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REVIEW OF THE GOLF/SOHO HELIOSEISMIC RESULTS AND PERSPECTIVES

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Abstract. Helioseismic measurements aboard SoHO deliver new facts useful to improve our understanding of Sun and stars. After more than a decade of measurements aboard SoHO, we present the helioseismic results obtained with the GOLF instrument. If the first published papers of this community have mainly contrained the internal microphysics, these last 5 years have revealed an unprecedent insight on the impact of the solar cycle on the outer layers thanks to acoustic modes and on the radiative zone dynamics thanks to gravity mode studies. We will show why GOLF appears as an excellent instrument for this purpose and what we have learned from 10 years of observation aboard SoHO with this french-spanish resonant spectrometer. The progress done today by Doppler velocity measurements aboard SoHO (GOLF+ MDI) and by ground networks (BiSON and GONG) opens a totally new perspective for solar and stellar physics. So we then mention the questions that might be solved with the next generation of instruments already in construction in different european laboratories including GOLF-NG. They lead to two formation flying missions DynaMICCS and HIRISE proposed in the framework of the ESA Cosmic Vision perspective. An european strategy of measurements is suggested to maintain this discipline in the best conditions for the two next decades in order to get quantitative estimate of the effective role of the solar variabilities along time.

This review is dedicated to the memory of Jacques Charra who was the project manager of GOLF and to Maryse Charra, his wife. Both of them have continued, after the realization of the instrument, to take care of it along the whole period of observations, allowing the best conditions for an upper class scientific return.

1 Introduction

The SoHO satellite (Domingo 1995) was the first milestone of the programme ESA Horizon 2000. It was launched in December 1995 and appears today like a real success. Effectively, this mission cannot be only considered as a unique opportunity to understand how the Sun is working. SoHO has also largely enriched this transition period between a classical view of stars and a more dynamical and complex view that we begin to build. This success is partly due to the fact that helioseismology has revealed the properties of million of modes not yet reachable for any other type of stars, this important fact allows a new, strong and large scientific return with some problems solved and totally new emerging questions. This transition period takes also advantages of the development of the asteroseismic observations since the launch of MOST then COROT and soon KEPLER mission in 2009. These missions will deliver a smaller number of modes but the stellar evolution community will benefit from the diversity of the observed stars and from the experience accumulated along the 12 years of SoHO observation. It will result a complete revolution in the way we will describe the stars in different stages of evolution and masses and a better understanding of the very active stages like for example the supernova explosion where acoustic instabilities may be a need (Foglizzo 2002).

After more than a solar cycle of continuous observation with the SoHO satellite, it is time to overview the information we have obtained on the solar interior thanks to the european seismic instruments placed aboard this satellite. In the present document we shall critically review the results obtained by the GOLF instrument, realized and analyzed by a french-spanish team listed at the end of the paper. Our objectives are to enlighten the advantages and the limitations of such an helioseismic instrument in order to deduce the future improvements. In the first section, we shall recall the characteristics and objectives of this instrument, the second section will be devoted to the results and their implications for solar-like stars, and the last section will be dedicated to the future for this specific discipline in the broader context of ESA Cosmic Vision.

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2 Comparison of measurement methods and characteristics of GOLF

Among twelve instruments aboard SoHO, three of them were dedicated to internal solar oscillations and consequently to the solar interior. The american Michelson Doppler Instrument (PI: P. Scherrer) looks to the Sun locally which allows to detect a large number of acoustic modes. This instrument has been particularly successful in investigating for the first time the motions in the convective zone and the way the differential rotation profile disappears inside the Sun, showing the importance of the transition region between radiation and convection in the understanding of the dynamo effect connected to the 11 year solar cycle. It has also contributed to confirm and identify some low degree acoustic modes which were at the detection limit of the GOLF instrument. The european VIRGO instrument (PI: C. Frolich) has been mainly dedicated to the time evolution of the total irradiance. It is a photometric instrument with limited capability for detecting low degree low frequency modes because of the effect of the turbulence at the photosphere level.

