INSIDE THE SUN : UNSOLVED PROBLEMS

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ABSTRACT. As it is impossible to approach all the problems concerning the inside of the Sun, a number of questions will not be taken into consideration during the meeting. In this brief overview of the presently unsolved questions I shall insist on some special aspects of the solar properties : the variations of the solar radius, the generation of the solar wind, some interesting effects due to the presence of a strong gradient of ^{3}He, the history of the rotating Sun. The presence of the planetary system suggests that the Sun might have been a T Tauri star, with an accretion disc and may have started on the mains sequence as a fast rotating star. A sketch is given of the possible consequences.

1. Presentation of the symposium.

We understand the Sun and nevertheless we do not understand it . In other words, the gross properties of the Sun are clear : the energy generation, the radiative transfer, the general stability and instability properties, the convective zone and even the existence of a dynamo mechanism. But, when we want to have a quantitative agreement with the same precision than the observations, then we get into trouble. Do we have forgotten some major things in building up our models, or is it the physics which fails ? It is hardly necessary to recall, in presence of the best experts of the world, that the more information we have, the more difficult it is to understand what is really going on in the Sun : from the solar neutrinos to the shape of the circulation which drives the solar activity, with the funny names of *rolls* or *bananas*; from the distribution of the angular velocity inside the Sun, to the properties of the solar wind (so important for the loss of angular momentum), from the oscillation frequencies of the Sun to the surface abundances of the nuclearly processed elements.

In all these problems, we are facing difficulties which may come of all parts of physics. This is the reason for calling for this meeting, putting together physicists and astrophysicists. From the point of view of the astrophysicist, this is like asking the physicists to provide life-jackets before drowning.

I have discussed several times with particle physicists about the astrophysicist's statements concerning the inside of the stars. They are quite disturbed by the confidence which we show sometime when speaking of systems of 10^{57} particles. And, perhaps, they are right : part of this

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meeting will be devoted to some of the collective behaviours which may turn out to be of the greatest importance for the understanding of the Sun. You will forgive me if I leave the problems of nuclear reactions, equation of state and opacities to the specialists ! The point is that I believe that there is still a lot to do about the motions inside the Sun and that we meet almost immediately non-linear problems, even when considering very slow motions like those induced by the circulation. I would like to take here my first example.

There will be a discussion about the turbulent diffusion mixing coefficient D_T in the radiative zone. Following here the suggestion of J.P.Zahn (1983), I shall accept the idea that differential rotation generates a 2-D turbulence on horizontal surfaces and that when the Rosby number Ro :

$$Ro = \frac{u}{l\,\Omega}$$

becomes larger than one it decays into a 3-D turbulence, with a turbulent diffusion coefficient :

$$D_T = \frac{4}{5}\,\frac{L\,r^3}{G\,M^2}\left|\left(1 - \frac{\Omega^2}{2\,\pi\,G\,\rho}\right)\right|\ \min\left[1,\ \frac{\Omega^2\,r}{g}(\nabla_{ad} - \nabla_{rad} + \nabla_\mu)^{-1}\right],$$

The quantity under the sign <u>min</u> has the meaning of an efficiency coefficient and must be smaller than one. The boundary of the convective zone is reached when $(\nabla_{ad}-\nabla_{rad}) = 0$ (in a chemically homogeneous region). In the Sun, the quantity $(\nabla_{ad} - \nabla_{rad})$ becomes equal to $(\Omega^2 r/ g)$ three kilometers below the boundary of the convective zone. The turbulent diffusion coefficient is very large, of the order of 9.10^5 $cm^2 s^{-1}$. The condition on the Rosby number give the possibility of estimating the turbulent velocity, 1.8 cm s^{-1} and the scale of the turbulence, of the order of 5 kilometers. This has to be compared with the distance of penetration of convection from the convective zone. By the way, this is another controversial problem. Two arguments are in favour of a very small penetration : (i) the constrain which come from the presence of Lithium,so easily nuclearly processed , and suggests an exponential decrease of D_T with a vertical scale of just a few kilometers; (ii) a penetration with an exponential decrease of the velocity, with a vertical scale which, for high Rayleigh numbers Ra, varies like Ra^{-6} (Zahn *et al,* 1982,Massaguer *et al,*1984). However, this is valid only for an hexagonal planform with motion upwards along the axis of the cells. It is interesting to notice that these three vertical scales are of the same order of magnitude and are compatible with heliosismology. The heliosismology data are well interpreted by a discontinuity of the derivative of the gradient $(\partial\nabla^*/\partial r)$ at the boundary of the convective zone.

