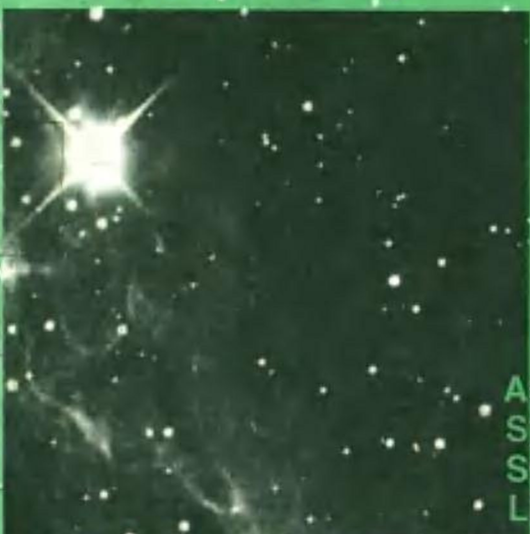
Inside the Sun

Gabrielle Berthomieu
Michel Cribier
(editors)



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INSIDE THE SUN

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INTERNATIONAL ASTRONOMICAL UNION,
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edited by

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PRÉFACE

Ce livre contient les exposés des orateurs invités au colloque IAU 121 « Inside the Sun » qui s'est tenu à Versailles du 22 au 26 mai 1989. Le but de « Inside the Sun » était d'accroître nos connaissances sur l'intérieur du Soleil et la physique qui lui est reliée, il a permis, espérons-le, un échange d'idées, de théories et d'informations entre les différents groupes. Cette conférence représente le premier pas vers une évaluation globale des idées importantes, tant théoriques qu'expérimentales, nécessaires à la compréhension de l'intérieur du Soleil. Les 175 participants de 24 pays sont la preuve qu'une communauté vivante, concernée par ce sujet existe bien. Quel endroit plus approprié que Versailles, la ville du Roi Soleil, Louis XIV, pour tenir, exactement deux siècles après les « Etats Généraux », cette sorte d' « Etats Généraux » du cœur du Soleil! A la fin de ce livre les deux petits textes historiques sont la réminiscence de cette conjonction spatio-temporelle. Enfin, bien que le temps soit resté magnifique durant toute la semaine, l'audience n'a jamais faibli.

Comme le faisait remarquer Jean Audouze dans son discours inaugural, le centre du Soleil est un sujet très interdisciplinaire. Dans les vingt dernières années, le problème des neutrinos solaires soulevé par l'expérience de Davis nous a conduit au choix suivant : soit repenser nos connaissances sur la structure du Soleil et l'évolution stellaire, soit modifier les propriétés fondamentales du neutrino avec toutes les implications que cela comporte pour les théories les plus achevées qui unifient toutes les forces fondamentales. Pendant le même laps de temps, l'héliosismologie s'est développée et a été capable de contraindre sévèrement la structure du Soleil presque jusqu'au centre. De nombreuses expériences, tant sur terre que dans l'espace, sont en cours ou en projet, et vont apporter des informations encore plus précises. Le champ magnétique, la rotation et les mouvements à grande échelle sont connus avec beaucoup plus de détails. Nous proposons d'appeler « heliophysiciens » tous ces spécialistes venus d'horizons divers qui se mettent en commun pour comprendre le problème de l'intérieur du Soleil. Une première illustration concrète : le comité d'organisation de la conférence réunissait des astrophysiciens et des physiciens des particules élémentaires.

Ces comptes rendus contiennent presque tous les textes des 30 orateurs invités et 7 des papiers soumis, sélectionnés et présentés pendant la conférence. Le plan est essentiellement celui suivi pendant la conférence. Nous commençons par la modélisation du Soleil, avec le modèle standard (qui a suscité des discussions très actives), et les exposés sur les opacités et l'équation d'état. Les résultats expérimentaux sur les neutrinos solaires précèdent les idées théoriques sur les masses des neutrinos. L'héliosismologie, présentée sous ses aspects expérimentaux et théoriques, permet depuis peu l'étude de la rotation interne du Soleil. La dynamo solaire et les phénomènes de transport sont inclus dans la même partie que les cycles solaires. Nous avions demandé aux auteurs de faire un effort de pédagogie dans leurs exposés écrits. Le rapport final de D. Gough fait le point sur tout ce qui reste à comprendre.