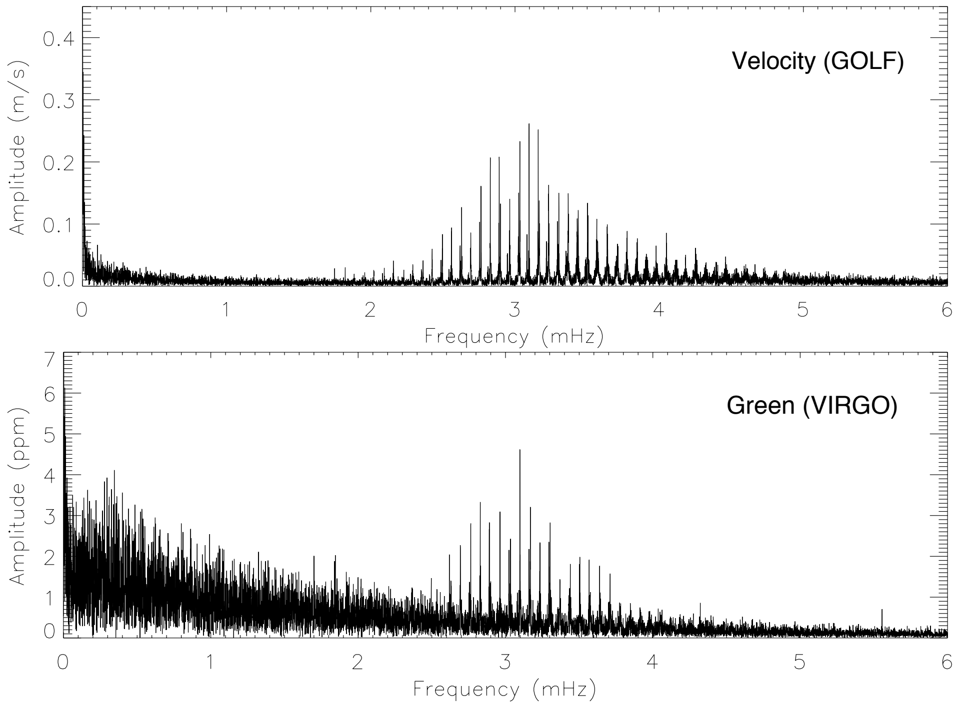

Fig. 1. Comparaison of the two instruments which look to the Sun globally aboard SoHO. GOLF uses the Doppler velocity technique and VIRGO observes the variability of the luminosity in different wavelengths. It is clearly visible after 20 days of observations that the Fourier transform of the signal favours largely the first technique at low frequency where acoustic modes are not perturbed by the solar cycle and where the gravity modes are waited (below 0.4 mHz). In fact in this range this technique appears a factor 10 to 30 better than the intensity one (Bedding and Kjeldsen, 2006)

The french spanish collaboration builds the GOLF instrument which means Global Oscillation at Low Frequency (PI: A. Gabriel). It was effectively designed for the measurement of low degree low frequency modes, that means the modes which penetrate deeper in the radiative zone. This instrument measures the variability of the Doppler velocity by the resonant spectrometer technique on the three sodium D1, D2a and D2b lines (Gabriel et al. 1995). This method has been invented by Brook, Isaak & van der Raay (1978) and used previously in IRIS and BiSON ground networks. The GOLF instrument filters the solar wavelengths corresponding to these lines and the corresponding photons, left or right polarised, are absorbed by those of a hot sodium cell and reemitted in a narrow band shifted thanks to the presence of a permanent magnet which produces a Zeeman effect. The Doppler velocity is deduced from the comparison of the left and right circularly polarised emitted photons. Its time variation is measured every 10s. The Fourier transform of the velocity signal is shown on Figure 1. Despite the malfunctioning of the quarter wave plate motor, this measurement has been possible on one wing (left or right depending on the period of observation) along the 12 years of the SoHO mission (García et al. 2005). This has been possible thanks to the presence of a small modulation of the magnetic field.

