THE MAGNETISM OF THE SOLAR INTERIOR FOR A COMPLETE MHD SOLAR VISION

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Abstract

The solar magnetism is no more considered as a purely superficial phenomenon. The SoHO community has shown that the length of the solar cycle depends on the transition region between radiation and convection. Nevertheless, the internal solar (stellar) magnetism stays poorly known. Starting in 2008, the American instrument HMI/SDO and the European microsatellite PICARD will enrich our view of the Sun-Earth relationship. Thus obtaining a complete MHD solar picture is a clear objective for the next decades and it requires complementary observations of the dynamics of the radiative zone. For that ambitious goal, space prototypes are being developed to improve gravity mode detection. The Sun is unique to progress on the topology of deep internal magnetic fields and to nderstand the complex mechanisms which provoke photospheric and coronal magnetic changes and possible longer cycles important for human life. We propose the following roadmap in Europe to contribute to this "impressive" revolution in Astronomy and in our Sun-Earth relationship: SoHO (1995-2007), PICARD (2008-2010), DynaMICS (2009-2017) in parallel to SDO (2008-2017) then a world-class mission located at the L1 orbit or above the solar poles.

Key words: Sun; solar magnetism; solar rotation; gravitational moments; celestial mechanics; general relativity

1. Introduction

Magnetic field plays a fundamental role in the Universe. Most of the celestrial bodies are rotating and dynamo action produces or amplifies magnetic field in stars, planets and galaxies. But different kinds of dynamo must be studied, it is now believed that the initial conditions are important to understand stellar and galactic magnetic fields (Rudiger & Hollerbach 2004). We need to determine magnetic field saturation growth and which magnetic configurations are stable (Spruit 2002). We have today a very poor information on this difficult ingredient of Astrophysics and it is partly why it is absent from most of the present simulations. Nevertheless, its role is extremely crucial in star formation, to reproduce the extension of the convective zone in young stars (D'Antona et al. 1998, Piau & Turck-Chièze 2002), and probably to model massive pre-supernovae... Moreover, it begins to be an important ingredient to precisely estimate the Sun-Earth relationship and to predict coming and possibly different solar cycle(s).

Nowadays 2D-3D simulations are quickly developing, although the capabilities of the more advanced computers are still limited for realistic simulations. Observational constraints are extremely important to orientate this effort; the Sun is the only star for which detailed internal dynamical phenomena can be observed. Thus new solar missions are crucial for next decades, in parallel to the development of asteroseismology and exoplanet finding.
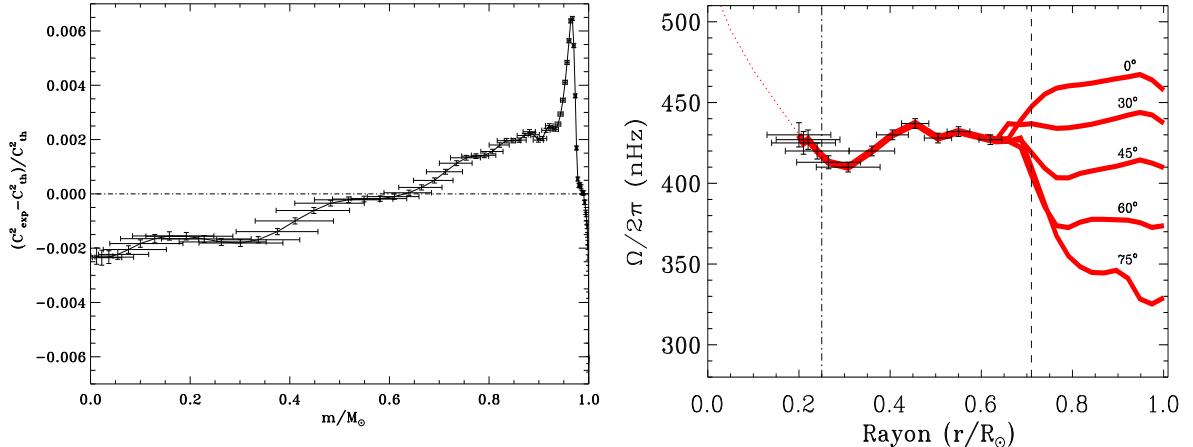
Figure 1. Left a) Relative squared sound speed difference between a standard model (Turck-Chièze et al., 2001a) and the Sun, using GOLF+MDI observations (Bertello et al, 2000), versus the fraction mass. One notices a spatial resolution of about ±6% in mass and an absolute determination of the sound speed of the order of 10^{-4} (Turck-Chièze et al, 2001b). The transition between radiation and convection in located at about 98% in mass fraction. Right b) Solar rotation profile deduced from acoustic mode observations done by GOLF/MDI aboard SoHO (Kosovichev et al 1997, Couvidat et al. 2003a, Garcia et al. 2004).

The classical stellar structure equations include a rich microphysics and indirect rotation effects but they still ignore magnetic field and magnetic field transport effects. 3D Magneto Hydro Dynamics simulations tentatively describe the internal motions for portions of stars with a limited description of microphysics and limited timescale. We need observational internal constraints on the dynamical processes from the core to the surface and beyond to build a realistic complete MHD description of stars and their environmental planets. In this respect, we cannot ignore the dynamics of the solar radiative zone which represents 98% of the solar mass (Fig 1a). Direct and indirect informations on internal magnetic fields will come from new space solar observations.

The SoHO mission has been successful to induce the first step towards this complete MHD vision of our Sun; the most important results are rapidly summarized in section 2. As the already programmed missions will largely improve the convective zone, photospheric phenomena and corona, we will mainly focus on the radiative region which needs continuous activities during the next two decades. The dynamical processes connected to rotation, magnetic field and internal waves are introduced in section 3. The great interest for complete MHD simulations is demonstrated in section 4 and the open questions for observers are recalled in section 5. Gravity modes are the extremely promising probes for the radiative zone (section 6): they are actively searched with the SoHO satellite and stimulate coordinated efforts to improve the signal/noise ratio in the next generation of instruments. The last section 7 is devoted to the missions which must fly during the next two decades. Two techniques are presently studied and must be launched quickly to be validated: a prototype of a space Resonant Spectrometer will be installed in Tener-ife in 2006 and another prototype of a Magnetic Optical Filter at Dome C. In confronting the open questions, the present scheduled missions and the improved techniques, we build a roadmap for Europe which converges to our objective: a complete MHD solar vision at the horizon 2018 with a world-class mission at the Lagrangian point or above the solar poles.

