Pulsations Along Stellar Evolution
VIII LAPIS Summer School
AAA Workshop Series 12, 2021
M. Kraus & A.F. Torres, eds.

Observing Techniques and Missions

M. Kraus[1]

[1]*Astronomical Institute, Czech Academy of Sciences, Fričova 298, 251 65 Ondřejov, Czech Republic*

Abstract. Stellar pulsations can cause variability in the brightness of the star as well as in the shape and radial velocity of photospheric lines. To determine the periods and modes of pulsations, two different but complementary observational techniques are in use: photometric light curves to measure the brightness variations, and spectroscopic time series to analyze the time-dependent motions at the stellar surface. In the first part of this Chapter, both observing techniques and their sources of errors and limitations are presented. In the second part, an overview of the various space and ground-based missions for both photometry and spectroscopy is given. Considering all the currently available and newly planned instruments, the future for research in variable and pulsating stars is bright.

Key words: asteroseismology — stars: oscillations — stars: atmospheres

1. Introduction

Pulsations modify the observable properties of stars. The motion of the surface elements cause variations in both the velocity and the stellar flux. Changes in flux are primarily due to temperature variations[1] and can be traced by photometric monitoring. The velocity variations are detectable in spectroscopic time series.

Most stars pulsate in more than one mode and observations provide only the combined effect of all modes simultaneously. A simple example is shown in Figure 1, in which two sine-curve modes with different period, amplitude and phase superimpose to the total observable signal shown in the right panel. The combined signal can be either a photometric light curve or a radial velocity curve. The aim of any data analysis is to deconvolve the observed signal into the contributions of each individual mode thereby determining their properties, i.e., frequency, amplitude, and mode identification. These are the fundamental sets of data in asteroseismology.

To disentangle the various contributing modes, suitable frequency analysis techniques are needed, which are described in other Chapters of this book. Here, the focus is on another aspect: The quality of the data used for the analysis. Because both photometry and spectroscopy require different instrumentation and

[1]Unless the star undergoes large-amplitude radial pulsations. In this case, photometric observations are also sensitive to the changes in stellar radius.

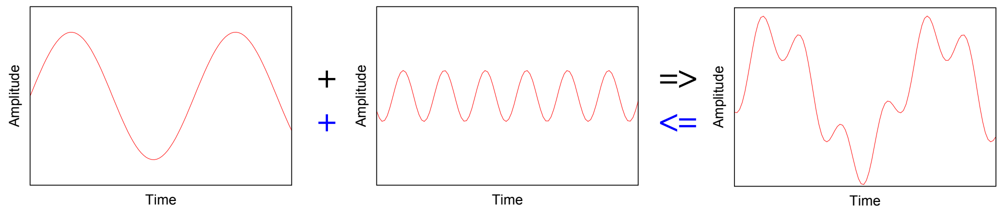

Figure 1. Example of two periods (left and middle panels) with different frequencies, amplitudes, and phases that superimpose (black path) to the total, observable signal (right panel). To extract information about pulsations, the observed signal needs to be deconvolved into the individual contributions (blue path).

observing conditions, these two observing modes are described separately. But before coming to the details, a few general terms need to be introduced and discussed as well, which are relevant for both photometry and spectroscopy[2].

Precision The most relevant parameter in asteroseismology is precision. As we will see later (Section 4), asteroseismology and the search for and characterization of exoplanets post the same demands on instrumentation. Consequently, space missions as well as high-duty-cycle ground-based projects dedicated to one of them, also delivers data for the other scientific branch. And the need for extremely high precision is the ultimate driver for instrumental development to satisfy these requirements.

During the past ~ 50 years the precision in astronomical photometry has increased from ~ 0.01 mag to a few μmag. Equally, the precision in radial velocity determination has increased from $\sim 1\,\mathrm{km\,s^{-1}}$ to 10s of $\mathrm{cm\,s^{-1}}$. In both, an improvement by four orders of magnitude has been achieved. Each observer should make every effort to minimize errors and to improve the precision because only the best data will deliver meaningful results. As a matter of fact, the higher the precision in both photometry and spectroscopy the larger are the sets of identified frequencies.

