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THE CHANGING SUN, OUR STAR

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This lecture is dedicated to the memory of three solar physicists, three old friends, recently deceased : Edith Alicia MÜLLER, Philippe DELACHE, Constantin MACRIS

RESUMEN

El Sol rige la vida terrestre. El sistema formado por el Sol y la Tierra no siempre estuvo organizado de la misma manera que ahora; por otra parte, el Sol evoluciona permanentemente en diferentes escalas de tiempo. No sólo su campo magnético varía siguiendo un ciclo de 11 años, sino que además, su luminosidad y su radio varían en correlación con el ciclo magnético y tal vez, también de manera secular. Se pasa revista aquí a los hechos principales ligados a esta variabilidad solar, la cual influencia fuertemente la Tierra, a través del geomagnetismo y de múltiples variaciones climáticas a gran escala. ¿Es el Sol, el principal responsable de una eventual evolución catastrófica en el clima terrestre? ¿O será la humanidad? Los depósitos de ciertos elementos radioactivos en la Tierra dan una idea acerca de las variaciones de la actividad y de la radiación solar en el pasado. Estos hechos abren nuevas perspectivas de investigación solar y permitirán quizás responder a la interrogación precedente afin de *"dar al César lo que es del César"*.

ABSTRACT

The Sun rules all life on Earth. But the Sun-Earth system was not permanently organized as it is now; moreover, the Sun itself is evolving at several different time-scales. Not only does its magnetism follow an 11-year cycle, but also its luminosity and radius are changing in correlation with the magnetic cycle and perhaps, also in a secular way. A quick review is given of the main features of this variability. The changing Sun strongly influences the Earth, through both the geomagnetism and the many large-scale climatic variations. But, is the Sun mainly responsible for some catastrophic evolution of the Earth's climate? Or is it man himself? On Earth, the deposits of some radioactive elements are proxies for the past variations of solar activity and solar radiation. These facts provide us not only new ways to study the Sun but also a probable answer to this question in such a way that we could *"render unto Caesar what belongs to Caesar..."*

Key words: **SUN – GENERAL**

1. SUN AND MANKIND

Clearly, the Sun has been ruling all life on Earth for billions of years. And hopefully, it will do so for several more billions of years... Man has always put the Sun at the center of his preoccupations. Is it not an emblematic figure of the Uruguayan flag?... Poetry and painting have illustrated that fascination, a fascination responsible for mixed feelings: often, it is the fear of the overbright Sun as the sad fate of Icarus or of Phaeton; it has influenced the fearful attitude of Dürer (in his "Melancholia"), of Brueghel (in the Fall of Icarus), or of Gérard de Nerval, later, in his poetry; and most artists only dare a look at the setting Sun, yellow or red (such as Monet, Van Gogh, Chagall, Klee, Magritte and many others) or as the poets (Baudelaire, Rimbaud, ...) who focus their feelings on "le Soleil bas taché d' horreurs mystiques".

Even the great French poets born in Montevideo, Isidore Ducasse, "dit le Comte" de Lautréamont (1846-1870), in his "Chants de Maldoror", Jules Laforgue (1860-1887), in his "Complaintes", or Jules Supervielle (1884-1970), in "Gravitations", have been deeply influenced by the stars of the southern sky of Uruguay, still more than by the Sun itself... And Pablo Neruda (and others) were inclined to dream about the "Noche Marina" more than about the sunny day!

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2. THE SUN-EARTH CHANGING SYSTEM

The illumination of Earth and hence its climate, depends greatly upon the relative position of the Sun and Earth. But the daily and the seasonal variations are not the only ones to be considered. As noted by Milankovitch years ago, the Earth's illumination is affected by the precession of equinoxes (period 26000 yrs), by the change of Earth's position on its orbit during the precession period, by the variation of the inclination of Earth's axis (between 22°and 25°) and by the eccentricity of the orbit, all these effects being combined in a complex way. As computed recently by Berger, the main components of the Earth's insolation by the Sun, or the "climatic signals" resulting from this computation fit rather well the observed signals, as found in the deep sea sedimentary cores. These signals are of about 100 kyr, 53 kyr, 41 kyr, 23 kyr and 19 kyr. Other changing factors are perhaps to be considered, such as the Trellis effect (small inclination of the magnetic axis in relation to the rotation axis).

