FUTURE PROSPECTS OF HELIOSEISMOLOGY FROM SPACE

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ABSTRACT. In view of their costs, space-borne instruments should be considered only for their exclusive capabilities in helio-and asteroseismology. Space-borne high resolution spectrometers and photometers operate free of atmospheric pertubations, can be put on special orbits offering continuous (uninterrupted) observations and therefore offer the best opportunity for high signal-over-noise ratio. The recent data obtained on board the Phobos-2 mission clearly evidences this fact. The ESA-NASA SOHO observatory will be the first mission of its kind carrying a comprehensive set of instruments to analyse the gravity and acoustic modes of solar oscillations over an uninterrupted period of at least 2 years. Projects also exist to observe oscillations of the solar diameter. Long term observation of the solar constant may provide a clue to the understanding of the origins of the solar cycle. Simultaneous out of eliptic measurements may nicely complement our data set and offer unambiguous views on the asymmetries of the solar interior. Space observations are probably the only means to get access to the deep solar interior through the detections of g modes. They offer the only prospect in the exploitation of asteroseismology over a larger number of stars.

1. INTRODUCTION

Like most branches of astronomy, helioseismology started in ground based observatories and has up to now flourished and provided very impressive results without the contribution of space techniques. In the past 10 years our understanding and our knowledge of the interior of the Sun has been confronted to helioseismological data obtained with the observations made from the ground of either the global or resolved motions of the solar surface as induced by the acoustic modes of intrinsic solar oscillations. The detailed analysis of their fre-quencies and the use of complex inversion techniques made possible through the availability of modern and powerful computers has already allowed to determine the variation along the solar radius of the sound velocity and to infer from it the temperature throughout the

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convection zone down to a depth of approximately 0.5 solar radii (Gough (1988)). The set of reliable data already obtained which spans more than half a solar cycle, yields already some clue as to the relationships between the cycle and the convection zone, and the variation of the asphericity of the velocity of sound.

Furthermore, differential rotation has been inferred which already gives some indication on the dynamics of the solar interior down to 0.5 solar radii.

Helioseismology is such a rich field and so much has been obtained from the ground that one may, rightfully, question the necessity to start exploiting this field from space. This being said, the advent of space techniques and the initiation of several space missions or experiments devoted to helioseismology lead us to discuss briefly the role that these techniques might play in the future and what progress can be expected from them.

2. WHY SHOULD WE GO TO SPACE ?

We should not go to space when our goals can be fulfilled from the ground. This statement is of a general nature and applies particularly well to the case of helioseismology. This is why we will not speak here of measurements which can be made, and very well, from the ground such as those of zonal velocity and magnetic fields or zonal temperatures (Kuhn et al. (1988)).

On the contrary, space offers intrinsic absolute advantages but these should always be judged against the necessarily expensive nature of space borne experiments. The advantages for helioseismology can be summarized as follows :

2.1 The elimination of atmospheric pertubations.

The presence of the earth atmosphere limits the quality and the nature of helioseismological data obtained from the ground. The degradation by atmospheric turbulence of the surface patterns induced by p-modes with degrees larger than a few hundreds is very substantial as shown in the excellent report published by NASA (Noyes and Rhodes (1984)). For example, the precise determination of the abundance of helium in the subphotospheric layers require observations with $\underline{l}$ ranging between 400 and 1200 which are not possible from the ground.

The measurement of the variation in the dimension of the solar diameter is definitely very difficult if not impossible from the ground as was clearly demonstrated by R. Sofia (1989). Even a perfectly stable atmosphere would not be free of refraction effects. Such effects have been invoked in order to explain the 160 min oscillation whose existence has, for a long time, been a very controversial issue (Elsworth et al. (1989)).

2.2 The possibility of photometric measurements

Photometric data play a very important role in helioseismology. Due to their very small amplitude (intrinsic solar radiance or irradiance variations are usually measured in fractions of millionths) they cannot easily be disentangled from atmospheric pertubations and require quasi essentially the use of space techniques.

Photometric measurements are preferred when one wants to look very close to the solar limb due to the rapid fall-off of velocity oscillations there, although the rms amplitude of the modes over the intrinsic solar noise make them less easy to use. This is particularly serious for low degree and g modes whose amplitude is well known to be very small. However, the relative simplicity of the instrumentation (a photometer) may easily overcome this drawback and in addition one can select the best spectral band for the optimum detection of surface patterns. This possibility indeed couples the advantages of 2.1 and 2.2 : from space there is no more wavelength limitation since atmospheric absorption has vanished. The ultra-violet spectrum is especially suited to the study of oscillations near the region of the temperature minimum.