Duty Cycle Besides precision, the duty-cycle of observations is of great importance. Generally speaking, the duty-cycle is a measure for the fraction of the observing time spent on the variability of the target. Ideally, one would wish for a duty cycle of 100%, because every gap in the observations can lead to confusion in frequency determination. Therefore, space missions are best suited for following the variability of objects. But these have enormous costs. For ground-based observations, the duty-cycle is usually much smaller, typically less than 50% for single site observations for a short time span under good weather conditions.

Time The principal data of asteroseismology are time series, either in photometry (light curve) or in spectroscopy (radial velocity curve). Time series

[2]Parts of this Chapter are based on and follow the excellent textbook of Aerts et al. (2010).

allow us to derive asteroseismic frequencies. For reliable results, the time of the observations must be known to high precision.

In asteroseismology normally the Coordinated Universal Time (UTC) which depends on the Earth's rotation is used as reference system[3]. But the UTC is not a uniform timescale because the length of the day has an annual variation of about a millisecond. Moreover, long term drifts appear as well due to the tidal interaction between the Moon and the Earth. Therefore, a sort of "leap seconds" are introduced to keep UTC in phase with the atomic time. For the most precise studies, however, a constant, "ephemeris time" scale without leap seconds is needed.

Depending on the desired precision, the effects of the Earth's motion about the Sun, or about the solar system barycenter are removed and times are converted to Julian Dates. The term "Julian Date (JD)" was introduced by Joseph Justus Scaliger in 1583 at the time of the Gregorian Calendar reform, who set the starting point to noon Universal Time (UT), 1 January 4713 BCE (before current era). Because of this historically chosen zero point, JD is nowadays a huge number, and astronomers often opt to use the "Modified Julian Date (MJD)", which is defined as JD-2400000.5, which reduces the number and also eliminates the half-day offset. Another convention is the "Heliocentric Julian Date (HJD)", which provides the observation time corrected to the solar center by accounting for the disturbances introduced by the orbit of Jupiter. For many purposes in astronomy and asteroseismology based on single site data this is a sufficiently precise timescale.

Better precision is achieved when the observation time is corrected to the barycenter of the solar system ("Barycentric Julian Date (BJD)"), whereas the ultimate precision is obtained when the leap seconds are subtracted. This is called the "Barycentric Julian Ephemeris Date (BJED)". BJD or BJED should be used for long-term (years) data sets as well as for data collected from multiple sites.

Every astronomer has to make sure that the time base(s) are correct, especially when merging data sets from different sources and sites. An easy time trap when being careless with the use of the time base can lead to the detection of a planet in the signal which is, however, not related to any new discovery, but just due to the Earth's orbit.

2. Photometry

The most widely used tool to study stellar variability is by measuring precisely the changes in stellar intensity. This is done by means of photometry.

The quality of detectors has drastically changed over the past centuries. Observations started with the human eye which can provide visual observations with an accuracy of about 0.05–0.10 mag. Such kind of data are sufficient for the study of large amplitude pulsators, e.g Mira variables.

---

[3]The reader interested in the complexity of the precise time is referred to the website of the U.S. Naval Observatory: https://www.usno.navy.mil/USNO/time

A considerable improvement in precision was achieved with photographic plates. This technology started in the 19^{th} century and dominated the measurement of stellar brightness until the CCD era started in the 1990s and revolutionized astronomical observations. While photographic plates are still occasionally in use, CCDs are nowadays ubiquitously established and will be the predominant method of measuring stellar intensity and its variations in the 21^{st} century.

While ground-based photometry has reached precisions of 10s of μmag, space photometric missions are capable of μmag precision. Considering that the mean magnitude of a star may be known only with an accuracy of a few millimag, the variations in stellar brightness, and hence the amplitudes of the pulsations, can be determined to precisions 1000 times better.

2.1. Sources of Error in Photometry

A number of effects exist that can cause errors to the photometric measurements. Some are due to the limitations of the technical equipment, others are because of restrictions set by the observing conditions.

