HELIOSEISMOLOGY IN THE FUTURE*

(Invited Review)

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Abstract. We review the observables of helioseismology that can contribute to our knowledge of the physical conditions in the solar interior. We discuss the limitations which presently prevent helioseismology from reaching its ultimate goal. We finally present a list of projects which either are already underway or that are planned for the near future, and we conclude by showing the crucial role that space observations may play in the future.

1. Introduction

Helioseismology is a recently born technique whose ultimate aim is to infer the physical conditions and the dynamical properties of the solar interior, starting from the top of the photosphere down to the centre. It derives from the techniques usually applied on Earth to study the internal structure of our planet through the properties of the vibrations induced by Earth quakes. As shown by Gough (1983), these techniques imply the mathematical inversion of an integral, whose results are model dependent. In this summary, we will not deal with this mathematical aspect that we assume to be sufficiently well mastered at present. We will on the contrary concentrate on the possible means of observation (and their limitations) that can be used for probing the solar interior, which is yet inaccesible to direct observation, except for the last two hundred outer kilometers and possibly the central core. By probing we mean inferring the density stratification, the chemical composition, the rotation and possibly studying the structure of large-scale convection (Gough and Toomre, 1983), and their possible variations with time.

2. The Observations Which Can be Used in Helioseismology

2.1. Neutrinos

We disregard the most direct messenger from the Sun's centre, the neutrino, because the matter of its detection has been dealt with extensively in other instance and would lead us much too far beyond the scope of this paper.

2.2. Routine observations of activity related manifestations and differential rotation

Helioseismology (in the broad sense) got a first observational support nearly 140 years ago at the time when the first systematic recordings of sunspot number and position were

* Proceedings of the 66th IAU Colloquium: *Problems in Solar and Stellar Oscillations*, held at the Crimean Astrophysical Observatory, U.S.S.R., 1–5 September, 1981.

Solar Physics **82** (1983) 487–493. 0038–0938/83/0822–0487$01.05.

undertaken. Indeed, the so-called 'butterfly diagram' which they serve to construct tells us something about phenomena which occur beneath the photosphere and about their relaxation time. More recently the high precision continuous measurement of the differential rotation by Howard and LaBonte (1981) and of its latitudinal variations indicates that a tight relationship exists between differential rotation and the solar cycle. This fact would not have been discovered without the careful and relentless work of dedicated observers.

These two examples are given here to illustrate the worthiness of routine observations which may well provide in the future some powerful clues to our understanding of solar subsurface phenomena.

However, in the past years, new techniques have developed or have reached a point of maturation that gives the observers and the theorists new means of investigation.

2.3. Radius variations

For example, one explanation offered to the neutrino deficiency is that the Sun's radius is shrinking at a substantial rate. Measurements of the solar diameter with high accuracy are the only possible way to check this explanation. Recently, Parkinson *et al.* (1980) have shown that combined data sets of the Mercury transit and total solar eclipse observations provide no solid basis for this assumption, at least over the past 250 years or so. However, there is some evidence that periodic changes of about 0.02% may have occurred on time scales of several tens of years.

2.4. Solar constant variations

The recent measurements, made from two artifical satellites, SMM and Nimbus 7, of the variations of the solar constant on time scales of days or weeks in association with the appearance of sunspots, may be indicative of modifications in the large scale convection that are deep seated in the convection zone. These measurements correspond to an accuracy of a few hundredths per cent and it is only through the use of space techniques and the continuous monitoring of the solar energy output that they have been made possible. A moderate spatial resolution at the disc surface would allow one to judge whether solar constant variations reflect similar variations in the luminosity or whether they are the result of time dependent inhomogeneities. The blocking by sunspots is not the only process that can cause luminosity variations. Such variations result from changes in the balance between thermal, gravitational and other forms of energy (Gough, 1980). Such changes modify the hydrostatic structure of the Sun and lead to variations both in luminosity and radius, that depend on the depth in the Sun of the perturbation that produces them. Simultaneous measurements of luminosity and radius are therefore of considerable interest.

2.5. Global oscillations

It is undoubtedly through the accurate measurements of periods and phases of dynamical oscillations that helioseismology can yield information about the solar interior, from the surface to the core. Provided the modes of oscillations can be identified, their frequencies can be used to diagnose the solar interior in a way similar to that which allows seismic waves to probe the interior of the Earth. The observations concern both velocity and luminosity oscillations.

The observations of each type fall into two groups: those that detect high-degree modes and require good spatial resolution (Deubner, 1975) and those that detect low-degree modes and concern integrated properties of the Sun (Claverie *et al.*, 1979; Grec *et al.*, 1980). The latter provide a nearly direct measure of conditions in the interior, in opposition to the first category which allows the sounding of only a fraction of the solar volume beneath the photosphere. Both categories have led to the conclusion that the standard model that fits the observations best has a relatively high helium content.