2.3 The possibility of uninterrupted observations

From space we can have access to unique observing sites, such as full-sun orbits. On Earth this possibility exists but only at the poles and for a limited number of days per year, weather permitting, or using networks of stations like those in the GONG (Harvey (1988)) and IRIS (Fossat (1988)) projects. In space no such problems remain. Uninterrupted observations are essential to get access to the highest frequency resolution which is a key parameter for the detection of the low amplitude, long lived g modes, not yet achieved from the ground. For example, with 2 years of uninterrupted data one can achieve a resolution in frequency of 0.02 micro-hertz which is essential for separating the various g modes whose frequencies are increasing like $1/\nu$. This unique advantage derives from the fact that discontinuous data sets introduce side lobes in the frequency spectrum which broaden the observed frequency of individual modes.

Furthermore, orbits can be selected which minimize the line of sight velocity thereby increasing the S/N ratio for velocity oscillations. From space, stereoscopic observations are also achievable opening a completely new prospect for helioseismology.

3. WHAT PARAMETERS ARE BEST SUITED FOR SPACE-BORNE OBSERVATIONS ?

The term "helioseismology" is used here in the brodest sense, encompassing observations which carry information on both the physical conditions and the dynamics of the interior of the Sun even though they are not exactly concerned with the so-called gravity or acoustic vibration modes.

3.1 The Solar constant

The total solar irradiance has been monitored nearly continuously from space since 1980 with the Active Cavity Radiometer Irradiance Monitor (ACRIM) on the Solar Maximum Mission and the NIMBUS-7 (Willson and Hudson (1988)) satellite and there is clear evidence that it varies in phase with the solar cycle by at least 0.1% between maximum and minimum. Kuhn et al. (1988) and Gough (1988) have discussed this variation in terms of an asphericity of the sound velocity inside the Sun. It can be shown that latitudinal temperature variations can be made responsible for part of the observed variation which indicate that the source of the cycle is rooted at least as deep as the bottom of the convection zone. Future progress will come from a continuation of the measurements from either SMM or any future mission. A few years ago COSPAR issued a resolution recommending that there should always be at least one radiometer at work in space. Such devices as ACRIM are small enough to be carried on any sun-pointed spacecraft or part of a spacecraft like the solar arrays for example.

3.2 Intensity (radiance) oscillations

Intensity oscillations measured with a photometric accuracy of at least 10^{-7} may be our best way to study g modes in the frequency range between 1 and 150 micro-hertz. It has been shown that for low frequencies, which characterize g mdoes, the relative contribution of perturbations (noise) due to supergranulation is much smaller for intensity than for velocity measurements.

The new results presented by Fröhlich (1990) at this colloquium prove without ambiguity the very strong interest in having long term, continuous intensity oscillation measurements and may give an indication of what amplitude might be expected for the observation of g modes. In addition, spectral irradiance measurements at selected wavelengths may provide some information of their propagation properties, through phase and amplitude differences between the various modes.

It is also important to have some spatial resolution on the disc in order to be able to identify and to separate the modes with different $\underline{l}$ numbers.

3.3 Velocity oscillations

Velocity oscillations, either global or resolved on the disc, provide the best means of studying the high frequency portion of the power spectrum which is filled uniquely with acoustic modes.

High resolution observations give access to modes which are trapped just underneath the photosphere and which, up to now, have not been observed from the ground due to viewing limitations. On the contrary, low degree modes but of high order represent good tools for the probing of the deep solar interior.

3.4 Solar diameter measurements

The variations in luminosity might well be associated/correlated with variations in the solar diameter. An accuracy of a few 10^{-3} arcsec is now within reach and these measurements may offer the best way to determine the low frequency modes (the g modes) and to probe the deep interior.

4. NEAR TERM PROSPECTS

We now focus on three main space projects which in the near term should cast some new light on the overall properties of solar oscillatory modes. At the time of writing this paper the brilliant data obtained with IPHIR have not yet been fully processed and analysed and are still our first hope of detecting the gravity modes or of fixing upper limits to their amplitude relative to the noise. The next major step will come when the SOHO mission and its comprehensive set of instruments will fly.

