

The Importance of Long-term Synoptic Observations and Data Sets for Solar Physics and Helioseismology

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Abstract A casual single glance at the Sun would not lead an observer to conclude that it varies. The discovery of the 11-year sunspot cycle was only made possible through systematic daily observations of the Sun over 150 years and even today historic sunspot drawings are used to study the behavior of past solar cycles. The origin of solar activity is still poorly understood as shown by the number of different models that give widely different predictions for the strength and timing of future cycles. Our understanding of the rapid transient phenomena related to solar activity, such as flares and coronal mass ejections (CMEs) is also insufficient and making reliable predictions of these events, which can adversely impact technology, remains elusive. There is thus still much to learn about the Sun and its activity that requires observations over many solar cycles. In particular, modern helioseismic observations of the solar interior currently span only 1.5 cycles, which is far too short to adequately sample the characteristics of the plasma flows that govern the dynamo mechanism underlying solar activity. In this paper, we review some of the long-term solar and helioseismic observations and outline some future directions.

Keywords Sun · observations · helioseismology

1 The Need for Synoptic observations

Although we may consider the Sun to be a constant star, there is considerable evidence that the level and character of its output changes with time. It is of particular interest to know if these changes are purely superficial or whether they are due to changes in the solar interior. There are only two ways that we currently know to probe the interior: the detection of solar neutrinos or helioseismology, the study of the acoustic waves that permeate the Sun. Of these, helioseismology is by far the more flexible and feasible. The solar output varies on both short (seconds to days) and long (months to millennia) time scales, with an emphasis on the approximately 11-year length of the sunspot cycle. There is thus a need for observations that are continuous over many cycles. Once cross calibration is established, there is also the possibility of using proxies of solar variation which can be used to follow behavior over millennia. The ^{10}Be and ^{14}C concentrations in the Earth's crust are examples of these proxies. We will come back to these in the section on activity but here we just point out that these proxies are by their nature only approximate and lacking in detail.

The solar physics community is currently developing the next generation of solar telescopes with large aperture sizes (~ 4 meters) such as the Daniel K. Inouye Solar Telescope (DKIST, originally known as the Advanced Technology Solar Telescope or ATST) in the US and the European Solar Telescope (EST) in the European Union. The large aperture of these telescopes will provide solar observations at an unprecedented angular resolution and will allow precision measurements of the physical parameters of the solar plasma at high spatial and temporal resolution. These detailed measurements will provide important clues about physical processes and structures at the finest spatial scales resolvable, such as the evolution of the quiet Sun magnetic flux, its emergence and concentration in the intergranular flux tubes, their role in chromospheric heating, fine structure of Evershed flow, sunspot umbral and penumbral flux tubes, solar filaments and prominences etc.

Having detailed observations at hand allows us to confront numerical solar models with reality and therefore allows us to refine the models. Highly refined models could

provide a better understanding about the solar variability in parameters such as the total solar irradiance. However, a bigger challenge is to understand the solar dynamo, which operates inside the Sun and makes the number of sunspots wax and wane on a 10- to 13-year time scale. Our current understanding of this operating mechanism behind the solar cycle is rather poor and various models (empirical or physical) gave a wide range of predictions for the strength and timing of cycle 24 (Pesnell 2008).

In order to understand the solar activity cycle, i.e., the generation and decay of the magnetic field, we need high-resolution observations of the Sun together with full-disk synoptic (continuous and comprehensive) observations of the Sun in different wavelengths and polarizations. While the high-resolution observations shed light on the details of small scale magnetic fields, such as local dynamo processes, flux emergence, cancellation and surface diffusion, the synoptic observations of solar oscillations allow us to study the subsurface dynamics of the Sun, such as the profile of solar differential rotation, meridional and zonal flows, and their variability. These phenomena play important roles in the solar dynamo operation.

In addition, the field of space weather is increasingly important for our technology-dependent world, and the useful forecasting of space weather impacts from flares and CMEs requires a reliable source of continuous real-time measurements of the magnetic field vector in solar active regions. It is therefore desirable to complement the quest for high-resolution observations of the Sun with a parallel effort that seeks to modernize and extend our existing sources (e.g. BiSON, GONG and HMI) of synoptic observations that provide essential information about the solar interior through helioseismology.

1.1 Helioseismology

The physical foundation of helioseismology rests on the natural resonances of the Sun arising from the propagation of acoustic-gravity waves in the interior. While the amplitude of these standing waves peaks at a frequency ν of around 3 mHz (periods of around 5 minutes), their periods are observed to range from 200 to more than 1000 seconds. The sampling theorem requires that, if a harmonic signal is to be faithfully recorded, it must be sampled at least twice per period of the wave. In order to increase the signal-to-noise ratio (SNR), data are usually collected at intervals of no longer than one minute. Further, the resolution in ν is $1/T$, where T is the total length of the observations. There is thus a need to make T as large as possible.

Global helioseismic oscillations are evident in both “Sun-as-a-star” (unresolved) and resolved observations: Sun-as-a-star data are only sensitive to modes with the largest horizontal length scales (modes with low values of spherical harmonic degree $\ell < 5$). However, these are the modes that sample the solar core. Resolved observations broaden the spatial spectrum of modes that can be observed, with degrees ℓ up to and even greater than 1000 being detected.

The sound waves are not purely sinusoidal signals but are stochastically excited and intrinsically damped, which produces a very highly structured power spectrum as discussed in Anderson et al. (1990). The spectrum of the oscillations contains a wealth of features arising from both the Sun and the observing method. This makes helioseismology a powerful diagnostic tool but it carries with it penalties. In order to clearly resolve and track solar properties over multiple sunspot cycles, the data need to be taken at a relatively rapid cadence as just indicated, over very long periods of time and, for reasons that will be explained, the data sets should be nearly continuous.

These constraints can be satisfied but they require long-term commitments to funding and an understanding of the nature of synoptic observations.

1.2 The Sunspot Cycle

Astronomy is an observationally-based science, and it is not possible to absolutely perfectly repeat a measurement. When we analyze solar data we typically look for long term cyclic behavior. However, there will also be trends that may repeat on timescales that are long by comparison with human lives but short compared with the thermal timescale of the Sun. The most obvious time scale to be considered here is the period of the solar sunspot cycle. The earliest known records of sunspot observations come from China around 364 B.C. and sporadic records of naked-eye observations were made in both Western and Eastern civilizations over the subsequent 1900 years. In 1610 through 1613, the invention of the telescope resulted in a flurry of nearly-simultaneous European observations of and publications about sunspots from Thomas Harriot, David and Johannes Fabricius, Christoph Scheiner and, most famously, Galileo Galilei. The realization that the spots were actually on the Sun and were not clouds or other planets led to the first measurements of the solar rotation and the discovery that the Sun did not rotate rigidly but that its rotation rate is a function of solar latitude.

Since then the appearances and solar heliographic locations of sunspots have been recorded, forming the fundamental set of the first synoptic observations of the Sun. As a result, the daily number of sunspots is now a 400-year long time series displaying the variable solar magnetic activity. In the first half of the nineteenth century, Heinrich Schwabe and Rudolf Wolf detected the sunspot cycle, the discovery of which had been delayed by the Maunder Minimum, the period of 1645 to 1715 during which the Sun was nearly spotless. This long record of observations clearly shows the approximately 11-year period of the number of sunspots on the solar disk (known as the Schwabe cycle), but it was not until Hale was able to measure the solar magnetic field in the early twentieth century that it was realized that the activity cycle is actually around 22 years since the polarity of the Sun's magnetic field reverses during each Schwabe cycle. A longer period cycle of 87 years, known as the Gleissberg cycle, can be seen in the amplitude envelope of the Schwab cycle, and periods of pronounced sunspot maxima and extended grand minima can be identified. Figure 1 shows the last 140 years of the sunspot number record along with a label identifying each cycle. We are in Cycle 24 as of the writing of this paper.

Sunspots are locations of activity in the form of flares and CMEs. **These events are responsible for creating the extreme type of space weather, which otherwise is a mostly steady solar wind. Flares and CMEs produce high levels of radiation primarily in the form of charged particles and X-rays that are two or more orders of magnitude higher than those typically present in the background solar wind.** These blasts can strike the Earth and its magnetic field, creating geomagnetic storms, generating currents in the Earth's crust, and disrupting the ionosphere. Space weather can adversely impact many common technologies including GPS, telecommunications, space activities, military operations, navigation, power grids, financial markets, emergency services, surveying, agriculture, and air travel. A fundamental goal of synoptic observations is understanding the physical processes inside the Sun with sufficient detail so that accurately predicting the level of solar activity becomes possible.