2. Fifteen years of seismic solar investigation

Ground networks and the three space seismic instruments aboard SoHO have dramatically changed our stellar vision. From a static picture, we have slightly evolved towards a more dynamical view, thanks to the detection of most of the acoustic modes. Some theoretical concepts as meridional circulations or latitudinal flows have become reality in the upper convective zone. The slow migration from high latitudes to the equator of the superficial spots have been followed in time and in depth during the last half cycle showing migrating bands rotating faster or slower. The torsional oscillations corresponding to time variations of the solar rotation (Howe et al. 2000, Antia & Basu 2000, Vorontsov et al. 2002) are nowadays confronted to non linear axisymmetric mean-field dynamo model (Vorontsov et al. 2003). The solar rotation profile (Fig 1b) has been nowadays properly established down to the limit of the nuclear core (Kosovichev et al, 1997, Chaplin et al. 2001, Couvidat et al. 2003a, Garcia et al. 2003). In contradicting all the theoretical predictions it represents today a strong challenging information for theoreticians (see sections 3 and 4). The thin width of the tachocline (transition region from differential rotation to flat rotation) of about 5% solar radius, plays a strong role in the understanding of the solar dynamo (Brummell, Cline & Cattaneo 2002 and section 4). The sound speed profile is

now very precisely established (Fig 1a, Turck-Chièze et al. 2001a,b; Couvidat et al. 2003b)) down to 6% R$_\odot$ but this information is extracted from the low frequency acoustic modes, which are less influenced by the turbulence and the magnetic field of the superficial layers. However the spatial resolution is not sufficiently good to get a proper determination of the density profile.

Despite these unprecedent advances useful not only for the Sun but also for all the stars, magnetic field is only directly constrained just below the photosphere, elsewhere only upper limits are presently available.

3. The internal radiative solar (stellar) dynamics

Considering that the American project SDO will largely improve our knowledge of the convective zone, we will mainly concentrate in this presentation on the radiative zone. The main stellar results come from classical stellar evolution codes which suppose that the star is spherical and is not influenced by magnetic field.

In these models, radiation zones are treated as stable regions, where no motion occurs, apart from rotation in some specific cases. But various observations (i.e. surface abundances, sound speed profile) show that these zones are the seat of mild mixing. The most likely cause of such mixing is the (differential) rotation, which drives a large scale meridional circulation and gives probably rise to shear turbulence. This process has been described in a self-consistent way, namely taking into account the transport of angular momentum which modifies the rotation profile (Zahn 1992, Maeder & Zahn 1998). Series of models have been built which include these processes, called rotational mixing (Talon et al. 1997, Meynet & Maeder 2000, 2005), and for massive stars, the agreement with observations is largely improved. However, rotational mixing alone cannot explain the almost uniform rotation of the radiative interior of the Sun, as revealed through helioseismology (Couvidat et al. 2003a, Thompson et al. 2003). Therefore, another more powerful process is probably operating, at least in slow rotators.

Two ideas have been proposed to explain the quasi-flat solar rotation profile, namely magnetic torquing (e.g. Charbonneau & MacGregor 1993, Gough & McIntyre 1998, Garaud 2002) and momentum redistribution by internal gravity waves (Talon et al. 2002). Much theoretical work is currently done in order to take into account these physical mechanisms. A new theoretical frame suggests to treat simultaneously the core of the radiation zones and the tachoclines (Mathis & Zahn 2004), in order to capture the mixing which occurs there (Spiegel & Zahn 1992, Brun et al. 2002). Also better prescriptions now exist to describe the anisotropic turbulent transport (Maeder 2003, Mathis et al. 2004) as well as equations to consistently introduce the effect of a fossil magnetic field (Mathis & Zahn 2005) as was attempted previously by Mestel et al. (1988). The only way to treat the unstationary problem in a consis-
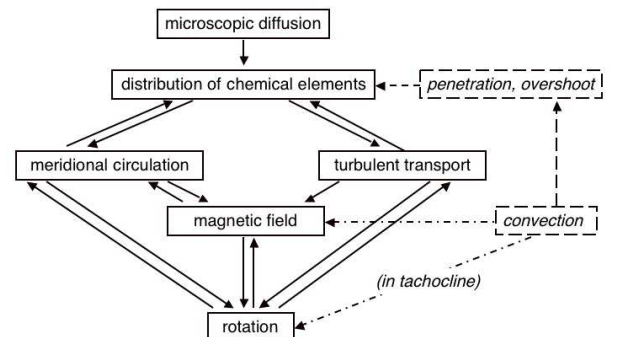

Figure 2. Transport and mixing processes in stellar interiors with magnetic field: a highly non-linear problem.

tent way is to take into account the advection of the field by the meridional circulation, the production of toroidal field (by shearing the poloidal field through the differential rotation), but also the feedback of the magnetic field on the rotation profile and on the circulation, through the Lorentz force (see figure 2). Presently, work is in progress to implement these equations in stellar evolution codes.

In the case of internal gravity waves, Talon & Charbonnel (2005) recently developed a formalism to describe the evolution of the rotation profile over evolutionary time-scale, by modeling the effect of the rapidly oscillating shear layer generated by waves just at the base of the surface convection zone and originally described by Ringot (1998), see also Kumar, Talon & Zahn (1999). For a given wave flux generated by turbulence in the convection zone, it is now possible to predict the state of radial differential rotation at the solar age, which, for conservative estimates of the wave flux, is rather flat (Charbonnel & Talon 2005). Details regarding the core rotation rate are crucial to distinguish between the two mechanism exposed here.

4. Radiative Interior MagnetoHydrodynamics

Many models and simulations have been developed to understand the complex interactions between convection, turbulence, rotation and magnetic field seen at the solar surface and in its upper atmosphere. Most of these studies have been carried out in the context of the solar dynamo puzzle or in an attempt to model the intricate solar atmosphere, but very few to study the dynamics of the solar radiative interior. It is now time to develop a global model of the solar dynamics and magnetism from deep within its radiative interior up to its corona and extended wind.