4.1 The SOHO spacecraft

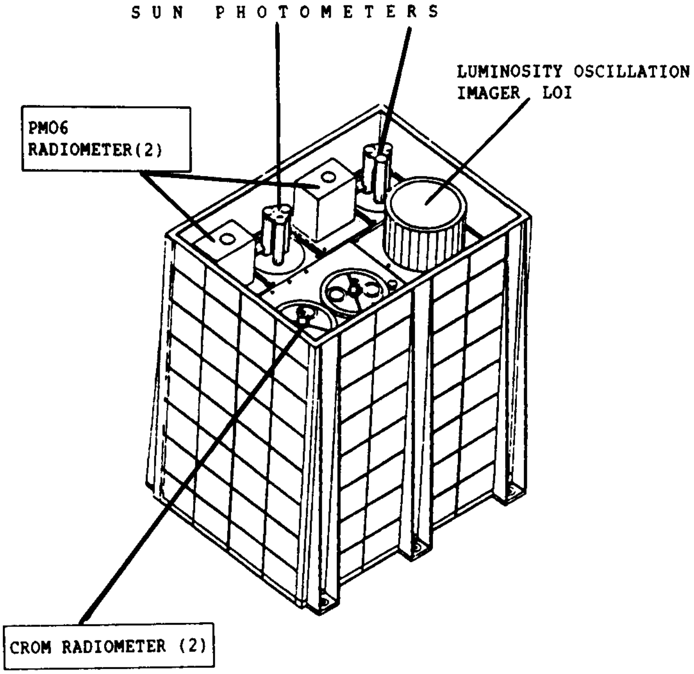

Fig. 1 - Schematic of the VIRGO experiment on-board SOHO, consisting

Table 1 - The main characteristics of the Virgo Experiment

Principal investigator :	C. Fröhlich Davos, Switzerland
Main scientific objectives :	. low degree ($\ell = 0-7$) irradiance oscillations . precision $< 10^{-6}$ (for 10 s integration) . solar constant measurements : absolute accuracy : 0.15% precision : $10-50.10^{-6}$
Technique :	. active cavity radiometers . sun photometers operating at 335,500 and 865 nm . luminosity oscillation imager (55 mm telescope, f=1.3 m, solar image formed on 16 separate pixels)
Mass :	14.6 kg
Power :	16.6 W
Bit rate :	0.1 Kbps

2 PMO6 a of d 2 CROM radiometers, 2 sets of 3 sunphotometers each operating at 335, 500 and 865 nm ($\Delta\lambda$ = 5 nm). The LOI consists of a 55 mm Cassegrain telescope with a servo controlled secondary mirror. The detector is a 16 element diode array offering the capability to resolve modes with l numbers from zero to seven.

SOHO is the first ever mission dedicated to helioseismology. A complete description can be found in Domingo and Poland (1989). The project is part of the Solar Terrestrial Science Programme of ESA which also includes the four Cluster spacecraft and is conducted in cooperation with NASA. ESA will build and integrate the spacecraft, and NASA will launch its experiments and operate it during its nominal two years lifetime. ESA and NASA share the payload. The launch of the mission could be envisaged for 1995 on board an American expendable vehicle. SOHO will be placed on a special 180 days halo orbit around the L_1, Lagrangian point located at 1.5 million km from the Earth, providing the required uninterrupted full Sun capability and minimizing the spacecraft radial velocity with respect to the Sun, an important requirement for the measurement of velocity oscillations. This velocity will be known with an accuracy better than 2 cm/sec. The spacecraft is 3-axis stabilized and provides an absolute pointing accuracy of 10 arcsec and a stability of 1 arcsec over 15 minutes of time. The spacecraft weight is about 1.3 metric tons including approximately 150 kg of propellant and the telemetry bit rate is 40 Kps with no interruption in the data coverage. For the Solar Oscillation Imager, MDI, the bit rate can reach 200 Kbps for real time transmission or for tape dump.

All experiments have been selected and are in the process of development in the various institutes. Not all of them are devoted to helioseismology but only 18% of the payload mass i.e. $\simeq$ 90 Kg and 30 % of the power, i.e. $\simeq$ 102 W. Three instruments will share the payload, VIRGO (Fröhlich et al. (1989) the Michelson Doppler Imager or MDI (Scherrer et al. 1989) and GOLF (Gabriel et al. 1989)) which will investigate, irradiance oscillations, highly resolved velocity (high l) and possibly solar diameter oscillations, and global oscillations respectively. Tables 1, 2 and 3 summarize the main characteristics of these instruments. More details can be found in Domingo and Poland (1989)). It should be noticed that VIRGO will indeed have the capability of resolving modes of l values between zero and 7 (fig. 1).

