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The future of helioseismology

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Abstract. Helioseismology is the only possibility to probe the conditions inside the Sun, which advances our understanding of the solar structure and the Sun's influence on the Earth. The field of helioseismology has been developing rapidly since the 1980s thanks to dedicated projects like the Solar and Heliospheric Observatory (SOHO) and the Global Oscillation Network Group (GONG). The field is now about to take a giant leap forward with the successful launches of the Solar Dynamics Observatory (SDO) and the PICARD mission with vastly better spatial and temporal resolution. This now allows to make use of the full potential of local and global helioseismology techniques to study inhomogeneities in the solar interior which are connected to solar dynamo action. In addition, new ground-based instruments are being developed for complementing in unique ways the space observations by establishing physical relationships between internal solar properties and magnetic activity in the solar atmosphere. This paper summarizes the new goals, possibilities, and prospects of helioseismology.

Key words: Sun – helioseismology

1. Introduction

Before thinking about the physics of the Sun's interior and the future of helioseismology in detail, it might be instructive to start this article with having a closer look on an important global physical property of the Sun. As most readers of this article will know the Sun's surface temperature is about 5700 K. Compared to the melting temperature of iron of 1812 K, this already explains that it is impossible to prepare a space mission to probe the Sun's interior. This is why helioseismology besides theoretical concepts is the more or less only "experimental" possibility to learn about the Sun's constitution and internal processes. Only the detection of the solar neutrinos can give a view on the Sun's core, but neutrinos are difficult to capture.

Theoretical knowledge on the structure of the Sun can be obtained based on first principles: conservation of energy, mass, and momentum. From them it follows that a theoretical model can be built on these fundamental physical laws. Pressure and gravity are in balance, *i.e.*, the Sun is in a stable hydrostatic equilibrium. In more detail, standard solar models result in a core temperature of about 15 million K and a surface temperature of about 6000 K. In the bulk of the solar interior energy is transported by radiation, only in the outer third convection is the main mechanism of energy transport.

The possibility to study the solar interior "experimentally" came into reach with Leighton's measurements of the solar "five-minute oscillations" (Leighton *et al.*, 1962). The detection of the solar oscillations came by accident. Leighton *et al.*'s original intention was to determine the lifetime of granules. They determined characteristic changes in difference maps of spectral line shifts due to the Doppler effect of the granular velocity field along a slit and as a function of time t. The surprising result was that the difference of the Doppler measurements vanished periodically roughly every five minutes and not only for $t = 0$.

The theoretical explanation for this finding was given by Ulrich (1970) and Leibacher & Stein (1971): the Sun swings, *i.e.*, it can be excited to oscillate in its resonant eigenmodes. Small deviations from the hydrostatic equilibrium, as they are realized, *e.g.*, in sound waves generated by the turbulent granular velocity field, can lead to oscillations around this stable equilibrium. The superposition of such sound waves can lead to amplifications or cancellations of particular wave modes, which finally leads to the excitation of the Sun's fundamental mode and the higher harmonic overtones to nominal amplitudes. The theoretical prediction was that the Sun is subject to p and g modes, *i.e.*, modes with either the pressure gradient or gravity as restoring force, resp. (for in-depth studies see also the modern textbook of Aerts *et al.*, 2010). The oscillation energy should show discrete eigenmodes arranged along ridges of the same radial order as a function of harmonic degree and frequency. Such a diagnostic diagram, or an $k - \omega$ *diagram*, which displays the Sun's oscillation spectral energy density as a function of wavenumber and frequency, was first shown by Deubner (1975).

This was the birth of the seismology of the Sun. As waves of different frequencies and different wave numbers propagate to different depths in the solar interior, they carry different information about the structure of the Sun. By precisely measuring the Sun's eigenfrequencies it is possible to conclude from these sounds on the structure of the Sun.

2. The past

Based on improved measurements of the solar eigenfrequencies the first helioseismic measurements helped improving the solar models. This included a precise determination of the depth of the solar convection zone (Christensen-Dalsgaard *et al.*, 1975) and the temperature in the solar core of 15.7 million K. The latter was important to help in solving the problem of the too low measured solar neutrino rates on the Earth (Christensen-Dalsgaard, 2002). As shown by Kosovichev *et al.* (1997) the agreement between the solar model and the helioseismic measurements was very good. The relative difference in the sound speed was in the order of 2% only with significant differences at the base of the convection zone and in the solar core.