Trois sessions posters ont été organisées. La première session, présidée par James Rich (Saclay) était consacrée aux neutrinos solaires et aux modélisations du Soleil (26 contributions), la deuxième (29 contributions), animée par Eric Fossat (Nice) traitait l'héliosismologie et le problème de la diffusion, la troisième (36 contributions), co-organisée par Elisabeth Ribes (Meudon) et Françoise Bely-Dubau (Nice) couvrait la convection, la dynamo et le transport. Les posters restaient exposés en permanence et une très brève présentation orale au début de chaque session a permis, semble-t-il, des discussions très animées par la suite devant les panneaux. Solar Physics réunit dans un numéro spécial les papiers résultant des séances posters qui lui ont été soumis. A ce point il faut remercier les président(e)s de ces sessions qui se sont magnifiquement acquittés de cette tâche bien difficile.

Le comité d'organisation est heureux de remercier pour leurs appuis, tant financier que moral les organismes ou les sociétés suivantes : l'Institut de recherche fondamentale du Commissariat à l'énergie atomique (IRF-CEA), l'Union astronomique internationale (UAI), l' Agence spatiale européenne (ESA), le Centre national d'études spatiales (CNES), le Centre national de la recherche scientifique (CNRS), le Laboratoire d'astrophysique théorique du Collège de France, IBM, Matra Espace, Rank Xerox, la Mairie de Versailles, la Société européenne de physique (EPS), la Société française de physique, *the International Union of Pure and Applied Physics* (IUPAP)

Le comité scientifique international, présidé par E.Schatzman (Meudon) était composé de J.N.Bahcall (Princeton), R.M.Bonnet (ESA Paris), T.Brown (Boulder), R.Davis (Philadelphie), F.Deubner (Würzburg), W. Dziembowski (Varsovie), E.Fossat (Nice), D.O.Gough (Cambridge), H.Harari (Rehovot), T.Kirsten (Heidelberg), M.Koshiba (Tokyo), A.Maeder (Genève), T.Montmerle (Saclay), A.Renzini (Bologne), P.Roberts (UCLA), M.Spiro (Saclay) et G.T.Zatsepin (Moscou). Nous les remercions de toutes leurs suggestions et de leur participation active à l'élaboration du programme de la conférence.

Le comité d'organisation comprenait : F.Bely-Dubau (Nice), G.Berthomieu (Nice), J.Boratav (Saclay), M.Cassé (Saclay), M.Cribier (Saclay), W.Däppen (Saclay), B.Foing (Verrières-le-Buisson), E.Fossat (Nice), P.O.Lagage (Saclay), Y.Lebreton (Meudon), T.Montmerle (Saclay), E.Ribes (Meudon), J.Rich (Saclay), E.Schatzman (Meudon) et D.Vignaud (Saclay). Il souhaite exprimer ses remerciements très chaleureux à Jacqueline Boratav pour toute son aide, si précieuse, avant, pendant et après le colloque. Il remercie également Mmes Simone Roussiez, Dominique Brou et Mireille Kalifa ainsi que Jean-Pierre Soirat, Jacques Mazeau et Henri de Lignières pour leur appréciable soutien technique pendant les différentes phases de la conférence et de l'édition des comptes rendus.

Gabrielle BERTHOMIEU Michel CRIBIER

Editeurs

PREFACE

This volume contains the invited talks to the IAU colloquium 121 "Inside the Sun" held at Versailles, May 22-26, 1989. "Inside the Sun" aimed at increasing the knowledge on the solar interior and the underlying physics and hopefully contributed to the cross-fertilisation of ideas, theory and observations of all the groups. This conference was a first step to proceed to an assessment of all these current theoretical and experimental progress, in a global way. The 175 participants from 24 countries illustrate the existence of a lively community concerned by this subject. What site could be a better chance than Versailles, the city of Sun King Louis the XIVth, to hold exactly 200 years after the "Etats Generaux" a kind of "Etats Generaux" of what is happening in the heart of the Sun. At the end of this book, two texts are an illustration of this time-space conjunction! In spite of a wonderful weather during the whole week, the attendance was always very high.

