Observational Astrophysics
25. Asteroseismology

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1 Introduction

Asteroseismology is the study of the internal structure of stars by means of their oscillations. Asteroseismology is not an observing technique by itself. You might then be wondering why did I decide to include separated notes on asterosesimology in this course about observational astrophysics. Studies of asteroseismology can make use of both photometry and spectroscopy. Photometric data are used for measuring the variability in the stellar flux and spectroscopic data for measuring velocity variations caused by motions on the stellar surface. There are two interesting points that motivate a separated look at instruments and missions for asteroseismology. The solutions for photometry and spectroscopy can be used in somewhat different ways, as the goal is not to record an image or spectrum, but to make precise measurements of flux variability or Doppler shifts. The other, is that these goals provide an important motivation for improving the precision with which such measurements can be done (these goals are also shared by exoplanet searches). For asteroseismic applications, one is interested to push photometry to the μmag precision and radial velocities to the cm s^{-1} level. This need for higher and higher precision of course has an impact on instrument development. So what we will discuss here is what the instruments and missions need to take into account for the data to be measured with the precision required by asteroseismology. We will not discuss the theoretical aspects of asteroseismology neither the frequency analysis techniques used to extract information from the data.

2 Read these texts

If you are interested on a general introduction to asteroseismology, please have a look at Chapter 1 of the book "Asteroseismology" by Aerts et al. (2010)[1]. For the instrumentation needs of asteroseismology, please read Chapter 4 of the same book.

[1] https://link.springer.com/book/10.1007/978-1-4020-5803-5

3 Summary of concepts

- The oscillations compress and expand the stellar photosphere[2]. When compressed, the photosphere warms up. When expanding, the photosphere cools down. This is reflected on fluctuations in the stellar flux, which is what one tries to detect using photometry. At the same time, these effects cause motions of the stellar photosphere, which induces a Doppler shift on the spectral lines. Those shifts are what one tries to measure with spectroscopy.

- Such variations are, however, very small. We can be looking at changes of the order of 10^{-3} K which cause shifts of about 15 cm s^{-1} (5×10^{-6} Å at 1μm) and about 3×10^{-6} in brightness variation.

- Note here that what is important for asteroseismic measurements is their precision, not their accuracy. One is not concerned with what is the absolute value of the magnitudes, but what is the amplitude of their variations.

- And because these amplitude are very small, the instrumentation needs to be precise and stable, and the measurements need to reach high signal-to-noise ratio.

- An important concept to have in mind when performing and analysing asteroseismologic data is the duty cycle of the observations. The duty cycle is a measure of the fraction of time that is spent observing a target. The cycle will be a complex function of several factors, including the day-night cycle, weather variations, telescope schedule, technical downtime, etc. One should be aware that time gaps in data might introduce confusion in the determination and interpretation of the pulsations frequencies. The day-night cycle, for example, introduces a time function of something between 8-12h which introduces a frequency of 11.57 μHz in the spectral analysis.

- To avoid such problems, one might send instruments to space (although, of course, that is expensive and has its own technical challenges) or build ground-based networks to attempt continuous observations, such as GONG (Global Oscillation Network Group, Harvey et al. 1996)[3] or BiSON (Birmingham Solar Oscillations Network, Chaplin et al. 1996)[4].

- Without going into the theoretical details that explain the numbers (see Appourchaux & Grundahl 2013, and references therein for those), there are three factors to be taken into account for designing the instruments for asteroseismology: i) the sampling time of the time series which is motivated to the cut-off of the frequencies in the stars that should be observed (something around 49s in a 0.8 $M_\odot$ star used as example by Appourchaux & Grundahl); ii) the acceptable background noise, which is related to the mode amplitude that should be detected; and iii) the observation duration, which is related to the lifetime of the mode. Modes at the low frequency end have long lifetimes that can require observations at the 1 year duration to be resolved.

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[2] The photosphere is broadly defined as the layer from which optical radiation can escape from the star. The photosphere is one of the regions of the stellar atmosphere (which also includes the chromosphere and the corona).

[3] A network of six stations located around the Earth to obtain nearly continuous observations of the Sun. See https://ui.adsabs.harvard.edu/abs/1996Sci...272.1284H/abstract for the paper and https://gong.nso.edu/ for the web page of the project.

[4] Another global network of six ground-based telescopes monitoring the Sun. See https://ui.adsabs.harvard.edu/abs/1996SoPh..168....1C/abstract for the paper and https://www.birmingham.ac.uk/research/activity/physics/astronomy/solar-and-stellar/helioseismology/bison/index.aspx for the project web page.