2 Signatures of Solar Activity

The number of sunspots visible on the disk is the most obvious signature of solar activity, but it is by no means the only variable that is observed. **In addition, it is surprisingly hard** to actually count the number of sunspots on a given day. Variations in the Earth's atmosphere can hide small spots, human observers can make different choices as to how many individual spots are in a group, and telescope optics can degrade with time (Svalgaard 2012). The effect of these issues are mostly avoided in the other signatures of activity discussed here.

2.1 Sunspot Number

We are interested in the variations in the magnetic field inside the Sun but, since this is very difficult to measure directly, we resort to using proxies for the magnetic field. The obvious and original proxy is the variation in the number of sunspots that are observed on the visible disk of the Sun. Since it is not so simple to just count the number of spots, this method is open to considerable personal interpretation and there has recently been a revision in the historical record to remove some of the discrepancies. Svalgaard (2012) has shown that only two adjustments are necessary to reconcile the Group Sunspot Number with the Zürich Sunspot Number. The first of these adjustments involves increasing the values after the 1940s by 20% due to weighting of the sunspot counts according to spot size. Svalgaard also shows that the Group Sunspot Number before about 1885 is too low by about 50%. The application of these adjustments results in a single sunspot number series and has the consequence that there is no longer a distinct Modern Grand Maximum (Clette et al. 2015).

At the beginning of each activity cycle, the location where sunspots apparently emerge from the solar interior starts at a solar latitude of about 40° . This emergence latitude moves towards the solar equator as the cycle progresses. Thus, plots that record the location of sunspot emergence as a function of solar latitude and time display a pattern known as the butterfly diagram. This is shown, along with the sunspot number, in Figure 1.

2.2 Sunspot field strength, polar fields

Sunspots are the most visible and familiar aspect of the solar cycle, but it is the magnetic field that is actually the fundamental controlling factor of solar activity. Sunspots are very large regions of very strong magnetic field that alters the thermal structure of the solar atmosphere and redirects energy into a number of complex paths, including explosive reconnection events in the form of flares. The maximum magnetic field strength observed in sunspots is typically around 3500 G, although there may have been a spot with 6000 G strength observed in the 1940s (Livingston et al. 2006). There has been considerable interest in the possibility that the central magnetic field intensity and relative darkness of sunspot umbras has been decreasing over the last two solar cycles, implying that sunspots would disappear in the next cycle (Livingston et al. 2012) and lead to a Grand Minimum perhaps akin to the Maunder Minimum. This conclusion was contradicted by the work of Kiess et al. (2014), and has since been retracted (Watson et al. 2014).

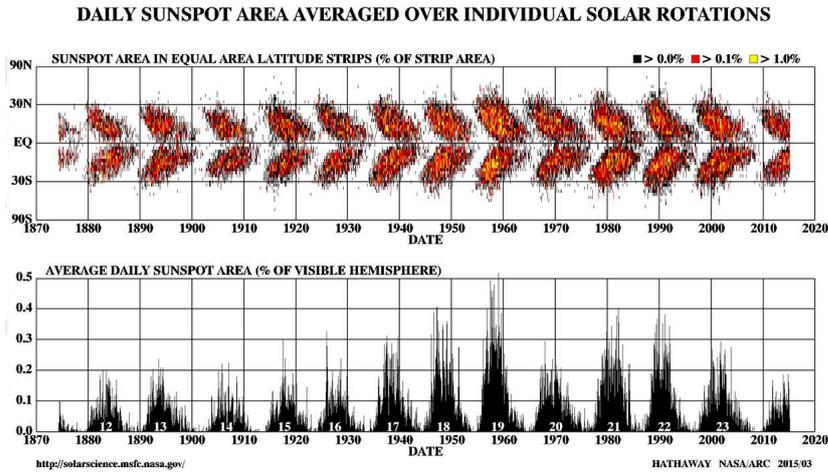


Fig. 1 Sunspot cycles from 1875 through March 2015. Top: The butterfly diagram, showing the locations where sunspots emerge as a function of solar latitude and time. Lower: The time history of the number of sunspots. Image courtesy of David Hathaway, NASA/ARC.

While the sunspot field strength is now thought to be constant across solar cycles, it has been established that the strength of the fields at the Sun’s north and south poles is not. Indeed, the strength of the polar field at solar minimum is highly correlated with the peak amplitude of the next cycle (e.g. Svalgaard et al. 2005). The reversal of the polar fields, driven by the meridional flow (north-south) of the solar plasma on the surface, is now taken to be one of the major indications that solar maximum has been reached (Petrie et al. 2014; Upton and Hathaway 2014). However, the timing of the reversal can be complicated as the northern and southern solar hemispheres typically have asymmetric behavior, as seen in the current cycle 24 (Svalgaard and Kamide 2013).

2.3 Irradiance Measurements

The amount of solar radiative energy reaching the Earth, integrated over all wavelengths of light, is called the total solar irradiance (TSI), with an observed value of 1361 Watts/m^2 above the Earth’s atmosphere and at a Sun-Earth distance of 1 AU. The TSI varies on time scales of days due to the presence of sunspots as the solar rotation carries them across the disk, however the most significant variation is an increase of about 0.1% during solar maximum (Fröhlich 2013). Many models of the detailed variation in TSI have been constructed based on the surface magnetic field of the Sun, some of which can be found in Velasco Herrera et al. (2015), Yeo et al. (2014a), Yeo et al. (2014b), Dasi-Espuig et al. (2014), Fontenla et al. (2014), Chapman et al. (2013), Foukal (2012), Ulrich et al. (2010), Pap et al. (2010), Jones et al. (2008), Wang et al. (2005) and Lean et al. (1998).

Measurements of the TSI have been made by a number of satellites, starting with electrical substitution radiometers (ESRs) on the Nimbus 7 satellite in November 1978 (Hickey et al. 1980; Kyle et al. 1994). These

have been continued with the Active Cavity Radiometer Irradiance Measurement (ACRIM) instrument on SMM (Willson et al. 1981), the Earth Radiation Budget Experiment (ERBE, Barkstrom and Smith 1986), two more ACRIM experiments on UARS and ACRIMSAT, the VIRGO instrument on SOHO (Fröhlich et al. 1995), and SORCE (Woods et al. 2000). There are considerable differences between these measurements even when they overlap in time and reconciling the differences has been challenging (e.g. Fröhlich 2006).

While the TSI is integrated over all wavelengths of light, there are also variations of solar output that depend on the spectral region being studied. The Spectral Solar Irradiance (SSI) has been measured since 2003 with the SORCE space mission (Woods et al. 2000), and these measurements have shown that variations in the SSI can be either in or out of phase with the TSI changes depending on the spectral band (e.g. Harder et al. 2010). This complex behavior is thought to be linked to the detailed effect of magnetic fields on the radiative transfer of the light as it passes through the photosphere (Haberreiter et al. 2010; Fontenla et al. 2011).

Long term variability in both TSI and SSI can potentially lead to climatic variations via changes in Earth's upper atmosphere, global sea temperatures etc. Thus, climatologists try to understand the role of solar variability among other causes which lead to climate changes on the Earth. Therefore, in order to make progress it is imperative that we keep consistent records of solar irradiance measurements systematically, **and this has been challenging as outlined above**. All of the models of TSI and SSI depend on synoptic measurements of the solar magnetic field.

2.4 Chromospheric Indices

Chromospheric indices measure the intensity integrated over specific and narrow wavelength bands in spectral lines that are formed mainly in the chromosphere, and are thus special cases of the SSI discussed above. The most popular spectral line that is used for these measurements is the Ca II K line at 3933.7 Å. This line is very broad, and displays features in its core that vary in strength over the solar cycle. The most prevalent chromospheric index is the 1-Å Ca K emission index (Keil and Worden 1984; Scargle et al. 2013), which is essentially the excess intensity of the central 1 Å of the spectral line as compared to some reference line profile. This index varies in phase with the solar cycle, and is also easy to observe in more distant stars, which makes it useful for comparisons of solar and stellar activity cycles.

Another widely used measure of the level of the solar activity **that is emitted from the chromosphere** is the radio flux measured at a wavelength of 10.7 cm (known as F10.7). This has been systematically recorded since 1947 and clearly shows a correlation with the level of solar activity. Unlike the sunspot number, the F10.7 signal does not drop to zero at solar minimum and the relationship between these two proxies for the solar activity is not linear. Livingston et al. (2012) discuss this relationship and show that it has changed since about 1990 in a manner that is consistent with their measurement that the intense field in the center of dark sunspots has been declining. They use this to argue for the approach of a Grand Minimum.

