

THE DYNAMICS PROJECT

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ABSTRACT

The DynaMICS (Dynamics and Magnetism from the Internal core to the Chromosphere of the Sun) space project is devoted to the long trend (decades or centuries) global properties of the Sun. Its main scientific objectives are the following: (1) to get a complete 3D rotating and magnetic picture of the Sun from the central core up to the chromosphere, (2) to deduce from it the different sources of dynamo and their interplay, (3) to build models and predictions of the great maxima and minima solar activities, (4) to produce outputs useful to quantify the different aspects of the solar contribution on the earth climate. We outline here the instruments: GOLFNG, SODISM, PREMOS, MOF that we are developing to reach this goal. They will detect from space solar acoustic and gravity modes together with radius and irradiance variations and will improve our knowledge on the transition region between photosphere and chromosphere. Understanding the magnetic field of the radiative zone is a new and crucial objective as this ingredient must play a role in the long-term Sun-Earth relationship and also in the knowledge of stellar interiors. These instruments will observe the Sun from an orbit around the Lagrangian point L1 for a decade to ensure continuity, stability and measurements of tiny variations.

Key words: Solar interior, Magnetic cycles, Sun-Earth relationship.

1. INTRODUCTION

SoHO has been extremely successful in improving our knowledge of the solar interior. It has opened a new era on the internal dynamics and the origin of the solar magnetism (Christensen-Dalsgaard 2002, Turck-Chièze these proceedings). Consequently, we propose a world-class project to study the long trend of the global solar properties in complement to the missions STEREO (2006-2009), SDO (2008-2013) and the european project SOLAR ORBITER which are mainly dedicated to high resolution measurements and space weather implications. The DynaMICS project includes successful European techniques used aboard SoHO or in PICARD (2008-2011). The dedicated instruments: the spectrophotometer GOLFNG (France/Spain), the radiometer PREMOS (Switzerland), the intensity measurement at the limb SODISM (France) and a magneto optical filter MOF (Italy) instruments have been recently improved for a next space mission. DynaMICS needs continuity and stability to measure all the global quantities: acoustic and gravity modes, radius, shape deformations, irradiance at different wavelengths. Some of them produce very low signals and most variabilities are known to be lower than 10^{-3} . The best conditions for such a mission are:

- an orbit around the Lagrangian point L1
- about 10 years of observation after 2011

DynaMICS will also provide an insight into the photosphere up to the chromosphere dynamics by measuring Doppler velocity at different heights in the atmosphere and with different elements Na, K, Ca.

2. THE SCIENTIFIC OBJECTIVES

Magnetism plays a fundamental role in our Universe. The presence of magnetic fields is not only seen in the Galaxy and star formations. They are present in the elliptic galaxies and more and more attention is given to the magnetism of the stars and the relationship between the Sun and the Earth thanks to space missions as Ulysses, SoHO, TRACE, CLUSTER. But this fundamental ingredient is still poorly known and is absent from most of the equations currently used to describe our Universe. It is interesting to remark that although the 22 years solar cycle is now observed and established for centuries, it is not yet possible to predict without ambiguity the position of the next maximum nor the intensity of the coming cycle 24 (Dikpati et al. 2005; Schatten 2005). One may note also that the magnetic field is not present in the current description of the life of stars. Therefore, describing the magnetism of the solar interior represents an important objective for the next decade. From the observations of SoHO, we have tremendously improved our knowledge of the solar internal dynamics (Christensen-Dalsgaard 2002). Some crucial quantities are now observed as the sub-surface meridional flows, the zonal flows and the profile of the rotation down to the limit of the core. We can even follow them with time along the 22 year cycle and some smaller periodicity of 1.3 year near the tachocline region is suggested by the helioseismic observations in different instruments (Howe et al. 2000, Jiménez-Reyes et al. 2003, 2004). Dynamo models have been developed following Parker (1993) as an oscillatory dynamo in the Sun to drive the solar activity cycle. Important progress has been achieved these last years to predict more and more realistic dynamo models which are able to explain not only the mean period but series of cycles. But the prediction stays difficult and controversy is still present on the way to get the answer.