- The fact that the disk of most stars is not resolved, and therefore integrated light only is measured, does filter out modes of higher orders (Dziembowski 1977).

- The BiSON instruments measure Doppler shifts in the potassium Fraunhofer line at 770 nm (averaged over the whole disc) with respect to the same line created by a heated potassium vapour cell subjected to a magnetic field (see about the GOLF instrument below for a description of the technique).

- The GONG instrument uses a different approach, called "phase-shift interferometry" or also "Fourier tachometry" (Harvey & GONG Instrument Team 1995; Harvey & GONG Team 1998)[5]. It measures the line-of-sight Doppler shift of the Ni I line at 676.8 nm. The line is isolated with a hybrid filter of 1 Å passband that combines a two-cavity interference filter and three birefringent elements (a Lyot filter)[6]. The Michelson interferometer uses a polarizing beam splitter with mirrors in the two arms. When rotating the analyzer, the presence of the spectral line causes modulation. The mean signal value is a measure of the intensity of the line. The phase of the modulation is a measure of the Doppler shift.

- The GOLF instrument (Global Oscillations at Low Frequency, Gabriel et al. 1995)[7], on-boad of the SOHO (Solar and Heliospheric Observatory Domingo et al. 1995)[8] mission, measures the Doppler shift of the Na D Fraunhöfer doublet in integrated solar light (D1 at 589.6 nm and D2 at 589.0 nm). The measurement is made in comparison to sodium lines from a vapour cell which are split into their Zeeman components.

- The way the GOLF instrument makes the measurement is the following. First, there is a filter in the path of the solar light, which selects a narrow wavelength range around the Na line. The Na D line has about 500 mÅ of FWHM. A first lens focus the light and a second lens creates a collimated beam. This beams then goes through the sodium vapour absorption cell. The thermal properties of the vapour result in an absorption line of about 25 mÅ. The cell is actually subject to a magnetic field which can split the absorption into two Zeeman components separated by 108 mÅ. The photons being absorbed by the sodium vapour come only from the wings of the solar Na line. If there is zero line of sight velocity, the two Zeeman components produce absorption lines of the same intensity, given that they are positioned symmetrically with respect to the center of the Na line (which has symmetric wings). If the line of sight velocity is not zero, then one of the Zeeman components will produce stronger absorption in comparison to the other (the lines are no longer positioned at symmetric places at the wings, so one has more photons available for absorption in comparison to the other). The difference in intensity between the two lines is proportional to the velocity (see Fig. 2).

- How is that difference in the two absorption lines measured? Using the polarization properties of the Zeeman components. After the first lens in the optical path there is a linear polarizer. After the linear polarizer there is a quarter wave plate. So the light that reaches the vapor cell is circularly polarized to one direction. So at that given time, we get one Zeeman component

[5]See https://ui.adsabs.harvard.edu/abs/1995ASPC...76..432H/abstract and https://ui.adsabs.harvard.edu/abs/1998BASI...26..135H/abstract

[6]See Evans (1949) for a discussion. A Lyot filter, named after its inventor, the French astronomer Bernard Lyot, uses a combination of birefringent plates and polarizers. As we discussed before, the phase delay introduced by a birefringent plate is wavelength dependent. So the polarizer is aligned to create a wavelength dependent loss of optical power. For a short biography of Lyot, see https://link.springer.com/referenceworkentry/10.1007/978-0-387-30400-7_878.

[7]https://ui.adsabs.harvard.edu/abs/1995SoPh..162...61G/abstract

[8]https://ui.adsabs.harvard.edu/abs/1995SoPh..162....1D/abstract

only. Of course, absorption of the photons is followed by re-emission, which is symmetric to all directions. A fiber located at 90 degrees with respect to the beam direction collects part of the re-emitted light, sending that light to a photomultiplier detector. To record the second absorption, the orientation of the quarter wave plate is changed, creating circular polarization in the opposite direction, allowing the measurement of photons re-emitted by the second Zeeman component.

- Instead of using just one line, instruments like HARPS (High Accuracy Radial velocity Planet Searcher, Mayor et al. 2003)[9], enable asteroseismic measurements because they are designed for high spectral stability and precise wavelength calibration over a large wavelength range. The biggest disadvantage of spectroscopy with respect to photometry, is that such ultra-stable instruments are usually single object.