As far as mixing by diffusion is concerned, the quasi-singularity of D_T at the boundary of the convective zone is not very important. The WKB approximation does not suffer from the singularity, and the only important quantity is something like

$$\langle D_T \rangle = \left(\frac{1}{r_1 - r_2} \int_{r_1}^{r_2} \frac{dr}{\sqrt{D_T}} \right)^{-2}$$

which obviously does not show any singularity.

It is clear, that in order to obtain the exact efficiency of mixing, it is necessary to improve as much as possible the modelling of the turbulence in the radiative zone. This does not mean naturally that everything is said about turbulence in the convective zone!

2. One word on the convective zone.

The recent observations of Laclare (1987) of the variations of the radius of the Sun, and the analysis by Delache (1988) seem to confirm the XVII th century observations of Picard (1666-1682) recently discussed by E.Ribes (see the analysis of Ribes *et al* 1987). The variability of the apparent diameter can be due to a change of limb darkening (T.Brown, 1987, Brardsley *et al* 1989) or to a change of the surface temperature (Kuhn *et al* 1988). Atmospheric effects can also modify the apparent solar diameter. It should be mentioned that light scattering produces an apparent increase of the diameter : the measured diameter might depend on the variations of the amount of water vapour in the Earth atmosphere. However, a correlation between the solar sunspots, the diameter variability and the onset of stratospheric winds has been reported (Labitske, 1987; Ribes *et al* 1988). If confirmed, it would indicate a causal relationship between the solar cycle and the Earth atmosphere properties.

The anti-correlation between the solar radius and the solar activity (Delache et al 1986) can receive a simple explanation which has already been considered by Endal, *et al* (1985): the effect of the magnetic field. On a large scale, in the presence of a very entangled magnetic field, the compressibility γ is larger. A convective zone, starting from the same level, but with a larger compressibility, will have a greater thickness, given by :

$$\frac{\Delta H}{H} = \frac{\Delta \gamma}{\gamma (\gamma - 1)}$$

When the activity is weak, we can think that the magnetic field is located deep inside the convective zone, and as this corresponds to the higher temperature, we can expect the effect on the thickness of the convective zone,

$$H = \frac{\gamma - 1}{\gamma} \frac{\Re T}{g \mu}$$

to be the largest; on the contrary, during the phase of activity, when the magnetic field is located near the surface, the effect on the thickness of the convective zone is smaller. Such an explanation of

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this sort of breathing of the Sun is very attractive; it appears as being connected with the dynamo mechanism, but when looking at numbers, the situation does not seem so good. The change of γ is $(4/15)(B^2/8\pi P)$. In order to obtain a change of the thickness of the convective zone of about 400 km, it is necessary to have a magnetic pressure of about 0.005 P, which gives at the bottom of the convective zone about $3 \cdot 10^6$ Gauss, of the order of 100 times what is expected from the simple principle of equipartition with the density of cinematic energy. However,this of the order of magnitude which Durney(1988) expects from the effect of differential rotation on the magnetic flux tubes, and is compatible with an estimate of the magnetic field strength derived from an extrapolation of the value of the magnetic field in sunspots to its value at the bottom of the convective zone. It fits also with the estimates of Dziembowski *et al* (this meeting).Altogether, despite the fact that the physics seems reasonable, it is still necessary to build up a consistent theory.