In fact direct measurement of the internal magnetic field has not been obtained and we have only limits on the mean field at different positions inside the Sun (Couvidat, Turck-Chièze & Kosovichev 2003a). Nevertheless, the activity of the outer layers along the solar cycle are followed by global acoustic modes. The corresponding magnetic field is estimated of the order of 10 kG and the variation along the solar cycle smaller than 100 G (Li et al. 2003). An upper limit for the magnetic field of 300 kG is given below the convective zone and 3MG for the core. This last value is deduced from the estimated deformation of the Sun (Friedland & Gruzinov 2004). So, the pursuit of helioseismic observations with improved instruments is crucial to get quickly the complete dynamics down to the core and to catch the different actors. In parallel 3D MHD calculations of portions of Sun are developing. They have the objective to reproduce and explain the solar internal dynamics. A new challenge is to reproduce the flat radiative rotation profile (Thompson et al. 2003, Couvidat et al. 2003b) and the thin tachocline potentially sustained by the development of a magnetic field in the radiative zone to block the extension of the differential rotation downward (Brun, Miesch & Toomre 2004; Brun

& Zahn, 2006, Miesch, Brun & Toomre 2006).

SoHO has also determined with an unprecedented accuracy the total solar irradiance variation of about 0.1 % along the 11 year solar cycle and a peak to peak variation following the rotation rate of 0.2% (Fröhlich & Lean, 2004). This variation is in phase with the solar cycle and dominated by the plages around the active regions or by the variation of the solar radius (smaller at maximum of activity) but to really understand the different processes which explain this phenomenon and its implication on the earth, one needs to better describe what produces the cyclic variabilities in different wavelengths, in particular in ultraviolet. One needs also to establish if there is a slow time evolution of the luminosity on a scale of centuries.

The satellite SDO (Solar Dynamical Observatory), scheduled to be launched in 2008, will substantially improve the present dynamical picture of the convective zone. The improved resolution from MDI to HMI will give access to deeper, time-varying meridional circulation and will determine if different cells are simultaneously present. The CNES microsatellite PICARD, scheduled also for 2008, will measure the global quantities as diameter and irradiance at different wavelengths and their variations during three years. From helioseismology, it has been extracted a double sheet: the region just below $0.99 R_{\odot}$ seems to evolve in phase with the solar cycle although the region above seems in opposition of phase (Lefebvre & Kosovichev, 2005). This effect needs a little more explanation and the photospheric variation of the radius along the solar cycle needs to be definitively established.

A complete dynamical picture of the Sun needs to include also the motions of the radiative zone, the corresponding magnetic fields and the rotation down to the solar core including the profile inside the core. Such quantities will be reached only by the detection of gravity modes. Gravity waves are generated by strong plumes at the base of the convective zone, they can carry efficiently angular momentum during the first stages of evolution (Talon & Charbonnel 2005). Some of them created modes which are trapped inside the radiative zone. The theoretical predictions (Andersen 1996, Kumar et al., 1996) have shown that the gravity modes equally spaced in period have a visibility at least a factor 10 smaller than those appearing in the upper part of the gravity frequency range. Moreover, they have shown that their surface velocity may be fraction of a mm/s. Gravity mode candidates have been identified with the GOLF spectrometer in the upper frequency range of frequency (Turck-Chièze et al., 2004a,b). Such patterns are very sensitive to the core and the tachocline dynamics. On the lower part of the spectrum one has detected a strong signal compatible with the asymptotic behaviour of the dipole modes (Garcia et al. 2006 submitted). These two analyses both suggest that the rotation seems to be higher in the solar core than in the rest of the radiative zone as a relic of the young Sun. Such information is extremely important to put constraints on magnetic fields in the solar nuclear core. Unfortunately one has reached the limit of detection of the present instruments so we are strongly encouraged to improve the

capability of detection to open the golden era of gravity mode physics which will reveal the dynamics of the whole radiative zone.

