On the Solar Shape and Some Consequences or Towards "Helioclimatology"

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Solar radiation varies at different time scales, as a consequence of solar activity. The energy received from the Sun on our atmosphere is one of the natural drivers. Since this energy is not constant, it has been postulated that our climate may response to any irradiance variations. Although differences in the amplitude of centennial temperature variability have been widely discussed in the literature, the picture with relatively small variability is arguably best known by a wider audience. But how subtle variations of solar radiation are produced? Despite all the efforts, climate and weather still remains an unsolved puzzle. To try to go further, an element that has been investigated is the similarity of periodicities between several solar activity indices and different meteorological/climatic parameters. The literature contains a long history of "pseudo" correlations (positive or negative) between weather and climate parameters like temperature, rainfall, droughts, etc. and, solar activity cycles like the 27-day one, those of 11-years, 22-years, 80–90 years or even longer. An indisputable physical mechanism, is through the so-called "asphericity-luminosity parameter *w*", which might act to produce these relationships. In this review paper we will first show how the solar shape may influence the irradiance (an attempt to answer to the above-mentioned question), and then, we will progress on the way the different cycles can be analyzed in the scope of determining solar influences on terrestrial climate. We denote these causal relationships by the term "helioclimatology" and we will conclude by emphazing the need of new dedicated satellites such as SDO or DynaMICS.

Introduction

The Sun is often pointed out as a "banal" star. In fact, if the Sun is "banal" as far as some parameters are concerned, such as spectral type, effective temperature, diameter, etc., it is not so common star if we think in terms of evolution of the ideas. It would certainly not have been possible to find magnetic activity, differential rotation, radial displacements in stars if before, one would have not highlighted them for the Sun. Asteroseismology would not have been achievable without helioseismology. On the same way, exobiology is strongly pushed by Solar-Terrestrial analogues. Finally, solar shape distortions, due to the non-uniform distribution of mass and rotation inside the body, are today beginning to be studied on stars by means of improved techniques on the VLTI for instance, after being put in evidence on the Sun [1, 2].

Such deviations to sphericity are not anecdotal. In principle, if one is able to accurately measure the asphericities, it is possible to deduce the behavior of the internal layers constituting the body in rotation. In the same way as geodesians define the "geoid" for the Earth, it is possible to define a "helioid" for the Sun, and a "stelloid" for stars. These words can be used to show how the surface of such bodies differ from a sphere, under their own rotation and likely by their magnetism. Thus, the free surface has a physical meaning, being an equipotential of gravity. The determination of such a level is possible, by means of space techniques. Conversely, any departures to the reference level (the helioid in the Sun's case) will show how the distribution of density and rotation inside the body is perturbed. This fact was first underlined by G.Issak in a Florence meeting under the sentence "a new window opens over the Sun's interior" [3].

If we are beginning to understand the strong physical character of such equipotentials of gravity, which are characterized by a number (the gravitational moments), we are far to know if "asphericities", and their corresponding moments, are variable. However, it can be reasonably thought that a temporal variability of such parameters might be due to the temporal variation of the internal structure. In such a way, the outer shape would be also time dependent, and this could explain, in the solar case, some tiny fluctuations of the irradiance. It is thus of interest to explore the whole chain, starting from the core up to the surface to well understand the mechanisms of solar activity, then to get a better prediction, and then to understand how the solar output may influence the atmosphere of our planet. One can judge such an investigation as ambitious, but we are today compelled to carefully examine all the sources of the solar variability to get a scientific opinion on the solar forcing, and even it is to reject one of the processes.

Shape distortions

The outer shape of a fluid is distorted under the non-uniform distribution of mass and velocity rates. In theory, the problem is simple and has been first tackle for stars by Milne in 1923 [4] and fully achieved by Chandrasekhar in 1933 [5]. However, the study was conducted with a constant angular velocity, and this is not the case for the Sun, and likely for a number of other stars. It was necessary to await Maeder in 1999 [6] to examine the case of the effects of the differential rotation, but on the surface only. Rozelot et al gave for the first time a version in the solar case [7, 8].