Photon Statistics The process of photon detection has a normal distribution. Consequently, if we denote with N the number of detected photons, the statistical error is given by $\sqrt{N}$, and the signal-to-noise ratio goes as $S/N = N/\sqrt{N} = \sqrt{N}$. In principle, the noise level can be reduced by improving the signal, i.e., by increasing the integration time. However, very long integrations for a highly reduced error due to photon statistics is not useful in case the signal that is supposed to be detected has short periods. And many pulsating stars, such as pulsating white dwarfs, roAP stars, solar-like oscillators, or sdB stars have rather short variability timescales but are faint objects. For those targets, a large telescope can help in increasing the signal, but it is still limited by photon statistics.

Atmospheric Sources of Errors – Extinction Variations In the absence of clouds, the extinction of the Earth's atmosphere is a further factor influencing and disturbing photometric observations. It measures the amount of starlight that is removed along the line of sight as a function of the airmass. By definition, Earth's atmosphere has an airmass (X) of unit 1 for observations towards the zenith, and increases towards the horizon, because of the longer light path through the atmosphere. If one approximates the atmosphere with a plane-parallel slab model, the airmass for the observation of an object under the zenith distance angle z would simply be $X = \sec(z)$. To account for the curvature of the Earth's atmosphere, a polynomial approximation has been derived and is generally in use (Hardie, 1964),

$$X = \sec(z) - 0.0018167(\sec(z)-1) - 0.002875(\sec(z)-1)^2 - 0.0008083(\sec(z)-1)^3.$$

This relation is precise for zenith angles up to $z = 85°$, which is much closer to the horizon than the angle under which observations are usually carried out. In many cases it is even sufficient to use just the first two terms of this equation. The reduction of the observable starlight due to the airmass is thus just a function of the zenith angle.

However, in reality the sky transparency is always variable in time and in both zenith angle and azimuth. The reason is, that the atmospheric conditions depend not only on the airmass, but also on other parameters, such as temperature and humidity, and on the levels of dust and aerosols in the atmosphere. The timescales of these variations in sky transparency are on the order of 15 min and longer. These transparency variations thus cause an atmospheric noise that depends on frequency and that has higher amplitudes at lower frequencies. It is referred to as "pink" noise. To account for this variable atmospheric extinction, in particular in photometric observations of stars with pulsation periods (much) longer than about 15 min, it is required to observe also non-variable standard stars for comparison.

A cloudless night with no highly variable dust or aerosols in the atmosphere is usually called "photometric".

Atmospheric Sources of Errors – Scintillation With the term scintillation one refers to the variable refraction in the atmosphere, which makes the stars "twinkle" when observed with the naked eye. The Earth's atmosphere consists of many gas cells. Each of them has a radius of 10s of cm, and the gas within each cell has slightly different values of pressure, temperature and humidity thus causing a slight variation in refraction from cell to cell. The light path from the top of the atmosphere down to the telescope hence passes through many cells, and at each of them it changes slightly its direction. Moreover, the positions of these cells are not fixed but depend on and travel with the wind conditions, so that the total amount of light that reaches the detector is variable. In this way, scintillation causes a "white" noise in the signal, i.e. a noise with no frequency dependence. It is thus the dominant source of error in a photometric night for periods shorter than the 15 min limit set by the atmospheric extinction.

The noise caused by scintillation follows also (as photon statistics) a normal distribution, because the light simultaneously passes through many independent cells, and its level drops with the square root of the number of gas cells along the light path. As the number of scintillation cells increases with increasing telescope aperture, the amount of noise decreases. Big telescopes are therefore better suited for observations of pulsating stars with scintillation as the limiting noise source.

Instrumental Sources of Noise The technical equipment used for photometric observations has also sources of errors. Some are periodic, others random.

Every CCD has pixel-to-pixel sensitivity variations. For the high-quality CCDs that are nowadays in use these variations can still be on the order of 1%, which is too high to be ignorable. Other sources of CCD noise are dark currents, bias, and read-out noise. They can be accounted for by collecting additional calibration images along with the science frames.

- *Bias images.* These have zero second exposures. They are taken to remove any internal bias structure across the chip such as the amount of counts accumulated during the reading out of the CCD.

- *Flat-field images.* Flats contain the information about the pixel-to-pixel variation. They are obtained by illumination of the entire CCD with a constant light source.