The amplitudes and relative phases of velocity and intensity oscillations depend on the reaction of the upper layer of the convection zone to oscillations with periods comparable with the eddy turnover time, and thereby they provide a valuable clue to our understanding of the solar convection zone. Some degree of spatial resolution is needed to provide direct information about the angular dependence of the modes.

In principle, rotational splitting of the nonaxisymetrical modes can provide us with information about the internal rotation κ of the Sun. If many modes are available the angular momentum distribution within the solar interior can be estimated, provided the modes originate from different portions of the solar interior. The condition required to obtain accurate measurements is that the oscillations maintain phase for several rotation periods and that they are observed continuously throughout that time.

3. The Present Limitations in Helioseismology

As stated in the introduction, helioseismology is in its infancy. However, we are already in a position where we can identify what are its observational limitations. With no pretention of being exhaustive, we isolate four areas in which present observations are now reaching their limits and where we think that considerable progress can be expected in the future.

3.1. Lack of continuity

Ground-based as well as space-borne instruments are affected by the quasi-periodic eclipses of sunlight at night. This limitation is of no effect on routine observations that span large periods of time, but it affects substantially the analysis of shorter time periods. For example, the Fourier analysis of both the intensity (Deubner, 1981; Frölich, 1981) and the velocity oscillations suffers from side bands in the power spectrum, due to the quasi-periodicity of day/night cycles. These spurious signals can affect the detectability of frequencies which may be crucial for mode identification.

By observing from the South Pole, Grec *et al.* (1980) have already gone one step further by observing continuously for 5 concecutive days. The Birmingham group intends to observe from several ground based stations separated in longitude, and allowing in principle a continuous coverage.

From another point of view it is quite obvious that the dominant dips which appear in the records of the solar constant made from the SMM (Willson *et al.*, 1981) would not have been resolved by measurements performed once every month or every year, and had an isolated measurement been made during the period of such dips, the result would have been misleading.

3.2. The short duration of observations

The outcome of routinely collected data easily illustrate the importance of long duration observations. The excellent data of Grec *et al.* obtained from the South Pole also point out how important it is to have more than a few hours of continuous data. We have already mentioned the importance of long duration observations for the accurate measurement of the rotational splitting. It is necessary to follow the phase over several rotation periods for the effect to be measured precisely. Theory predicts that the low order modes which probe the whole solar interior, but have rather low amplitudes should maintain phase for several months, or longer.

The measurement of low order *p* modes quite certainly requires the use of spectrometers that are able to achieve a sensitivity of a few mm s^{-1}. Such performance would also be adequate to resolve *f* and low order *g* modes. Long observing times therefore appear as a necessity to help reducing the noise.

The measurement of periods like the 2^h40^m oscillations and longer, requires also that the observations be conducted for several months or years.

Talking of luminosity variations associated with changes in the hydrostatic structure of the convection zone and with the solar cycle, automatically implies that observations which would cover less than a substantial fraction of a solar cycle would be of poor value if any.

3.3. The Earth's atmosphere

Nearly all the observations analyzed in Section 2 are performed through the Earth's atmosphere.

Differential refraction, atmospheric oscillations and turbulence put strong limitations on the quality of measurements of the solar radius. The best sites offer a resolution of 0.3 arc sec, while the needs require an improvement of a factor 3 to 10, a goal yet impossible to reach from the ground.

The accurate photometric measurements of the solar constant and of white light oscillations are also strongly affected by the presence of the Earth's atmosphere and it is only through the use of space-borne instruments that it is possible to reach the accuracy of a few parts per million (Hudson, 1983), required to measure some of the modes of low order and to detect the minute variations in the solar total output.

The best measurements to date of the global velocity oscillations, by Grec *et al.* (1980), show that the low frequency region of the power spectrum where *f* and *g* modes are supposed to be found is very noisy. The source of this noise is either the Sun itself, or the instrument or the Earth's atmosphere. The precision of a few mm s^{-1} required to detect these modes is impossible to reach to day. By observing from space we can at least eliminate the atmospheric contribution and be able to substantially improve the solar signal.

https://doi.org/10.1017/S025292110009583X Published online by Cambridge University Press

4. Future Projects

We give now a summary list of projects that we are aware of and that may contribute to some progress in solar seismology. For the sake of coherency these projects are separated into two categories, i.e. ground-based and space borne. Again, we have no intention to be exhaustive and we apologize for any omission that may exist in this list.