As pointed out by Jean Audouze in his introductory talk, the interior of the Sun is a very interdisciplinary subject . These last decades, the solar neutrino problem raised by the Davis' experiment has led to the alternative of revising our view on the solar structure and stellar evolution theory or to explain it by fundamental properties of neutrinos, related themselves to the most achieved theories unifying all fundamental forces. At the same time, helioseismology developed greatly and was able to put very strong constraints on the structure of the Sun down to very near the centre. Many terrestrial and space experiments are under way or planned for the next years to obtain more accurate data. The magnetic field, the rotation and the large scale motions are also now observed in more details. We propose to call "heliophysicists" all these specialists from different fields which unite to understand fully the problem of the solar interior. To illustrate this, the organizing committee joined astrophysicists and particle physicists together.

The proceedings contain nearly all of the 30 invited papers, as well as 7 contributed papers presented during the Conference. We retain mostly for the proceedings, the plan adopted during the Conference. We thus begin by the solar modelling, including the Standard Solar Model - the related discussions were very active during the meeting - and the main inputs of physics (Equation of State, Opacities). The experimental results on solar neutrinos precede the recent theoretical ideas on neutrino masses. The subject of Helioseismology is presented both from a theoretical and experimental point of view, pointing out the recent results on the solar rotation and on the structure of the solar core. The problems of Solar Dynamo and of Transport processes are presented in connection with the Solar Cycles. The authors were asked to write their contribution from an educational stand-point. The final talk by D. Gough makes the inventory of questions that remain to be solved.

Three poster sessions were organized. The first was devoted to Solar Neutrinos and Solar Models (26 contributions), it was chaired by James Rich (Saclay), the second one (29 contributions), conducted by Eric Fossat (Nice) treated Helioseismology and Diffusion problems and the third one (36 contributions), co-chaired by Elisabeth Ribes (Meudon) and Françoise Bely-Dubau (Nice) covered the subjects of Convection, Dynamo and Transport. The posters were displayed during the whole Conference, and a brief presentation of the subject took place at the beginning of the session. The discussions were very active in front of the panels during all the breaks. Contributions presented during the poster sessions will be published in a special issue of Solar Physics. We want to thank the chairmen of these sessions who succeeded in the difficult task of allowing at the same time a short presentation of the subject, and of conducting an active discussion among the participants.

The Organizing Committee is glad to acknowledge the moral and financial support of : the *Institut de Recherche Fondamentale du Commissariat à l'Energie Atomique* (IRF-CEA), the International Astronomical Union (IAU), the European Space Agency (ESA), the *Centre National d'Etudes Spatiales* (CNES), the *Centre National de la Recherche Scientifique* (CNRS), the *Laboratoire d'Astrophysique Théorique du Collège de France*, IBM, *Matra Espace*, Rank Xerox, the *Mairie de Versailles*, the European Physical Society (EPS), the *Société Française de Physique*, the International Union of Pure and Applied Physics (IUPAP)

The members of the International Scientific Committee, chaired by E.Schatzman (Meudon) were J.N.Bahcall (Princeton), R.M.Bonnet (ESA Paris), T.Brown (Boulder), R.Davis (Philadelphia), F.Deubner (Würzburg), W. Dziembowski (Warsaw), E.Fossat (Nice), D.O.Gough (Cambridge), H.Harari (Rehovot), T.Kirsten (Heidelberg), M.Koshiba (Tokyo), A.Maeder (Geneva), T.Montmerle (Saclay), A.Renzini (Bologna), P.Roberts (UCLA), M.Spiro (Saclay) and G.T.Zatsepin (Moscow). We are very grateful to them for suggestions and active participation in the elaboration of the program.

The Organizing Committee was composed of F.Bely-Dubau (Nice), G.Berthomieu (Nice), J.Boratav (Saclay), M.Cassé (Saclay), M.Cribier (Saclay), W.Däppen (Saclay), B.Foing (Verrières-le-Buisson), E.Fossat (Nice), P.O.Lagage (Saclay), Y.Lebreton (Meudon), T.Montmerle (Saclay), E.Ribes (Meudon), J.Rich (Saclay), E.Schatzman (Meudon) and D.Vignaud (Saclay). This Committee wishes to express special thanks to Mrs Jacqueline Boratav for her dedicated work before, during and after the Colloquium. He wishes to thank Mrs Simone Roussiez, Dominique Brou and Mireille Kalifa as well as Jean-Pierre Soirat, Jacques Mazeau and Henri de Lignières for their valuable technical support in the different parts of the Conference and of the edition of these Proceedings.