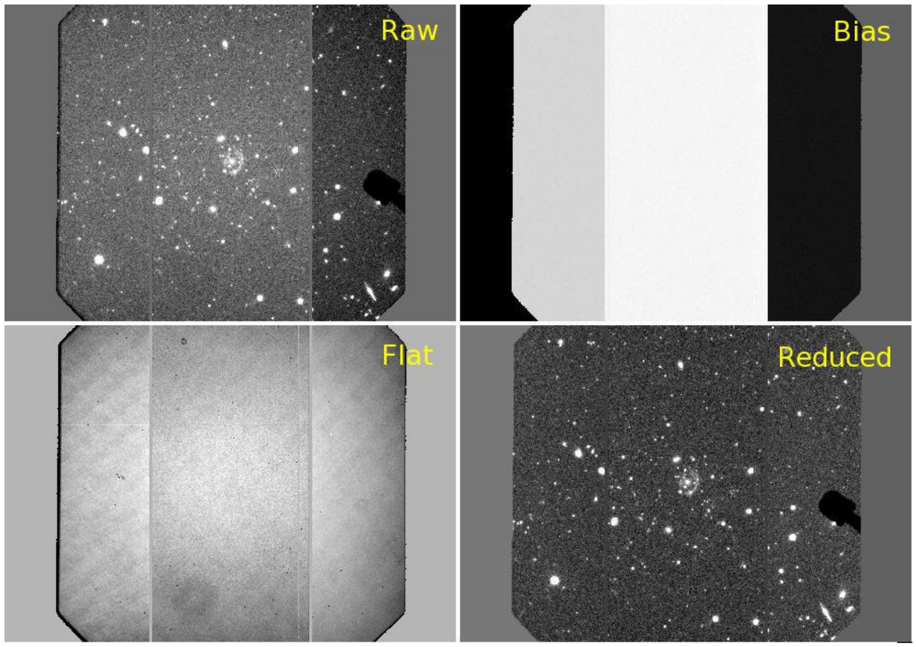

Figure 2. Example set of photometric observations. The raw image needs to be corrected for bias and flat frames to achieve a reduced image suitable for reliable intensity measurements.

- *Dark images.* Darks are long exposure images taken with the shutter closed. These are only necessary in case of a considerable dark current in the CCD. Most modern CCDs have no significant dark current so that dark images are usually not required anymore.

Examples of the calibration images (bias and flat) and their impact on the science frames are shown in Figure 2 for demonstration purpose. For a comprehensive description of CCDs and data reduction the interested reader is referred to the Handbook of CCD Astronomy by Howell (2006).

For the most precise photometry, it is essential to keep a stellar image fixed at the sub-pixel scale to avoid that stars are moving over the CCD, but no telescope can track to that precision. Therefore, autoguiding is needed. The use of autoguiding also eliminates another instrumental effect which might cause an artificial periodic signal. This is the periodic error in the right ascension drive in the telescope which, in the absence of autoguiding, injects a signal into photometric time series with the frequency of the telescope drive. Typical drive periods are 2 or 4 siderial minutes. They can cause confusion with stellar periods for stars pulsating in that frequency range such as roAP stars, solar-like oscillators, sdBV stars, or pulsating white dwarfs. To identify and eliminate such periodic instrumental signals it is necessary to have a standard star observed, ideally in the same field of view as the target.

2.2. Filters

Photometric observations provide information about the stellar brightness in a certain wavelength range, defined by the used filter. Many different filter systems exist, and the interested reader might inspect the work of Bessell (2005) for an overview of the various broad and narrow band systems as well as of the observational complications with standard photometry. The three most commonly used systems are Johnson $UBVRI$, Strömgren $uvby$, and the Sloan Digital Sky Survey (SDSS) $u'g'r'i'z'$ filters (Fukugita et al., 1996).

Every filter has its defined wavelength coverage, transmission curve, and sensitivity curve. Therefore, the use of identical filters is important when combining data from different facilities, or when organizing multi-site campaigns, because the amplitudes and phases of stellar pulsations are wavelength dependent. Changes in stellar brightness caused by oscillations are predominantly due to temperature variations, which manifest themselves particularly in the blue spectral range. Consequently, the monochromatic amplitudes of the pulsations due to temperature variations are highest in the blue as well.