3. SUN AS A STAR AND AS A VARIABLE STAR

A star is usually defined, in the classical views, as a sphere of ideal gas of a given luminosity L, a given radius R, a given mass M and a given chemical composition (H, He, metals). This uniqueness is now questioned by recent determinations of the solar radiation using spacecraft showing the variation of the "solar constant". Indeed, this is not a measurement of the solar luminosity, as our privileged position (very near to the plane of the solar equator) somewhat biases our views. Now, infrared radiation (E. Müller and associates) seems to vary not in phase with the "solar constant": the observations also show that the distribution of the brightness on the solar disc is not uniform.

More indicative of the true change of luminosity is the observed variation of the neutrino flux, now, over more than 20 years. This neutrino flux is seemingly correlated (Davis and Cox) with the solar magnetic activity.

All this leads us to suggest strongly that all other parameters (L perhaps, R certainly, the magnetism of course and all various solar proxies of the Earth's climate) are changing with time and not only with the period of the solar activity cycle. In any case, the solar model is a complex one and the Sun a very intricate dynamo far from linear. All phenomena are coupled with each other within the solar machinery: convection, rotation, differential rotation, magnetism, etc. A global theory is still far from being reached and perhaps the physics of isolated phenomena (flares for example) might help us to build this theory to take into account the couplings put clearly in evidence by the observations.

3.1. Convection and Magnetism as Coupled Mechanisms

The convection is seen through the granulation. Macris has clearly seen its correlation with the solar cycle. Detailed studies performed by R. Müller and associates, show that the granules are only the top of the convective layer: in their organisation, some bright points, appearing in the inter-granular space, are at the same time proxies for the large cells of super-granulation, linked with deeply rooted convection and also with magnetic features of the corona. Topka and Title have also shown, in the most convincing way, that local activity on the Sun, even at small level, perturb completely the granulation pattern and hence, the convection. Considerations on the structure at large scales of the convective layer, have convinced theorists that the pattern of convection (in toroidal rolls, as suggested by Nesme) is a function of the phase during the solar cycle.

Superficial motions reflect also global oscillations of the Sun, a phenomenon well-known today. The acoustic modes of these oscillations are reflecting the differential rotation of the Sun (in latitude and in depth) and their frequency varies following the solar activity cycle with a rather high degree of correlation. The **differential rotation**, as derived from these oscillations, or directly measured on the Sun, from the XVII-th Century, **is thus a function of the solar activity**.

3.2. Luminosity and Activity are Coupled Together

One can consider the neutrino flux as correlated with the overall luminosity, as produced in the very high temperature core of the Sun. But now it is quite clear that the neutrino flux is coupled with the activity and hence, the latter is correlated with luminosity. In addition, **the solar radius and neutrino also seem coupled together** according to Laclare, Delache, Gavryusev, Gavryuseva and others.

The measurements of the radius with adapted prism astrolabe are indeed quite reliable and one must not to be surprised to have found (Laclare) a correlation between neutrino flux and radius. Of course part of the radius variations is due to a solar deformation linked on the one hand with the "royal zones" (about 20°- 30°of heliographic latitudes) where the existence of spots diminishes the measured brightness and as a consequence the measured radius, and on the other hand with the high latitude activity zone (70°- 80°) where faculae have the inverse effect. But a residual effect remains probably there...

