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Understanding the origin of the solar cyclic activity for an improved earth climate prediction

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Abstract

This review is dedicated to the processes which could explain the origin of the great extrema of the solar activity. We would like to reach a more suitable estimate and prediction of the temporal solar variability and its real impact on the Earth climatic models. The development of this new field is stimulated by the SoHO helioseismic measurements and by some recent solar modelling improvement which aims to describe the dynamical processes from the core to the surface. We first recall assumptions on the potential different solar variabilities. Then, we introduce stellar seismology and summarize the main SOHO results which are relevant for this field. Finally we mention the dynamical processes which are presently introduced in new solar models. We believe that the knowledge of two important elements: (1) the magnetic field interplay between the radiative zone and the convective zone and (2) the role of the gravity waves, would allow to understand the origin of the grand minima and maxima observed during the last millennium. Complementary observables like acoustic and gravity modes, radius and spectral irradiance from far UV to visible in parallel to the development of 1D–2D–3D simulations will improve this field. PICARD, SDO, DynaMICCS are key projects for a prediction of the next century variability. Some helioseismic indicators constitute the first necessary information to properly describe the Sun–Earth climatic connection.

Keywords: Solar interior; Helioseismology; Gravity waves; Solar magnetic field

1. Introduction

In the 1930s, Bethe has established that nuclear reactions in the solar core produce energy which equilibrates the luminosity loss at the surface, finding consequently a solution to the great age of the Sun (4.6×10^9 years). Then stellar evolution has developed quickly by solving four structural equations which describe the conservation of energy and mass together with the production and the radial transfer of energy. In the 1960s, a systematic description of the stellar evolution on very long timescale (millions or billions years depending on mass) has been developed. In this framework, the Sun appears as a typical star which dissipates only 10^{-8} of its energy in 100 years at the present age. Such small variation is considered as negligible so one deduces from the observed luminosity of $L_\odot = 3.846 \pm 0.004\,10^{33}$ ergs/s, the "solar constant" of 1367.6 W/m^2 (estimated as $L_\odot/4\pi d_{\rm SE}^2$ where $d_{\rm SE}$ is the distance between the Sun and the Earth) which is the energy released by the Sun to the Earth per surface unit. Considering the orientation of the Earth, a mean value of 342 W/m^2 reaches the high atmosphere. With an earth albedo of about 30%, 239 W/m^2 is received by the ground.

The present global climatic models use these numbers to describe the impact of the Sun on the Earth climate. The tectonic plates and the earth orbital parameters lead to the great variations of the climate in the past and to the corresponding frequencies of 100, 43, 24 and 19 k years, predicted by M. Milankovitch, and confirmed by evidence in the marine sediment data. But in fact, the measurements of the time luminosity variations (Fröhlich and Lean, 2005 and references therein) show that such a scheme is probably

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too simple. The total irradiance varies by about 0.1% during the 11 year cycle (even more daily due to the rotation of the Sun). Greater variations (10% in UV and 100% in EUV) are also clearly connected with the Sun activity (Fig. 1), mainly to the evolution of the sunspots and plages. Accordingly, the slow variation of only 10^{-8} per century predicted by the solar model is clearly too simple to reproduce the real Sun even though a real long-term trend of the luminosity is not yet established. Consequently, the present observations suggest a more complex Sun–Earth relationship involving the role of the irradiance variations in different wavelengths, an impact of UV on the ozone production in the stratosphere and also an influence of the solar modulation of the cosmic rays on the clouds in the earth atmosphere.

In this review, we would like to show recent results of seismic observations of the solar interior which must help to progress on this field. This progress is driven by some new theoretical investigation of the internal dynamical processes and the development of multidimensional simulations. Such advances give confidence that we can understand and possibly predict also the great extrema noticed in the sunspot records. The instrumental side continues to develop, so we are able now to measure all the important quantities which put constraints on the existence of different solar variabilities. In Section 2, we recall the external observations which put in evidence potential different solar cyclicities. Section 3 is a short introduction to helioseismology. Section 4 is devoted to the space Solar Heliospheric Observatory (SoHO) results, Section 5 to the dynamical processes which will appear in solar models in the next 5 years. Section 6 shows the space perspectives, the open questions and how we will try to solve them.

