

## What Can We Learn From the Sun's Interior Useful for Understanding Solar-Terrestrial Links?

J.P. Rozelot

Observatoire de la Cote d'Azur, Gemini Department, France, rozelot@obs-azur.fr

*The baryonic Universe is mainly composed by plasma and so, magnetism plays a fundamental role. However, magnetism is still poorly known. Equations of magnetic field are not yet taken into account in all the equations describing our Universe, and in particular in stellar (and solar) equations. Nevertheless, it is known that the magnetism of the solar interior has a key role. Understanding this role will permit also to understand better our terrestrial climate, as all the interplanetary medium is bathing into this magnetic field. New results from various space and ground-based experiments monitoring the radiative and particle emissions of the Sun, together with their movement in space and their terrestrial impact, have opened a new era in both solar and atmospheric physics. These studies clearly show that the variable solar radiative and particle output affects the Earth's atmosphere and climate in many fundamental ways. The main goal of this paper is to emphasize the Sun as a unique object for which we may hope a quantitative approach before generalization to other more energetic objects. The slow and organized activity of the Sun is not a superficial phenomenon: it implies the core, where most of the mass is concentrated, and we are still far to control mechanisms (rotation, spin,...). The surface manifestation of the irradiance might be not only a surface manifestation of the magnetic activity, and could take its origin in deeper layers. Some dedicated space joint missions, such as SDO, GOLF-NG or PICARD will help us to make significant progresses on this way.*

### Introduction

At the beginning of this 21<sup>st</sup> century, the solar astronomy showed an exceptional vitality, and major discoveries were made. One may quote, just as an example, the depiction of the tachocline and that of the leptocline. The first one is certainly the seat of the solar magnetism, and the second, those of strong temporal size inversions in the stratification layers just below the surface.

One of the essential openings is the attempt to understand the phenomena taken more and more in their globality. It is a very difficult task to want to apprehend the whole coupling Sun, i.e. the heliosphere-magnetosphere links. While being interested in each "object" composing this single system, Sun, solar corona, interplanetary medium, terrestrial magnetosphere, ionized planetary environments, the studies in progress seek to answer some major scientific questions which can be summarized as follows, at least limited to the Sun and its nearest environment:

What is the origin of the solar magnetic cycle? What is the internal topology of the magnetic field? What is its evolution in time? What is the fine structure of the tachocline, a singular transition zone between two different physical modes? In the deepest layers, ( $r < 0.2 R$ ) what is the rotation rate? What is the direction of the axis of rotation? How is this directly related with the cyclic activity? And with the luminosity?

What is the exact structure of the magnetic field above the photosphere, and how it takes its roots at the photospheric level? What is the link between the structured patterns and "the take-off" of the protuberances and the coronal mass ejections?

It is not useless to identify such questions as magnetism is still poorly known. Equations of magnetic field are not yet taken into account in all the equations describing our Universe, and in particular in stellar (and solar) equations.

What we see on the surface is the manifestation of intense physical processes which are initiated in the core, and we hardly begin to "see" how these mechanisms progress from the deepest layers up to the surface. The slow and organized activity visible of the Sun's surface is not a superficial phenomenon alone: it implies the core, where most of the mass is concentrated, and we are still far to control all the mechanisms, mainly rotation and, spin. On the same way, the surface manifestation of the irradiance might be not only a conversion of the magnetic activity, but could take its origin in deeper layers. In this paper we will make a review of the internal solar layers, from the core to the surface.

### The solar core: still an enigma

The major part of the solar mass is concentrated in the core: about 25% is distributed between 0 and  $0.48 R$  and about 98% up to  $0.71 R$ ! If we look below to  $0.2 R$ , some important questions are still pending, that we can summarize as follows:

- what is the rotation in the solar nuclear core, is it rigid rotation or is there a latitudinal dependence ?
- is there a relic of the formation of the solar system: is there a higher rotation profile in the core?
- can we see magnetic field effects coming from the core and could we follow their temporal variability?
- is there an oblique rotator?