4.1. Ground-based experiments

4.1.1. *Solar Radius Measurements*

Several groups are presently involved in developments in this area. Hill in the U.S.A. will measure the variations in the solar diameter through changes in the limb darkening at 6 positions around the solar circumference as defined by six 100 arc sec long slits placed tangentially to the Sun's limb.

The High Altitude Observatory is already involved in a monitoring programme.

Rösch and Yerle at Pic du Midi intend to continue their accurate measurements of the solar diameter through a comparison with a ULE rod calibre.

4.1.2. *Velocity Oscillations*

Two techniques are presently exploited which can help solving the continuity and long duration requirement.

The first one consists in a ring of stations located all around the world. This is the technique proposed by the Birmingham group. It has the drawback of multiplying the equipment and the number of observers. In addition, no one can never be sure that all stations do benefit from good weather conditions.

An alternative is to exploit the South Pole station that proved its efficiency with the pioneering observations of Grec *et al.* Several groups of observers are already developing equipments and planning their observations from this unique site: Stebbins and Harvey in the U.S.A., and the group from Nice University which intends to come back with a new equipment in 1982–1983.

Of course, like ground based observations, the success of this solution is severely weather-dependent and suffers from the presence of the atmosphere. This is the reason why the concept of a tethered balloon floating 5 km above the south polar cap has been considered in France. The severe requirement of knowing the relative velocity of the balloon with respect to the Sun with a precision of about 1 mm s^{-1} makes this project a very difficult one.

4.2. Space-borne experiments

In this category, only projects that are under study at this time can be quoted, and we do not know of any experiment yet in the planning stage. We list them according to their chronological entry on the stage:

(i) OGIS (Oscillations of the Global Intensity of the Sun) is a project which has been under discussion for more than three years between the Crimea Observatory and several eccentricity orbit and should measure the oscillations of the solar intensity in several bands of the visible and ultra-violet spectrum. The programme of this mission is still under question.

(ii) The 'Birmingham–Crimea' project consists in measuring velocity oscillations also from a Prognoz satellite. A feasibility study for the instrumentation has been undertaken in England but, as for the OGIS project, the mission is not yet programmed.

(iii) DISCO (Dual Investigation of the Solar Constant and Oscillations) is a project presently undergoing a Phase A study at the European Space Agency (E.S.A.). It is by far the best-studied space project among all those described here. It consists in measuring global velocity and intensity variations and oscillations from a spinning satellite located at the Lagrangian point L_1 which lies between the Sun and the Earth–Moon system. The lifetime of 2 years envisaged for DISCO and the use of a stable high resolution spectrometer should in principle provide the required accuracy of 1 mm s^{-1}. The rest of the instrumentation, consists of high accuracy radiometers, white light and broad band photometers, with limited (a few arc min) angular resolution capability, and of an extreme UV spectroheliograph providing a spatial resolution of 15 arc sec, sufficient to observe coronal holes and active regions. A detailed description of this mission can be found in the assessment study document ESA–SCI(81)6, November 1981. The decision to proceed after the completion of the phase A study will be taken at the beginning of 1983.

(iv) The Solar Internal Dynamics Mission (SIDM) is a NASA mission which was probably proposed before DISCO. However its state of definition is much less advanced and its concept not even defined yet. Its goals are similar to those of DISCO, except that it may offer more spatial resolution capability. If this is the case the SIDM would likely consist of a two or three axis stabilised spacecraft and therefore be of a higher degree of sophistication than DISCO.

(v) The Solar Diameter Measurement Instrument on Spacelab. This instrument has merely been suggested, and not yet formally proposed. It is an improved version of the Pic du Midi instrument and would consist of a 1 m × 10 cm telescope placed on Spacelab or a space station.

5. Conclusion

The future observations in helioseismology require progress in several directions. First, our discussion clearly indicates the role that space techniques can play in this context since they can resolve simultaneously all the three problems of continuity, long observing time, and perturbations by the Earth's atmosphere. This potentiality however has been discussed only recently, but there is little doubt that the most decisive progress in helioseismology will have to await the existence of a 'seismology observatory' or of instruments capable of measuring the parameters identified in Section 2.

We assume that the instrumentation itself has no intrinsic limitations. Those instruments which have already contributed substantially to the field, like the balloon radiometer of Frölich (1981), the ACRIM instrument on the SMM, the sodium optical resonance cell of Grec *et al.*, the potassium cell of the Birmingham group do not require a dramatic improvement in their performance in order to achieve the range of accuracy that is needed here.

More progress can be expected also in the near future in the area of data analysis, more specifically of ground based data, in particular for the detection of modes of low frequency, since it appears that this analysis has not always been conducted with enough precaution. Special care should be taken to eliminate all kinds of false periodicity effect of either instrumental or astronomical origin.

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https://doi.org/10.1017/S025292110009583X Published online by Cambridge University Press