- On the other hand, when doing photometry with CCDs, then we can obtain data for several objects at the same time. What limits ground-based photometric observations for asteroseismic purposes is scintillation noise.

- To repeat what we discussed earlier, during the lectures on the effects of the atmosphere, "scintillation is the random variation in the intensity of the arriving light; the effect that causes the twinkling of the stars. Scintillation mainly affects systems of small aperture (including the human eye); for large telescopes the effect is averaged and becomes less important. However, there are areas of research that require high-precision photometry (e.g. exoplanets, asteroseismology) where scintillation can be a worry (see a related discussion in Osborn et al. 2015)[10]." However, for ground based photometry to reach the precision needed for asteroseismology, we would need telescope diameters of the order of 50 m or more (Appourchaux & Grundahl 2013).

- In stars like the Sun, radial velocity measurements can be made with higher signal-to-noise ratio (SNR) when compared to intensity measurements (SNR with respect to the background). It is then possible to detect more modes with spectroscopic data, as exemplified in Figure 1. However, high-resolution spectroscopy is more demanding in terms of photons that can be detected in a certain time interval.

- The alternative to ground-based photometry is of course space-based observations. Besides eliminating the scintillation issue, measurements from space do not suffer from the day-night cycle and targets can be observed for long duration, and a large sky coverage can be achieved.

- The pioneer mission used for asteroseismology was WIRE (Wide field InfraRed Explorer, Hacking et al. 1999)[11]. Originally WIRE was a mission aiming to carry out a four-month infrared survey of the entire sky. However, some flaws in the spacecraft resulted on the premature loss of all its cryogenic cooling. The mission was then re-purposed and its star tracker camera used for the long-term asteroseismic monitoring of bright stars (Buzasi 2000)[12].

- The first real asteroseismic space-based mission that worked and was planned as such, was MOST (Microvariability & Oscillations of STars, Matthews et al. 2000)[13]. MOST was catadioptric telescope with a primary mirror of 173 mm but the aperture stop (at the corrector

[9] https://ui.adsabs.harvard.edu/abs/2003Msngr.114...20M/abstract
[10] https://ui.adsabs.harvard.edu/abs/2015MNRAS.452.1707O/abstract
[11] https://ui.adsabs.harvard.edu/abs/1999ASPC..177..409H/abstract
[12] https://ui.adsabs.harvard.edu/abs/2000mons.proc....9B/abstract
[13] https://ui.adsabs.harvard.edu/abs/2000ASPC..203...74M/abstract

lens) limited the useful area to 150 mm of diameter. Individual exposure times were of less than 1 minute for proper sampling. The selected detector was a frame-transfer CCD, to minimize the overhead needed for CCD read out. The mission was launched by the Canadian Space Agency in 2003 (see also Rucinski et al. 2003; Walker et al. 2003)[14].

- Previous microsatellites had problems to achieve pointing stability better than 1 or 2 degrees. The requirement for MOST was stability of 25 arcsec (with goal of 10 arcsec; although during commissioning and science operations, updates in the software resulted in MOST achieving 1 arcsec rms precision). Anticipating that the image could wander by $\pm$25 arcsec on the CCD (and knowing the lack of on-board flat fielding), MOST used a design to obtain an extended (defocused) pupil image on the CCD, where the image moves by about 0.1 pixel if the star beam moves by 25 arcsec. An array of 6$\times$6 microlenses is located in front of the science detector. Each microlens focuses an image of the target star into a 54 arcsec diameter field stop and creates a 44 pixel diameter ($\sim$ 1500 pixels) image of the telescope entrance pupil on the CCD. This "superpixel" has greatly increase storage capacity, eliminates the problem of image wander, and decreases the impact of CCD pixel-to-pixel response variations.

- The BRITE constellation (Weiss et al. 2014) is the next example of nano-satellites designed for asteroseismology. This is a set of five (originally planned as six)[15] almost identical[16] nanosats built by a consortium of Institutes from Austria, Canada, and Poland. Each satellite has an instrument that is sensitive either in a red (550 -700 nm) or in a blue (390 – 460 nm) passband. Performing measurements in two wavelength ranges offers a way to recognise independently the pulsation mode geometry for a typical BRITE target (massive stars). The telescope has an aperture of 30 mm and a field of view of 24 degrees in diameter. The focal plane scale is of about 27 arcsec per pixel and the PSF has about 8$\times$8 pixels. The large PSF is inspired by the MOST case, to obtain precise photometry (but not sharp imaging). It was not made bigger, in a compromise to reduce contamination by background stars.