Answers to such questions are significant to elucidate the formation of the magnetic field, the origin of the solar cycle, hence, its predictability, which is a key point for the solar-terrestrial links.

Inspection of Fig. 1, where it is plotted the rotation velocity rate versus the fractional solar radius, indicates that the solar core may rotate at a higher speed, likely 500 nHz instead of 435 nHz in the central part of the Sun ( $0.2 < r < 0.6 R$ ).

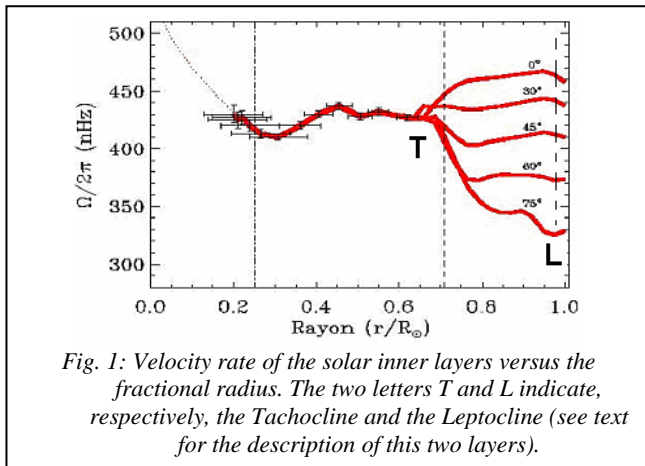


Fig. 1: Velocity rate of the solar inner layers versus the fractional radius. The two letters T and L indicate, respectively, the Tachocline and the Leptocline (see text for the description of this two layers).

## Two major layers: the tachocline and the leptocline

The tachocline is located at the interface between the latitude-dependent rotation of the convective zone and the rigid radiative interior (around 435 nHz). We can emphasize three main reasons why this layer is of particular interest. First, the shear turbulence inside this zone may provide a mechanism for mixing material between the radiative and the convective zones. The profiles of density (and sound-speed) show a difference with the standard model which has been explained by a depletion of Lithium, likely the relic of the ancient Sun. Secondly, the tachocline may be the seat for angular momentum transport processes that could lead to the observed rigid rotation rate of the radiative interior. The vertical shear may be hydrodynamically unstable near the base of the convection zone at  $r = 0.713 R$ , but this region of instability is confined to low latitudes and does not extend deeper than  $r = 0.695 R$  (the thickness of the tachocline is approximately  $0.02R$ , and the question is to know why this zone is so thin). Thirdly, the tachocline is the seat for an oscillatory solar dynamo which is believed to be responsible for the solar 22-year magnetic cycle. Moreover, Hove et al. [1] have detected changes in the rotation with a period of 1.3 years at low latitudes (Fig. 2). At last the tachocline appears prolate ( $r_x = 0.67R$  and  $r_y = 0.73R$  where  $r_x$  and  $r_y$  are the semi-axis of an ellipse). An excellent review of the tachocline has been made by Garaud [2].

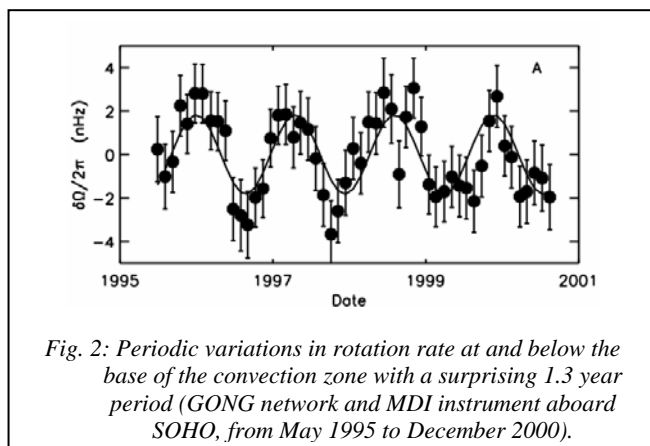


Fig. 2: Periodic variations in rotation rate at and below the base of the convection zone with a surprising 1.3 year period (GONG network and MDI instrument aboard SOHO, from May 1995 to December 2000).