One might interpret photometry through filters as sort of spectroscopy, just at very low resolution. But we need high-resolution spectroscopy to extract additional and viable complementary information about the pulsation properties of stars.

3. Spectroscopy

Spectroscopic observations provide an important tool, not only for asteroseismology, but for all fields of astronomy and astrophysics. With respect to stellar astronomy they are used for spectral classification, for the derivation of stellar parameters such as effective temperature and gravity, as well as for the determination of the atmospheric chemical abundances. Spectroscopic data are also vital to derive the mass-loss rates of stars, and to characterize circumstellar environments. Moreover, whenever spectroscopic time series are at hand, they can provide information on stellar multiplicity or the presence of a planet, or they can be used to analyze and classify stellar variability either due to surface spots, magnetic fields, or pulsation activity.

High-resolution spectroscopic data, suitable for asteroseismology, can to date only be acquired with ground-based facilities. Different types of spectrographs exist, ranging from linear single order to echelle systems, but they all usually consist of a collimator, a prism or grating for dispersion, and a CCD camera. While every instrument needs its own reduction procedure, for which often an instrument pipeline exists, the basic steps are the same for most spectrographs.

As for photometry (Section 2), calibration images need to be taken along with the target frames. These are again bias, flats, and eventually dark frames. However, in contrast to photometry, also calibration lamp spectra need to be secured. An example of how the required observational sets look like in both single order and echelle spectroscopy is shown in Figure 3 and 4, respectively, and detailed descriptions of spectroscopic observations and data reduction can be found in Massey & Hanson (2013).

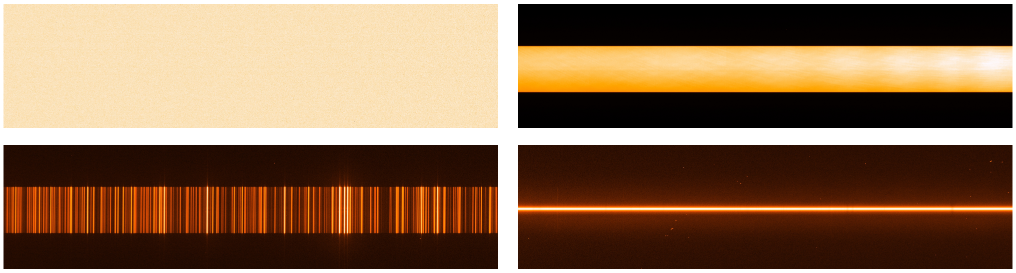

Figure 3. Example set of spectroscopic single-order observations. These are: bias (top left), flat (top right), and comparison lamp spectrum (bottom left) which are needed along with the stellar spectrum (bottom right) for correction and calibration.