The computation of the centrifugal potential is here complicated and cannot be reduced to computation of potentials on successive cylinders (or thin zonal rings) in which the rotation is taken as uniform. Thus, the complexity of the rotation profile indicates that the photospheric shape is highly sensitive to the interior structure. That is why measurements of the limb shape distortions, (“asphericities”, i.e. departures from the “helioid”, the reference equilibrium surface of the Sun), combined with an accurate determination of the solar rotation provides useful constraints on the internal layers of the Sun (density, shear zones, surface circulation of the plasma...). Fig.1 shows such asphericities that can be seen at a given spatial resolution.

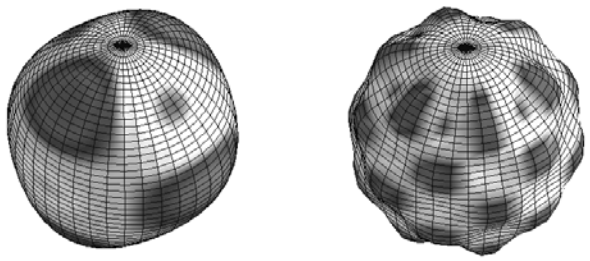

Fig.1. A fluid in rotation shows deviations to sphericity. To first order, the outer shape is oblate. Depending on the distribution of mass and velocity rate inside the body, asphericities can be seen as “small” or “larger” departures, as far as the order is increasing. Left: order 4. Right order 6 [42].

Alternatively, theoretical upperbounds could be inferred for the flattening which may exclude incorrect/biased observations. Even if we know that the theory, called "Theory of Figures", can be limited due to truncation errors, the learning is rich.

Rotation rates

Space observations have tremendously increased our knowledge of the solar rotation. Several studies have been made concerning the tachocline, an important layer believed to be the seat of the differential rotation. Maintained in the convective zone, this differential rotation suddenly disappears at around 0.7 *R* to be replaced by a rigid rotation in depth at a velocity rate corresponding to the 40° rotation of the surface layers. Below 0.7 *R*, the radiative zone covers 70% of the internal radius, or 98% in mass, indicating its importance for the gravitational moments.

However, some crucial questions remain to be solved, concerning mainly the rotation down to the core itself, or the behavior of the very near surface layers. Just to illustrate these two points, does the velocity rate of the rotation of the very deep layers increase to reach about 500 *nHz*, as it is today suspected from analysis of the first detection of the gravity modes [9]? Does the layers closest to surface show an inversion of the radial gradient of rotation at about 63° of latitudes, as it is suspected through helioseismology and as the theory predicts? How such physical features participate to the solar activity? Does this impact the irradiance variability? Two satellites are scheduled to answer such questions (among many others): SDO (**S**olar **D**ynamics **O**bservatory) and DynaMICS (**Dyna**mics and **M**agnetism from the **I**nner **C**ore to the Chromosphere of the **S**un) [10], scheduled to be launched by 2008-2010. They will aim at revealing the different sources of dynamo down to the core and the interplay of internal magnetic fields. One of the ultimate goals is to improve our understanding of the solar activity cycles, including large minima, with predictions for the next century. Hence, a better description of the Sun’s output will give better information of its impact on Earth’s climatic change.

Using SOHO/MDI data for the last 9 years and more precisely the temporal variation of f-modes frequencies, Lefebvre and Kosovichev [11] have computed the variation of the radius of sub-surface layers of the Sun by applying helioseismic inversions. The main result (Fig. 2) is that the radius of the subsurface layers of the Sun changes non-uniformly: the near surface layers are contracting while the deeper layers are expanding with the increase of the solar activity.