3. Angular momentum.

The loss of angular momentum (Schatzman,1959,1962), which turns out to be of great importance for the history of the solar rotation and for the internal structure of the Sun, is governed by the rate of mass loss (the solar wind), and by the average surface magnetic field (the average being taken over spans of time much larger than the period of activity), its topology and its strength (Roxbugh 1983, Mestel and Spruit 1987). The solar dynamo just as any stellar dynamo, is dominated by non-linear effects. The growth of the magnetic field can reasonably be described by the linear effects, but the limit on the intensity of the magnetic field is essentially non-linear.

Recently, Kawaler (1988), Pinsonneault et al (1989) have worked out models of the solar spindown with a parametric expression of the mass loss rate. I noticed especially in the paper of Kawaler (1988) that there is no indication of a time dependence of the rate of mass loss. However, would it be only from the observational point of view, the rate of mass loss is not the same from a young main sequence star and for an old one, the activity depending on the Rossby number (Noyes, 1983; Mangeney and Praderie, 1984). Durney and Latour (1978) have avoided the problem by assuming that the velocity of escape is simply given, in order of magnitude, by $(GM/R)^{1/2}$.

In order to study stellar evolution with mass loss, Fusi-Pecci and Renzini (1976), have made some assumptions on the amount of mechanical energy which is carried out of the convective zone, based essentially on the analysis of Proudmann (1952) of the production of acoustic waves by the turbulence in the convective zone. Unno (1966) extended the work of Proudmann by considering also the monopolar and the dipolar contribution and not only the quadripolar. But it is well known that there is some difficulties in the theory of the stellar wind:

-it is difficult to fit the observations with the theoretical models;

-the production of the wind is due both to the injection of energy and to the injection of momentum;

-the process itself implies all kinds of dissipative mechanism, from shock waves to a variety of plasma dissipative effects in which the topology of the magnetic field is involved,

-the important quantity is the average mass loss, coupled with the strength of the magnetic field : the Alfvenic distance and the mass loss are not the same for the quiet Sun and for the active Sun.

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What I claim here, is that the production of the solar and stellar winds is an internal structure problem; its source is in the convective zone with its turbulent motion; it involves these terms in the equations of motion which describe the compressible effects - which are usually neglected in the study of the convective zone - and finally it should take into account the presence of the magnetic field- and we know how difficult is the theory of the MHD turbulence.

We find here a fundamental problem. Magnetohydrynamics as well as hydrodynamics are based on deterministic equations. But can we say that the problem of mass loss and loss of angular momentum is also determined in the usual sense of the word determinism ? We see, in galactic clusters, that among stars which seem to obey to a common law, a few stars look anormal, just as if something different had append to them. Were the initial conditions different, with for example an anomalous initial angular momentum, or did they have a different history because they crossed a branching point which the other ones did not notice? did they have a different chaotic behaviour ? How does this apply to the Sun ? Billions of years ago, the Sun did not have the same period of rotation and if it had a periodic activity, the period was certainly not the same. Is it possible to see in billion years old sediments some trace of it, just as we see it in hundred millions years old ones ?

It is certainly a great temptation, in front of these difficulties, either to use an oversimplified model (and it is what I did ! : see section 5) or to use a completely phenomenological model, with adjustable parameters. This last method has the advantage that orders of magnitude can be derived from the comparison with the observations. But on the other hand, it hides entirely the possibility that some important physical effect has been forgotten.

4.Stability and instability.

It is well known that in the outer part of the Sun, ^{3}He is produced through the classical series of reactions (Schatzman, 1951 a, b):

$$^1H + {}^1H \Rightarrow {}^2D + e^+ + \nu$$

$$^2D + {}^1H \Rightarrow {}^3He + \gamma$$

and destroyed mainly by the reaction

$$^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H$$

Building of ^{3}He only takes place in the outer half of the Sun, whereas destruction takes place in the inner half, the maximum concentration of ^{3}He being found at about one half of the solar mass or 0.3 solar radius. In the present Sun , the maximum concentration in mass is about 3 . 10^{-3}.