Indeed it is key to realize that 98% of the solar mass is contained in the solar radiative zone and that complex magnetohydrodynamical processes that continuously shape the upper atmosphere activity take place rather deep in the Sun. Understanding the dynamical properties
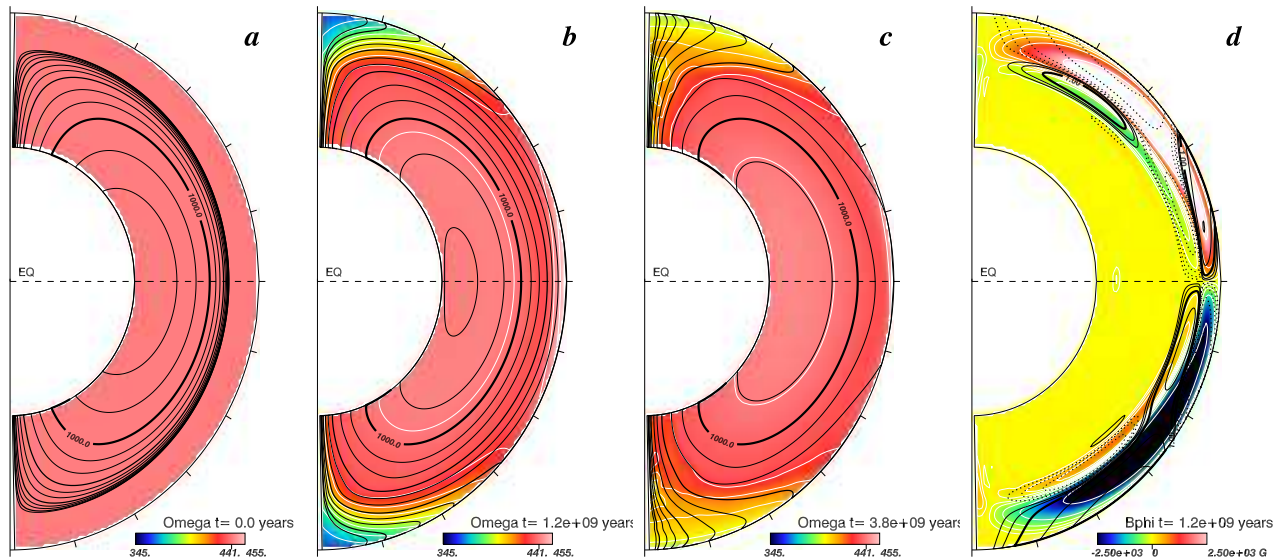
Figure 3. *a-c) Temporal evolution of a dipolar magnetic field in the presence of rotation and shear. We note the connection of the field lines in the imposed top shear and the resulting Ferraro's law of isorotation at high latitude. d) The associated toroidal field and meridional circulation at t = 1.2 Gyr. The presence of a large scale shear helps the magnetic field to reach a more stable mixed poloidal/toroidal configuration (from Brun & Zahn 2005).*

of the deep interior is thus one of the major challenges that solar physicists have to address/confront by developing news observational and numerical tools. Major questions remain to be solved such as:

- the dynamical influence of rotation and magnetic field
- the origin of the internal solid body rotation
- the main agents responsible for the redistribution of the angular momentum
- the topology, strength and influence of a fossil field
- the role of the g-modes and progressive internal waves in the overall internal dynamics
- the nature of nonlinear interactions between the dynamo and fossil fields
- the presence of large scale flows, their amplitude and shape and their mixing properties
- the presence of hydrodynamical or magnetohydrodynamical instabilities and their coupling
- the nonlinear interaction and coupling between the radiative and convection zone
- the profiles, degree of ionization of the chemical species and the transport of photons in dense plasma
- the role and influence of the tachocline on the internal structure and composition

The interaction of a stably stratified zone with either rotation or magnetic fields have been addressed for quite a long time: Von Zeipel 1924, Sweet 1950, Tayler 1973, Pitts & Tayler 1985, Mestel & Weiss 1987, Moss et al. 1990, Zahn 1992, Spruit 2002 and references therein. They note that the dynamical properties of rotating magnetized radiative interiors are much more complicated than expected, and give rise to a large range of both HD or MHD instabilities.

The discovery of the so-called tachocline (see section 2) has put forward the urgent need for the solar community to better understand the MHD of the radiative interior and of the tachocline and their coupling to the upper layers. It seems now well established, that the tachocline plays a crucial role in the solar dynamo since it is most likely the layer where the mean toroidal magnetic field, thought to be at the origin of the surface sunspots and butterfly diagram, is streched, amplified (by at least a factor of 100) and stored until it becomes magnetically buoyant (Parker 1993, Caligari et al. 1998, Fisher et al. 2000, Rempel 2003). However little is known about the dynamics of the solar tachocline: is it turbulent or laminar, what type of circulations are present, what is the dynamical influence of the magnetic fields, why is it so thin extending at most over 5% of the solar radius? (Spiegel & Zahn, 1992) were the first to address directly some of those questions but in the purely hydrodynamical context. They showed that if no processes were present to oppose its radiative spread, the solar tachocline would extend over 30% of the solar radius after 4.6 Gyr, in complete contradiction with current helioseismic inversions (Corbard et al. 1999). They demonstrate that the anisotropic turbulence could hinder the spread of the solar tachocline to only few % of the solar radius. Elliott (1997) confirmed their results numerically with a 2–D axisymmetric hydrodynamic code. Miesch (2003) using a thin layer version of the ASH code (Clune et al. 1999, Brun et al. 2004), showed that the coupling between randomly forced turbulence and an imposed shear flow gives rise to Reynolds stresses that transport angular momentum such as to reduce the shear. However several authors (Rudiger & Kitchatinov 1997; Gough &

Mc Intyre 1998; MacGregor & Charbonneau 1999; Garaud 2002) have proposed that the magnetic torques exerted by a weak internal fossil magnetic field (if it exists) could oppose the inward thermal hyperdiffusion (or viscous diffusion when thermal effect are neglected) of the solar tachocline. Such models favor a slow, rather laminar version of the tachocline. Gilman and collaborators (Dikpati, Cally & Gilman 2004 and references therein) developed a series of models that showed that the tachocline could become unstable through magnetic instability of toroidal structures embedded within it, resulting in a latitudinal angular momentum transport that suppress the shear and limit its inward diffusion. Forgacs-Dajka (2004) considered the effect of an oscillating dynamo field and found that it could also suppress the spread of the solar tachocline. This increasing number of solar tachocline models demonstrates how important it is to characterize the dynamical properties of the solar radiative interior.