4.2 The Solar Disc Sextant

The SDS is an instrument dedicated to the measurement of the oscillations of the Solar diameter. This instrument (Sofia (1989)) is already operating onboard a balloon and is proposed to NASA in the framework of their small explorers series. The required accuracy for the measurement is 0.003 arc seconds which is impossible to achieve directly at the focus of an imaging telescope. However, relative measurements with this accuracy are achievable once we can compare two fields of view separated by a broad angle.

Table 2 - Main characteristics of the Michelson Doppler Imager

Principal investigator :	P. Scherrer Stanford University
Main scientific objectives :	. High degree (ℓ / 4500) velocity oscillations, with a . precision of 0.002 cm/s over 2 years ($\frac{1}{16\ \mathrm{nhz}}$), Solar noise limited . Solar limb oscillations : 0.04 arc sec /pixel or 7.10^{-4} arc sec for oblateness
Technique :	Fourier tachometer : phase of the line profile gives doppler shift. Resolution : 4 and 1.5 arc sec
Mass :	43.4 kg
Power :	55 W
Bit rate :	5 (+160) Kbps

This is the case for the SDS as shown in fig. 2. The key element in the design is a glass wedge defining a very stable angle of ≃ 1000 arcsec which, in combination with a classical Cassegrain telescope image two opposite limbs of the Sun along the same diameter. A set of five linear array detectors are used to measure the light fluctuations incurred by variations in the solar diameter.

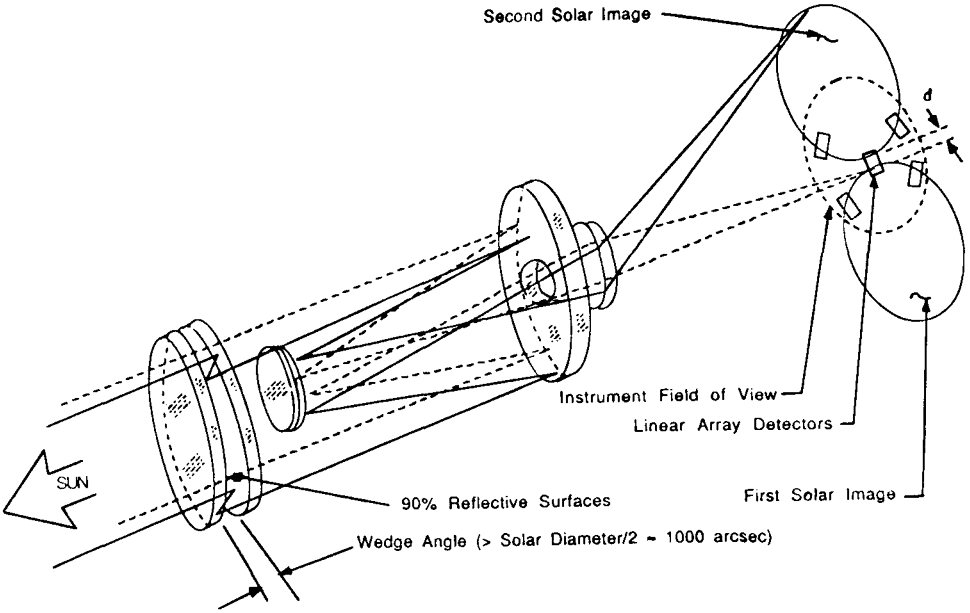

Fig. 2 - The Solar Disc Sextant optical principle offering a 0.003 arcsec accuracy for the measurement of variations of the solar diameter

Table 3 - Main characteristics of GOLF

Principal investigator :		A. Gabriel LPSP/IAS, Verrieres-le-Buisson
Main scientific objectives :	.	Low degree velocity oscillations g modes, low order p modes
	.	Precision $\simeq 0.1$ mm/s
	.	Solar noise limited
Technique :		Na vapour resonant scattering cell using Zeeman splitting in $\vec{B} = 4700$ G Global measurement on the $\odot$
Mass :		31.2 kg
Power :		30 W
Bit rate :		0.128 Kbps

The SDS has already flown twice on board a balloon. It is not yet clear when it will fly on board a spacecraft.