2.5 Further Activity Proxies

There are other ways of monitoring the solar activity level which are either spectroscopic (for example the core to wing ratio in Mg II at 280 nm or the equivalent width of the He II line at 1083 nm) or involve direct measurement of the strong magnetic field. In addition, the long-term record of solar activity covering thousands of years has been inferred by measuring the relative concentration of certain radioactive isotopes, particularly ^{14}C and ^{10}Be , in ice cores. The production of these isotopes is modulated by the flux of cosmic rays hitting the Earth's atmosphere, and this flux is anticorrelated with the solar activity. Studies of these records suggest that the level of solar activity since the middle of the twentieth century is amongst the highest of the past 10,000 years, and that Maunder minimum-like epochs of suppressed activity of varying durations have occurred repeatedly over that time span (Solanki et al. 2004). It also shows that, during the Maunder minimum, the cyclical change of the solar magnetic field persisted even without apparent sunspots.

The temporal correlation between several activity indices displays hysteresis, as shown by Bachmann and White (1994). This suggests that there are delays between the onset and decline of activity reflected in variables that are sensitive to conditions in various solar layers, such as the corona, chromosphere, photosphere, and interior.

2.6 The response of the oscillations to solar activity

The normal modes of oscillation of the Sun fundamentally depend on the speed of sound in the solar interior. While this is primarily a function of the local temperature and composition, the magnetic field can also be important. This is particularly so in the outer regions of the Sun where the magnetic pressure and the gas pressure are of comparable magnitude. It is therefore to be expected that the properties of solar oscillations change in phase with the levels of solar activity. A key point here is that the examination of the changes in the observed p-mode properties throughout the solar cycle provides information about solar-cycle-related processes that occur beneath the photosphere.

2.6.1 Frequency shifts

Soon after the first detection and identification of the oscillations, people looked for signs of the frequencies being sensitive to the level of solar activity. The earliest such evidence was found in the mid 1980s when it became clear that the frequencies of oscillations in intensity as observed from space using the ACRIM instrument on the Solar Maximum Mission (SMM) satellite varied throughout the solar cycle with the frequencies being largest when the solar activity is at maximum (Woodard and Noyes 1985). The measurement was based on a comparison of the signal near solar maximum in 1980 and near minimum in 1984. This was an important step forward but what was really needed were continuous measurements throughout the cycle to show reversals in the frequency shift when the activity reverses. This was provided about five years later using low-degree data collected with the early phase of the Birmingham Solar Oscillations Network (BiSON). The features of BiSON are discussed later in section 4.3.1. These data followed the activity through the minimum of 1984/5 towards the maximum in about 1990 (Pallé et al. 1989; Elsworth et al. 1990). **Further years of**

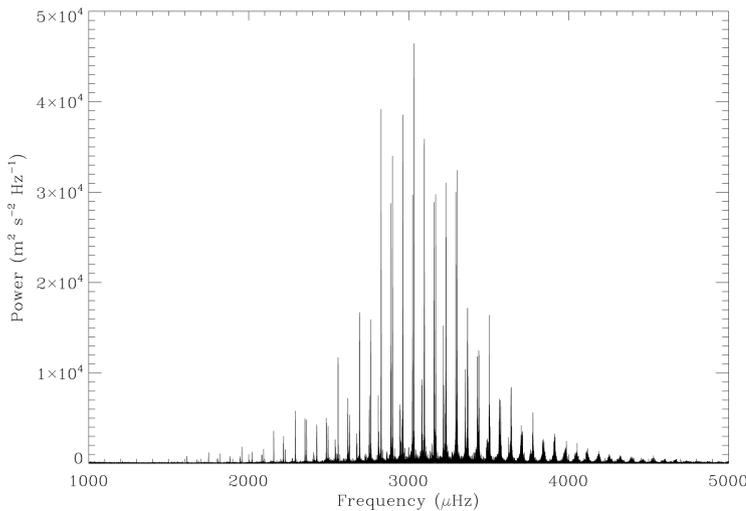


Fig. 2 Typical “Sun-as-a-star” BiSON spectrum of low-degree p-mode solar oscillations.

data, much improved fill and better analysis techniques emphasized the clear relationship between solar activity and the frequencies of the low-degree p-mode oscillations with spherical harmonic degree $\ell < 5$ (Elsworth et al. 1994; Chaplin et al. 2001; Jiménez-Reyes et al. 2003, 2004, 2007; Verner et al. 2004, 2006). For a historical perspective and a discussion about the impact of the treatment of line asymmetry on the determination of the individual frequency shifts see Howe et al. (2015).

Solar-activity related frequency shifts at higher values of ℓ were originally observed at Big Bear Observatory (Libbrecht and Woodard 1990) and have been studied extensively ever since (Howe et al. 1999; Rhodes et al. 2002, 2011; Rabello-Soares et al. 2008; Rabello-Soares 2011; Tripathy et al. 2007, 2010, 2013, 2015; Jain et al. 2000, 2009, 2011, 2012, 2013).

2.6.2 Extracting the frequency shifts from Sun-as-a-star data

BiSON is in a unique position to study the changes in oscillation frequencies that accompany the solar cycle as it has now been collecting data for well over 30 years. The best data start from when the full network was operational in the early 1990s but the older data have unique historical importance.

In order to obtain the shifts in the p-mode frequencies with time the BiSON data must be split into short subsets. However, the longer the time series the more precisely the mode frequencies can be obtained. Therefore, the duration of the subsets must represent a balance between being long enough to accurately and precisely extract mode frequencies and short enough to resolve solar cycle variations.

Commonly chosen lengths of data are 108 d, 182.5 d or 365 d. A typical BiSON spectrum is shown in Figure 2. Each of the peaks represents a different mode of oscillation. Around 3000 μHz the SNR of the oscillations is large and the individual peaks are well resolved. At lower frequencies, the SNR decreases and sets a lower limit on the range of frequencies one can consider. At higher frequencies the modes become more

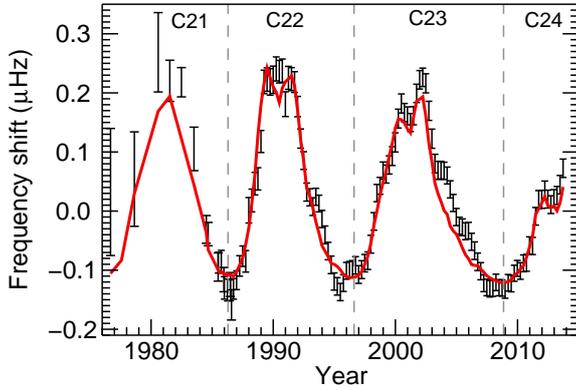


Fig. 3 Average frequency shifts of “Sun-as-a-star” modes with frequencies between 2.4 and 3.5 mHz. The results were obtained from 365 d time series that overlapped by 273.75 d. Also plotted in red is a scaled version of the 10.7 cm flux, a well known proxy for solar activity.

rapidly damped, meaning they have broad profiles in a frequency spectrum (see right panel of Figure 4). At high frequencies, therefore, it is difficult to resolve individual peaks and obtain precise mode frequencies. Thus there is also an upper limit on the range of frequencies that one can consider. Estimates of the mode frequencies are extracted from each subset by fitting a modified series of Lorentzian profile models to the data using a standard **maximum likelihood estimation** (MLE) method, which was applied in the manner described in Fletcher et al. (2009). One could also use Bayesian methods, which give more robust estimates of the parameters. However, it has been shown that the frequencies from MLE are reliable and are much easier to obtain (Howe et al. 2015).

For each investigation we first define a frequency range of interest. For this range, a reference frequency set is chosen by averaging the frequencies in subsets covering a pre-determined time period. While the choice of subsets used to make the reference frequency set determines the absolute values of the frequency shifts, the main results described here are insensitive to the exact choice: A different choice will transpose the frequency shifts to higher or lower values but the variation with time will remain the same. Frequency shifts are then defined as the differences between frequencies given in the reference set and the frequencies of the corresponding modes observed at different epochs (Broomhall et al. 2009). This gives one value of the frequency shift for each epoch and frequency range. Note that it is, in general, not possible to get an instantaneous reading of the frequency shift. They are, by definition, averages.

Figure 3 shows mean frequency shifts of the p modes observed by BiSON (also see Broomhall et al. 2009; Salabert et al. 2009; Fletcher et al. 2010). Here the reference frequency set was created by averaging over all subsets. A scaled version of the 10.7-cm flux is also plotted in Figure 3. The flux has been scaled by fitting a linear relationship between the 10.7-cm flux and the frequency shifts. The 11-year cycle is clearly visible.

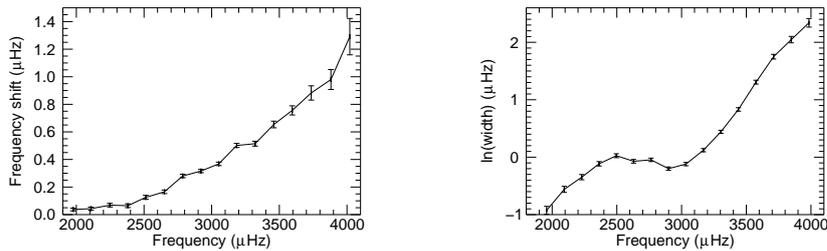


Fig. 4 Left: Maximum-minimum frequency shift as a function of frequency obtained from BiSON data. The average frequencies observed during the maximum of cycle 23 were compared to the frequencies observed during the minimum between cycles 23 and 24. Right: Natural logarithm of typical widths of Lorentzian profiles fitted to mode peaks in a BiSON spectrum, plotted as a function of frequency.