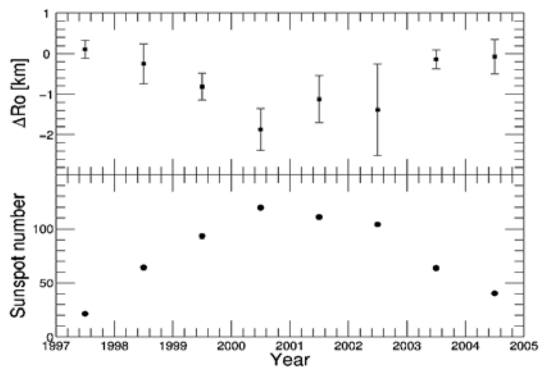

Fig.2. Measurements of the "seismic" solar radius along time [10, 11].

It is shown that a variability of the "helioseismic" radius is in antiphase with the solar activity, with the strongest variations of the stratification being just below the surface, at around 0.995 R. Besides, the radius of the deeper layers of the Sun, between 0.975 *R* and 0.990 *R* changes in phase with the 11-year cycle. These results imply a non-homogeneous variation of the radius with depth and time. This result could eventually lead to a deeper understanding of this new transition zone just below the photosphere, that we called "leptocline", where act complex physical processes such as partial ionisation of the light elements, opacities changes, superadiabaticity, strong gradient of rotation and pressure (see Lefebvre et al. [12]).

Fig.3 shows a first schematic view of the complex physics in this zone. This shear zone is notably the seat of the radius variations and probably also the seat of in-situ magnetic fields. A better knowledge of this zone, which corresponds to the border between the interior of the Sun and its atmosphere, is in development through the use of local helioseismology, thanks to high resolution images and time propagation of the sound waves. The aim is to give a better physical description of the leptocline, a sub-surface transition region (between the outer atmosphere and the convective zone). It has been put in evidence by Godier and Rozelot [13] and is a very thin shell constituted by two layers, one located at around 0.989 *R* and the other at the very near surface, around 0.994 *R*. This last one is 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 [14]. This can be also interpreted as the reversal of the rotational radial gradient ($\partial\Omega/\partial r$), which is <0 from 0° to around 50°, then cancel and being >0 afterwards. A typical sketch shortening this 3-D vision can be found in [15, 16].

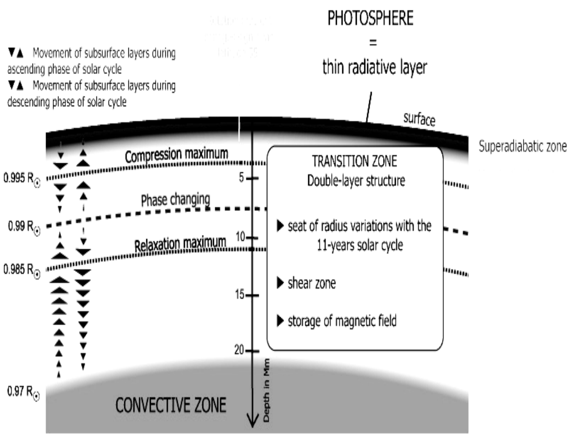

Fig.3. A schematic cut of the sub-surface layer of the Sun [11].

Three regions appear thus very important for modelling the internal solar dynamo(s): the core, the tachocline and the leptocline. Such tasks will be tackled in a near future through SDO and DynaMICS, mainly by following the splittings of solar oscillations with time, an assignment extremely useful for the interpretation of the global variabilities.

Irradiance and solar shape variabilities

In theories of stellar evolution, the luminosity is thought to compensate the production of energy from nuclear fusion in the core. So, this production rate appears constant, at least on time scale of hundred or thousand years. This might not be true, and especially in the solar case, since some energy from the core could be stored or transformed in the convection zone (or in another place). The gravitational energy could play a role, as a reservoir, where the energy can be stocked or released. If the production rate in the core is lower than is inferred from the luminosity, the Sun shrinks, converting energy into heat, the process being reversible. This mechanism is one of the most plausible that can be put forward to explain variations of the diameter of the Sun [17, 18, 19]. One needs also to take into account how magnetic pressure varies just in the sub-surface layers. The knowledge of the radius changes requires high precision observations to understand their origin and astrophysical consequences, up to debates on the general relativity [20]. Thus, a lot of efforts have been made to measure radius variations with time, at least since early 1979, when Sofia and Endal [21] pointed out that the solar constant could undergo variations if the solar diameter changed.