Magnetic fields, dragged by convection from the deepest part of the Sun below the convective zone, command the behaviour of the outer layers of the Sun, including the corona. As a consequence, the physics of the solar wind expanding into the interplanetary medium around planets, is certainly commanded by the features of the solar magnetism. Therefore, the analysis of active phenomena (prominences, flares of various intensities, radio bursts, X-ray flashes and all phenomena injecting some matter into the solar wind) is a precious guide to its study. The flare mechanism together with the structure of the magnetic fields in the interplanetary medium (between the Sun and the heliosphere bounded by shock with the interstellar medium), command the influence of the Sun upon the planets. Of special interest are the mechanisms of bubbles of coronal structures ejected in the wind (observable in the Lyman α pictures of the Sun), or, still better, the beautiful flare developments observed above the solar surface in the hottest parts (10^6 - 10^7 K) of the solar corona, as displayed by the magnificent pictures obtained in the X-ray domain by the Japanese satellite *YOKKOH.*

The study of the solar magnetic cycle shows some regular features like the Spörer law, the butterfly diagram, etc. Nevertheless, going back into the past, one observes that the solar cycle of activity is far from periodic. There are long intervals during which the activity reaches only relatively small values at the time of its maximum. One had recognized for a while the Maunder's minimum, in the interval 1640–1750. But the interval 1800–1870 seems also relatively quiet: at this epoch maxima were not very intense. Nevertheless and keeping this irregularity in mind, we must ask now the following question :

How do solar active phenomena or how does solar activity cycle, affect the Earth's various layers: stratosphere, atmosphere, oceans?

4. SOLAR ACTIVITY AND EARTH'S PHENOMENA

All the variable solar phenomena affect the equilibrium of heat fluxes on Earth. Individual events, as for example flares, are correlated with various climatological features as shown by statistical studies. Such is the case of the vorticity area index, the geomagnetic index, the drought occurrence (Fig. 1), the temperature of oceans and of emerged lands, etc. In some cases, the correlation with the cycle itself is indicative enough as in the case of geomagnetism, closely linked to the activity cycle. Above solar active regions, the structure of the solar corona is, so to speak, shaped by this activity phenomena.

Clearly, the motion of ionised particles in the magnetic fields is at the origin of avoidance regions above the centers of activity, a phenomenon discovered by Roberts and the author in 1954, and splendidly confirmed by the X-ray images of the Sun, displaying "coronal holes" obviously linked with the deep Sun (as proved by the fact that their rotation is solid-like and not differential). These kinds of studies reveal strange relations such as the one between the well-known *El Niño* phenomenon and the solar activity (Fig. 2). The delay between the maximum of solar activity and the maximum (or minimum) of terrestrial effects varies from phenomenon to phenomenon. Sometimes the correlations can even be lost as happens for precipitations. The correlation is completely hidden by local phenomena in moderate latitudes and near the equator but they are closely linked with solar activity when monitored in the polar meteorological stations.

5. THE RADIOACTIVE ELEMENTS ON EARTH

Two important proxies, the content of C_{14} and of Be_{10} (but also of O_{18}) are used to study the deep-sea core, the polar ice cores, etc. in which —they are, so to speak, frozen-in. It seems that the cosmic radiation is modulated by the solar wind, itself highly correlated with the solar activity. This modulation leads to a deposit more or less important in the atmosphere (soon dissipated) but stabilized in the sediments and in the ice-cores or in the vegetation and animal life. The half life-time of Be_{10} is about 3 10^6 years, that of C_{14} only 5730 years. The correlation of the C_{14} variation studied from "dendrochronology" and the solar activity, justifies (for the period prior to the direct measurements of solar activity) the deduction of solar activity from C_{14} measured in coral reef structures (until about 15000 years before now) and to detect only the Maunder minimum (1740–1850) and the Dalton interval (1800–1870), but prior to them, the Spörer minimum (around 1350–1500), the Wolf epoch (around 1350) and the medieval warmth (around 1200 A.D.). ΔBe_{10} and ΔO_{18} allow to study the periods prior to these. Power analysis of these fossil radioactive data seem to indicate typical periodicities of 19 kyr, 24 kyr, 43 kyr and 106 kyr and show the dominant role of the Milankovitch-Berger r parameters.