For a low-degree mode at about $3000 \mu\text{Hz}$, the change in frequency between solar maximum and minimum is about $0.4 \mu\text{Hz}$. At higher frequencies, the frequency changes are larger but they become more difficult to detect as the line-widths of the modes themselves also increase. **For frequencies below $3000 \mu\text{Hz}$, the response to the activity is reduced.** Although the mode line width is also decreasing, at some point no cycle-related changes in the mode frequencies are detectable. The data for this are shown in Figure 4.

2.6.3 Physical causes of the frequency shifts

The dependencies of the solar cycle frequency shifts, $\delta\nu_{n,\ell}$, on both angular degree, ℓ , and frequency, $\nu_{n,\ell}$, are well known (see e.g. Libbrecht and Woodard 1990; Elsworth et al. 1994; Chaplin et al. 1998; Howe et al. 1999; Chaplin et al. 2001; Jiménez-Reyes et al. 2001). These dependencies indicate that the observed 11-year signal must be the result of changes in acoustic properties in the few hundred kilometers just beneath the photosphere. This is a region where higher-frequency modes are much more sensitive to conditions than their lower-frequency counterparts because of differences in the location of the upper boundaries of the cavities in which the modes are trapped (Libbrecht and Woodard 1990; Christensen-Dalsgaard and Berthomieu 1991). The detail of this is further discussed in Elsworth et al. (2012) and we briefly summarize it here.

Solar p modes are trapped in cavities in the solar interior. The upper turning point is relatively independent of ℓ (for low and intermediate ℓ) since, near the photosphere, all waves travel in an approximately radial direction. However, the position of the upper turning point depends on frequency. At fixed frequency the lower- ℓ modes penetrate more deeply into the solar interior than do the higher- ℓ modes. Hence, higher-frequency modes are more sensitive to surface perturbations. Libbrecht and Woodard (1990) discuss the origin of the perturbation. If the perturbations were to extend over a significant fraction of the radius, asymptotic theory implies that the fractional mode frequency shift would depend mainly on $\nu_{n,\ell}/\ell$. However, the observed $\delta\nu_{n,\ell}$ is not well described by a function of $\nu_{n,\ell}/\ell$. This implies that the relevant structural changes occur mainly in a thin layer. This thin layer must be near the surface because if it were buried an

oscillatory frequency dependence in $\delta\nu_{n,\ell}$ would be observed (Thompson 1988). Libbrecht and Woodard (1990), therefore, conclude that the oscillations are responding to changes in the strength of the solar magnetic activity near the Sun’s surface. As modes below approximately $1800\ \mu\text{Hz}$ experience almost no solar cycle frequency shift it is reasonable to conclude that the origin of the perturbation is concentrated in a region above the upper turning points of these modes.

Measurements of the strong magnetic field on the surface of the Sun can be made in a manner that allows one to see the distribution of the magnetic field with latitude on the Sun. This is particularly interesting as the low-degree modes also show a latitudinal distribution. Chaplin et al. (2004) explore the variations which were observed in the low-degree solar p-mode frequencies during solar cycles 22 and 23, and their relation to global and spatially decomposed magnetic-field proxies of the surface activity. They regressed the BiSON data sets against the longitudinal magnetic field measurement made by Kitt Peak Observatory. The magnetic data were projected on to different spherical harmonic components in order to search for enhanced correlation between the mode-frequency shifts and the measured fields when the latitudinal dependence of both components was considered. They found some evidence for this. For the higher- ℓ modes this agreement is much more pronounced (see Howe et al. 2002).

None of the activity indices discussed earlier perfectly follow the variation in the frequency of the low-degree, solar p-modes but they all show rough agreement. It is found that in some cycles one particular index is best, but in another cycle the best choice is a different activity index (see Chaplin et al. 2004). In addition, frequency changes over the solar cycle also display hysteresis (Tripathy et al. 2001).

In summary, we have the situation where a variety of surface and solar-atmosphere proxies of solar activity agree with the variations that are seen in the p-mode frequencies. The ultimate goal is to link these phenomena together with some fundamental physics. To take this further, we now look at the periodicities that are observed in the frequency changes and discuss ways that the seat of the variation can be localized.

2.6.4 Two-year and eleven-year signals in frequency variations

Over the past twenty years it has become apparent that significant quasi-periodic variability in activity is also seen on timescales shorter than 11 years, particularly between 1 and 4 years (e.g. Benevolenskaya 1995; Mursula et al. 2003; Valdés-Galicia and Velasco 2008). This same phenomenon is visible in the p-mode frequencies (Broomhall et al. 2009; Fletcher et al. 2010; Broomhall et al. 2010; Simoniello et al. 2012, 2013) and is seen very clearly in Figure 3. The period of this structure is approximately two years and so it is known as the quasi-biennial signal. Fletcher et al. (2010) showed that the signal was visible in both BiSON and GOLF data and Broomhall et al. (2010) demonstrated that the quasi-biennial signal was also evident in Variability of solar IR-radiance and Gravity Oscillations (VIRGO; Fröhlich et al. 1995) data. VIRGO consists of three sun photometers (SPMs), that observe at different wavelengths, namely the blue channel (402 nm), the green channel (500 nm), and the red channel (862 nm). The results are similar for each individual channel. Simoniello et al. (2012) demonstrated that the signal is also present in the resolved GONG data. We can conclude from this that the signal is not a function of making Sun-as-a-star observations from the ground or in velocity. It is likely to be a solar phenomenon.

In order to extract these shorter periodicities, we subtracted a smooth trend from the average total shifts by applying a boxcar filter of width 3 years. This removed the

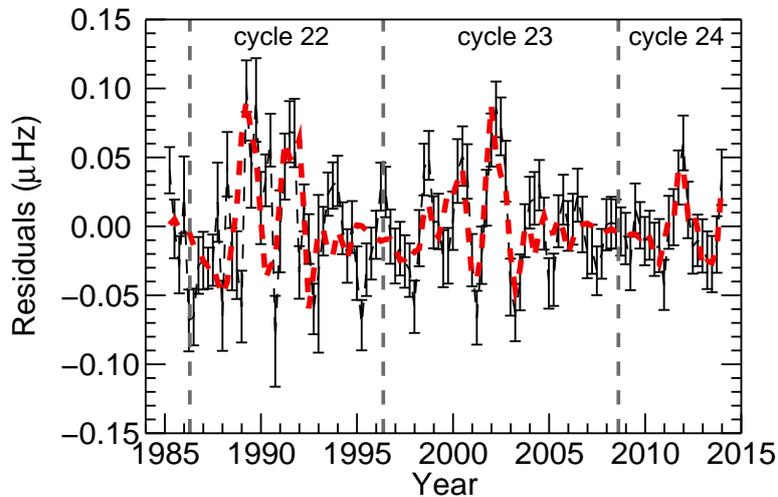


Fig. 5 Rapidly varying component of the oscillation frequency shifts obtained from 182.5-d BiSON data sets that overlap by 91.25 d. The 11-yr component was removed by subtracting a smoothed component (obtained by applying a 3-yr box car smoothing). Plotted in red, for comparison, is a scaled version of the 10.7-cm flux.

dominant 11-year signal of the solar cycle. Note that, although the width of this boxcar is only slightly larger than the periodicity we are examining here, wider filters produce similar results. The resulting residuals, shown in Figure 5, show a periodicity on a timescale of about two years. Comparison with the 10.7-cm flux shows that the signal is consistent with surface and atmospheric measures of solar activity.

Using unresolved data observed during cycle 23 Broomhall et al. (2012) found that the QBO shows some frequency dependence but that this dependence is not as strong as that observed in the 11-year cycle. Simoniello et al. (2013) found similar results with resolved helioseismic data, also observed during cycle 23. Salabert et al. (2015) recently observed a periodicity, longer than the QBO but shorter than the 11-year cycle, in the frequency variations of low-frequency (1.8 to 2.4 mHz) modes during the rising phase of cycle 24 (originating in 2006). This periodicity was not present in the frequency variations observed in higher-frequency modes. However, the amplitude of the QBO in cycle 24 cannot truly be assessed until the next minimum, since the amplitude of the signal itself varies with time and is largest around solar activity maximum.