A lot of reviews have been made on this subject. Let us quote two of them: the compilation of all existing measurements of the diameter of the Sun first made by Toulmonde [22], has been after revisited and upgraded by Rozelot [23, 24]. These measurements go back as far as A.D.1650 and a critical analysis of all the data up to now is available in Pap et al. [25]. Let us briefly recall that past observations were mainly made by J. Picard, P. La Hire and T. Mayer from 1650 to 1760 and were also analyzed by Wittmann [26]. In spite of the fact that instruments at that dates were not of high accuracy, the measurements should not be disregarded since the meticulousness in the transcription of the data permits an a posteriori statistical computations of the uncertainties. For instance, such errors bars computed and plotted in the left side of Fig.2 in [24] are obviously subject to some criticism, as the precision on a single measurement is about 3 *arcsec*, and some of the past observations may be spurious. But, they can be considered today as the best ones that can be used. Modern values are of higher quality and all data are compared with these deduced from solar eclipse observations from 1715 to 1991 [27]. One objective of dedicated new space missions is to improve this situation (and also measure the deformation at the solar limb).

Latitudinal variations (asphericity) as seen above are key parameters 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 from purely thermal effects. Early estimates of the pole-equator temperature difference (reviewed by Altrock and Canfield [28]) were only able to set upper limits of a few *K*. After removing the facular contribution, Kuhn et al. [29], 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 towards 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 3 *K* and 1 *K*, respectively, relative to the temperature minimum at mid-latitudes. The pole-equator temperature has been recently revisited by Fazel et al [30] 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, but of no more than dT = 1.2 *K* and dR = 10 *mas* (*milliarc-second*) in amplitude (over the cycle), two values consistent with the most recent observations made at Kitt Peak by Livingston et al [31] for the photospheric temperature and by Kuhn et al [32] on board SOHO for the solar radius. Furthermore, Fazel et al [30] 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 ($w = \Delta\, lnR \,/\, \Delta\, lnL$) [14], 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. Indeed, a larger value of w would imply luminosity production in layers deeper inside the Sun (a smaller one would mean that the luminosity is produced in the uppermost layers). This parameter is of importance to understand the variability of the irradiance, and hence, variations on the top of the stratosphere. Up to now, few studies have been made, taking into account the asphericity-luminosity variations.

Solar cyclic variabilities

The surface of the Sun (and its atmosphere) exhibits a wide range of magnetic processes, which can be orderly on deterministic scales for some of them and on chaotic scales for some others. The Hale 22-year cycle based upon sunspot eruptions, is characteristic of a global magnetic activity (taking into account the reversal of the sunspots polarity). A new cycle obeys at very well defined rules for field parity, and as the cycle progresses, sunspots migrate from mid-latitudes (±45°) to equatorial ones (±5°). Coexisting with these large-scale magnetic structures, small-scale and sometimes intense magnetic fluctuations emerge on the solar surface. Such features are still unpredictable and may appear at any time during the solar cycle. The 22-year cycle results from dynamo processes occurring within the Sun in a spherical shell of strongly turbulent convection occupying about one third of the outer radius below the solar surface. The observed large diversity of magnetic phenomena must thus be linked to two conceptually different dynamos: a large-scale/cyclic dynamo and a turbulent small scale one (see for instance [33, 34, 35]). Although magnetic dynamo action is traditionally associated with rotation, fast dynamo theory shows that chaotic flows, even without rotation, can act as efficient small-scale dynamos. Numerical simulations suggest that granular and supergranular convection may generate locally a substantial part of the field in the quiet photosphere.