The Leptocline has been put in evidence by Godier and Rozelot [3-5]. This thin shell is indeed constituted by two layers, one located at around  $0.989R$  and the other at the very near surface, around  $0.994R$ . They are the seat of a strong radial shear leading to a distorted outer surface, with a bulge

near the equator and a depression at the top of the royal zone, the whole shape remaining oblate [6]. This can be also interpreted as the reversal of the rotational radial gradient ( $\partial\Omega/\partial r$ ), which is  $< 0$  from  $0^\circ$  to around  $50^\circ$ , then cancel and being  $> 0$  afterwards. Finally, the leptocline is closely associated with the photospheric radius. It has been recently shown that the variability of the “helioseismic” radius is in antiphase with the solar activity, with the strongest variations of the stratification being just below the surface, around  $0.995R$ . In addition, the radius of the deeper layers of the Sun, between  $0.975$  and  $0.99$ , changes in phase with the 11-year cycle.

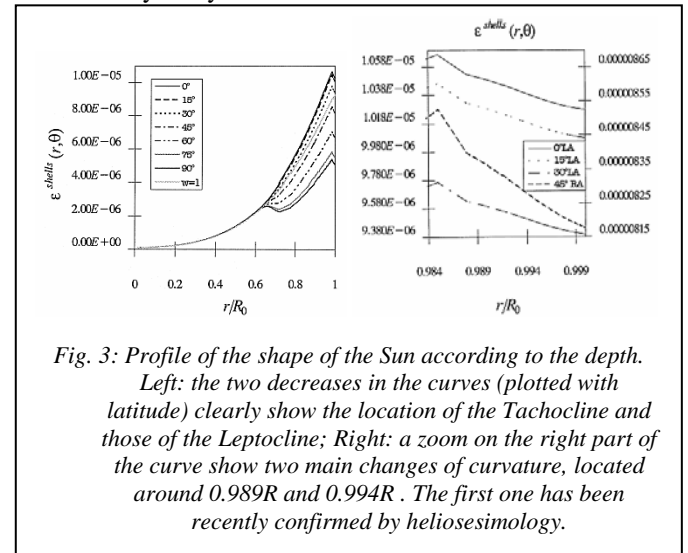


Fig. 3: Profile of the shape of the Sun according to the depth. Left: the two decreases in the curves (plotted with latitude) clearly show the location of the Tachocline and those of the Leptocline; Right: a zoom on the right part of the curve show two main changes of curvature, located around  $0.989R$  and  $0.994R$ . The first one has been recently confirmed by heliosesimology.

This complexity must be taken into account for understanding the way the surface magnetism is produced and observed.

## Solar irradiance variability: a new approach

Latitudinal variations (asphericity) as seen above are a key parameter in the solar machine. Thermal asphericity induced by convective motions may give rise to latitudinal irradiance variations in the photosphere which can in principle be measured. However, in practice, such variations are dominated by magnetic features such as sunspots and faculae, making it difficult to distinguish purely thermal effects. Early estimates of the pole-equator temperature difference [7] were only able to set upper limits of a few K. After removing the facular contribution, Kuhn et al. [8] report residual irradiance variations which they interpret as latitudinal temperature variations. The temperature peaks at low latitudes in warm bands which correlate well with the magnetic activity belts (or royal zone), propagating toward the equator as the cycle progresses. A second component is also present, consisting of warm poles which exhibit little variation over the course of the activity cycle. The amplitudes of the low and high-latitude maxima are about 3K and 1K, respectively, relative to the temperature minimum at mid-latitudes. The pole-equator temperature has been recently revisited by Fazel et al. [9] who reported that, if the magnetic network (spots and faculae) causes the largest part (around 95%), of the observed modulation of the irradiance (which is around 0.01% over the solar cycle), the remaining could be explained by radius and effective temperature variations (of no more than  $dT = 1.2$  K and  $dR = 10$  mas in amplitude,