We thus believe that we are at the beginning of a new era of great discoveries regarding the solar interior. With the advent of powerful supercomputers we start to non linearly study the solar radiative interior and tachocline in full 3–D MHD simulations for the first time but lack the important and more detailed observational constraints that are required to progress in our understanding of the magnetohydrodynamics of the solar radiative interior. A space project constraining the solar radiative dynamics is clearly required to support and guide our 3-D simulations.

We here briefly summarize some simulations of Brun & Zahn (2005) and the dynamical properties that we should look for in the next generation of solar seismic probes dedicated to the solar core. The ASH code (Clune et al. 1999, Brun et al. 2004) is used to model the solar radiative interior from $r = 0.3$ to $r = 0.71 R_\odot$, assuming a stable stratification throughout the computational domain deduced from the 1–D solar model (Brun et al. 2002).

Figure 3 displays the temporal evolution of the angular velocity Ω for one model of the solar radiative interior, with the poloidal field lines superimposed in black. The left panels represent both the initial solid body rotation state of the radiative zone and the purely poloidal field (here deeply confined) used to start the temporal evolution. We see on the middle panels that the imposed shear starts to propagate in the radiative interior at rather high latitudes. After about 4 Gyr, the angular velocity profile in the radiative interior is not more solid. Wherever the field lines cross the top boundary, the imposed shear has propagated all the way down to the bottom of the domain.

It is interesting to note that helioseismic inversions of the rotation of the radiative interior infer an almost flat profile (solid body rotation down to 0.2 R$_\odot$) that rotates to a value very close to the value of 441 nHz which balances torques at the interface of the convective zone (Gilman et al. (1989). This means that the exchange through the interface between the convection and the radiation zone are nearly balanced, with only a weak torque operating there. How the angular momentum lost through the solar wind and resulting in the spin down of the Sun influences the redistribution of angular momentum in the radiative interior and in the tachocline, constitutes a major puzzle that needs to be answered. The simulation also reveals the presence of a weak multi-cells meridional circulation per hemisphere in the tachocline, directed poleward at the top of the domain.

These simulations allow to follow the temporal evolution of the kinetic and magnetic energies (decomposed in axisymmetric and non axisymmetric components). We note a strong amplification of the mean toroidal magnetic field (TME) by the so-called ω-effect. Even more interesting, the non-axisymmetric kinetic and magnetic energies (FKE & FME) grow by many order of magnitudes. This has to be expected, since following Tayler (1973), we know that a purely poloidal field is unstable. In the simulation, the magnetic field has evolved from a purely dipolar configuration to a mixed poloidal/toroidal configuration, those strengths are about the same, thus confirming Tayler's theoretical work (see also Brainwaith & Spruit 2004).

It is important to probe the solar interior in order to put some constraints on these models and try to estimate if such complex/mixed poloidal-toroidal magnetic field configurations are realized.

It appears that a fossil dipole field is not that efficient at limiting the inward thermal hyperdiffusion of a latitudinal shear, once its field lines have connected with the region where the shear is imposed, unless we bury it deeply enough. By burying the initial seed field deep enough we succeed at limiting the spread of the tachocline at low latitude. Whether in the real Sun, the fossil field lines connect or not with the convection zone is another challenging question to be answered.

5. THE OPEN QUESTIONS FOR OBSERVERS

We now list some fundamental questions which will greatly help the MHD simulations and constitute a challenge for observers. We will consider three parts: the knowledge of the Sun itself, the Sun for stellar physics, the Sun for fundamental physics.

The Sun is our star
The future instruments must be prepared to answer to the following questions:

− what is the rotation in the solar nuclear core, 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 potential variabilities with time ?
− could we quantify the real present energy balance including the redistribution along time between different sources of energy mentioned in Fig 4, a more serious

transport of photons across the star and finally get the proper sound speed profile.

It is only after having established such a complete representation of the Sun, that we will be able to predict the slow luminosity variations along human scales and answer to the questions connected to the observation of great minima, the Wolf, Sporer, Maunder minima:

- Can we may imagine several kinds of dynamos, even in the radiative zone, several cycles ?
- What is the interconnection of the radiative magnetic field to the convective one ?

3D MHD simulations have to be guided by more observations of the solar radiative zone to determine which magnetic field configurations act in the solar radiative interior.

The Sun for Astrophysics

The Sun is a unique star where million modes can be detected, it allows detailed comparisons with simulations:

- the low degree modes are the only modes we may detect for other stars, so any technical improvement will be generalized to other stars,
- the Sun has always stimulated stellar advances, it stays the best case to check the new theoretical assumptions, in parallel to the growing asteroseismogy which multiplies the physical sites (COROT launch 2006 and "Life and Stars" proposal for the present Cosmic Vision). The Sun is a key to build an unified view of the stars. Effectively, if we understand the internal magnetic field of the Sun and stimulate complete MHD calculations, we will get a complete renewal of stellar evolution. The magnetic effects that we lack in present stellar evolution appear much more important in the first and final stages, so the same equations will describe very properly all the stars from their formation to their death.

The complete MHD vision of stars is fundamental to understand the magnetic relationship between stars and planets, the SNIA physics for cosmological perspectives and massive supernovae for enrichment of galaxies.

The Sun and fundamental physics

Determining the central part of the Sun by helioseismology has been determinant to estimate the neutrino fluxes emitted by the Sun independently of constant new advances in the ingredients of the solar models: we can quote today abundance redetermination (Asplund et al. 2002): carbon oxygen, neon may be ..., provoked by a better description of the turbulent atmosphere. After thirty years of experimental progress, we have reached a level where a perfect agreement within the two probes (waves and neutrinos) is established (Turck-Chièze 2004b,2005b). This example illustrates the importance of observational facts for improving our solar knowledge.

The seismic probe will continue to inform us on the more complex physics of the radiative zone and will put stronger limits on dark matter (Lopes, Bertone & Silk 2002 and references therein).