4.3 Measurements of the Solar Constant

Because of their relative simplicity, several Solar Irradiance variability instruments are foreseen to fly in space in the near future.

A Solar Irradiance Variability instrument called SOVA placed under the responsibility of P. Crommelynck will be carried into space for at least 6 months on board the European Retrievable Carrier (EURECA) of ESA, scheduled for a launch onboard the space Shuttle in 1991. A second ACRIM instrument will measure the solar constant during 15 minutes every orbit on board NASA's UARS mission to be launched also in 1991. This instrument, together with the first ACRIM onboard SMM, and SOVA, will probably yield the most accurate evaluation ever of the solar constant and of its variation with time.

According to Noyes (1988) it is intended that successors to ACRIM may fly on the US series of Geophysical Orbiting Environmental Satellites (GOES) although this has not been confirmed. It is also very likely that similar instruments will be proposed on the polar platforms which are part of the set of platforms built by the US, ESA and Japan and which are connected to the International Space Station.

Finally, the Soviets have in their planning a solar project called KORONASS that will include a solar irradiance oscillations instrument. The implementation of this project is foreseen in the 1991-1993 time scale.

5. LONGER TIME PROSPECTS

Present limitations in either the developed instrumentation or the duration of observations may affect or even hamper the detection of g modes which are our ultimate hope of getting access to physical conditions at the deep core of the Sun. Future solar probes such as those foreseen in ESA, NASA and even the Soviet programme may provide a means to detect these modes through their effect on the trajectory of the probe, if carefully monitored. Fig. 3 shows the ballistic profile of the Vulcan mission which is under study at ESA (Bertotti et al. 1988). None of these probes is foreseen to fly before the end of this century.

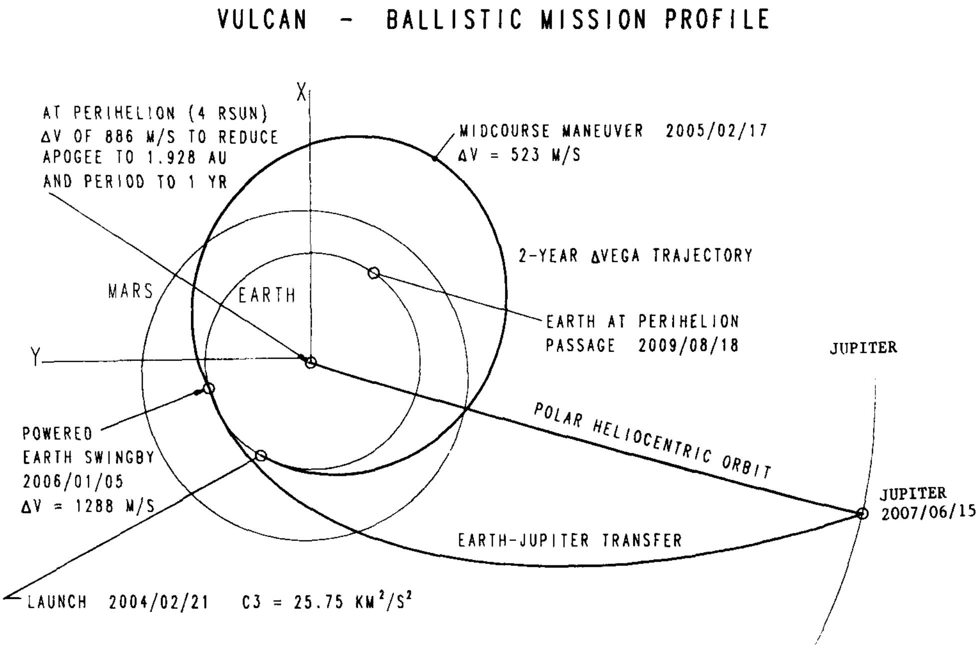

Fig. 3 - Ballistic profile of the Vulcan mission presently under study at ESA

In the even longer term we may witness future progress coming from the great potentiality of two possible, although not yet even proposed, missions. After the launch of Ulysses (presently foreseen on 5 October 1990) and its hopefully successful operation, it may well be envisaged that a successor to what is presently the first out of the ecliptic mission appears as a next logical step in the understanding of the interplanetary medium and of the Sun itself. Such a mission should logically include helioseismology instruments and certainly an irradiance monitor like ACRIM, or a VIRGO type instrument. Latitudinal effects such as those reported by Kuhn in the distribution of zonal temperatures may henceforth be unambiguously interpreted. ESA in its Horizon 2000 plan (Bonnet and Bleeker (1984)) and also the National Academy of Science (Donahue (1988)) have such missions in their very long term plans.