The intensity technique used in VIRGO has been limited up to now to the range located above 2.3 mHz. Figure 1 shows the superiority of GOLF compared to the photometric one. On the first two years of observations, one has noticed up to a factor 10 to 30 gain in the Fourier transform at low frequency and in particular in the range of the gravity modes located between 10 to 400 microHz. This is due to two factors. First the GOLF velocity is extracted in the solar atmosphere at an height of 300 to 500 km and this region is less turbulent than the photosphere. Secondly, the GOLF instrument has been specifically designed to detect very low amplitude signal at low frequency (down to 1 mm/s which was supposing to be the amplitude of the first gravity modes). This performance is obtained in using 2 photomultiplers which count typically 1.2 10^7 ph/s associated to a very stable electronics which secures that the noise instrument is a factor 10 smaller than the statistical noise already choosen as low as possible in relative value.

In parallel to the development of the space instruments, three ground networks have been deployed: GONG, BiSON and IRIS. The BiSON network (PI: Y. Elsworth), looks also to the Sun globally like the space GOLF instrument for now 30 years. So one can compare space and ground performances and their potentiality to produce the best science. The duty cycle of the space experiments is practically 100% DC aboard SoHO along the 10 years except during the vacation of 4 months in 1998. On ground when the network is fully operational, the DC may reach 90-92 %. Moreover, space measurements avoid any atmospheric perturbation which creates on ground some noise at low frequency. Nevertheless the performances of the present ground networks allow the same number of detected acoustic modes in a duration about 3 times greater than in space (30 years instead 10 years). So science on ground is possible and these networks represent also a good basis to work on new concept of detection. But the determinant progress needs up to now space instruments and no detection of g-modes has been claimed with the ground networks. However, the continuity of the measurements along several solar cycles benefit strongly from the permanent network observations.

3 The scientific results

The GOLF instrument has been successful in solving the different questions for which it has been designed. There are three domains where it has given very positive answers: (1) the description of the solar core and the neutrino puzzle thanks to the detection of previously unknown low degree acoustic modes, (2) a better understanding of the solar variability with the solar cycle, and (3) the capability to detect gravity modes with Doppler velocity technique.

3.1 The solar core and the neutrino puzzle

The GOLF instrument has enlarged the number of detected low degree acoustic modes which led to a precise determination of the sound speed in the solar core. In reaching radial modes below 1.8 μHz down to 0.5 μHz and also non radial degree 1 and 2 (Bertello et al. 2001, Garcia et al. 2004) in the same range, we have been able to determine very precisely the sound speed down to 6% of the solar radius (Turck-Chièze et al. 2001). The importance of detecting these modes is due to the fact that they are not polluted by the variability of the external layers along the solar cycle. This point was important to properly constrain the microphysics of the solar core and to predict without ambiguity the solar neutrino fluxes. This has been obtained in building a seismic model which is a classical evolved solar model respecting the sound speed deduced from the detection of these modes (Turck-Chièze et al. 2001; Couvidat et al. 2003a; Turck-Chièze et al. 2004a). Such neutrino predictions appear to be in excellent agreement with the detection of different energetic neutrinos (those associated to reaction rates producing boron 8 or using beryllium7) obtained with the SNO detector (Ahmad et al. 2001) and the Borexino one (Arpesella et al. 2007). This compatibility between totally different ways to probe the solar core strongly contrasts with the situation we had during two decades before the development of space helioseismology and of the new generation of neutrino detectors where a total disagreement was existing between prediction and detection. This agreement stays valid despite the recent new estimate of the solar composition which deteriorates the agreement between the standard model sound speed and the observed sound speed profile because the neutrino predictions are based on the seismic solar model. Such success allows to attack nowadays new fundamental questions in particle physics on the properties of the neutrinos: their capabilities of changing of flavours in vacuum or in matter depending on their energy. If the corresponding parameters of the neutrino oscillations seem today more and more clearly established, the final objective stays the determination of the neutrino masses and of their magnetic moment, which are not yet obtained.