In the present context it is also interesting to notice that the successive solar gravitational moments that determine the solar moments of inertia, are still poorly known. However, these moments tell us how much the Sun's material contents deviate from a purely spherical distribution and how much the velocity rate differs from a uniform distribution. Thus, their precise determinations give indications on the solar internal structure. The dynamic study of the gravitational moments until now is mainly based on solar observations (helioseismology, solar diameter) and solar models of rotation and density (Pijpers 1998, Roxburgh 2001). Various methods (stellar structure equations coupled to a model of differential rotation, theory of the Figure of the Sun, helioseismology) lead to different estimates of J_n, which, if they agree on the order of magnitude, diverge for their precise values (Rozelot et al. 2004, a, b, c).

If, from a physical point of view, these multipolar moments lead to distortions of the solar surface, called asphericities, they also have a dynamic role in the light deflection or in celestial mechanics. In the ephemerids computation, the determination of J_2 is strongly correlated with the determination of the Post-Newtonian Parameters (PPN)characterizing the relativistic theories of the gravitation. Lastly, the ignorance of J_2 is also a barrier to the determination of models of evolution of the solar system on the long term.

The relativistic aspects are crucial in the dynamic approach of the solar parameters and open interesting prospects for the future. In this context, it is interesting to obtain a dynamic constraint of J_2, independent of the solar models of rotation and density, being used thereafter to force the solar models. Such a study is relevant in the scope of space missions such as BeppiColombo (better determination of the PPN; possible measurement of the precession of the apside line of Mercury as a function of J_2), GAIA (better determination of the PPN, possible decorrelation PPN–J_2 thanks to the relativistic advance of the perihelion of planets and minor planets) and obviously the space version of GOLF-NG or DYNAMICS (precise determination of the rotation of the core where half of the mass is concentrated). Another key parameter of the solar models, which could also be constrained in a dynamic way is its spin, from the spin-orbit couplings which is introduced in celestial mechanics. From present Solar System experiments (Lunar Laser Ranging, Cassini Doppler experiments, etc, see Pireaux and Rozelot, 2003), it turns out that General Relativity is not excluded by those, as shown in the most up to date values in Fig. 4a. However, General Relativity would be incompatible with the Mercury perihelion advance test if $J_2 = 0$ was assumed. But with a non zero J_2, General Relativity agrees with this latter test, and there is still room for an alternative theory too (see Fig. 4b). The prepared next generation of instruments should provide the necessary J_n measurements.
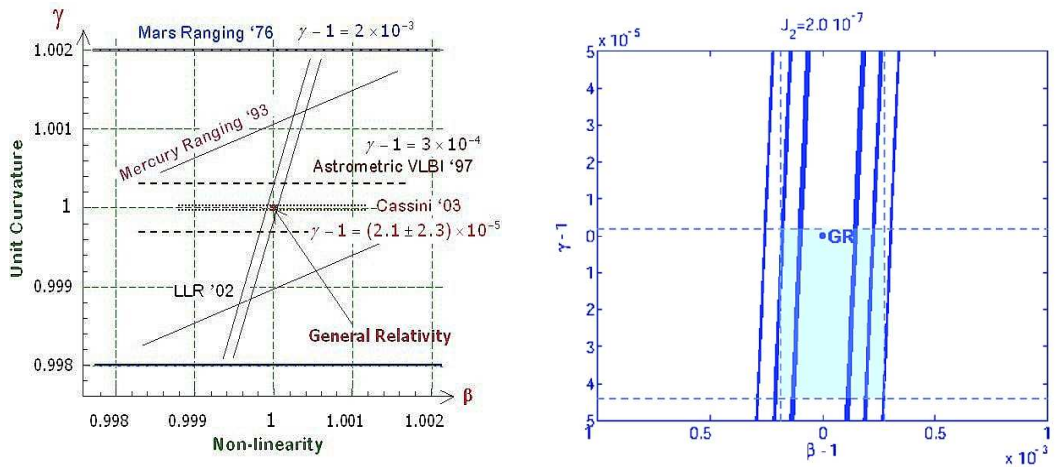
Figure 4. Left (a): Thirty years of testing General Relativity from space. Right (b): A given value of J_2 constitutes a test of the PN parameters β and γ. In the β and γ plane, the 1σ (the smallest), 2σ and 3σ (the largest) confidence level ellipses are plotted. Those are based on the values for the observed perihelion advance of Mercury, Δ_{wobs}, given in the literature and summarized in Pireaux and Rozelot (2003). General Relativity is still in the 3σ contours for the allowed theoretical values of J_2 quoted on the upper part of the chart.

6. Gravity modes and the core dynamics

The solar core dynamics has a too small effect on acoustic modes to determine the rotation profile of the solar nuclear core without ambiguity. Effectively these acoustic modes are mainly sensitive to the differential rotation of the superficial layers (Garcia et al. 2001, Couvidat et al. 2003a). On the contrary, gravity modes are mainly sensitive to this central region and must reveal different aspects of the deep internal dynamics if they are detected. They have been searched for thirty years.

But these modes produce very small intensity fluctuations at the surface or velocities of probably no more than fraction of mm/s (Kumar et al., 1996). The first limit from ground observations was 7 cm/s (Delache & Scherrer 1983, van de Raay 1988). Then the limit has decreased to 1 cm/s for single peaks (Appourchaux et al. 2000), a limit which has been reduced to 6 mm/s for the GOLF instrument after two years of observation (Gabriel et al. 2002).

In fact, the only hope to detect some gravity modes with the present observing instruments and to learn some information on the dynamics of the core is to look for patterns in the low frequency asymptotic region after a very long and continuous observation time (Garcia et al. in preparation) or to look for multiplets in the higher part of the gravity mode spectrum, that means in the region of mixed modes. These modes have their amplitudes greater by one order of magnitude than the other gravity modes.

Following this second idea, the analysis of the GOLF instrument, built with a very low intrinsic noise, has fixed the detection limit for the mixed modes to 1 mm/s (Turck-Chièze et al. 2004a). At that limit, interesting patterns have emerged as quintuplets or sextuplets and have been followed in time. It is interesting to note the presence of multiplets containing five peaks (instead 2 or 3), after 2975 days of observation, with more than 98% confidence level not to be pure noise in 10 μHz (Fig 6a, Turck-Chièze et al. 2004a, c). Of course these patterns may be noise, but they can also reveal some interesting physics as mixing between adjacent modes, or an increased central rotation (as shown in Fig 1b) and some signature of internal magnetic field (Fig 6b). The two persistent cases (fig 10 of Turck-Chièze et al. 2004a) correspond to two regions where an $\ell = 2$ ($\ell = 1$) are seated on an $\ell = 5$ ($\ell = 4$). The presence of different modes at the same frequency may lead to an amplification of the signal (Cox & Guzik 2004). Moreover the lifetime of these modes is now predicted as considerably reduced and reexcitation is possible (Dintrans et al. 2005).