two values consistent with the most recent observations made at Kitt Peak by W. Livingston for the photospheric temperature and by Kuhn et al. on board SOHO). Furthermore, Fazel et al [9] underline a phase-shift (correlated or anticorrelated radius and luminosity variations) in the (dR, dT) parameter plane, in agreement with what happens in the leptocline. They suggest also a mechanism to explain faint changes in the solar shape due to variation of magnetic pressure: as the flux tubes are confined between the granulation cells and do not interact with the granules, the magnetic pressure may contribute to their contraction in size during the rise of magnetic activity and to their expansion during the declining phase. Such an interpretation is supported by an estimate of  $w$ , the asphericity-luminosity parameter, found to be  $-3.5 \cdot 10^{-3}$ . This value implies an effectiveness of convective heat transfer only in the very outer layers of the Sun.

### Sun-Earth coupling

The whole system Sun-magnetosphere-ionosphere-thermosphere-atmosphere is obviously extremely complex. Its study goes presently through a double approach:

- first, to understand in detail all the components of the system and, in particular, their response to the solar energy emitted through multiple ways; such an approach can be found for instance in [10];

- then, to predict solar variability and, thereafter, the chain of foreseeable effects in the magnetosphere and the ionosphere.

In this chain, still a puzzle, it is necessary at a very first step to recognize the active areas of the Sun where solar flares and coronal mass ejections (CMEs) may be born. Then, measurements in an advanced point on the Sun-Earth line (such as a Lagrange L1 point) will allow obtaining invaluable information on the propagation and the development of these CMEs, approximately an hour before they do reach the Earth orbit. At the interior of the magnetosphere, knowledge of the radiation belts, their structure, their dynamics, their association with solar events is absolutely necessary and require multiple satellites on adapted orbits (see for instance [11]).

From a prospective point of view, we suggest privileging the coherent and concerted programs, such as the International "Living With a Star" program (ILWS) set up and coordinated by NASA. This program comprises several "links", but among them the three following satellites useful for our study:

- The Solar Dynamic Observatory (already decided, launching in 2008) which will study the nature and the solar variability sources, the variations of the magnetic field, and the relations of this field with the ejection of mass and energy;

- The PICARD microsatellite scheduled to be launched by 2008. The scientific objectives of this mission are primarily turned towards the improvement of our knowledge of the relations between the climate of the Earth and the Sun, by simultaneous in orbit measurements including the solar constant, the shape of the Sun, the UV radiance and their variability in time; complementary helioseismologic measurements (g-modes) will make possible to reach the internal structure of the Sun. This mission is based on climatic historical data which tend to associate the reduction of the solar constant to the observed variations in the Earth

global temperature [12] and hence seeks to explain how such effects can be implemented and may affect the thermal and dynamic structure of the stratosphere and troposphere [13].

- The GOLF-NG microsatellite, already decided and expected to be launched by 2008-2009, whose fundamental objectives are to reach the solar core by detection of the g-modes and to try to get a 3-D vision of the Sun [14]. Observational diagnoses on the structure and the dynamics of the Sun remain the strong points of this mission which pursues many goals with an undeniable originality.

The atmosphere is the final link of the Sun-Earth chain, and is the place where energy converts and where our close environment is influenced. This last link is surely the most complex and its study will certainly still take a long time.