I just want here to draw attention to a very unexpected effect of the ^{3}He gradient in the outer half of the Sun. Let us recall the usual definitions :

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$$\nabla = \frac{d}{d \log P} \ ; \ \Delta\nabla = \nabla_{ad} - \nabla_{rad} \ ;$$

The 3-D turbulent flow induced by the differential rotation is inhibited by the μ-gradient (Zahn, 1983) if the non-thermal part of the Brunt-Väissälä frequency - which will persist even in the presence of strong thermal diffusion - is larger than the turnover frequency of the smallest eddies present in the turbulent spectrum, those of the Kolmogorof scale. This condition can be written :

$$\nabla\mu \, (\Delta\nabla + \nabla\mu) > \frac{4}{5} \frac{1}{\nu} \frac{L r^8 \Omega^4 H_P}{G^3 M^4} \tag{8}$$

With X_3 of the order of 10-3, the μ-gradient due to 3He turns out to be , in the present Sun, of the order of 1O-4. At that level, the stability condition (8) gives $\nabla\mu > 3 \cdot 10^{-6}$ in the present Sun. With no mixing ,the μ-gradient due to 3He, would have stabilized the 3-D turbulence produced by the meridional circulation when the Sun was about two billion years old. On the other hand, it is possible to see that the rise of μ due to the production of 3He would not have stopped the meridional circulation. With a maximum concentration $Y_3 = 0.003$ reached at $t = 4.6 \cdot 10^9$ years, the μ-excess is $\Delta\mu = 0.0011$. In order to stop the meridional circulation, we should have :

$$\Delta\mu > \frac{L \, \Omega^2 R^3}{G^2 M M_r^2} r \, t_{Sun} \cong 0.015$$

and this condition is not fulfiled.

Beginning about two and a half billion years ago, diffusion of 3He towards the surface of the Sun concerned only the outer half of the hill of 3He concentration. It remains to check if this leads to a reconsideration of the constraint on diffusion coming from the surface abundance of 3He.

5. History of the rotating Sun.

5.1. BASIC ASSUMPTIONS

What we are concerned her are the initial conditions. A standard view is to consider the approach to the main sequence of a solar like star along the Hayashi track, with an initial rotational velocity close to the rotational breaking. The loss of angular momentum is such that the equatorial velocity hardly increases or even decreases, depending on the model of angular momentum losses and transport inside the star during the contraction (Pinsonneault et al, 1988), and the star reaches the main sequence with an equatorial velocity of the order of 20 km s^{-1}, as it appears to be the case for the slow rotators in the Pleiades (van Leuwen and Alphenaar, 1982; Soderblom, Jones and Walker,

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1983; Stauffer et al, 1984; van Leeuwen, Alphenaar and Meys, 1987) and in α Per (Butler et al, 1987; Balachandran , Lambert and Stauffer 1988; Stauffer et al 1988) .

However, both the Pleiades and α Per contain fast rotators (up to 200 km s^{-1}), which are as well on the main sequence. It seems possible to compare the situation to the existence of two kinds of T Tauri stars (Cohen and Kuhi 1979), the wide lines T Tauri surrounded by a disk detectable by its infra-red emission (Mendoza 1968; Cohen and Kuhi 1979; Bertout, Basri and Bouvier 1988) and the narrow lines T Tauri which do not have a disk. When there is a disk it appears to be in strong interaction with the central star. The proportion of T Tauri with a disk seems to be of the order of 10% among all T Tauri stars. It seems possible to imagine that the late presence of a disk has the effect of feeding the central star with a large amount of angular momentum. This could explain the presence simultaneously in the Pleiades and in α Per of slow and fast rotators. Stars having lost their disk at an early phase of their evolution would have reached the main sequence at a moderate equatorial velocity.