The envelope of the two-year signal is modulated by the 11-year signal. However there must be some additive component because it is still present when the 11-year signal is at minimum. Furthermore, because it is more visible at lower frequencies than is the 11-year signal, the two-year signal must have its origin in significantly deeper layers (Broomhall et al. 2012), which may be positioned below the upper turning

point of the lowest frequency modes examined (since the depth of a mode's upper turning point increases with decreasing frequency). The upper turning point of modes with frequencies of 1.8 mHz occurs at a depth of approximately 1000 km, whereas the influence of the 11-year cycle is concentrated in the upper few 100 km of the solar interior. Put together, this all points to a phenomenon that is separate from, but nevertheless susceptible to, the influence of the 11-year cycle. This is discussed in more detail in Elsworth et al. (2012) where the results from structure inversions are used to illuminate the discussion.

The activity minimum between cycle 23 and cycle 24 was very unusual in both its duration and its depth. It was also, at the time, unexpected. A closer analysis of the BiSON data shows that there was evidence that could have predicted that something strange was happening. Basu et al. (2012) applied boxcar smoothing to the frequency shifts to remove the influence of the two-year signal and then compared the behavior of the F10.7 activity proxy with the smoothed shifts in three frequency bands. They showed that, although in the two higher frequency bands, the frequency shifts followed the activity proxy, for the low-frequency band this was not the case. It was noted that, for this third band, the frequency shift responded less well to the variations in the activity and the frequencies varied less than expected. This effect started during the declining phase of cycle 23. They interpreted this as evidence for a thinning in the extent of the magnetic layer which influences the mode frequencies. It will be interesting to see if this effect persists into cycle 24.

2.6.5 Variations in mode amplitude, line width, and energy supply rate

In addition to conditions in the interior, the solar acoustic power spectrum also provides information on the physics of the modes themselves over the solar cycle. The key measured parameters are the amplitude A of the modes, their line width in the solar spectrum, Γ , which measures the lifetimes of the modes, and the energy supply rate \dot{E} , which is proportional to $A\Gamma^2$. At low degrees, the change in \dot{E} is small and consistent with a zero change, as found by (e.g. Chaplin et al. 2000; Jiménez-Reyes et al. 2003). Studies of the variations of these parameters for modes with $\ell > \sim 20$ over the cycle show that, as activity increases, A decreases, Γ increases (indicating shorter mode lifetimes), and \dot{E} decreases (Komm et al. 2000b,2000a; Rhodes et al. 2011). These results suggest that the energy that excites the intermediate and high-degree modes is slightly reduced at high activity. Since convective downdrafts are thought to be the main driver of the oscillations, this further suggests that granulation is suppressed as activity increases. This is supported by the study of Komm et al. (2002) where the source of the width and amplitude variations is found to be concentrated in the locations of activity.

3 Solar Interior and Helioseismology

Since the magnetic field and activity cycle must originate from inside the Sun, knowledge of the changes in the dynamics and structure of the solar interior on decadal time scales is vital if we are to understand the physical mechanism of the solar dynamo. This information can only be obtained from long-term helioseismic observations. In this section we briefly review the status of some of these topics.

3.1 Internal dynamics

Information about the changes in the solar rotation rate is obtained from frequency splittings, which are the differences in ν between global modes with the same values of spherical harmonic degree ℓ and radial order n but with values of azimuthal degree m differing by 1. The splittings contain information about solar internal dynamics and departures of the solar shape from a perfect sphere. The dominant source of the splittings is the differential rotation of the Sun as a function of depth and latitude. Solar cycle variations of the splittings are primarily the result of the zonal flow known as the torsional oscillation, which is discussed in Brun et al. (2013). Another source may be a periodic 1.3-year fluctuation in the rotation rate at the base of the convection zone (Howe et al. 2000, 2011), but this is unconfirmed (Antia and Basu 2000). However, there is evidence that the position as well as the transition of the rotation rate across the tachocline, where the internal solar rotation rate changes from differential to rigid, show some temporal variations (Antia and Basu 2011).

A major research area of solar physics concentrates on local helioseismology, where the oscillations are analyzed in a variety of techniques that do not consider the Sun as a global entity but instead focuses on specific localized areas (Gizon and Birch 2005). In terms of long-term solar cycle variations, these techniques have the great advantage that they are not restricted to results that are symmetric across the solar equator. They can thus reveal north-south hemispheric asymmetries in both the zonal and meridional flows (González Hernández et al. 2010; Komm et al. 2014, 2015) that can be correlated with the hemispheric asymmetries in the magnetic field discussed earlier.

3.2 Internal structure

Helioseismic studies of the internal structure focus primarily on inversions for the wave speed, which depends on the temperature, composition, and magnetic field of the internal solar plasma. Unfortunately, it is not possible to reliably separate the effects of these three physical quantities since, unlike for velocity, they do not depend on the propagation direction of the wave. Nonetheless, it is possible to detect changes in the subsurface wave speed over the cycle (Basu and Mandel 2004; Basu et al. 2007, 2013; Baldner and Basu 2008; Baldner et al. 2010). These changes are usually attributed to the surface magnetic field, but they may well have an additional thermal component. **In addition, deeply situated magnetic or thermal variations at the base of the convection zone could explain some of the observed variations (Baldner and Basu 2008).**

4 Observing strategies

4.1 Getting continuous data

In making observations of solar oscillations we must consider the detailed structure of the Sun's acoustic spectrum. The fundamental repeat period of the different radial orders is about $137 \mu\text{Hz}$ and the typical splitting between the $\ell = 0$ and $\ell = 2$ modes is around $10 \mu\text{Hz}$. Great care must be taken to minimize any artifacts in the spectrum that could overlap with the solar features. It is therefore unfortunate that

24-hour diurnal interruptions from the Earth's rotation produce features at multiples of $11.57 \mu\text{Hz}$. Early measurements from single geographical sites were very vulnerable to this problem. The solutions are three fold. One can make the measurements from a suitable orbit in space which has a constant view of the Sun (Scherrer et al. 1995), observe from Antarctica during the Austral summer (Jefferies et al. 1988), or invest in a ground-based network. This latter solution was the one adopted by BiSON and by GONG.

4.2 Advantages and disadvantages for working from Space and from the Ground

Space-based observations have the advantage of higher spatial resolution, image stability and access to high-energy ultra-violet and X-ray wavelength regions. There are numerous space-based solar programs that are currently in operation such as the *Hinode* Solar Optical telescope (SOT), Solar Dynamics Observatory (SDO), Interface Region Imaging Spectrograph (IRIS), Solar TERrestrial RELations Observatory (STEREO), SOLar Heliospheric Observatory (SOHO), and Reuven Ramaty High Energy Solar Spectroscopy Imager (RHESSI). More are planned in the near future including Solar Orbiter, Solar Probe Plus, Aditya, and Solar-C. While satellites provide high-quality observations, they always have a risk of failures that cannot be easily fixed. Further, they tend to have associated high costs of development and operation, no possibility to upgrade, and limited lifetimes. For long-term variability studies of the Sun this can be a disadvantage. One such example is the TSI measurements by various satellites since 1978. Although all data sets show solar cycle variations, they disagree due to differences in sensitivity and calibrations. Therefore, only relative scaling can be applied (assuming one of the TSI series to be correct) to derive a continuous TSI temporal profile. This non-uniformity in data sets makes it difficult to compare, for example, the TSI value during the minima of three solar cycles.

Ground-based observations have potentially unlimited lifetimes, and thorough calibrations can be carried out when instruments are upgraded to keep track of long-term variability of the parameters. Ground-based instruments can use the latest in technology while space-based technologies have to be proven to be space qualified. High rates of data telemetry are easy to achieve on the ground, and ground-based instrumentation can be quite large in size, such as the Daniel K. Inyoub Solar Telescope (DKIST) and European Solar Telescope (EST) projects of 4-m apertures that are in planning now. The biggest challenge for ground-based observations is the atmospheric seeing caused by turbulence. New techniques are being developed to address these challenges, such as adaptive optics (including multi-conjugate adaptive optics for extended field-of-view), active temperature control of the telescope optics and mechanics to control instrument seeing, detectors with low readout noise and high frame rates such as pn-CCD detectors (being tested by IMPRS for fast polarimetry to reduce seeing variations), large aperture etalon development (e.g. the Visible Tunable Filter being developed for the DKIST by the Kiepenheuer-Institut für Sonnenphysik (KIS)), post processing of images to enhance spatial resolution (speckle interferometry) and so on.

4.3 Networks

4.3.1 *BiSON*

The Birmingham Solar-Oscillations Network (BiSON) (Chaplin et al. 1996; Davies et al. 2014) makes Sun-as-a-star (unresolved) Doppler velocity observations, which are sensitive to the p modes with the largest horizontal scales (or the lowest spherical harmonic degrees, ℓ). Consequently, the frequencies measured by BiSON are of the truly global modes of the Sun. These modes travel to the Sun’s core, however, their dwell time at the surface is much longer than at the solar core because the sound speed inside the Sun increases with depth. Therefore, the low- ℓ modes are most sensitive to variations in regions of the interior that are close to the surface and so are able to give a picture of the influence of near-surface activity.