We summarize here the main scientific questions to be answered as breakthroughs by the DynaMICS project:

- How do the gravity waves enter in competition with the magnetic field to maintain a flat radiative rotation profile between 0.4 to $0.7 R_{\odot}$?
- Is there a differential rotation in the solar core ?
- How do the dynamical phenomena evolve with time ?
- How the magnetic field of the radiative zone and of the convective zone interact ?
- What is the strengths of the toroidal magnetic fields in the radiative zone?
- Can we understand sufficiently well the origin of the external magnetism to anticipate its effect along the next century and quantify how the Sun participates to the climatic evolution on earth ?
- Can we quantify properly the irradiance at different wavelengths, radius and solar deformation variations on several decades ?
- Can we deduce and predict grand maxima and minima of activity from such information as one has already observed in medieval period or during the Maunder minimum ?

3. THE DIAGNOSTICS

In parallel with the scientific progress on the solar internal dynamics, our capability of diagnostics has been also substantially improved. We concentrate here on the instrumental improvements affecting the global quantities.

3.1. The dynamics of the radiative zone: GOLFNG/SODISM

The radiative zone represents 98% of the total solar mass and cannot be ignored when one would like to study the long trend evolution of the Sun and the origin of magnetic activities at timescale of centuries. All the questions on the deep dynamics of the Sun will benefit from the detection of gravity modes. Effectively the sensitivity of the acoustic modes is maximal in the outer layers and their probe of the radiative zone needs to properly extract the information coming from the most external layers (Garcia et al. 2001). On the contrary, the sensitivity of the gravity modes is maximal in the solar core.

Gravity modes have been searched for more than 20 years. The limit of detection on ground was 4-7 cm/s (Delache and Scherrer, 1983; van der Raay 1990). The satellite IPHIR using luminosity variations has not really improved the detection limit: 1.3 ppm at 20 μ Hz corresponds to some cm/s (Frölich et al. 1991). The GOLF/SoHO instrument, measuring the Doppler velocity has been specifically designed to detect velocities down to 1 mm/s thanks to a very low instrumental noise and

has allowed to find interesting patterns at this level in two regions of the gravity range (Turck-Chièze et al. 2004a,b; Garcia et al. 2006 submitted). They represent probably the first manifestation of the gravity modes (see Turck-Chièze 2006a for a review and Garcia et al. these proceedings). In fact there are three reasons to detect these modes with difficulty :

- their surface amplitude is particularly low (≤ 1 mm/s) because they are evanescent in the convective zone,
- the solar granulation is presently the main source of noise, in the range where the gravity modes are expected so one needs to improve the signal to noise ratio in both reducing the solar noise and in amplifying the gravity mode signal to detect a maximum of modes in a minimum of times (typically one or two years and not 10 years),
- the spectrum of these modes is dense. so one needs to develop different techniques to identify the components of the observed patterns.

The optimistic aspect of this quest is that one needs only several unambiguous detection of gravity modes between 100 to 400 μ Hz to tremendously improve our knowledge of the solar core. Moreover the lower region analyzed globally will also put strong constraints on the core rotation profile and also on the magnetic field in the nuclear core which contains half mass of the Sun. It is why since 1998, we develop two new instruments which integrate the knowledge of the different techniques.