The existence of the planetary system around the Sun strongly suggests that the Sun had a disk and that it can possibly have been a fast rotator.

It seems therefore necessary to consider two scenarios for the history of the rotating Sun, and to study the consequences both for the transfer of angular momentum and for the transport of passive contaminents.

5.2. STANDARD MODEL

The loss of angular momentum depends on several effects : the geometry of the magnetic field, which determines the fraction of the stellar surface which is occupied by open lines of force, the surface value of the magnetic field, which is related to the dynamo mechanism, and the rate of mass loss. The problem of the geometry of the magnetic field has been considered by Roxburgh (1984) and more recently by Mestel and Spruit (1987). The result depends on the choice of the structure of the magnetic field (dipole, quadrupole or a distribution of bipolar magnetic spots). The value of the magnetic field at the Alfvenic distance is then related to the surface value in a complicated way.

A parametric expression of the loss of angular momentum has been given by Kawaler (1988). We shall follow here, as Durney and Latour (1978) the simple assumption of flux conservation, $B \propto r^{-2}$. Similarly, the simplest assumption concerning the non-linear dynamo is to assume that the maximum rate of growth of the magnetic field is compensated by the losses due to buoyancy (Schatzman 1988). Finally, following Durney and Latour (1978) we shall assume, as shown by Parker (1975) that the velocity of escape of the stellar wind for solar like stars (Linsky 1985) is proportional to the velocity of escape from the surface of the star, $(G\, M / R)^{1/2}$.

We shall assume that the rate of loss of angular momentum is given by :

$$I \frac{d\Omega}{dt} = - K_F \, \Omega^{7/3}$$

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The model of Schatzman (1988), does not give the exact value, but, without any parametric adjustment, provides nevertheless an excellent fit with the observed equatorial velocity of the Sun. We have the asymptotic expression :

$$\Omega = \left(\frac{4}{3} \frac{K_F t}{I} \right)^{-3/4}$$

with $(4/3)K_F = 1.16 \,.\, 10^{44}$. It should be noticed that the $t^{-3/4}$ law, which differs from the Skumanich relation (1972) has been obtained by Bohugas et al (1976).

It is easy to obtain the order of magnitude of the angular velocity gradient which, at the boundary of the convective zone, is sufficient to carry away the flux of angular momentum. With a turbulent diffusion coefficient of the order of 1000 and the present rate of loss of angular momentum, it turns out that an angular velocity gradient

$$(d\,\Omega/d\,r) \cong 5.10^{-16}$$

is sufficient to carry away the angular momentum from the bottom of the convective zone.This corresponds however to a logarithmic gradient

$$(d \ln \Omega/d \ln r) = 8.6$$

The Richardson-Townsend condition of instability of the turbulent shear flow leads to a critical value :

$$(d \ln \Omega/d \ln r)_{crit} \cong 30$$

The vertical shear flow gradient does not allow the generation of turbulence, but it should be noticed that, compared to the results of heliosismology (Dziembowski et al 1989) this is very large. It would correspond to a a change of Ω by a factor 2 over 5% of the Solar radius ! We are meeting here one of the major problems concerning mixing inside the Sun : the turbulent diffusion coefficient for the transport of angular momentum is much larger than the turbulent diffusion coefficient for the transport of passive contaminents. When considering the quasi solid body rotation from 0.7 R_O to O.3 R_O we have to introduce a turbulent diffusion coefficient at least of the order of :

$$D_T = (0.16 R_O^2/t_O) \cong 6000$$

that is to say 6 to 10 times what is needed in order to explain Lithium burning. Tassoul and Tassoul (1989) introduce a turbulent diffusion coefficient $D_{T\Omega}$ which is 10 to 20 times the coefficient D_{TX}, and Pinsonneault et al (1989) meet the same problem. It is clear that the vertical shear flow, at the boundary of the convective zone, is at most