BiSON is a network of autonomous ground-based observatories that are strategically positioned at various longitudes and latitudes in order to provide nearly continuous coverage of the Sun. The network began with just one station and gradually expanded over the course of 17 years, finally becoming a six-site network in 1992. There are four sites in the southern hemisphere and two in the northern hemisphere. The current set of sites is Izaña, Tenerife; Sutherland, South Africa; Carnarvon, Western Australia; Narrabri, New South Wales; Mount Wilson, California and Las Campanas, Chile.

The quality of the early data is poor compared to more recent data because of limited time coverage but is invaluable because it represents an epoch where other observations are sparse. Calculations have shown that 6 sites is the minimum required to give data fills which are above 80% over periods of months and which lack very regular breaks that give rise to strongly periodic features in the spectra (Hill and Newkirk 1985). Mid-latitude sites are chosen because they represent a reasonable compromise between having the Sun high in the sky and typically high insolation levels. The evolution of the BiSON duty cycle is shown in Figure 6 from 1976 to 2009.

4.3.2 *GONG*

The Global Oscillation Network Group (GONG; Harvey et al. 1996) obtains full-disk solar data with a nominal resolution of 1024×1024 pixels at a cadence of one image per minute. GONG is a six-site network located at Big Bear Solar Observatory, California; Mauna Loa Solar Observatory, Hawaii; Learmonth Solar Observatory, Australia; Udiapur Solar Observatory, India; Observatorio del Teide, Spain, and the Cerro Tololo Interamerican Observatory, Chile. These sites were selected after a six-year site survey that measured the transparency of the sky at 15 locations (Hill et al. 1994a,1994b). GONG was deployed in 1995 with a small-format detector that was upgraded to the current camera in 2001 (Harvey et al. 1998). The median daily duty cycle for GONG over its lifetime to date is 91%.

4.3.3 *Other networks*

Three other networks have been deployed for helioseismology, but are no longer operational. The International Research on the Interior of the Sun (IRIS) network operated from 1990 to 2001 with a single-pixel integrated-light resonance cell like that of BiSON but operating with a sodium vapor (Fossat 1988, 2013). IRIS had six stations

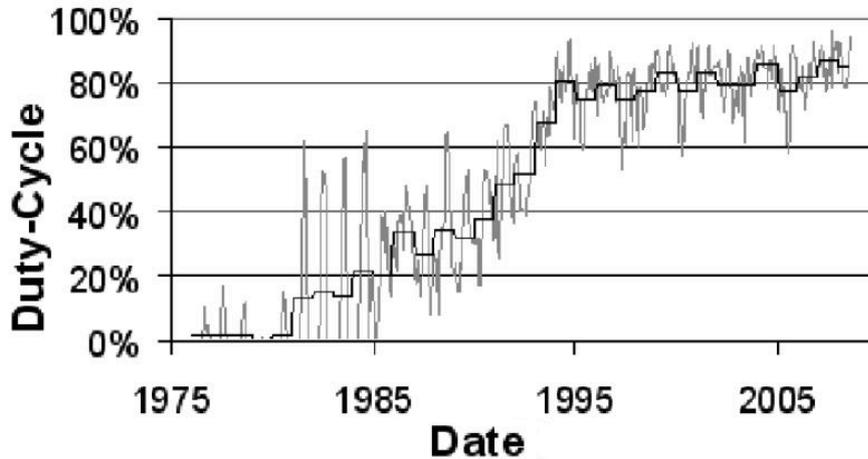


Fig. 6 Evolution of the BiSON duty cycle 1976-2009 in 4-week blocks. The staircase black lines are yearly averages. Adapted from Allison et al. (2009).

at Kumbel, Uzbekistan; La Silla, Chile; Stanford, California; Oukaimeden, Morocco; Izaña, Tenerife; and Narrabri, Australia and had a typical duty cycle of 80%. The Tawain Oscillation Network (TON) used a 1024×1024 camera to obtain full-disk solar intensity images in the Ca K spectral line from 1994 to 2002 with three sites at Teide Observatory (Tenerife), Huairou Solar Observing Station (near Beijing), and Big Bear Solar Observatory (California) (Chou et al. 1995). Finally, the Experiment for Coordinated Helioseismic Observations (ECHO) network was a more developed version of the LOWL instrument (Tomczyk et al. 1993, 1995), which consisted of a magneto-optical filter using sodium. ECHO was composed of two sites, at Teide Observatory and Mauna Loa, and operated briefly in the mid 1990s.

4.4 Space observations

Purposely designed continuous helioseismic observations from space have been obtained since 1995. In that year, the Solar and Heliospheric Observatory (SOHO) was launched carrying, among other instruments, three devices with the primary goal of probing the solar interior (Domingo et al. 1995). The Global Oscillations at Low Frequency (GOLF) instrument (Gabriel et al. 1995) is an integrated-light sodium vapor resonance cell in a longitudinal magnetic field that could sample the two wings of the sodium absorption line before one of the modulators failed. The Variability of solar IRradiance and Gravity Oscillations (VIRGO) experiment is a three-channel photometer with a 12-pixel low-resolution imager (Fröhlich et al. 1995). The final SOHO instrument is the Michelson Doppler Imager (MDI), a full-disk imager of 1024×1024 pixels to measure the surface Doppler shift and magnetic field (Scherrer et al. 1995). However, the orbit of SOHO at the L_1 Lagrangian point restricted the telemetry bandwidth such that MDI was only able to return full-disk measurements for two or three months per year. During the remaining time, the MDI images were binned down on board SOHO to decrease the spatial resolution and fit within the allowed telemetry rate.

SOHO was **supplemented** by the Solar Dynamics Observatory (SDO) mission, which launched in 2010. SDO carries the Helioseismic and Magnetic Imager (HMI), which obtains full disk observations with a 4096×4096 pixel detector that records an image every 45 s. Since SDO is in a geostationary orbit, it can return all of the data obtained by HMI and the other instrumentation. SDO is currently the primary source of space-based helioseismology data. **SOHO continues to return data from a number of instruments, including GOLF and VIRGO.**

4.5 Instrumentation

Helioseismology requires that the entire solar disk be sampled simultaneously in order to remove the phase differences in the waves that would result from scanning parts of the Sun at different times. This essentially eliminates spectrograph-based instrumentation as options for helioseismology observations. Devices that can sample the disk as a unit are filters, Fabry-Perot etalons, Michelson interferometers, magneto-optical filters, and single-pixel integrated light instruments such as resonance filters.

The BiSON and IRIS instruments use single-pixel integrated light resonance filters, which provide an accurate and stable frequency reference for Doppler shift velocity measurements. In these devices, the incoming solar light is scattered from a vapor composed of an element with a resonant atomic line. Two lines are generally used in helioseismology – the 769.9-nm line of potassium, used by BiSON, and the 589.6-nm sodium line used by IRIS. The potassium line is relatively free from interference from telluric lines and solar blends, and also is at a wavelength at which photodetectors are efficient. Sodium vaporizes at a lower temperature than potassium making it easier to work with. At the heart of these instruments is a small glass cell, containing potassium or sodium vapor permeated by a longitudinal magnetic field. The magnetic field causes the laboratory line to be split into two Zeeman components thus allowing for measurements to be made of the steepest part of the solar absorption line of potassium or sodium. See Brookes et al. (1976) and Brookes et al. (1978) for a detailed discussion of the BiSON device. The details of the instrumentation have evolved over the years to take account of improvements in electronics – particularly with the advent of microcontrollers. The IRIS instrument is very similar to the BiSON device except for replacing the potassium vapor with that of sodium (Grec et al. 1991). The GOLF instrument on SOHO is also a sodium resonance filter.

Note that there are other important consequences to the choice of spectral line for helioseismology. In particular, spectral lines are formed at different heights in the solar atmosphere, and they have different sensitivities to magnetic fields. Thus using different spectral lines can reveal how waves propagate as a function of height in the solar atmosphere, and how they interact with the magnetic fields they encounter.

Atomic resonance cells are also at the heart of magneto-optical filters, but here the transmitted rather than the scattered light is observed by placing the detector along instead of perpendicular to the magnetic field (Cimino et al. 1968; Agnelli et al. 1975; Cacciani and Fofi 1978; Lin and Kuhn 1989). In this case an image can be formed and spatially resolved, as in ECHO (Tomczyk et al. 1993) and the Magneto-Optical filters at Two Heights (MOTH) instrument (Cacciani et al. 2003; Finsterle et al. 2004a,2004b), which exploits the separation of the height of formation of the potassium and sodium lines to study wave propagation in the solar atmosphere.