4 Additional reading

If you are interested in the concept of spectrographs that can measure very small radial velocity variations, and on what the limits for such measurements are, have a look at the paper "Absolute Astronomical Accelerometry" by Connes (1985)[17].

For more information on asteroseismology observations from the ground and space see Appourchaux & Grundahl (2013). Above, I did not add discussions about the CoRoT and Kepler satellites. For details on CoRoT see Auvergne et al. (2009, and references therein)[18]. For Kepler, see Koch et al. (2010, and references therein)[19].

[14] https://ui.adsabs.harvard.edu/abs/2003AdSpR..31..371R/abstract and https://ui.adsabs.harvard.edu/abs/2003PASP..115.1023W/abstract

[15] One of the two Canadian satellites failed to properly separate from the upper stage of the rocket, and did not become operational.

[16] The optics o Heweliusz, one of the two Polish satellites, was designed with differences to try to achieve a smoother PSF profile in comparison with the other satellites.

[17] https://ui.adsabs.harvard.edu/abs/1985Ap%26SS.110..211C/abstract

[18] https://ui.adsabs.harvard.edu/abs/2009A%26A...506..411A/abstract

[19] https://ui.adsabs.harvard.edu/abs/2010ApJ...713L..79K/abstract

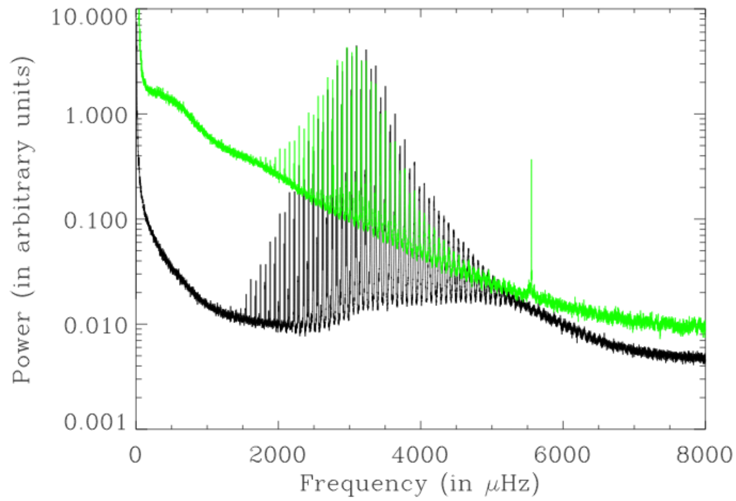

Figure 1: Comparison between power spectra from stellar radial velocity and intensity measurement of the Sun. In black, radial velocities measured by GOLF. In green, intensity measured by the LOI (Luminosity Oscillations Imager) also on-board of SOHO. The difference is related to the granulation background, which is much smaller in solar radial velocity. The SNR obtained is 30 in intensity and about 300 in radial velocity. Credit: Figure 1.4 from Appourchaux & Grundahl (2013).

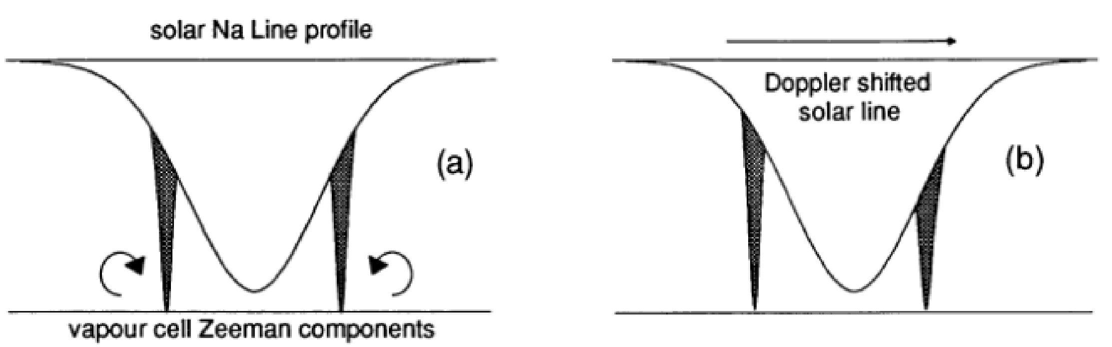

Figure 2: The relation between the solar line and the vapour cell Na lines used in the GOLF line of sight velocity measurement. Credit: Top part of Figure 1 from Gabriel et al. (1995)

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