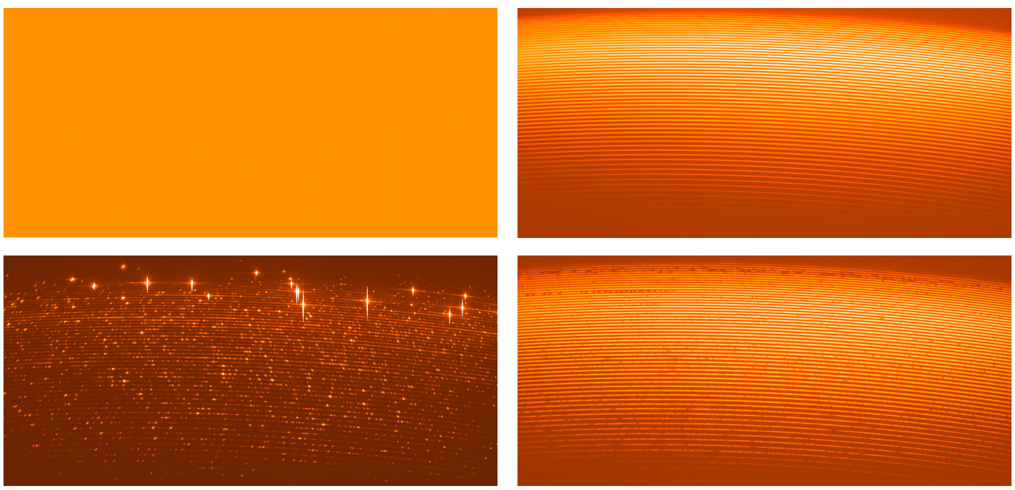

Figure 4. Example set of spectroscopic observations taken with an echelle spectrograph. Shown are the same set of observations as for single-order spectroscopy: bias, flat, calibration lamp and stellar spectrum with the different spectral orders projected parallel to each other on the CCD. Note that in the shown calibration lamp spectrum several intense lines are saturated causing bright artifacts.

In brief, the raw images need to be corrected for dark current (if available), then the bias needs to be subtracted and the images have to be divided by the master flat, which is created from a number of flats taken throughout the observing night (depending on stability of the spectrograph). Then the stellar spectrum has to be extracted whereby the sky background is subtracted. For echelle data, each spectral order needs to be identified and extracted separately thereby correcting for the so-called blaze function. Afterwards, the spectrum needs to be wavelength calibrated by using the comparison lamp spectrum. Finally, the wavelength calibrated spectrum needs to be shifted to the solar system barycentric reference frame.

Any changes in pressure, temperature or humidity within the environment in which the instrument is located lead to small shifts in wavelength. Modern spectrographs are therefore placed in a room with stable conditions. Nevertheless, observations taken during a night can still display some wavelength drifts on a timescale of hours. These drifts cause a low-frequency noise in the amplitude spectrum of the radial velocity variations, in analogy to the low-frequency noise in photometry due to extinction variations.

For exoplanet studies a precision in radial velocity measurements down the level of $\mathrm{m\,s^{-1}}$ or better is required. In this case, it is advised to implement an iodine cell into the light path. The iodine imprints its rich I_2 molecular line spectrum onto the stellar spectrum for very accurate wavelength calibration. The downside of using an iodine cell is that it requires detailed modeling of the molecular lines and their deconvolution from the stellar spectrum. Even worse, it reduces the S/N of the spectrum, because the iodine reduces the incoming starlight by about a factor of two. Therefore, this method of wavelength calibration is usually not used for asteroseismology.

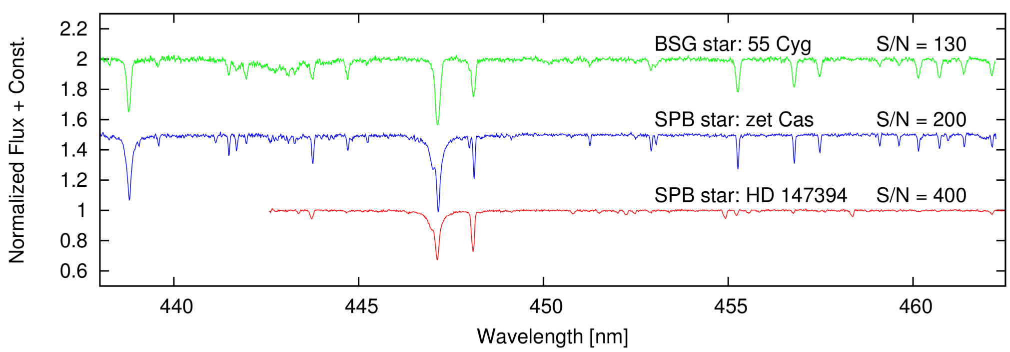

Figure 5. Examples of final, normalized spectral pieces of the pulsating B supergiant (BSG) 55 Cyg (top) and two slowly pulsating B (SPB) stars (middle and bottom). The upper two stars are of early B-type, the bottom star is a late-type B star. Data have been taken with the single order spectrograph at the Perek 2-m telescope at Ondřejov Observatory providing a resolution of $R \sim 18\,000$ around 450 nm.