The GONG instrument (Harvey et al. 1996) is based on the Fourier Tachometer concept (Beckers and Brown 2013) and uses a polarizing Michelson interferometer and a rotating half-wave plate to sweep and interference fringe across the Ni I 676.8-nm spectral line. The MDI and HMI instruments also use Michelson interferometers, but in combination to essentially create a tunable narrow-band filter. MDI used the same Ni I 676.8-nm line as GONG, while HMI uses the Fe I 617.3-nm line. In the future, Fabry-Perot etalons may be the instrument of choice for multi-wavelength multi-height observations, as described in the section on Future Directions.

5 Future directions

There have been a number of recent articles about future directions for helioseismology (Hill 2009; Hill et al. 2013; Toomre and Thompson 2015), focusing mainly on multi-height and multi-viewpoint observations. The main path towards multi-viewpoint observations is the Solar Orbiter mission, covered in the article by Löptien et al. (2014). Here we cover some other possible future directions.

5.1 New Observational Techniques - Multi-wavelength observations

Multi-wavelength observations can be thought of as coming in two flavors: those with a small separation in wavelength between observations (different points across a single spectral line) and those with a large separation (different spectral lines). As a spectral line is formed over a range of heights in the solar atmosphere and different lines have different ranges, multi-wavelength observations are generally equivalent to multi-height observations.

Observing the Doppler velocity and intensity variations simultaneously at different heights in the solar atmosphere offers some important advantages over traditional single height observations and has been touted as a future direction for helioseismology (Hill 2009; Roth 2011). The first advantage is that multi-height observations provide a means to improve the accuracy and precision of our seismic mapping of the solar interior, in particular, in the vicinity of magnetic regions (Hill 2009). The reduction in systematic errors (i.e. improved accuracy) comes through two paths. The first is a better understanding of the physics of the oscillation modes such as the effects of magnetic field on the p modes, or the origin of the correlated component of stochastic excitation, etc. (e.g. Mitra-Kraev et al. 2008; Kosovichev et al. 2009; Cally 2009; Baldner and Schou 2012; Moradi and Cally 2013; Hansen and Cally 2014). The other path is to enforce, during the data analysis, the prior knowledge that the morphology and dynamics of the interior should not depend on the spectral line used for the observation. Whereas the former has received some attention (Jain et al. 2006b, 2006a, 2008), the latter has yet to be developed. The gain in precision comes by leveraging, during the data analysis, the fact that the coherence of the solar background signal decreases with height in the solar atmosphere (Lefebvre et al. 2008; Espagnet et al. 1995) to improve the spectral SNR (García et al. 2004). We note this gain only applies to oscillation modes with lifetimes shorter than the observing time (Appourchaux et al. 2007). Improving the SNR for modes with lifetimes that are longer than the observing time is significantly more difficult as the challenge lies in separating the oscillation signal from the convective background signal without loss of spectral resolution (which

is needed for detection due to the small line widths and amplitudes of the modes): this separation requires the measurement of several independent realizations of the solar noise. Although different solar noise realizations can be obtained during the observing period by looking at different spatial areas on the Sun (García et al. 2009), the resulting degradation in the spatial window function causes any oscillation signal to be dispersed across a number of sidebands, thus most likely negating any gain in SNR from the reduction of the solar noise.

A second advantage of multi-height observations is that they allow studies of the properties of the magneto-acoustic gravity (MAG) waves that are omnipresent in the solar atmosphere. This opens the door for seismic mapping of the atmosphere (Finsterle et al. 2004a,2004b; Nagashima et al. 2009) and also allows us to ascertain the role the MAG waves play in the transport of convective energy through the atmosphere (Jefferies et al. 2006; Straus et al. 2008). Both studies require knowledge of the effective heights for each of the observations. This is readily obtained from the data via the gradient of the phase difference signal above 5 mHz in the velocity-velocity cross spectrum (Fleck and Deubner 1989). There is one small caveat, however, the heights obtained in this manner are with respect to some fiducial height (i.e. spectral line) and are not absolute. One area where multi-height observations offer significant potential to improve our understanding of the dynamics of the solar atmosphere is the study of internal (atmospheric) gravity waves (AGWs). These waves, which can transport energy and momentum over large distances and interact with large-scale flows (Mihalas and Toomre 1981), have received little attention up to now due to the difficulties associated with observing them. However, multi-height observations acquired with high-spatial resolution could enable in-depth studies of AGWs using correlation methods similar to those used in time-distance seismology of the solar interior (e.g., Figure 7).

On a related matter, we note that recent multi-height observations acquired with SDO/HMI and MOTH (Finsterle et al. 2004b) indicate the presence of traveling waves that have the signature of internal gravity waves (opposite group and phase velocities) at low-spatial frequencies below and between the p-mode ridges. The origin and nature of these “anomalous” waves, so-called as they are unexpected by theory, is a mystery (see Figure 8). However, it is clear that there is a likely interaction with the p modes that needs to be understood.

Currently, the majority of multi-height helioseismic studies are performed using a mixture of velocity and intensity data from disparate instruments. However, there is a price to pay for mixing observables, it complicates the interpretation of any results. Ideally, at this stage in the evolution of multi-wavelength seismology, measurements should be in Doppler velocity: the velocity spectrum has a lower level of solar noise than the spectrum of intensity measurements (Harvey 1985), which is important for the detection of the low-frequency p (and g) modes that probe the deep interior, and is generally easier to interpret. Moreover, the measurements should be made with the same (or similar) instrument(s) to minimize systematic errors.

Some first steps in this direction have already been taken. The next generation MOTH instruments use magneto-optical filters, which inherently have high zero-point wavelength stability, to spatially resolve the full-solar disk with 4-arcsec resolution simultaneously in velocity, intensity and line-of-sight magnetic field using the Na (589 nm), K (770nm), Ca (422 nm) and He (1083 nm) solar spectral lines. The HELioseismic Large Region Interferometric DEvice (HELLRIDE; Staiger 2011)) makes use of a Fabry-Perot based 2D spectrograph combined with a fast pre-filter exchange matrix

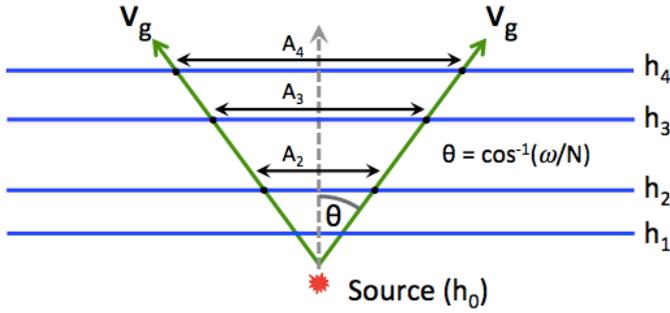


Fig. 7 This cartoon shows a cross-correlation analysis method for tracking gravity waves. The first step is to fix the radius of the annulus A_i in the data for height h_i . The next step is to frequency filter the data to admit waves in a narrow range of frequencies around ω . For gravity waves this then sets the propagation angle θ and the source height h_0 if the waves are to pass through the annulus (as gravity waves obey the relation $\omega = N \cos \theta$ where N is the Brunt-Vasaila frequency). Selecting the frequency therefore selects the radius of the second annulus for the cross-correlation, A_{i+1} . The cross-correlation between the two annuli A_i and A_{i+1} are then computed as the frequency (and thus θ and the radius of A_{i+1}) is varied. The detection of a gravity wave passing through A_i is shown as a maximum in the cross-correlation function versus frequency data. The whole analysis can be repeated for a range of different radii of A_i to build up signal-to-noise. We can gain additional confidence in the wave characterization by incorporating data from additional heights into the analysis. A plot of frequency versus $\cos \theta$ will show a linear trend if we are observing gravity waves. We note that the cross-correlation functions corresponding to gravity wave frequencies will contain information on the phase and group travel times of the waves between the observing heights (c.f. Finsterle et al. (2004b)).

that allows scanning through a chosen set of spectral lines in relatively short time (approximately 2s for up to 50 scan steps in wavelength). In contrast, spatially unresolved multi-wavelength velocity measurements have been implemented using both the multiple points across a spectral line and the multiple spectral lines methods. The former approach is used by the prototype next generation GOLF instrument, which observes at multiple wavelengths across the sodium D lines. The Stellar Oscillations Network Group recently demonstrated the latter approach using an Echelle spectrograph to observe global solar oscillations with extremely low noise by monitoring the scattered daylight signal (Pallé et al. 2013). An interesting possibility for the future is a high-stability, fiber-fed, cross-dispersed Echelle spectrometer that resolves the full solar disk with high-spectral but low-spatial resolution: the wavelength stability coming through the use of a molecular magneto-optical filter (e.g., iodine).