$$(d \ln \Omega/d \ln r) \cong 0.3$$

The physical question is then the following : what is the physical origin of this large turbulent diffusion coefficient ? Magnetic field is certainly the proper answer, as it is sufficient, in principle, to have a magnetic field such that the propagation of a perturbation at the Alfven velocity from the center to the surface takes less than $4.6 \,.\, 10^9$ years · This corresponds to a magnetic field of the order of 10^{-5} gauss. However, the exact nature of the magnetic field in the radiative zone is not known, and the recent discussions of Spruit (1986) and Mestel and Weiss (1987) have just shown the difficulty of the problem.

With a larger angular velocity the turbulent diffusion coefficient due to differential rotation varies like Ω^2, but the rate of loss of angular momentum varies like $\Omega^{7/3}$. The gradient of angular momentum at the boundary of the convective zone varies like $\Omega^{1/3}$. A factor 100 on the angular velocity corresponds to an increase of the angular momentum gradient by a factor 4.6 only, and this is still below the critical value for the vertical shear flow instability.

In such conditions,the major effect seems to come from the differential rotation.

Numerical solutions have been given by Pinsonneault et al (1989), but it is worth giving an analytical approach, as it give a better insight to the physical problem.

5.3. THE LITHIUM PROBLEM.

After the introduction of turbulent diffusion mixing as contributing to the surface abundance of the elements (Schatzman, 1969), it became clear that this would affect the abundance of Lithium through Lithium burning (Schatzman, 1977). Scalo and Miller (1980) have shown that the abundance of Lithium in giants can be interpreted as the result of the dredge up taking place in stars which have destroyed their Lithium on the main sequence. Schatzman (1981) and Schatzman and Maeder (1981) have shown that the surface abundance of Lithium is a measure of the turbulent diffusion coefficient which explains the amount of Lithium burning . Schatzman (1983) noticed that, with a correct value of the masses of giants, it is possible to obtain an agreement between the results of Alschüler (19), taking into account the remarks of Scalo and Miller about the paper of Schatzman (1977), and the role of turbulent diffusion mixing in the surface destruction of Lithium. Baglin *et al* (1984) used the turbulent diffusion coefficient of J.P.Zahn in order to calculate the abundance of Lithium in the Hyades and in the Sun. The model turned out to lead to a number of contradictions and, as will be shown briefly in the following, it seems that the introduction of the proper dependence of the turbulent diffusion coefficient D_T on time can lead to a consistent explanation of the observations. This will be discussed again in the paper of A.Baglin (this meeting).

Coming back to the equation of evolution of the Lithium concentration,

$$\frac{\partial X_7}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r} r^2 D_T \frac{\partial X_7}{\partial t} - K_7(r)\, X_7 \tag{10}$$

it is possible to factorize the variables by replacing $K_7(r)$ by a step function, $K_7(r) = 0$ for $r > r_{Burning}$ and $K_7(r) = \infty$ for $r < r_{Burning}$, where $r_{Burning}$ is the burning level of Lithium. Writing

$$\Omega = \Omega_0 \left(1 + (t/t_0)\right)^{-3/4}$$

it is possible to introduce a new variable t',

$dt' = (1 + (t/t_0))^{-3/2}\, dt$

and then to use the eigenvalue equation (1). With the relation

$$\Omega = \Omega_0 \left(1 + \frac{4\, K_F\, \Omega_0^{\;4/3}}{3\, I}\right)^{-3/4}$$

and assuming that the distance h from the bottom of the convective zone to the Lithium burning level is small, we have (Schatzman 1988):

$$c = c_0 \exp\left(-0.3 \frac{2\, L\, r^6\, \Delta\nabla^{-1}\, \Omega_0^2}{G^2\, M^3\, h\, H_P \frac{K_F}{I} \Omega_0^{4/3}} \left(1 - \left(1 \frac{4\, K_F\, \Omega_0^{4/3}}{3\, I} t\right)^{-1/2}\right)\right),$$

In the case of the Sun, this gives

$$c = c_0 \exp\left(- 5.6 \left(1 - \left(1 + \frac{t}{3.10^8 y}\right)\right)\right)$$

For $(t/10^{16}) = 12$, one obtains $c= 2.10^{-2}\, c_0$. A slight adjustment is necessary (which implies the model of the non-linear dynamo) and provides the proper value of the Lithium concentration.