Superposed to this more or less regular 11-year cycle, several other ones have been pointed out. The Gleissberg cycle results from the amplitude modulation of the 11-year periodicities, and is of 90-100 years. A bigger one of some 400-year is sometimes reported. Moreover, periods of suppressed activity appear regularly: grand minima of activity (ranging time 1010-1050, called Oort, then, 1280-1340, called Wolf, 1420-1530, called Spörer, and 1645-1715, called Maunder) and a medium minimum from 1780 to 1810, called Dalton. A next large minimum is awaited for the years 2017-2050 [36]. Such minima imply the contribution of the whole interior of the Sun, along not yet fully elucidated mechanisms.

Knowing the activity cycle, one cannot say yet confidently a date for a next maximum or minimum, nor the amplitude of the maximum, in spite of a lot of studies. All methods seem to fail (FFT, entropy, cyclograms, neuronal networks...): the Lyapunov exponent is of 4 years [37], indicating that the object is predictable (meaning that the knowledge of precedent values may serve as valuable data to estimate up to about 4 years; in other words, a maximum can be determined, at about 5.5 years after a minimum), but unforeseeable (meaning that the value itself is uncertain). A mapping of the Sun, in the phase space (Figs. 4 and 5) shows this character [38].

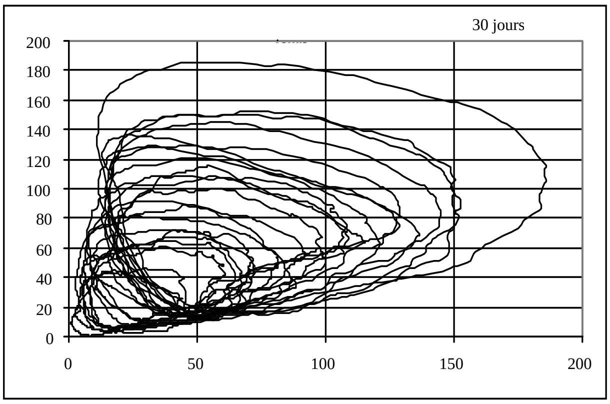

Fig.4. Phase portrait in a standard mapping: W(t)-W(t+1 month); 30-days averaged [38].

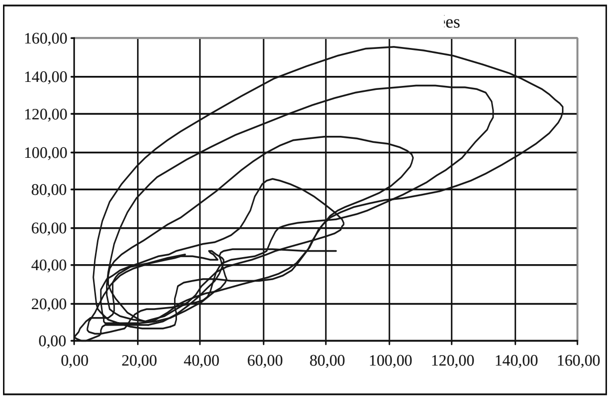

Fig.5. Mapping of the Great phase anomaly during the Dalton minimum: 1780-1815.The disorderly character contrasts with the standard mapping [38].

However, contrary to the apparent chaotic evolution of the cycles, Dikpati [39] and Dikpati et al [40] believe "that the morphology of a cycle is determined by the three or four previous ones and the seismic knowledge of the poleward surface meridional velocity flow inferior to 15-20 ms^{-1} ". So, the knowledge of the radiative magnetic field and the signatures of the dynamo effect are probably important to produce the grand minima periods corresponding to the medieval, Maunder or

Dalton minima, as well as for the modern maxima (the Sun is more active since ~1940 than in previous 1100 years).