An example of final, normalized spectral pieces of three pulsating stars is shown in Figure 5. The upper two stars are of early B-type, whereas the bottom spectrum is from a late B-type star. Noticeably, the spectral appearance changes with effective temperature and luminosity class of the star. Therefore, the choice of suitable lines for the analysis depends on the spectral type of the star. But also on the stellar rotation, which can lead to significant broadening and, hence, to blending of adjacent lines. When analyzing time series, one should make sure to focus on deep, unblended lines, ideally of metals.

A further important parameter is the S/N value of the spectra. The higher S/N, the more accurately the line profile parameters can be measured. However, to achieve a high S/N in high-resolution data for faint and short-period pulsators is a further challenge and not always achievable, requiring compromises.

3.1. Line Profile Variations

The profile of a spectral line contains a variety of information about the physical conditions within the line-forming region. While emission lines provide insight into the parameters of stellar winds and circumstellar matter, stellar absorption lines carry (besides temperature, gravity and stellar rotation) the information about the dynamical conditions within the atmosphere, that is at the surface of the star. Any change in the atmospheric kinematics, e.g., due to non-radial pulsations, causes temporal variations in the shape and center of gravity of line profiles. Nice examples of computed line-profile variations of stars pulsating in various non-radial modes can be seen, e.g., on John Telting's webpage[4].

To identify pulsations in spectroscopic time series, the profile variability can be visualized by various means as shown in Figure 6 for the example of β Cep. Overplotting the normalized profiles of a time series of an individual photospheric line (second panel) often shows already whether the profiles are constant and symmetric or not. In the shown example, the profiles vary in three ways: they change their shape and their intensity, and they move in wavelength, so that they seem to swing from one side to the other. When plotting the intensity variation of the lines in a gray-scale plot as a function of time (third panel), a sine-curve like variability pattern appears. Alternatively, one might compute the mean of all observed lines (top panel) which can then be subtracted from each individual line profile to obtain the residuals (fourth panel). These residuals can also be represented in a gray-scale plot as a function of time (bottom panel) to highlight the positive and negative deviations from the mean profile. The use of such gray-scale images has been invented by Gies & Kullavanijaya (1988). These plots guide the eye and in such way facilitate the identification of any features or patterns traveling across the profile.

However, not every periodically varying profile is automatically an indication of stellar oscillations. Other effects can cause variability as well. For instance, a companion (either star or planet) leads to periodic variability. But in this case, only a change in radial velocity is seen. Companions do not alter the shape of the absorption lines. A different scenario leading to line profile variability is due to spots caused by temperature or abundance patterns on the stellar surface. These spots are usually not (or at least not on short timescales) changing their sizes and distributions over the surface, so that the observable profile variability is due to (and follows) stellar rotation, and hence just a single frequency (and its (sub)harmonics) is detected. In contrast to these scenarios, stellar pulsations are typically multi-periodic and create highly complex variations in both radial velocity and profile shapes. Consequently, the analysis of spectroscopic time series of variable stars provides an important diagnostics for distinguishing pulsating stars from other objects with variabilities. Furthermore, it is an essential tool for a proper characterization of the pulsation behavior of oscillating stars.