This expression gives the decrease with time of the surface Lithium concentration. When h goes to zero, the Lithium concentration vanishes. For finite h, there is an asymptotic value of the concentration and this can explain the finite value of the Lithium concentration of the old population II stars (Spite and Spite,1982).

Solving the diffusion equation with the WKB approximation gives a better solution. The mass dependence of K_F and of the depth of the convective zone seem to provide a nice adjustment of the abundance of Lithium in the Hyades as a function of mass.

5.4. THE FAST ROTATING SUN

The presence, among fast rotators in α Per, of Lithium rich stars (Balachandran, 1988) (they are either not or slightly deficient) is quite remarkable.

Coming back to the expression of the turbulent diffusion coefficient, it can be seen that this coefficient do vanish at a certain level, given by

$$\Omega^2 = 2\,\pi\,G\,\rho$$

The effect is a diffusion barrier. However, the effect of the diffusion barrier is important only when it is located below the bottom of the convective zone. This is possible only for the early spectral types. For a mass of the order of O.9 $M_\odot$, T_{eff}=5140 °K, this would imply V_{equ}>23Okms^{-1}. This means that for later types, say for T_{eff}<5200 °K, it is necessary to find another explanation. The hypothesis of the presence of a disk provides simultaneously the explanation of the high equatorial velocity and of the presence of Lithium. The disk provides angular momentum <u>and</u> Lithium. The abundance of Lithium is then the result of a balance between the Lithium brought by accretion and the fast destruction inside the star.If p is the rate of Lithium destruction , X_7 the concentration in the disk, and X_7* the concentration in the convective zone, we have

$$X_7^* = X_7 \frac{K_F \Omega^{4/3}}{4\,\pi\,R^4 \left(\frac{r}{R}\right)^2 \rho\,H_P\,p + K_F \Omega^{4/3}}$$

For a 0.9 $M_\odot$ star, with T_{eff} = 5140 °K, Hp = 4.21 . 10^9, T = 2.33 . 10^6 °K,

ρ = O.41 g cm^{-3}, one finds p = 4.63 . 10^{-14} s^{-1} for an equatorial velocity of 200 km s^{-1} or Ω = 3.71 . 10^{-4}, and (X_7* / X_7) = O.57 , which is quite a reasonable value.

From these quantities, it is possible to calculate the mass which has to be transferred from the disc to the star in order to satisfy the condition of conservation of angular momentum. It is about O.O3 solar masses and is quite compatible with the order of magnitude given by Bertout *et al* (1988)

After the disappearance of the disc the spin down process can start. There must be a very rapid spin down of the layers immediately below the convective zone, in such a way that the turbulent diffusion coefficient drops quickly, otherwise there would no Lithium left in these fast rotators. The propagation of the spin-down from the outside to the inside is certainly a characteristic of initially fast rotating stars. In the case of the Sun, this suggests, deep inside the Sun, a possible memory of a high initial angular velocity (Vigneron <u>et al</u> 1989). When looking at the neutrino problem, this should be kept in mind.

6. Comments.

As it has been said at the beginning, as soon as we try to obtain simultaneously a consistent theory and an agreement with the observational data we discover that new problems have to be solved . It is the aim of this conference, in making more precise the limits of our reliable knowledge, to help starting new directions of theoretical research, to suggest new observations, and perhaps to succeed not only in finding new results in fundamental physics but also in explaining a few more of the solar mysteries.

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