Helioclimatology

Solar influences on terrestrial climate and natural hazards could be really understood and quantitatively estimated only by studying the solar-terrestrial system in their fullness and complexity, including all the mechanisms of solar energy transfer on the way from the Sun to the Earth. This requires identification of the most effective solar agents streaking the Earth and understanding the mechanism for solar energy transfer throughout the whole depth of the atmosphere.

Apart from cosmic rays which may influence clouds coverage, the main driver is the irradiance variability and CME (coronal mass ejection) which may act on a terrestrial regional area. Building up of new reliable knowledge aimed on better assessment of the risk for people, and sustainable development of the economy is achievable only within broad international multidisciplinary cooperation, and by integration of partners' observational, research and modelling capacities.

On these bases, a new program involving a score of country has been proposed for which the main scientific goal is to integrate the existing knowledge for the processes determining variability of the solar output energy, and in order to understand how these variations can affect the global and regional characteristic of climate, environment and human life. The synergy between different branch of the scientific research (solar physics, magnetosphere, ionosphere, and upper-, middle- and lower-atmosphere, where the climate and weather are formatted) is very important for:

i. better understanding of the mechanisms for energy transfer within the whole depth of the Earth atmosphere;
ii. optimization of the economics' models aiming on the mitigation the consequences of global warming and other hazardous events;
iii. finding the "optimal" policy solutions in protecting the environment and human life.

This new program could be thus a perfect instrument for integration of existing monitoring capacities and research infrastructures in South-East Europe (mainly the Balkan, Black and Caspian Sea Region countries network) for building up a quantitatively new knowledge, and to participate actively to the elaboration of a new science - the helioclimatology.

Conclusions

Solar variability is one of the most complex problems in solar physics. Controlled by dynamo processes, the internal properties can be tackled through helioseismology or, in a more difficult way, but fully complementary, through the measurements of the gravitational potential. To better understand how the solar engine works, we must:

i. understand how the internal layers rotate, with a particular attention on the core and the leptocline (the tachocline has been extensively studied these last decade);
ii. understand how sub-surface layers vary in time (see for example the phase change of the diameter);
iii. understand why activity was sometime suppressed in the past, over relatively large period of time;
iv. solve a paradox, i.e. better understand the quiet Sun to get more insight on its variability.

Needed data and open questions relevant to this problem can be listed as follows:

- Convincingly measure and separate spatial limb variations and thermal effects;
- Measure the latitudinal corrugation (due to thermal flux instability?) at the base of the convection zone (leptocline);
- Simulate a realistic fluid region large enough to confirm the turbulent viscosity or radial shears;
- Measure small changes in the solar shape to probe minute variations in the solar gravitational potential and interior stratification.

Progress will depend on discovering how changes in the solar interior affect energy flow from the radiative zone and convective zone out through the photosphere. Regarding the solar core dynamics, the subject is of high priority for new investigations. Space-dedicated missions, such as Golf-NG/DynaMICS in a joint effort with SDO, should provide a new insight on the question.

Starting less than a decade ago, mankind has entered into a new relationship with our planet. Unless we quickly and profoundly change the course of our civilization, we are faced with the doom of the worldwide ecological system. However, understanding the complicated chain that links the solar variable output to the complex physical state of the Earth's atmosphere is still a challenge to physicists. It is not possible yet to manage it completely, although some parts of the puzzle begin to be assembled. By contrast, it is possible to analyze the effects of the outflow of solar material on human technologies, on the ground or in space [41]. That is why we would emphasize the focusing on interdisciplinary collaboration relative to Sun-climate research as an important stimulus to solving some well identified research problems. Consistent with the recommendations of the COST policy (founded in 1971, COST is an intergovernmental framework for European Co-operation in the field of Scientific and Technical Research, allowing the co-ordination of nationally funded research on a European level; COST Actions cover basic and pre-competitive research as well as activities of public utility), the need for better research cooperation between solar physicists and climatologists must be reinforced.

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