2. External observations of the solar cyclic activity

In 1612, Galileo was the first to establish that sunspots belong to the solar photosphere. These observations demonstrate that the Sun was rotating. Then systematic observations of the sunspots highlighted the solar latitudinal rotation with an equatorial rotation about 30% quicker than the polar one. We have today a direct measurement of this phenomenon since four centuries. Large line-of-sight magnetic fields (3000–4000 G) have been measured in the sunspots, in contrast with the mean weak field of only few Gauss. Hale has also shown that these sunspots appear in regions where pairs of opposite polarities are present and that the north and south hemispheres have opposite polarities. This polarity reverses at each cycle leading to an approximate period of 22 years. If the magnetic solar origin of the double 11 year cycle is not a doubt, it shows however a large variation of its amplitude and a noticeable temporal duration (from 8 to 12 years) which are not clearly understood: see the complete and comprehensive review of Usoskin and Mursula (2003).

The time dependence analysis of the atmospheric ^{14}C cosmic rays detected in tree rings, exhibits fluctuations which are generally attributed to the solar wind. Damon and Jirikowic (1992, 1994) have noticed that the Sun behaves as a low frequency harmonic oscillator. They showed a recurrence period of 2115 ± 15 year with two powerful harmonics at 211.5 year and 88.1 year, generally called the Suess and Gleissberg cycles and suggested that these periodicities could modulate the Schwabe 11 year period and produce the extrema of the solar activity (Fig. 2a). They deduced a relationship between the Earth temperature variations of the last century and the sum of the different cycles. This curve presents a flat temperature profile in the seventies breaking a general warming of the Earth temperature dominated by the "solar" Suess cycle up to 2050 (Fig. 2b). Such behaviour may be compared to the observed mean Earth temperature evolution (National Climatic data center US), showing such a strange behaviour, encouraging the idea that the solar influence could reach today about 30% of the total Earth warming. Nevertheless, such a conclusion is not well established. Indeed, more recent studies show that the interpretation of the different observables (sunspots, ^{14}C and ^{9}Be) could be more complex. It has been established that the Gleissberg cycle presents large variability from 65 to 140 years (Ogurtsov, 2005 and references of the same author). Moreover, Kremliovsky (1995) analysed the solar activity in terms of chaotic dynamics with intermittency, this justifies more work to identify the real different dynamical instabilities. Different authors showed also the difficulty in forecasting the next solar cycles.

So it is certainly important to establish if the different "identified" cycles are independent, and have only a magnetic origin. Are the longest ones just a consequence of the diversity of the 11 year cycle? Are they produced by the internal dynamo or are they partly generated by other processes like the internal waves? Understanding the origin of the variability of the previous cycles will improve the prediction of the evolution of the Schwabe cycle. Today it is difficult to predict the characteristics of the beginning cycle 24 (Schatten, 2005; Dikpati and Gilman, 2006;

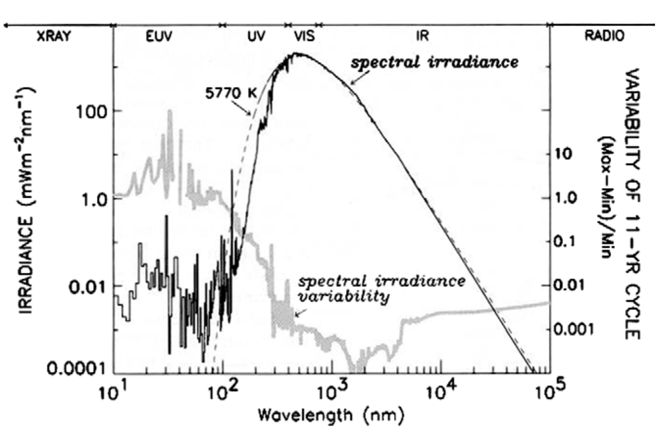

Fig. 1. Spectral solar irradiance and its time variability in grey along the 11 year cycle. From Lean, 2004.