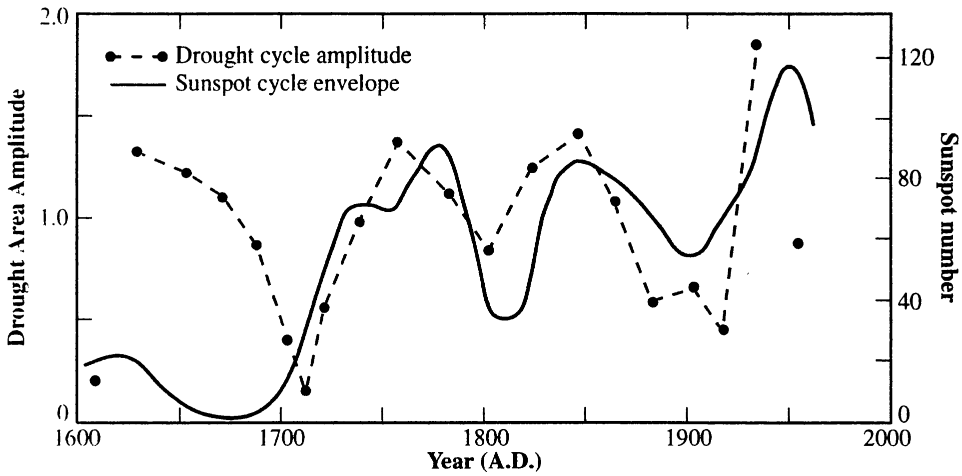

Fig. 1. The long-cycle periodicity of drought and sunspots (after Mitchell).

6. MAN-MADE VERSUS SOLAR FORCING OF EARTH'S CLIMATE

It happens that one can build models, either by modifying the solar constant (illumination of the Earth's ground) or by increasing the content of CO_2 in the atmosphere, a typical gas responsible for increasing the atmospheric temperature by the "greenhouse effect". It is remarkable to find that the effects are very similar in particular on such parameters as surface albedo, cloudiness, etc. Nevertheless, that kind of numerical experiments does not allow any definitive conclusion; it shows only that faced with climate changes, one might hesitate whether man activities are "the" evil or whether the responsible agent is the varying solar activity.

Actually, the time variation of the temperature as determined from ice cores analysis is quantitatively very similar to that computed from the known variation of the local illumination and from the observed dust deposited on the ground (and before, in suspension on the atmosphere) at least for the last 150000 years. The volcanic activity does not seem to be sufficient to account for the amount of deposited dust; it may come from man's activity although this appears unlikely for such a long period. One can note that in a period of only 30 days, the dust produced locally in industrialised areas is diffused over the whole world.

Actually, the study of the glacial archives of climate show undoubtedly an increase of CO_2, NH_4, N_2O and CO_2 in the atmosphere, since a long time ago (at least during three centuries); the rate of increase is larger now than in the past. What is curious is that a close examination of the CO_2 increment (determined from bubbles in the ice cores) does not display any obvious change of behaviour at the time of the industrial revolution; it rather displays some continuous exponential increase (Fig. 3). Whatever the reason of the increase of the "greenhouse gases", they are likely to produce an increase of temperature in the coming years, decades or centuries. One can note that, would the polar ices be completely melting, western Europe would be deeply affected. Holland and Denmark would be completely covered by water, as most of the British coasts, as the Rhone or the Po valleys, etc. ... and as the whole territory of Uruguay! So, be it human activities or the Sun's evolution, that we should blame for the further climatic evolution, there is nothing we can do about the Sun (except precision perhaps); **but there is a lot that mankind should do in order to limit strongly its own damages to the climatic evolution of our Earth.**

7. THE INTERPLANETARY MEDIUM

An important feature of the interplanetary medium, between the Earth and the Sun, and the Earth is the distribution of the magnetic field in "magnetic" sectors of alternate polarity; the velocity of particles of all kinds and their density are also distributed into sectors. The study of the interplanetary medium at all heliographic latitudes is now possible. Out-of-the-ecliptic rockets are being launched, with observing stations and in-situ detectors, such as the ESA instrumentation of the satellite *Ulysses*. This is a new artificial planet, located at some astronomical units from the Sun, on an orbit from which one can observe alternatively the North and the