3.2 *The Sun as a varying star*

The GOLF instrument has detected for the first time practically all the low degree acoustic modes (orders from 7 up to 40) and has followed the varying ones along a complete solar cycle (Gelly et al. 2002, Garcia et al. 2004). This important fact allows us to study the Sun like a star for which only these modes are available. The understanding of the properties of these modes and their evolution along the Hale 11 year solar cycle allows us to separate the range of frequency in three parts dedicated to different scientific information.

- It seems today that the modes above 3.8-4 mHz cannot properly deliver valuable scientific information of the internal solar structure due to the stochastic excitation of these modes which are reflecting very near from the turbulent surface. They have a poor lifetime and are difficult to be used to extract any structural information.
- The range of frequencies between 2 and 4 mHz is extremely useful to characterize the surface layers down to 0.98 solar radius. The variability of their frequency along the solar cycle is now properly established and their properties (intensity, width) well determined. These informations put some limit on the mean magnetic field of these layers and its varying component along the solar cycle (Nghiem et al. 2006). Nevertheless one needs yet to disentangle the effect of the solar radius variation from the effect of turbulence and magnetic field to definitively establish the history of activity of these layers. The use of these modes to extract information of the deep Sun have led to confusing interpretation in the past of the properties of the nuclear core. It is why these modes are now avoided in the most informative inversion.
- A large range of frequencies below 2-2.3 mHz (about $n < 16$) has been measured for the first time by the GOLF/SoHO instrument. They represent the best way to extract information of the radiative zone even they penetrate less deeply than higher order modes. Effectively, these modes are very stable (long lifetime) and they are not perturbed by the variation of the magnetic field along the solar cycle. Their use has led to the best constraints on the sound speed in the core (García et al. 2001) and to a precise extraction of the flat rotation profile down to 0.2 solar radius (Couvidat et al. 2003b), the limit for the splitting extraction may change with the duration of observation. The detection of these modes do not favor any deep variation during the period of observations (10 years) except may be a 1.3 yr period (Jiménez-Reyes et al. 2004) already mentioned in some studies and attributed to the tachocline region (Howe et al. 2000).

3.3 *The capability of reaching gravity modes and the rotation of the nuclear core*

The GOLF instrument has been specifically designed to detect some gravity modes. Nevertheless the publication of Kumar et al. (1996) just after the SoHO launch on their probably very low surface amplitude coupled to the malfunctionning of the polarisor motors have put some doubts about the capability of GOLF to detect any signal. Nevertheless, intensive studies have been dedicated to this field since the first years and a search strategy (among others) has been defined: first to look for multiplets (it improves the capability of detection of very low signal) in the region above 150 μHz where the velocities are the greatest and then to examine the low frequency region if the first research was successful.

In 1997, we have observed a pattern around 220 μHz visible during the whole duration of the observation (the gravity modes are supposed to have a lifetime greater than the acoustic modes). This first result has been reported in 1998 (see Turck-Chièze 2006a for a general view of the gravity mode search). Then a statistical analysis has been developed to estimate the probability that a multiplet structure could be associated to a real signal and not only to noise (Couvidat 2003). The significant patterns (more than 90% confidence level not to be pure noise) have been followed in time. Turck-Chièze et al. (2004b) have reported the detection of gravity mode candidates: patterns which may be associated to gravity modes by their apparence (number of components) and the proximity of their central frequency to the predictive theoretical value. We have first labeled some triplets observed as potential quadrupole gravity modes. Then the evolution of one of them (around 220.7 μHz) in the form of a quintuplet with more than 98% confidence level has led us to examine three possibilities: a gravity mode $l= 2$, $n=-3$ which shows a rapid rotation core with an oblique axis, a mixture of noise and of this gravity mode with a flat rotation in the core or a mixture of different modes.