In fact, the frequencies of the sun's acoustic (p) and gravity (g) modes are sensitive to the rotation and magnetism of the solar interior. Rotation, magnetism and other asphericities raise a degeneracy in the frequencies, leading to frequency splitting which has been used by helioseismology to map the internal rotation of much of the solar interior. The greater sensitivity of g modes to the solar core, compared with p-mode sensitivities, raises the possibility of detecting 'unexpected' core properties, such as rotation on an axis different from that of the solar envelope, or an oblique core magnetic field.

A global mode is characterized by its radial order n, degree l and azimuthal order m. If the rotation and magnetic field are axisymmetric m is a well-defined quantum number and frequency splitting gives rise to up to $2l+1$ observable frequencies for given n and l (i.e. $m = -l, \ldots, l$). The frequency splitting can then be decomposed into a part that is an odd function of m and another that is an even function. The odd component arises from rotation, and can be used to constrain that, whilst the internal magnetic field contributes to the even component.
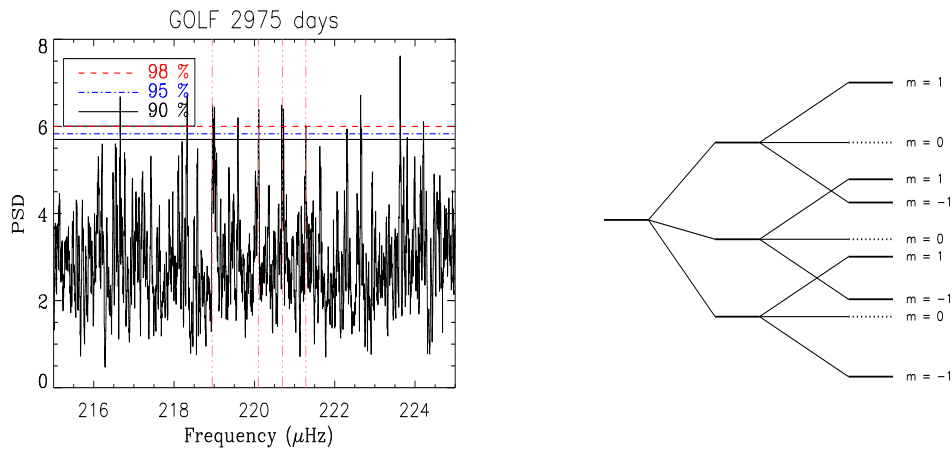
Figure 5. Left (a): Interesting quintuplet detected in GOLF/SoHO with more than 98% confidence level after 2975 days of observation (Turck-Chièze et al. 2004a, c); Right (b) Schematic of the origin of an hyperfine splitting for an l = 1 mode. In the non-rotating, non-magnetic case there is a single frequency (left). In a corotating frame, rotation and magnetic field split the frequency, but each of the three normal modes is, in the non-axisymmetric case, a mixture of different m values (middle). Transformed into the observer's frame, each m value is shifted and gives rise to hyperfine splitting (right). Dotted thick lines denote those components that would not be visible from the ecliptic plane in whole-disk measurements.

If magnetic field breaks the axisymmetry, e.g. an inclined field, then each eigenfunction is a mixture of m values. This leads to the so-called hyperfine splitting: in principle up to $(2l + 1)^2$ frequencies can be apparent in the observer's frame (figure 6b). Such hyperfine splitting may already have been detected for a g-mode multiplet (Turck-Chièze et al. 2004a, figure 6a).

This idea has been applied for inclined radiative zone rotation and for an inclined magnetic field of a relic field (Goode & Thompson, 1992). For spatially unresolved whole-disk measurements (such as GOLF), in the axisymmetric case only $l + 1$ components are visible (i.e. $l + m$ even). In the case of non-axisymmetric steady rotation, up to $(2l + 1)(l + 1)$ components are visible. How many of these are actually at visible amplitude depends on the mix of m values in each normal mode in the corotating frame. If unresolved, such hyperfine splitting may appear as excess mode linewidths. Based on published numerical calculations for p modes, one can estimate that in spite of their larger Ledoux factors, the hyperfine splitting of g modes can be dominated by a 10^8 gauss magnetic field in the Sun's core, producing splittings of as much as 5 μHz.

The idea that the solar core includes a potential relic of the planetary system formation is very exciting. SoHO observations will continue for two years but the quality of observation must be maintained. Already very few identified g-modes will largely improve our knowledge of the solar core. In parallel we need to improve the technique of detection which has been extended from ground networks. The objectives are to measure more quickly (typically every year) all the low-degree p modes and the g-modes up to $\ell = 5$ along at least two cycles as it is already the case for the solar luminosity and will be the case soon for the solar deformations.

7. DEFINING THE ROADMAP

We propose now a roadmap for Europe, in parallel to the American effort, to converge altogether to build a complete MHD view of the Sun from to the core to the corona. Let first describe quickly the already planned projects.

In addition to STEREO, launch 2006, which will enrich our solar 3D vision for the external phenomena, the American project HMI/SDO (launch in 2008) will follow MDI/SoHO with an increased resolution. This instrument will largely improve (1) our understanding of the convective zone dynamics and the related solar dynamo, (2) the origin and evolution of sunspots, active regions and other indicators of activity, (3) the sources and drivers of solar activity or disturbances. This instrument does not include any improvement for gravity mode detection, the knowledge of the nuclear core is considered in this project as a secondary objective.