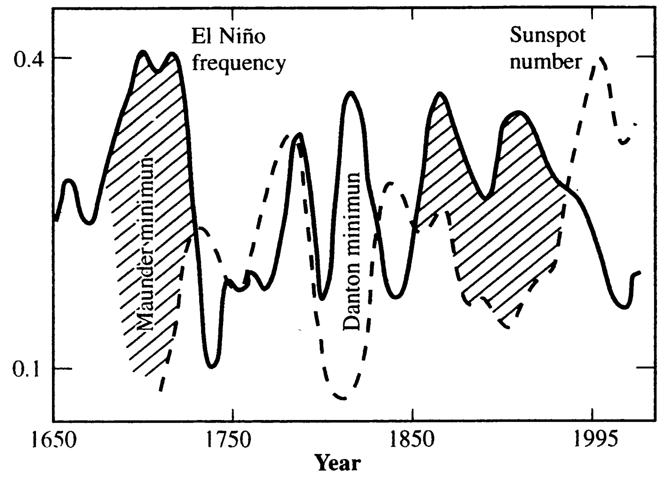

Fig. 2. The long-cycle periodicity of *El Niño* frequency and the solar activity (after Anderson 1990).

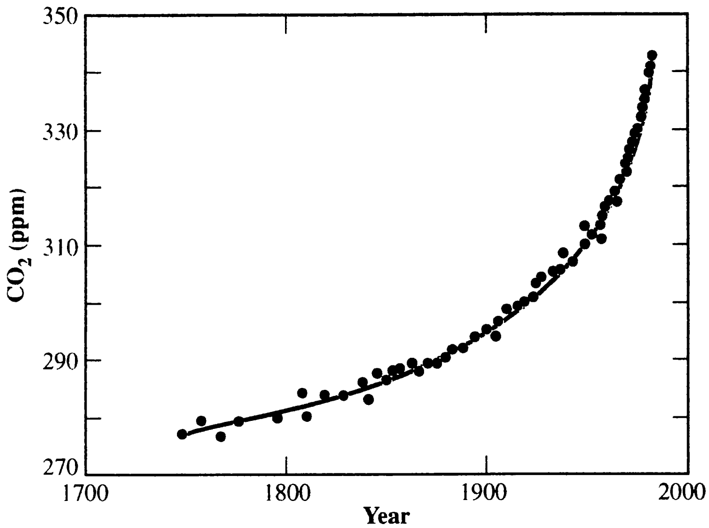

Fig. 3. Secular evolution of the atmospheric concentration of CO_2 from the analysis of air bubbles in ice cores and from direct measures during the last 30 years.

South solar poles. The results from *Ulysses* are already very promising and bring many replies to the questions asked by the astronomers. There is little doubt that in the future, the extension of "out-of-the-ecliptic" observations will be very fruitful.

8. SOLAR ACTIVITY AND STELLAR ACTIVITY

So, on one side, the Sun being our star, its study is essential for the understanding of the Sun-Earth relations. Astronomers have studied some stars by elaborate devices and they have been able (for example Donati) to map their magnetic fields and their temperature distribution. They have actually detected huge areas similar to spots. But small features, like the solar spots are, strickly speaking, not observable; clearly one shall need much better resolution in stellar imagery, now still far from reach, to understand fully the observations or to perform more detailed comparison with the solar physics.

Many stars of various types, many of the solar type or close to it, have been monitored for long periods. All kinds of behaviour have been found : strong activities, moderate activities and no activity at all. The cycles are quite comparable to the solar one. One has even found cases where the amplitude of the cycle of activity is changing from time to time: these stars undergo probably a "Maunder minimum". This does not prove that we are already able to understand stellar cycles. It is true that the methods of study are quite limited, that the observations are somewhat biased and, over all, that there are not two stars completely alike, the largest differences being precisely located in the magnetic phenomena.

But whatever the modest results obtained so far, we must stress that the Sun is still the closest star and the easiest to observe in its details. Perhaps not a real twin to any other star, it is nevertheless true that solar physics, better understood through detailed observations, from ground based (optical and radio) instruments or from space, will be an irreplaceable guide to stellar physics.

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Obviously, the bibliography on this question is enormous: in an hour we have covered, very quickly of course, practically all aspects of modern solar physics. Not to refer to any individual paper, let me only quote recent colloquia or collective books on the subject:

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