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The Editors

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INTRODUCTION

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ABSTRACT

1. Evolution of the modelling of the inside of the Sun, from "standard models" to the more empirical approach used now, and based on neutrino astronomy, solar sismology, and the interpretation of active phenomena. 2. New concepts introduced in the set of physical equations valid inside the Sun, under the pressure of new observations. 3. Similar trends seeming to affect in a comparable way the modelling of the solar cycle. 4. Other stars, and the improved knowledge of solar evolution may help to understand many observed features of rotation, magnetism, etc...Conclusion : the Sun is "one", - and it cannot safely be studied piecemeal.

1. For a very long time, and until only quite recently, it was customary to consider that the only informations one had about the physical conditions inside the Sun were the global informations concerning our star, namely its mass, its radius, its luminosity. The spectrum was also, in a way, a set of information : but the chemical composition of the atmosphere was not necessarily representative of the evolved composition of the core, unless completed by the age of the Sun (as inferred from solar system studies) and a theory of its evolution, in particular an history of how mixing has been operating since the start of nuclear reactions.

From this limited amount of data, "models" were built of an evolved Sun. A given initial composition of the gaseous sphere, the game of thermonuclear reactions, the use of radiative equilibrium (where allowed), of hydrostatic equilibrium, of thermodynamic equilibrium, and wherever necessary, a proper account of convective instabilities (using then, in convective layers, the mixing-length theory, with a somewhat arbitrary ratio l/H) - this set of equations being completed by oversimplified boundary conditions at the "solar surface" - this was in essence enough to be happy with, once one has succeeded, the computation finished, in matching the values of mass, radius, luminosity, and in insuring that initial composition, age, and actual atmospheric composition were at least compatible.

One of the greatest challenges in solar modelling was therefore not getting the necessary observations, but performing with accuracy the solution of very difficult systems of equations. As the

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author of an introduction is, I presume, free to express his own idiosyncrasies, I would define this period as dominated by numerical acrobatics, and regrettably far from physical insight or accurate data.

But it was clear, however, for almost any one in the field, that many phenomena, although well-known by the observers, were unduly ignored by the modelists. Rotation, and its latitudinal differential behaviour, convection, and the complex imbrication of convective cells and turbulent motions, magnetic active phenomena, and their obviously deep-rooted origin, cycles of activity and the general magnetic field of the Sun, - all these phenomena, and most of their interplays were known; but none was properly taken into account in modelling the inside of the Sun, and many were not even completely understood.

2. Fast progress came a few decades ago, from various new advances in techniques and in observations.

First of all, the quick development of high-speed performant computers allowed theoreticians to tackle more ambitious programs. But often, very gratuitous style exercises were performed, without enough attention being paid to the physical value of the game. At least, everything seemed to become possible...

Then the accuracy with which physical constants were known (cross sections of nuclear reactions, opacity tables, ionic and atomic processes), even improvements in such things as the equation of state, allowed the astrophysicists to work on safer grounds.

Finally, new phenomena were discovered. Not only was the explored electromagnetic spectral range considerably extended, allowing the discovery of such coronal features as coronal holes, bright X-ray points, etc..., but other messages from the Sun began to be deciphered ; the neutrino flux gives direct information concerning what happens in the Sun's core; and the oscillation frequencies spectrum can be inverted (as for sismic waves on Earth) and provides us with values of the sound velocity as a function of depth; even, in principle, it can also provide the solar physicist with the rotational velocity as a function of depth. But one can also state that abundances of ^{3}He in cosmic rays, or of ^{7}Li in the solar atmosphere may reveal much about the physical conditions at the bottom of the convective zone, and can be very useful clues.

Active phenomena, although still far from being understood in many of their more important aspects, give also clues during the various phases of the solar cycle, concerning the general behaviour of convective cells which act in dragging out magnetic tubes of force before they actually can emerge, and concerning the properties of the solar magnetic field embedded in the deep Sun. These clues request certainly much effort towards a real understanding of their meaning. But no theory can avoid to match these data, even if some of them are still ambiguous and perhaps compatible with quite different types of theories.

Thus, in a few decades, "modelling the Sun" became a completely different concept. From a very "abstract" approach, essentially a study a priori of gaseous spheres, based upon the solutions of the equations of internal structure, one has progressively been led to an almost "empirical" approach, where the ideal (standard) model serves only as a starting block, improved in its details on the basis of successive observational refinements.