A further important helioseismic inference was made on the Sun's internal rotation. Dynamo theories assumed an angular velocity decreasing with depth with isorotation contours parallel to the rotation axis. The first helioseismic inversions, however, showed an angular velocity rather parallel to radii and not to the rotation axis. A striking feature at the bottom of the convection zone in the helioseismic measurements is the "tachocline", where the differential rotation turns into a solid-body rotation. The thickness of this transition layer is about 5% of the solar radius. The core rotation agrees with the surface rotation measured around latitudes of $30° - 40°$. Current theories assume that the tachocline region is important for the working of the solar dynamo.

Another finding of early helioseismology was that the solar oscillation frequencies vary with the solar cycle (Woodard & Noyes, 1985). The low-degree oscillation frequencies are about $0.4\,\mu$Hz higher at a solar maximum compared to a solar minimum. Until now a detailed explanation of how the solar activity cycle affects the solar internal constitution and consequently the Sun's frequencies is missing.

Most of the first helioseismic studies were carried out based on the frequencies of the standing waves of the full solar globe. The results, therefore, present the global properties of the Sun averaged over longitude and symmetric across the equator over latitude. This helioseismic approach is nowadays known as "global helioseismology". The approach of determining more local properties of the Sun with "local helioseismology" techniques was developed from the mid eighties on. It makes use of the properties of the acoustic waves on localized areas and has four major concepts: the Ring-diagram Analysis (Hill, 1988), the Time-distance Helioseismology (Duvall *et al.*, 1993), the Fourier-Hankel Decomposition (Braun *et al.*, 1987), and the Acoustic Holography (Lindsey & Braun, 1990). These methods are very often limited to waves of high harmonic degree, which probe only the outer ≈ 20 Mm below the solar surface.

3. Modern helioseismology

In the last years helioseismology was based on the contiguous observations of the Birmingham Solar Oscillations Network (BiSON), the Global Oscillation Network Group (GONG), and the Solar and Heliospheric Observatory (SOHO).

The high quality data allow studying variations of the solar differential rotation with time and latitude (Howe, 2009). When plotted as a function of latitude and time, the residuals of the solar internal differential rotation, which are obtained by subtracting a long-term average from the single rotation measurements, banded zonal flows (also known as "torsional oscillations") become visible. These zonal flows show amplitudes of $\pm 5\,\mathrm{m\,s^{-1}}$ compared to the surrounding rotation. As a function of depth this pattern exists almost half throughout the convection zone. It is interesting to know that active regions emerge at the equatorward boundary of the flow (Howe, 2009). Moreover, the rotation residuals show variations in the tachocline region. With rising solar activity the characteristic time for this variation in the solar cycle 23 seemed to be 1.3 years. Since the solar maximum a clear periodic variation is not visible any longer (Howe, 2009). It will be interesting to see whether the periodic variation returns with the beginning of solar cycle 24. At the polar regions the rotation is slower than average during solar minimum and accelerates with progressing cycle. With the approach of the new minimum the rotation at high-latitudes and in the deep convection zone decelerates. This deceleration region rises to the solar surface.

Another flow relevant to flux-transport dynamo models is the meridional flow. So far this flow was only measured by local helioseismology techniques as global helioseismology techniques are only capable of determining solar properties symmetric to the equator. The local helioseismology measurements of the meridional flow were limited to the outer $\approx 20\,\mathrm{Mm}$ of the Sun. The general findings are that the flow is mainly poleward, the flow strength is variable between 0–60 $\mathrm{m\,s^{-1}}$. A weak equator-crossing flow is possible. In 2002 Haber *et al.* reported the existence of a counter cell on the Northern hemisphere, which started to evolve from 1998. These results could be contaminated in part by errors in the orientation of the MDI or GONG Dopplergrams (Zaatri *et al.*, 2006; Beckers, 2007). The residuals of the meridional flow show a convergence towards the mean latitude of activity (Zhao & Kosovichev, 2004). A doubtless evidence for a return flow was not found so far. Such a return flow has to be present since mass does not accumulate at the poles; it is believed to lie deeper down in the solar interior.

The technique of "acoustic holography" allows determining an acoustic image of the backside of the Sun ("far-side imaging"). Large active regions can be detected in such acoustic maps. Contiguously created, the solar far-side images allow tracking an active region during its evolution. This can then be used for predicting the appearance of an active region on the front side, which has implications for "space-weather" applications.

Studying in particular the structure of active regions and sunspots in details is mainly carried out on the solar front side with time-distance helioseismology. Kosovichev *et al.* (2000) showed variations of the sound speed and flows as a function of position below a sunspot.