The search for individual peak detection had put a limit of several mm/s for 90% confidence level (Gabriel et al. 2002). The gravity mode candidate determined at more than 98% confidence level after eight years of observation is compatible with velocity of the order of mm/s or lower (see also Mathur et al. 2007). A signal has been observed continuously in the VIRGO data at the position of 220.7 μHz corresponding to one of the highest component of the GOLF candidate showing that this signal is of solar origin.

Then a second analysis below 150 μHz has been done. In this range of frequencies, it is not possible to look for individual peak or multiplet (they have a too small amplitude and the mode spectrum is too dense for hoping any identification). So this search has used the asymptotic behavior of the modes (spaced in period) and the cumulative effect of 20 modes analyzed together. Such search has put in evidence a pattern compatible with the sum of dipole gravity modes at more than 99.7% confidence level (García et al. 2007). This detection favors a rotation quicker in the solar core.

Consequently, it seems rather clear that GOLF has detected some solar gravity mode signatures. Nevertheless the information on the rotation stays poor. It is nevertheless interesting to note that the two analyses are only compatible if the core of the Sun turns quickly and if the axis of the core rotation is oblique in comparison with the rotation axis of the rest of the radiative zone. Of course due to the very low amplitude of the signals, this conclusion needs to be confirmed by improved observations. Presently, the analysis of the other instruments has shown the superiority of the GOLF instrument for the gravity mode detection. So one can consider that all the objectives of GOLF have been reached, unfortunately the knowledge of g-modes is not yet sufficient to properly describe the dynamics of the solar core (Mathur et al. 2008) and its consequences on the deep magnetic field.

4 The next steps

Thanks to the progress done with SoHO, new questions appear dedicated to the active Sun:

- What is the dynamical influence of the internal rotation and magnetic field on the external activity ?
- Which processes are at the origin of the solid body rotation in part of the radiative zone ? What is the respective role of the agents responsible for the redistribution of the angular momentum: rotation, gravity waves, magnetic field ? Presently theoretical works do not agree with the suggested observed rotation profile. What are the consequences of a more rapid core? Is there another dynamo in the core?
- What is the topology, strength and influence of a fossil field ? How the progressive internal waves modify the overall internal dynamics ? Could we determine the nature of the nonlinear interactions between the convective dynamo and the fossil field if it exists ?
- How can we check the presence of large scale flows, their amplitude and their mixing properties in the radiative zone ? Could we put some constraints on the presence of magnetohydrodynamical instabilities in the radiative zone and their coupling with the convection zone ?

We develop complex 1D modeling of the solar evolution and 2D, 3D simulations of portions of Sun to partly answer to these new questions but these efforts must be guided by complementary measurements which will constrain the numerical part.

4.1 The GOLF- NG concept

We are presently developing an instrument that takes benefice of SoHO results. The GOLF-NG (Global Oscillation at Low Frequency New Generation) instrument measures, like GOLF, the global Doppler velocity variations. It is developed in CEA/France in collaboration with IAC/Spain. It results from a 30-year expertise on resonant scattering spectrometers (Brookes et al. 1978) used on the ground (IRIS and BiSON networks) and in space (GOLF/SoHO). The composition of the team and the characteristics of this instrument are described in Turck-Chièze et al. (2006). The improvements of this new concept consists of (1) measuring the velocity at eight positions in the solar atmosphere between the photosphere and the chromosphere to reduce the effect of the solar granulation in the range of g-modes. Effectively the observed patterns of the solar noise differ and consequently we hope to improve the signal over noise in the gravity mode range of frequencies. (2) Moreover the gravity mode spectrum is very dense so the identification of the observed pattern components will be easier in putting some masks at the entrance of the instrument. (3) Finally some configuration of the polarisers will give access to the measurement of the mean magnetic field and its time evolution. Detection and identification of degrees up to 5 for gravity modes is an objective for the coming decade and might allow a precise determination of the rotation profile in the whole solar core (Mathur et al. 2008). This instrument measures 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 line is extracted by the resonant photons in the vapour cell. It is split into its Zeeman components by means of a longitudinal magnetic field whose strength varies along its axis 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, including one fixed point at the center of the line. Moreover the analyzed flux has been increased by a factor 10 thanks to a good quantum efficiency of the detectors and 4 outputs by position to lower also the instrumental noise and to allow consecutive measurements of portions of the Sun. A second crystal polariser could be installed to get a spectrum of the mean magnetic field. There is a lot of technological challenges in this instrument which have been already solved this year and the resonance has been already obtained on the 31 detectors.