PICARD, a CNES microsatellite (launch mid 2008), will search for an increased visibility of the modes due to an amplification at the solar limb. The payload consists of two radiometers, three 4-channel sunphotometers and an imaging telescope on board a microsatellite placed in a sun-synchronous orbit. These instruments are under the responsibility of IRMB (B), PMOD (CH), and SA (F).The PICARD mission is a solar-climate relationship investigation. For that, its scientific objectives are the understanding the solar activity origin by measuring simultaneously several key parameters for solar modelling: (1) precise images of the Sun at several wavelengths to measure the solar diameter, asphericity, and limb shape and differential rotation as a function of the heliographic latitude, (2) frequencies of oscillations, (3) measurements of the total solar irradiance and its variation, (4) spectral irradiance

measurements relevant for the variation of the ozone concentration in the terrestrial atmosphere, and their variations as a function of time. In addition, ground based correlative measurements of the solar diameter will allow to investigate the role of the atmosphere by comparing with measurements obtained with the same instrument placed in orbit. The above measurements will allow the development of a solar and a climate model in which UV solar variability will be taken into account. This mission is named PICARD after the pioneering work of Jean Picard (1620-1682) who determined precisely the solar diameter during the Maunder minimum. Apart this project, the European mission Solar Orbiter (launch 2013) will dedicated its efforts to the external part of the Sun. An other project american Solar Polar Imager will look to the poles but will be also mainly focus on magnetic effects not too deep.

In parallel to these already programmed missions, two instruments are being developed to prepare a better signal/noise ratio for the detection of very low signals. These instruments have been proposed in 1999 to ESA in the framework of the F2 call for mission as part of the SOLARIS project. This complete observatory of the Sun has been judged too big for this class mission. For these two cases, prototypes have been built to demonstrate their feasibility.

GOLF-NG, an improved resonant spectrometer, is a french-spanish initiative. It is based on the measurement of the Doppler velocity through 15 points, every 10s on the sodium D1 line and a measurement of the continuum. A prototype is in construction to study the hard subsystems: variable magnet, thermal and mechanics of the cell, stability of the detector. It will be installed for ground tests in Tenerife in 2006. In this instrument, the mode velocities will be isolated from the magnetic perturbation of the line. This improvement will reduce the solar granulation noise which dominates the g-mode region, (Espagnet et al. 1995, Garcia et al. 2004). The signal/noise ratio will be increased by a factor at least 10 in the g-mode region (Turck-Chièze et al. 2001c, 2005a) and the photon noise statistics by the same amount. It will explore the gravity mode region and measure the variability of all the acoustic modes. The space version will contain different masks for the identification of the modes and will detect modes up to $\ell = 5$. An extremely precise time evolution of the sodium line, compared to a theoretical estimate of the line (Eibe et al. 2001) will also give magnetic information on the low atmosphere just above the photosphere. This instrument will benefit from previous works dedicated to the knowledge of the solar granulation, supergranulation and excitation of the modes (Roudier et al, 2001).

Another new Italian-American instrument is being built to measure the velocity, intensity and line-of-sight magnetic fields of the full solar disk, simultaneously at four heights in the solar atmosphere with a resolution of 4 arcseconds and a cadence of 10 seconds. The heart of the instrument is the magneto-optical filter (Cacciani & Fofi,

1978) that can be operated using vapor cells containing K, Na, Ca and He. The instrument is also designed to have a high-resolution imaging mode that will provide 1 arc-second resolution over a FOV of 450x450 square arcseconds. This instrument is scheduled for deployment to South Pole during the Austral summer of 2005/2006.

These two complementary techniques will improve our ability to detect gravity modes in space. Nobody believes today that it is possible to detect gravity modes from ground because of their very small signals, and the atmospheric perturbation and the low duty cycle on ground. So, we suggest and consider important to launch a small European mission we call "DynAMICS ": Dynamics and Magnetism of the Inner Core of the Sun, a microsatellite or a minisatellite just after the launch of PICARD in order to maximize the science return during the next solar cycle, on the solar core region and on the atmosphere. This mission could include GOLF-NG and MOF instruments (or at least one of them). With the mission DynaMICS in parallel to the other missions SDO and PICARD, we secure rapid progress on the dynamical effects from the core to about 600 km above the photosphere. Doing so and for a low supplementary cost, Europe will play one of the leading role in that important domain.

The next two cycles are determinant to put constraints on the topology of the deep internal magnetic field and its evolution with time and to determine the whole complex mechanisms which provoke magnetic changes at the surface (luminosity, eruptive activity and may be different kind of cycles...). We cannot any longer ignore the dynamics of 98% of the mass of the Sun contained in the radiative zone to describe the complete activity of the Sun. All the useful techniques must be qualified during the next solar cycle. With such intermediate step, we will be in a very good position to send a world-class mission, near the 2018 solar minimum, with already selected instruments to follow all the phenomena during another solar cycle. The final "world-class" mission will benefit from an orbit around the L1 lagrangian point or a mission around the solar poles (see Beleinos proposal). In parallel, supercomputers will be largely improved. So we will be able to leave our simple 1D representation to go towards a complete 3D evolution of the Sun during the next solar cycle with the necessary constraints coming from the central region of the Sun. The final mission will allow well mastered predictions of the solar activity on long (greater than the known 22 years) human timescales and their consequences for a complete understanding of the Sun-Earth connection applicable also to other planetary systems.

So, the roadmap is composed of 3 steps, it guarantees sucessful results, with step by step progress and a maximal scientific return:

– ground networks, SoHO and TRACE (1990-2007) ar the first step of this solar dynamical perspective;
– then SDO, PICARD and a small European project, DyNAMICS during the next solar cycle 2008-2017, to

obtain a detailed analysis of the the convective zone, and the tachocline, to follow the luminosity and radius variabilities, to qualify the stability of the instruments for the gravity mode search and to measure constraints on the core dynamics. This instrumental effort will guided the "3D MHD model" of our star.

- and finally a world-class mission launched in 2018 near the solar poles or around the L1 Lagrangian point to obtain all the necessary constraints to build a "predictable magnetic model" of the Sun and its relationship with our planet which we will extend to other stars and planets.