4. Future helioseismology

The expectations for the future of helioseismology evolve mainly around the 24th solar cycle. This cycle is the second sunspot cycle and therefore the first full magnetic cycle that could be covered completely by imaging helioseismic observations. Based on this it is interesting to know whether there are systematic changes in the internal dynamics between the two sunspot cycles. Is there any difference related to the global polarity reversal? Are there systematic changes in the tachocline region?

4.1. Scientific questions

Detailed scientific challenges arise from the goal of understanding the origin of solar activity. For this it will be necessary to know about the structural changes that go along with the solar activity cycle. This includes studying the deep solar interior not only by global helioseismology but preferred by local helioseismology techniques with the advantage of having information on local physical conditions in the solar interior, *e.g.*, sound speed variations and flow components. Important topics for the near future are studies of the variation in the spatial structure of the tachocline. Whether three-dimensional analysis with local helioseismology will be possible depends on the possibility to assess the properties of low-degree running waves with these techniques, as those probe the deep solar interior. In principle focusing seismically deep into the solar interior is possible with local helioseismology techniques, if *e.g.*, in the case of time-distance helioseismology large angular distances can be used to calculate the cross-correlation function. With the data delivered currently by GONG and SOHO this is technically not possible: as the oscillation signal is mainly radial at the solar surface and as the spatial resolution is about 2 arcsec, foreshortening besides the line-of-sight projection results in a strongly decreasing Doppler signal towards the limb. With HMI the spatial resolution is about 1 arcsec. This allows a much better resolution of the solar oscillations towards the limb and should allow for probing deeper into the convection zone. Fig. 1 gives a sketch on how a greater observing area on the solar surface moves the helioseismic focus deeper into the solar interior.

The same applies to seismic estimates of the deep meridional return flow which is of special interest to understand the solar dynamo. Based on mass conservation estimates the meridional return flow is expected to have a magnitude of 1–2 $\mathrm{m\,s^{-1}}$ at the base of the convection zone. Measuring such a weak flow is beyond the current capabilities of helioseismic methods. For measuring the deep meridional flow again modes that penetrate deep into the solar interior need to be considered for the analysis. Preliminary studies of the location of *averaging kernels* for the Fourier-Hankel decomposition give a good seismic focusing at greater depths based on the first HMI data (Doerr *et al.*, 2011).

Another possibility might be a more sophisticated approach of global helioseismology. When studying flows by global helioseismology, shifts of mode frequencies are taken for the analysis (see the textbook of Aerts *et al.*, (2010) for a detailed description). As an example, the differential rotation leads to a frequency splitting of otherwise degenerate mode multiplets. Theoretically, this is described by a perturbation theory. The meridional flow and other flow components lead to additional frequency shifts, too. However, these shifts are much smaller than the shift due to the faster differential rotation (Roth & Stix, 1999, 2008) and are due to effects of higher order. But when studying the perturbation to the eigenfunctions the effect of the meridional flow is of first order and might then be easier to measure. Based on this fact Schad *et al.* (2011) describe

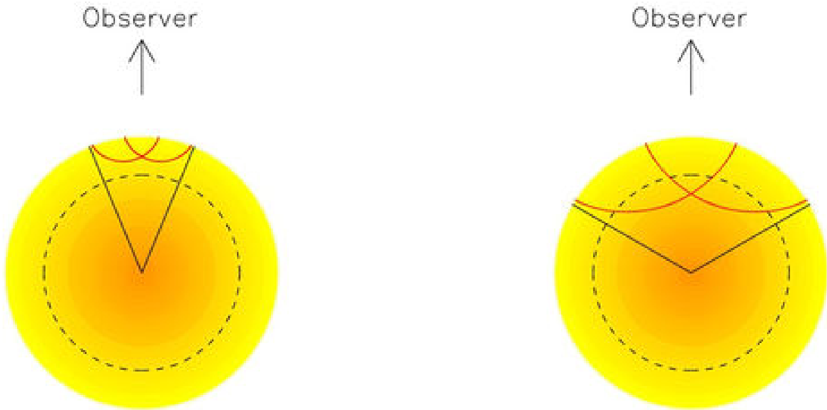

Figure 1. Sketch of the location of the helioseismic focus inside the Sun as a function of observing area on the surface. The red lines mark the raypaths of two wave packets. The intersection of the raypaths marks the helioseismic focus, *i.e.*, the two wave packets carry the same information about this point. Left: Waves with a small wave length propagate within a small and shallow angular region (black lines). The helioseismic focus is near the surface. Right: Wave packets traveling large angular distances can be used to focus seismically deep into the Sun.

a unified approach to measuring the meridional flow from global helioseismic time series, which in first tests works on simulation data (Schad *et al.*, 2010).