4.2 The DynaMICCS perspective

The questions mentioned previously show the need to understand the solar magnetism in its different forms. Several orientations of improvements have been expressed in documents prepared in the framework of the ESA Cosmic Vision (Turck-Chièze et al. 2005, 2007; Damé et al. 2007). The mission called DynaMICCS for Dynamics and Magnetism from the Core to the Corona of the Sun would like to reveal the different sources of the solar cyclic variability. To reach this objective, crucial internal regions of the Sun must be scrutinized: (1) the previously unexplored dynamics of the inner core thanks to gravity modes, (2) the time evolution of the radiative/convective zone interface layer thanks to a large number of acoustic modes, (3) the emergence of the flows from the photosphere to the chromosphere layers thanks to different lines and heights. Moreover the formation flying concept of the mission allows to follow simultaneously (4) the evolution of the low corona never explored continuously thanks to a permanent eclipse, (5) the total and spectral irradiance and finally (6) in-situ measurements of plasma/energetic particles/magnetic fields of the solar wind. This mission delivers simultaneously all the global quantities no other known mission has already provided. This information is important for understanding Space Weather and Space Climate and for advancing stellar and fundamental physics (neutrino properties, atomic physics, gravitational moments ...). To fully achieve these objectives, the DynaMICCS mission must provide uninterrupted observations of the Sun for about a decade. This mission uses an original concept studied by Thalès-Alenia Space in the framework of the CNES call for formation flying missions. The concept has been built upon the ASPIICS coronagraph study. It consists in obtaining an external occultation of the solar light by putting a small discal occulter supporting the main spacecraft located in front of the second spacecraft. The two spacecrafts reuse a LEO platform of the mini sat class, e.g. PROTEUS type which allow to define a distance of 150 m between the two satellites. The first one carries the helioseismic and irradiance instruments and the formation flying technologies. The latter spacecraft of the same type carries a visible and infrared coronagraph for a unique observation of the solar corona down to less than 1.1 solar radius and instrumentation for the study of the solar wind. The payload of each spacecraft has a mass of about 170 kg and a power consumption around 100 W. This mission must guarantee long (one 11-year solar cycle) and continuous observations (duty cycles higher than 94 %) of signals that can be very weak (the gravity mode detection supposes the measurement of velocity smaller than 1mm/s). This assumes no interruption in observation and very stable thermal conditions. The preferred orbit therefore is the L1 orbit, which fits these requirements very well and is also an attractive environment for the spacecrafts due to its low radiation and low perturbation (solar pressure) environment.

In parallel, another proposal HIRISE for High Resolution Imager and Solar Explorer puts the accent on the ultrahigh spatial spectral and temporal resolution of the solar atmosphere with some insight on the solar interior. It is also a formation flying mission but in using an Herschel platform for the occulter spacecraft, it allows more capabilities, an increase flow of data sent to the earth and consequently also a mission around the Lagrangian L1 point. Consequently the main objectives of DynaMICCS and HIRISE can certainly coexist on the same mission. The increased distance of 300 m between the two spacecrafts due to the size of the Herschel platform improves also the study of the low corona. So, the formation flying added to the reuse of european platforms allows a mission at relatively low cost, putting together all the instruments necessary for the 3D vision of the Sun with global and local information covering most of the questions of the whole european solar community. The complementarity of DynaMICCS and HIRISE leads to the most promising and exciting mission that we ever think for the solar exploration. It will definitively establish the complete 3D vision of the Sun and its real impact on the earth environment. We hope that such a mission will be realized during the next decade.

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