depends itself on the stellar mass and age, some spurious degree of correlation between surface fluxes and basic stellar parameters may be introduced.

A possible illustration of this effect was discussed by Mayer et al, 1984, in connection with the correlation of X ray activity and rotational periods for RSCVn stars.

To conclude I would like to discuss briefly some extensions outside the domain of late type stars.

Mangeney and Praderie, 1984, found a correlation between stsellar X ray luminosity as measured by Einstein and their pseudo Rossby number R_0^* in the form

$$L_X = (R_0^*)^{-1.2}$$

for all main sequence stars, irrespective of their mass.

This result was questionned (see for example Linsky, 1985, Rosner et al, 1985) because :

1) It appears to be in apparent conflict with Vaiana et al's results, 1981, mentionned above, who observed that L_X was apparently not connected with the stellar rotation rate, but scaled as the star's bolometric luminosity.

2) There are no reasons why a solar type of dynamo should be at work in early type stars ; thus this correlation valid for both late and early type stars appeared as doubtful.

However Mangeney and Praderie showed clearly that, if confidence could be lend to the models of very shallow convective zones of the earlier type stars, their result and Pallavicini et al's one where not in conflict, since $R_{0*} \sim T_{eff}^{-4}$ for a given equatorial velocity, and $T_{eff} \geqslant 10^4$°K. Second, the recent evidence we presented in section II on the working of the solar dynamo does not support the current views. Thus it may be that the second argument is not really very strong either.

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