A higher seismic sensitivity at greater depths would also be of interest for other applications. As an example studying the emergence, structure, and evolution of sunspots could profit from better helioseismic methods. Currently, there is a debate on how to interpret the results for sunspot structure and flows around sunspots correctly. As it has been shown by a comparative analysis on the same seismic data set containing a stable sunspot, the ring-diagram method and various versions of time-distance helioseismology resulted in wave speed perturbation measurements due to the presence of a sunspot with opposite sign (Gizon *et al.*, 2009). The explanation given could be that a sunspot strongly perturbs the eigenoscillations and the assumption of a weak perturbation due to the spot is no longer valid. The acoustic modes converted in the presence of a strong magnetic field into magneto-acoustic waves get lost for the acoustic wave field. This is why sunspots are known as being p mode absorbers. The energy absorption due to the spot could be in the order of 50% in the case of the f mode and clearly depends on the wave number (Braun *et al.*, 1988; Roth & Thompson, 2011). Consequently, it might be possible to use this absorption coefficient as a new analysis tool to learn about the structure of a sunspot.

When aiming at predicting the appearance of active regions the sensitivity of the seismic methods must be improved, too. The seismology of the solar far side and the daily flow maps on the solar front side are currently the most important application to serve as input for space weather predictions. However, it has to be shown how the far-side signal can be calibrated to also predict the magnetic field strength and the area of an active region.

Furthermore, a higher spatial resolution can help to develop new or improved helioseismic methods. As an example, the seismic studies carried out with data recorded by the IMaX instrument aboard the Sunrise mission give indications how such data can be used to learn about the excitation of p modes and the chromospheric heating if the spatial resolution is in the order of 0.15 arcsec (Roth *et al.*, 2010; Bello Gonzalez *et al.*, 2010).

In addition, helioseismic inferences obtained on the solar interior need to be linked with the processes in the solar atmosphere. Only then seismic methods can be developed with predictive power for solar activity. As an example, it will be interesting to learn which processes trigger flares. In addition, it will be important to obtain information on the waves at multiple heights in the solar atmosphere to follow also magneto-acoustic waves or the waves with frequencies above the acoustic cut-off. This will additionally provide information about the structure of the solar atmosphere. First numerical studies with the Co5BOLD code explain how high-frequency acoustic waves are converted, transmitted, or reflected by a complex magnetic solar atmosphere (Nutto *et al.*, 2010).

4.2. Latest instrumentation

A major leap to advance helioseismology further will be driven by new instruments that allow obtaining improved synoptic observations of the Sun. In 2010, two such new space missions were launched. First, the Solar Dynamics Observatory (SDO) is NASA's first mission in the "Living with a Star" program with a nominal life of five years, and expandables aboard that allow to hope for a decade-long mission. SDO carries a suite of instruments to study the solar atmosphere (AIA – Atmospheric Image Assembly), the Sun's magnetic field and the solar interior (HMI – Helioseismic and Magnetic Imager), and changes of the solar irradiance (EVE – Extreme ultraviolet Variability Experiment). The mission's primary goals are understanding the solar variations that influence life on the Earth and humanity's technological systems, obtaining a predictive capability of space weather, answering how the Sun's magnetic field is generated and structured, answering how stored magnetic energy is converted and released in the form of solar wind, energetic particles, and variations in the solar irradiance.

The HMI instrument is a new and improved version of the MDI instrument aboard SOHO. HMI measures a long sequence of Dopplergrams and magnetograms with a cadence of 45 s for Dopplergrams, line-of-sight magnetic flux diagrams, and continuum intensity. It has a cadence of 90 s for vector magnetic field measurements. The observing wavelength is the Fe I 617.3 nm line on a CCD of 4096×4096 pixels and a spatial resolution of 1.0 arcsec. The data flow of HMI is challenging, it delivers 550 GB per day and is the first instrument devoted to local helioseismology.

Second, PICARD is a CNES led satellite mission and was launched on June 15, 2010. The main mission objective is to measure the solar diameter, oblateness and limb shape with an unprecedented accuracy of a few milliarcseconds per image. PICARD studies a possible variation of the measured quantities with activity. This is achieved in the three different wavelengths of 535.7, 607, and 782 nm PICARD carries three instruments: The SOlar Diameter Imager and Surface Mapper (SODISM) is an imaging 11-cm Cassegrain telescope equipped with a 2048×2048 CCD detector. The SOVAP (SOlar VAriability PICARD) instrument consists of a small Bolometric Oscillation Sensor (BOS), a differential absolute radiometer (DIARAD) for total spectral irradiance (TSI) measurements. The PREcision MOnitor Sensor (PREMOS) consists of three Sun PhotoMeters (SPM) with four channels to measure the spectral irradiance in UV at 215 and 268 nm, in the visible at 535 nm, and in the near infrared at 607 and 782 nm. Furthermore, it has two absolute radiometers of type PMO6 for TSI measurements. The Sun photometers are operated at 10 s sampling for different spectral domains.