Due to orbit maintenance and the necessarily limited capacity of the gas tanks onboard SOHO the mission is limited in time and may, at most, span half a solar cycle. We are just starting now to see the influence of the solar cycle on the various helioseismology parameters and we may wish to see more of this effect in particular if it is proven that the source of the cycle is deeply rooted inside the sun (Gough (1988)) and in that respect repeated observations with the same instrumentation over several cycles might lead to important progress. What follows rests solely on the author's imagination at this stage but we may imagine that when the astronomical and scientific capabilities of a lunar site will be exploited, in other words when we will have in the course of next century an operational lunar base, the capability thus developed may include a helioseismology facility.

We may think for example of a network of small stations located near the lunar pole. At a latitude of 75 degrees, given the fact that the rotation axis of the Moon is inclined by 1.5 degrees on the plane of the ecliptic, a network of 4 stations regularly positionned on a circonference of only 2730 km will serve all the purposes required for uninterrupted observation of intensity and velocity oscillations. If we are clever enough, we could even conceive these stations so that one may look at some stars during the lunar night. Solar energy is plentiful on the Moon at the pole (there is no atmospheric absorption) and can easily be used to power each station of the network on a continuous basis. It is at times good to dream !

6. ASTEROSEISMOLOGY

Although the study of stellar interiors is not the main purpose of this meeting, we cannot talk about future prospects without mentioning the future prospects of asteroseismology from space. This topic was discussed in quite some extent by Noyes (1988) in terms of stellar magnitude, size of the telescope and integration time. For example, a star of V=12 would require 100 days of observations with a 1 m aperture telescope using broad band visible radiation. Noyes also clearly shows that the detection of velocity oscillations would require the use of very large telescopes, a solution which is not realistic if we want to sample a reasonable number of stars, although this might be envisaged for a small number of them. We list below a few projects which in the near future will perform stellar seismology observations.

6.1 The Hubble Space Telescope

An observation is planned on α cen A using the high speed photometer on HST which has the required sensitivity. This star is a prime target to compare with the Sun because of its well known mass, radius, and effective temperature, and also because it is possible to observe from the HST orbit for long uninterrupted periods. The launch of the Hubble Space Telescope is now foreseen for March 1990.

6.2 EVRIS

EVRIS is a project envisaged in the framework of the Franco-Soviet space programme and is foreseen to be placed on-board the Mars 94 mission, to be operated during the cruise phase.

brighter than V=4. During the mission, 30 such stars can be observed with integration times as high as 25 days. This modest instrument of 3.3 kg will be developed in the framework of a Consortium led by Dr. A.Baglin (Meudon Observatory) and G. Bisnovatyi-Kogan (IKI, URSS) and several co-investigators from Austria, Denmark, Spain, Switzerland and the United-Kingdom.

6.3 Asteroseismology from Cassini

Cassini is a NASA-ESA mission to Saturn and Titan, to be launched at the earliest in April 1996. (Lebreton and Scoon (1988)). During the cruise phase there are several opportunities to observe stars. Although the scientific package has not yet been selected, it is likely that there will be an asteroseismology instrument proposed on board.

7. CONCLUSIONS

This presentation and the discussion of future prospects of helioseismology from space is probably not complete. It should be seen in the context of the new results obtained with IPHIR, the only dedicated helioseismology experiment to have been operated in space so far. Because of their relatively high costs space experiments should be envisaged only when ground based observations bump on intrinsic physical limitations.

Clearly, space-borne measurements may provide in the future the best chance to detect if ever possible the long period gravity modes, which have so far resisted unambiguous determination from the ground. As usual, long uninterrupted sequences of observations are required. Observations for at least a complete solar cycle may provide a powerful means for detecting the source and inferring the mechanism(s) of the cycle.

Space techniques also offer unique advantages for the detection of stellar oscillation modes, essentially through broad band photometry. Several small scale projects envisaged on forthcoming interplanetary missions may open bright new perspectives in the not too distant future.

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