The Global Oscillation at Low Frequency New Generation (GOLFNG) instrument developed in CEA/France in collaboration with IAC/Spain (Turck-Chièze et al. 2006b) is a resonant spectrometer like GOLF which measures the Doppler velocity variations. Such technique has allowed the best determination of low signals for gravity and acoustic modes (Bertello et al. 2000, Garcia et al. 2001, Turck-Chièze et al. 2004b). The improvement consists to measure the velocity at different heights from the photosphere to the chromosphere which produces non coherent patterns of solar noise. The principle of the GOLF-NG instrument is to measure the Doppler shift of the D1 sodium Fraunhofer solar line by a comparison with an absolute standard given by the sodium vapour cell, the heart of the experiment. A small portion of the absorption line provided by the resonance of the light in the vapour cell is split into its Zeeman components by means of a static longitudinal magnetic field whose strength varies along the longitudinal axis in order to explore different heights of the atmosphere. By changing the circular polarization of the incoming flux, it is possible to select 8 points on the right wing of the line or 8 points on the left wing, with one in common at the center of the line. Moreover the analyzed flux has been increased by a factor 10 to lower also the noise level coming from the instrument and to allow consecutive measurements of portions of the Sun. In fact, large masks placed in front of the instrument will contribute to the identification of the modes and a second crystal polariser could allow the determination of the spectrum of the

mean magnetic field. A prototype of such instrument is in construction and will be set up in Tenerife in 2006.

In parallel using the fact that the gravity modes must be amplified at the solar limb (Wachter R., Haberreiter, M., Kosovichev, A. G.) a new intensity instrument called SODISM (described below) has been developed to improve the intensity detection, even one needs to reduce also in parallel the amplification of the solar noise. Such instrument allows to determine the oblateness of the Sun and will follow the change in radius during the three years of the PICARD mission.

We have demonstrated on SoHO that having different types of instruments is extremely useful to catch the low signals without ambiguity, so we are convinced that these two kinds of improvements have to be used together in order to guaranty the scientific return on gravity modes and the possibility to build a complete 3D picture of the Sun.

3.2. Time evolution of irradiance and radius: SODISM/PREMOS

The Earth has experienced several climate changes showing periodicities extending from several hundreds of millions of years to short periods of 2300, 100 to 400 and 20-30 years having no obvious geophysical origin. Nevertheless the variation of the total solar irradiance seems too small to generate climatic changes such as the cold period of the 17th century. So one believes that non-linear feedbacks are needed to amplify the direct radiative effect. These feedbacks are not well identified, but likely involve the UV variation which affects the dynamics and thermal structure of the stratosphere, and the propagation of the planetary waves (Haigh 1996, Schlesinger and Andronova 2004, Egorova et al. 2004). In the previous section we have shown how we can improve our picture of a dynamical Sun and try to find origins of different cycles. However, whatever the mechanisms are, a precise reconstruction of the total solar irradiance (TSI) is needed to validate climate models by comparison with climate records. This will allow to estimate the role of the solar irradiance variation, not only in the past but also for the present and the future, in order to separate the anthropogenic and the natural forcing. Moreover it is very important to follow the variation of irradiance in different wavelengths and also variation of the radius to better interpret the observed phenomena, in parallel with the measurement of cosmic rays which may affect the high earth atmosphere.

The SOLar DIameter and Surface Mapper (SODISM) has been developed at Service d'Aéronomie of CNRS/France (Thuillier et al. 2006 submitted) for the mission PICARD. It is made of an imaging Cassegrain telescope and a CCD 2048×2048 which collects the solar images in five wavelengths with an accuracy better than 1 mas. Such instrument will carry out solar diameter, solar asphericity, and some helioseismic observations using

the amplification of the modes at the limb and 16×16 macropixels of the whole Sun.

The PREcision MONitoring Sensor (PREMOS) is provided by the Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center (PMOD/WRC, CH). PREMOS sunphotometers consist of 3 identical instruments, where each unit has 4 channels with central wavelengths at 215, 268, 535, and 782 nm. Today, the absolute calibration of the spectral irradiance is of the order of a few percent in the visible and up to 10% in the UV so one needs in the future to find a way to characterize very low increase or decrease of the irradiance along decade which justify improvements of the technique used in SoHO (Haberreiter et al. 2005). This is why a new generation of precision filter radiometer is presently being studied. In addition PREMOS comprises two absolute radiometers which will measure total solar irradiance continuing the series of high accuracy TSI observations of VIRGO/SOHO and TIM/SORCE.