PICARD measures the solar limb in intensity every two minutes. As intensity oscillations are strongest at the limb (Toner *et al.*, 2010), one of the goals is to detect g modes as they are of a small amplitude. The imaging of the solar disk allows reaching an oscillations' harmonic degree of up to $l = 256$. With this helioseismology will be carried out in order to achieve the other mission's goal of studying the processes involved in the solar dynamo action.

4.3. Instrument development

For future helioseismology instruments that provide a higher spatial and temporal resolution are needed. The scientific questions that drive this instrumental development were discussed above. The conclusion is that a higher spatial resolution will be needed to resolve the solar oscillations at the limb. Furthermore, helioseismology can also provide important information about the physical processes in the solar atmosphere. For this a higher temporal resolution and observations at multiple heights are needed. One example of such an instrumental development is a new Fabry-Perot based device to be operated at the Vacuum Tower Telescope (VTT) in Izaña, Tenerife. The device developed by Staiger (2010) consists of a matrix on which up to 16 filters can be mounted. As these filters can be moved quickly, observations in multiple lines can be carried out at a high temporal resolution. First tests show that a full cycle through 16 spectral lines, each scanned with at least 15 wavelength steps, can be completed within one minute. The cadence for one line only is 1 s. Such an instrument is interesting not only for helioseismology. It will also find applications in other areas of solar physics when the tracking of fast events in the solar atmosphere is needed, *e.g.*, observations of Moreton waves or flares, and the tracking of shock fronts.

So far this instrument has a limited field-of-view of $100 \times 100\,\mathrm{arcsec}^2$, *i.e.*, only a section of the solar disk can be observed. Usually, there exist several areas of interest on the Sun that need to be observed. In order to obtain a holistic view of the Sun and to carry out synoptic observations, it is desirable to obtain data of the full solar disk. Then, these data should be available 24 hours a day and for many years. This would allow to follow not only short-term events but also to study long-term trends. A network of telescopes distributed around the world, *e.g.*, like the GONG network, could serve for this purpose. It is probably interesting to note that the amount of data obtained by such a telescope network will easily exceed the capacities of nowadays computing and data storage facilities.

5. Conclusions

The future goals of helioseismology are to observe and understand the interlinked processes of magnetic activity and internal dynamics. This includes to link the convection-zone dynamics and the processes involved in the solar dynamo action. Furthermore, it is expected that future studies will focus on learning about the origin and evolution of sunspots, active regions, and complexes of activity. Finding the sources and drivers of solar activity will be of major importance for helioseismology. This will also require to link the internal processes with the dynamics of the solar atmosphere. Precursor measurements of disturbances in the solar interior will be interesting for space weather forecasts. The newest instruments for helioseismology are the Solar Dynamics Observatory (SDO) and PICARD which provide a higher temporal, spatial, and spectral resolution than previous missions.

Based on these upcoming large amounts of better data, improved techniques allow gaining information on the dynamo process by measuring the flow components in the Sun with great precision, the rise of magnetic flux tubes, if the sensitivity in the tachocline region can be increased, the evolution and configuration of active regions, the small-scale flow components and their relations to solar activity, the solar activity cycle and its relation to large-scale flows, the triggering of flares by linking solar interior and atmosphere, and the deep solar interior.

Concerning the future instrumentation, synoptic observations of the full Sun are as important as high-resolution observations in smaller field-of-views, otherwise a full understanding of solar activity cannot be obtained. Future instrumental devices will, therefore, need as high temporal resolution as possible. The instrumental requirements include to observe in many atmospheric layers to allow tracking fast processes in the solar atmosphere. In addition, if such an instrument provides a view on the full solar disk, and if it has a high spatial resolution in the order of 0.15 arcsec, it could also be used for many applications in solar physics. Whether such an instrument might need adaptive optics to stabilize the image is a question that need to be addressed, too. Especially, how this is compatible with the need of recording long contiguous time series.

In summary, a lot of exciting results are expected from future helioseismology. In order to obtain them, a lot of work is ahead.

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