3. In this new approach, a close cooperation is necessary with the physicists, as contradictions appear between the refinements derived from different observational sources : as an example, we must note that the apparent depletion in the observed flux of neutrinos (compared with the expectations of standard models) has led to a stimulating interchange between physicists and solar physicists : has the solar structure to be modified ? or are the neutrinos behaving differently from what was previously thought ?

Improvements in the physics of the internal regions of the Sun are thus a by-product of this approach. Not only do they concern some basic physics (such as the neutrino physics), but also they imply the introduction of some concepts already known, but now thought to be relevant, in the equations of solar structure. For example, it is clear that diffusive processes have to play a part either by reintroducing in the core unprocessed matter, or by allowing some atoms, produced in the core, to reach the convective layers and to be observable in the spectra. But we have not yet reached a state of affairs where it is safe to assert quantitatively the effects of diffusion ... Clearly also, the phenomenological mixing-length theory has to be refined, to justify "the" good choice of the ratio l /H, and even to be replaced by some exact hydrodynamical theory. Above and below the convective layers, one has also to take into account overshooting : in itself, this process leads us to think that one cannot treat the transition layer between radiative inner or outer zones and convective zone as spherically symmetric. And departures from spherically-symmetric geometry yields to local instabilities which may well affect the transport of magnetic fields. Similarly, granulation affects the geometry of the photosphere, and abundance determinations may be sensitive to departures from spherically-symmetric geometry, - as they were already known to be sensitive to departures from local thermodynamic equilibrium. These sensitivities may, in their turn, affect the opacities.

4. Modelling the cycle of activity is developing more slowly than modelling the averaged Sun. Still the progress follows similar lines. A few years ago, one computed with great accuracy dynamo models of the Sun, which were assumed to be linear, and, even under their non-magnetic aspects, grossly oversimplified. Nowadays, the highly non-linear character of the solar dynamo has been widely recognized. Assuming the observed characteristics of the emergence of active regions to be strongly coupled with the general features of the magnetic field, and with the hydrodynamical properties of the Sun, one can think of some partly theoretical, partly empirical description of the solar cyclic behaviour. There is a little doubt that much progress will come from that kind of approach in the years to come.

5. For years, in the "old days" as well as more recently, much emphasis have been given, in an almost purely literary or philosophical perspective, to statements such as "the Sun is a star", or even "the active Sun is a star". True of course! ... But the present state of our knowledge of active phenomena in stellar atmospheres, as well, on another side, as the theory of stellar evolution which affects all stellar layers, allow us to consider that the Sun is a body on its way from birth to the normal stellar life, and finally to its death as a main-sequence star. One has to understand not only how is the Sun behaving the way it does, but why. Conservation of energy, of momentum ... allow to reconstruct pre-stellar conditions, or to account for the distribution of magnetism and rotation in the Sun, or even in the solar system.

CONCLUSION

Therefore, one cannot escape the conclusion, obvious and trivial, but important, that the Sun is one object, in which the different layers are coupled with each other, in which the past conditions commands the future. One cannot treat a given solar region - say the convective layer - without taking into consideration the boundary conditions linked with what happens in the surrounding (radiative, in the chosen example) regions. One cannot understand one aspect of solar physics without some idea on the history of the involved matter and of its behaviour. In other terms, solar and stellar physicists cannot divide in overspecialized groups without risking to loose the very essence of their problem. We are well beyond the first approximation, well beyond the linearizations, in front of a highly coupled, highly non-linear set of physical equations. Solar physics cannot be reduced to a simple-minded modelling, according the "standard" line, whatever its merits as a good starting point.

AKNOWLEDGMENTS

This meeting has been co-organized, under the auspices of the I.A.U., by physicists and by astronomers, which, in itself, happily symbolizes the spirit of the new solar astrophysics. In particular, I would like to acknowledge the important work, behind or in front of the scene, of J. Boratav and of the Saclay physicists, M. Cribier, T. Montmerle and D. Vignaud. The chairman of the Scientific Organizing Committee has been Evry Schatzman. One should outline the fact that almost all aspects of the solar physics have been successfully tackled by Schatzman; he has been a novator in many of them. I want to thank him personally, for all what I have learnt from him, over more than four decades.

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