Another interesting aspect is the study of the interaction between the higher atmosphere and the ionosphere of the Earth which is the central objective of the microsatellite TARANIS mission (Tool for the Analysis of Radiations from lightning and Sprites). The manifestations of the coupling with the active stormy cells are numerous: light outputs in the middle atmosphere ("sprites"), gamma emissions of terrestrial origin with considerable energies, associated electromagnetic waves. Among the possible linking mechanisms, an avalanche phenomenon of relativistic electrons initiated by the impact of cosmic rays could be with the source of the "sprites". In addition, the associated electromagnetic wave propagation could induce couplings with the terrestrial magnetosphere and consequently a loss inside the belts of radiation.

### Conclusion

We are entering an exciting new age in the exploration of the solar interior.

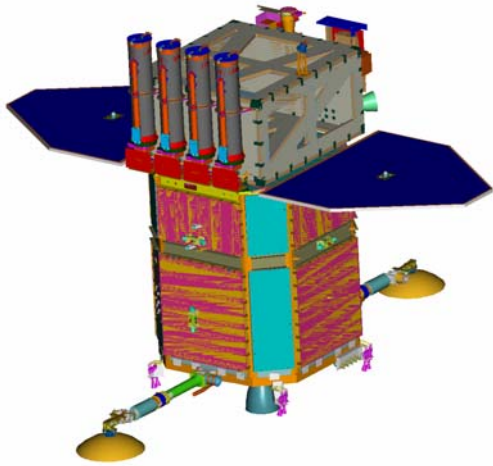
We are living in the extended atmosphere of an active star. While sunlight enables and sustains life, the Sun's variability produces continuous streams of high-energy particles and radiation that can affect life.

Under the protective shield of the Earth magnetic field, our planet is an island in the whole solar system where life has developed and flourished. The origins and fate of life on Earth are intimately connected to the way the Earth responds to the Sun's variations. Understanding the changing Sun and its effects on the Solar System, life, and society is therefore an important goal for our mankind.

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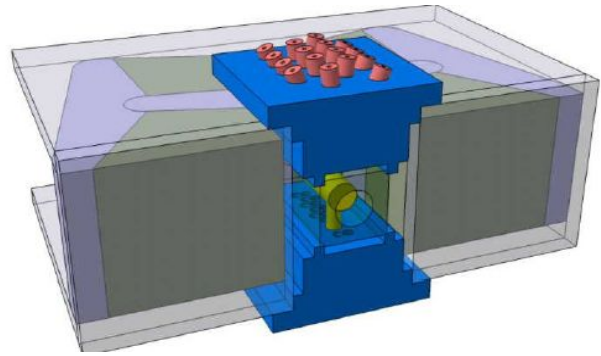


### SDO (Solar Dynamics Observatory) (2008-2013).

First Space Weather Research Network mission in the "Living With a Star" (LWS) Program of NASA. SDO is being designed to help us understand the Sun's influence on the Earth and Near-Earth space through the study of solar atmosphere on small space/time scales, in different wavelengths simultaneously (after Alan Title, PI Institution: Lockheed Martin Missiles and Space Advanced Technology Center).

The four main goals are:

- understand the solar cycle,
- identify the role of the magnetic field in delivering energy to the different layers of the solar atmosphere,
- study the space/time (from seconds to centuries) evolution of the outer regions of the Sun's atmosphere,
- monitor solar radiation (ex: UV, EUV) levels.



### GOLF-NG (Global Oscillation at Low Frequencies, New Generation) (2010-2012) : the main instrument.

Resonance spectrometer in the D1 sodium line. PI: S. Turck-Chieze SAp/DAPNIA/CEA – Saclay.

Through measurement of low-degree solar global acoustic modes and some gravity modes during at least one or two solar cycles, the mission aims at:

- understanding internal solar magnetic processes in the radiative region and their time evolution. Those are indeed at the origin of cyclic and non-cyclic surface magnetic phenomena,
- description of the solar core through constraints on the solar matter distribution and core dynamics,
- study of latitudinal rotation of the whole radiative zone.