3.3. From Photosphere to Chromosphere, the Magnetic flux: GOLFNG/MOF

Our main objectives are to follow all the global quantities, so it is important to get reliable information on the region located between the photosphere and the chromosphere, to see the emergence and the time evolution of the mean magnetic field. We propose in this project two complementary studies.

GOLFNG will explore 8 heights in the atmosphere with the sodium line from the photosphere up to 800 km and consequently will follow the time evolution of the line due to the variation of the magnetic field. It is a simple instrument well calibrated by the continuum for the different channels so it allows a direct comparison of the different heights to follow the impact of granulation, supergranulation, active regions and chromosphere (Espagnet et al. 1995, Eibe et al. 2001).

The Magneto-Optical Filter, MOF (Cacciani & Fofi, 1978), is used for imaged Doppler and magnetic field observations of the Sun. The strengths of the MOF lie in its wavelength stability, its narrow pass-band (approx. 0.005nm) and its high throughput. This instrument will use the Na at 589 nm, the potassium D-lines at 770 nm and the Ca I line at 422nm which is formed in the mid-chromosphere. So it will probe the acoustic properties of the low atmosphere below and beyond the cut off frequency located at 4.5 mHz, it can thus provide a probe both for velocity and magnetic field information together. It will map the spatial and temporal changes in the vertical travelling time between the mid chromosphere down to the photosphere. The MOF technique has been under development for ground observations for three decades and is used by different groups at different places: observatories and South pole (Tomczyk et al. 1995, Cacciani et al. 2003, Magri et al. 2005, Vecchio 2006). It is important also to mention that this technique allows the measurement of a large range of acoustic modes.

4. STRATEGY OF OBSERVATIONS

The DynaMICS project comprises a complementary instrumentation that addresses a very timely question of direct social impact :

What are the variations of the Sun that influence the terrestrial climate ?

DynaMICS will quantify the different global quantities which are at the origin of a climatic interaction between the Sun and the Earth. This project has not the ambition to deliver a complete answer to the real impact of the Sun on Earth, but it is the first link of the chain of processes which include the reacting magnetosphere, the formation of clouds, the aurorae ... Up to now it is important to notice that this first step is missing and only a constant irradiance is introduced in the climate model calculations. So it is absolutely necessary to build complex models of climate which include a better description of the variabilities coming from the Sun: this supposes not only measurements of such external phenomena but also a deep understanding of their origin. During the last 10 years, we have been able to develop new techniques which considerably enrich the picture of the dynamical Sun and give confidence that we will be able consequently to enrich also the inputs of the climatic models (see Lockwood 2005 fig 115).

Different strategies of observations are under discussion today justified by the importance of time continuity in global quantity measurements. Effectively, although sunspot indicators have been maintained for decades, useful helioseismic and irradiance measurements are only available for one or two decades and not for all the indicators and for all the wavelengths. We are convinced that all these informations must be measured continuously for several decades in order to establish the real climate Solar-Earth connection. It is why we are preparing actively reliable, low cost, low weight instruments which must be launched for long and uninterrupted observations.

We are also convinced that we need redundancies in methods to detect without ambiguity small signals and small time evolution. The DynaMICS project includes all these aspects and will be proposed in the framework of ESA Cosmic Vision, for a mission of about 100 kg of instruments orbiting around the Lagrangian point for a long duration, it must be a world class mission which will benefit from other agencies around the world.

In the meantime, SDO, PICARD and Solar Orbiter will improve other aspects of this problem and will carry parts of these instruments. We consider that we will largely improve the scientific return of the next decade if we are able to put in orbit all the instruments of DynaMICS (including GOLFNG). So, we are hoping synergies with other missions that are proposed for the time after 2011 like the NASA sentinels, the Chinese Kua Fu A mission, both missions observing at the L1 point, and we will not neglect any other opportunity.

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