References

Appourchaux, T. et al. 2000, ApJ, 538, 401

Antia, H. M. & Basu, S. 2000, ApJ, 541, 442

Brainwaith, J. & Spruit, H. C. 2004, Nature, 431, 819

Brummell, N., Cline K. & Cattaneo F. 2002, MNRAS 329, 73

Brun, A. S. et al. 2002, A&A, 391, 725

Brun, A.S., Miesch, M.S., & Toomre, J. 2004, ApJ, 614, 1073

Brun, A.S. & Zahn, J. P., 2005, A&A, submitted

Cacciani, A. & Fofi, M., 1978, Sol Phys, 59, 179

Caligari, P., Schuessler, M. & Moreno-Insertis, F. 1998,ApJ., 502, 481

Chaplin, W. et al. 2001, MNRAS , 327, 1127

Charbonnel, C. & Talon, S., 2005, in preparation

Charbonneau, P. & MacGregor, K.B., 1993, ApJ, 417, 865

Clune, T. L. et al. 1999, Parallel Comput., 25, 361

Corbard, T., et al. 1999, A&A, 344, 696

Couvidat, S., et al. 2003a, ApJ, 597, L77

Couvidat, S., Turck-Chièze, S., & Kosovichev, A. 2003b, ApJ, 599, 1434

Cox, A. & Guzik, J. A. 2004, ApJ, 613, L169

D'Antona, F., Ventura, P. & Mazzitelli, I. 2000, ApJ, 543, L77

Delache, P. & Scherrer, P. 1983, Nature, 306, 651

Dikpati, M., Cally, P. S. & Gilman, P. A., 2004, ApJ, 610, 597

Dintrans, B et al. 2005, A&A, in press, astro-ph/0502138

Eibe, M. T. et al., 2001, A&A, 371, 1128

Elliott, J. 1997, A&A, 327, 1222

Espagnet et al., 1995, Astron. Astrophys. Suppl. Ser., 109, 79

Fisher, G. H., Fan Y., Longcope, D. W., Linton, M. G. & Pevtsov, A. A. 2000, Solar Phys., 192, 119

Forgacs-Dajka, E. 2004, A&A, 414, 1143

Gabriel, A. et al. 2002, A&A, 390, 1119

Garaud, P., 2002, MNRAS, 329, 1

Gilman, P. A., Morrow, C. A. & DeLuca, E. E. 1989, ApJ, 338, 528

Garcia, R. A. et al. 2004, Sol. Phys. 220, 269

Goode, P. R. & Thompson, M. J. 1992, ApJ, 395, 307

Gough, D. O. & Mc Intyre, M. E. 1998, Nature, 394, 755

Howe, R. et al. 2000, ApJL, 533, L163

Kosovichev, A. G. et al. 1997, Sol. Phys., 170, 43

Kumar, P., Talon, S. & Zahn, J.-P., 1999, ApJ, 520, 859

Lopes, I. Bertone, G. & Silk, J. 2002, MNRAS, 337, 1179

MacGregor, K. B. & Charbonneau, P. 1999, ApJ, 519, 911

Maeder, A., 2003, A&A, 399, 263

Maeder, A. & Zahn, J.-P. 1998, A&A, 334, 1000

Mathis, S. & Zahn, J.-P., 2004, A&A, 425, 229

Mathis, S., Palacios, A., Zahn, J.-P., 2004, A&A, 425, 243

Mathis, S. & Zahn, J.-P., 2005, A&A, *in press* (astro-ph/0506105)

Mestel, L., Tayler, R. J., Moss, D., 1988, MNRAS, 231, 873

Meynet, G. & Maeder A,. 2000, A&A, 361, 101

Meynet, G. & Maeder A,. 2005, A&A, 429, 581

Miesch, M. S. 2003, ApJ, 586, 663

Moss, D. L., Mestel, L. & Tayler, R. J. 1990, MNRAS, 245, 550

Parker, E. N. 1993, ApJ, 408, 707

Piau, L. & Turck-Chièze, S. 2002, ApJ, 566, 419.

Pijpers, F. P. 1998, MNRAS, 297, L76

Pireaux, S. & Rozelot, J.P. 2003, Astron. & Space Science, 284, 1159

Pitts, E. & Tayler, R. J. 1985, MNRAS, 216, 139

Rempel, M. 2003, A&A, 397, 1097

Ringot, O., 1998, A&A, 335, 89

Roudier, T. et al. , 2001, A&A, 368, 652

Rozelot, J.P., Pireaux, S., Lefebvre, S. and Ajabshirizadeh, A. 2004a, SOHO 14/GONG 2004 Workshop, ESA SP-559, 532

Rozelot, J.P. and Lefebvre, S. 2004b, IAU Symposium No.215, Cancun, Ed. by A. Maeder and P. Eenens, 332

Rozelot, J-P., Lefebvre S. & S. Pireaux, S. 2004c, Proc. Intern. Conf. of Phys., Amirkabir University of Technology, Teheran (Iran), p. 647

Roxburgh, I. W. 2001, A&A, 377, 688

Rudiger & Kitchatinov 1997, Astron. Nach., 318, 273

Rudiger, G. & Hollerbach, R., 2004, The magnetic Universe, ed WILEY-VCH Verlag GmbH & Co, KGaA

Spiegel, E. A. & Zahn, J.-P. 1992, A&A, 265, 106

Sweet, P. A. 1950, MNRAS, 110, 548

Spruit, H. C. 2002, A&A, 31, 923

Talon, S., Kumar, P., Zahn, J. P. 2002, 574, L175

Talon, S. & Charbonnel, C., 2005, A&A, accepted

Tayler, R. J. 1973, MNRAS, 161, 365

Thompson, M. J., Christensen-Dalsgaard, J., Miesch, M. S. & Toomre, J. 2003, Ann. Rev. Astr. Astrophys., 41, 599

Turck-Chièze, S. et al., 2001a, Sol. Phys., 200, 323

Turck-Chièze, S. et al., 2001b, ApJ, 555, L69

Turck-Chièze, S. et al., 2001c, SOHO 10/GONG 2000 Workshop, ESA SP-464, 331

Turck-Chièze, S. et al., 2004a, ApJ, 604, 455 and 608, 610

Turck-Chièze, S. et al., 2004b, Phys. Rev. Lett., 2004, 93, 211102

Turck-Chièze, S. et al., 2004c, SOHO 14 / GONG 2004 Workshop (ESA SP-559), p.85

Turck-Chièze, S. et al., 2005a, Adv. Space. Phys., in press

Turck-Chièze, S. et al., 2005b, Nucl. Phys. Suppl. 143, 35; 145, 17

Von Zeipel, H., 1924, Astron. Nach., 223, 229

Vorontsov, S. et al. 2002, Science, 296, 101

Vorontsov, S. et al. 2003, ESA- SP 517, 35

Zahn, J.-P. 1992, A&A, 265, 115