5.2 New Observational Techniques - High-resolution, ground-based, observations

For the last twenty years helioseismology has been supported by experiments onboard a number of space missions (e.g., SOHO, SDO, *Hinode*). The likelihood of another long-term space-based helioseismology experiment in the near future, however, is small. The immediate future for new instrument concepts lies in ground-based experiments.

Ground-based observations of the Sun are always blurred due to the transmission of the solar signal through the Earth's turbulent atmosphere. The amount of blurring depends on the strength of the turbulence that in turn depends on the size of the

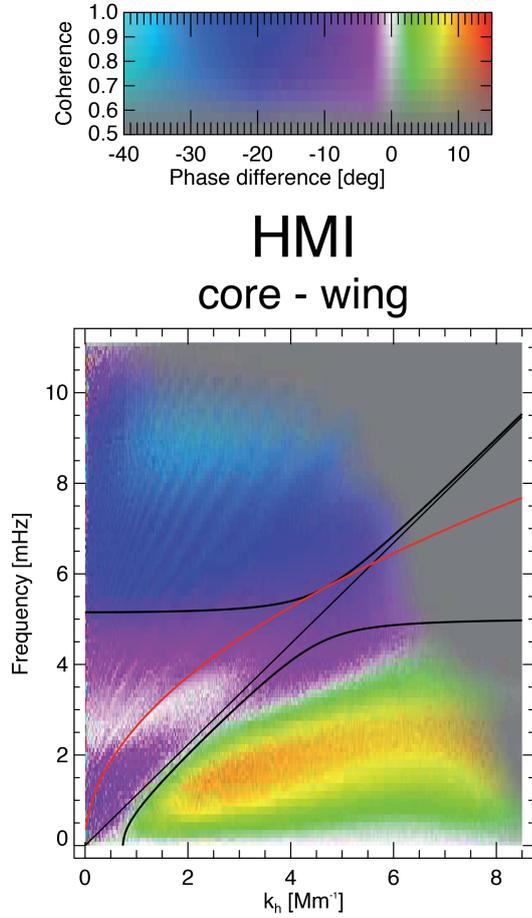


Fig. 8 The $k_h - \omega$ velocity-velocity phase difference diagrams for the HMI core-wing data (courtesy of Bernhard Fleck). The solid black lines indicate the propagation boundary curves for acoustic waves (top) and gravity waves (bottom). The former is a lower boundary the latter is an upper boundary. The diagonal black line represents the Lamb frequency (middle). The red line indicates the fundamental mode. The region of negative phase difference above the Lamb line, below the acoustic cut-off frequency and between the p-mode ridges indicates the presence of “anomalous” waves.

instrument aperture (D) and the coherence length of the atmosphere (r_0) during the observations: at a good solar site $r_0 \approx 10$ cm for an observing wavelength λ of 500 nm. This is commensurate with the typical aperture size of current helioseismology instruments and allows for long integration times (10s of seconds) without significant loss of resolution: $r_0 \approx D$ and the seeing-limited resolution ($1.22\lambda/r_0$) is close to the diffraction limited resolution ($1.22\lambda/D$). However, this will not be the case for future

large aperture solar telescopes, such as the ATST, observing at visible wavelengths. Here the turbulence strength is large ($D/r_0 \gg 1$) and the high-order adaptive optics systems that will be used with such telescopes will only partially mitigate the image blur and the resulting spatial resolution will be severely compromised. Additional methods are needed if the full resolution of the telescope is to be preserved so that we can study oscillations on the finest spatial scales.

Recent research into methods for high-resolution imaging through strong atmospheric turbulence has shown that high-quality imagery can be obtained by improving the synergy between the image acquisition and image restoration processes (Jefferies et al. 2013b) by arranging to observe the object of interest in a way that facilitates accurate estimation of both the atmospheric wave-front phase and the low-spatial frequencies of the object. One way to achieve this is to use high-cadence imaging and dual channel aperture diversity. Here the input light is split into two channels, each of which divides the full aperture into a number of sub-apertures. In one channel the aperture is divided into small rectangular patches using a micro-lens array, while in the other it is divided into concentric annuli. The signal from each sub-aperture is imaged separately onto a camera: the micro-lens data at a cadence that is shorter than the coherence time for the atmosphere, the annular data at the same cadence or less. Only the images from the largest annular sub-aperture contain spatial frequencies out to the diffraction limit of the telescope. All the other sub-aperture configurations yield imagery with lower spatial frequency content. The imagery from the micro-lens array is simply the data that are typically acquired using a correlating Shack-Hartmann wave-front sensor set up for solar adaptive optics. By taking advantage of the temporal behavior of the atmospheric wave front over short time scales (tens of milliseconds; Jefferies and Hart 2011) the micro-lens imagery can be post-processed to provide accurate estimation of the wave front phases at spatial scales smaller than the separation between micro-lenses (Jefferies et al. 2013a). The annular imagery and the micro-lens imagery both contribute to high-accuracy estimation of the low-spatial frequency of the target object during the restoration process. This, in turn, enables high-quality estimation of the high-spatial frequencies of the object (Jefferies et al. 2013b).

5.3 A new network – SPRING

The proposal to design and build the next generation of synoptic observing instruments is currently underway (Hill et al. 2013). The Solar Physics Research Integrated Network Group (SPRING) project, funded as a Joint Research Activity within the High-Resolution Solar Physics Network (Solarnet) by the European Union for a design study, is being currently led by KIS Freiburg. The scientific goal of SPRING is three fold. (i) To provide high quality context images of the full Sun in multiple wavelengths as a support for future generation of high resolution solar telescopes such as the DKIST and the EST. These large-aperture telescopes will only observe a small portion of the Sun (a few arcmin², or less than 5% of the solar disk area) with high angular resolution, and therefore will require context images of the full Sun at decent resolution (1 arcsec) or better, at a high cadence. Here many spectral bands will be chosen to have an overlap with existing synoptic full disk images of the Sun such as Ca K, H- α imaging etc. (ii) To replace aging ground-based helioseismology instruments such as GONG with a next generation instrument capable of multi-wavelength (multi-height) velocity measurements, and operating for another twenty years or more. (iii) Finally, to enhance

space weather prediction capability by making the first ever ground-based network of full-disk vector magnetographs, capable of measuring photospheric and chromospheric magnetic field vector at a cadence of few tens of minutes.

The requirement for the SPRING instrument to obtain spectral and spectropolarimetric imaging of the full disk in multiple lines puts constraints on its design. Instruments based on Michelson interferometers are optimized for a single spectral line while the design of MOTH has limited wavelength bands that can be observed. The measurement of velocity maps as well as magnetic maps of the full disk of the Sun at a cadence of one minute or better eliminates slit scanning instruments such as SOLIS, which takes about 20 minutes to complete a scan of the full solar disk in one spectral line. Even with multiple fibres and multi-slit approaches the measurement could be too cumbersome for the desired spatial resolution of about 1 arc-sec (0.5 arc-sec pixel). This leaves us with a filter-based spectro-polarimeter approach. The choice of Fabry-Perot (FP) etalons has proved to be successful for imaging spectropolarimetry of the Sun. Many designs exist such as the tandem telecentric design TESOS, the tandem collimated designs TIP, IBIS, SVM etc. The stability of the FP is an issue and for that good calibration procedures need to be devised. However, the versatility of the FP systems, rapid tunability and large wavelength range of operation, are definite advantages.

An instrument designed to obtain both vector magnetic field and high-cadence Doppler velocity measurements must necessarily compromise some aspects of the observations – either a lower signal-to-noise in the vector magnetograms, or slower cadence of the Dopplergrams. Thus one design goal of SPRING is to provide a platform that can accommodate multiple instruments that can be tailored for different scientific goals. This would allow different sets of instruments to be installed at different sites, as well as provide flexibility in funding and scheduling profiles.

5.4 Challenges of making observations of long-term changes

We have shown that there is evidence that the near-surface but invisible layers of the Sun are changing over several timescales. To draw these conclusions required data that were available over several decades. In spite of this, there are still unanswered questions and the need for even longer data sets. We know that the underlying Hale solar activity cycle actually covers 22 years rather than the 11 years on which we see the sunspot number vary. We have not yet had consistent helioseismic measurements over a single Hale cycle. The effects that we need to measure are not large and require consistency in the data over very long periods of time. We must be confident that observed variations are genuinely due to the Sun and not a consequence of a change in the observing methods. A key attribute of any robust detection is that there are multiple, independent observations of it. We have already seen this in the case of the quasi-biennial signal. On the other hand, it is important that instrumentation changes to take advantage of new improvements in technology. These changes should be arranged so that there are always periods of overlap for inter-calibration studies. We absolutely must have long-term consistent solar observations if we are ever going to understand the solar activity that underlies the potentially harmful effects of space weather.

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