---

[4]http://staff.not.iac.es/~jht/science/

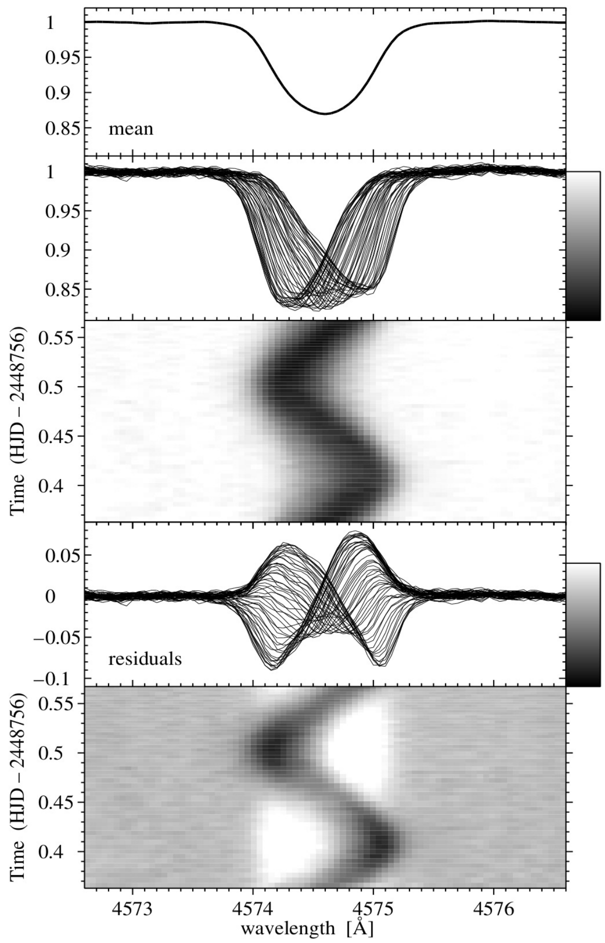

Figure 6. Representations of line-profile variability for the example of the SiIIIλ 4574 line in the pulsating star β Cep. From top to bottom: mean line profile of 620 observations – a subset of 54 normalized spectra – gray-scale image of intensity variations – 54 residual spectra (having the mean spectrum subtracted) – gray-scale representation of residuals. Figure is taken from Telting et al. (1997).

3.2. Specific Requirements for Spectroscopy

Before concluding this section on spectroscopy, the specific requirements for the data sets should be emphasized. Most important for the detection of the rather small deviations in shape and radial velocity from an unperturbed, symmetric line profile is the high quality of the data with respect to both resolution and S/N level.

The resolving power, R, at a given wavelength λ (for example, the laboratory wavelength of the investigated spectral line) is defined as $R = \lambda/\Delta\lambda$. The resolution should be at least 30 000. Certainly better are spectra with $R > 50\,000$.

The same principle holds also for the signal-to-noise ratio: the higher the better. However, the higher the resolution and the fainter the object, the longer is the integration time to achieve adequately high S/N values. Therefore, in reality one has to find the best suitable combination for the object that is supposed to be studied. As sort of a guideline, one should opt to sample the observed line profile in wavelength with about 50 points and to achieve a S/N value greater than 200.

But there are more constraints than just resolution and noise level. To unveil the signature of oscillations, there should be at least ten measurements distributed over each pulsation cycle. This can be achieved by observing over many cycles for a long time base, which also guarantees that at least some of the cycles are densely covered for a decent frequency spectrum, in particular for stars with multi-periodic oscillations and complicated beating patterns. For the data to be considered sufficiently time-resolved they are required to cover at least two points per cycle for all harmonics needed to reproduce the shape of the variability pattern which is usually the radial velocity curve.

Furthermore, the data also need to have a good temporal resolution. This means, that the integration time should not exceed about 1–2% of the pulsation period. Only in this case, the measurements can be considered as instantaneous. Otherwise, the signal appears to be smeared out, an effect which then needs to be simulated and corrected for.

Considering all these requirements, one should make sure to carefully adjust the observational setup and strategy according to the specific needs for the target under investigation and the research goal that one wishes to achieve.

Having introduced all the targeted demands for the observational data, we now turn to the various missions dedicated to (or useful for) the acquisition of data for different types of variable stars.

4. Space Missions

4.1. Observations of Variable Stars - How It All Started

The HIgh Precision PARallax COllecting Satellite (**HIPPARCOS**[5]) of the European Space Agency (ESA) was one of the most important and pioneering large surveys of variable stars. During its 3.5 years of operation from 1989 to 1993, the parallaxes of about 120 000 bright stars in the solar neighborhood were measured with unprecedented precision of 2 mas, and their proper motions with an accuracy of 2 mas/year. This accuracy has been achieved from about 100 individual observations per star that have been randomly distributed over the mission lifetime. The observations of HIPPARCOS have been performed with a broad-band white-light filter covering the wavelength range $400 - 800$ nm.

The satellite has been equipped with an auxiliary star mapper (the Tycho experiment) that pinpointed many more stars. Its accuracy was lower, but still good enough to determine the parallax and proper motion of a million fainter stars with an accuracy of 30 mas (per year). The total number of measured objects has been compiled in the Tycho 2 Catalogue, which has been completed

[5]https://www.cosmos.esa.int/web/hipparcos/home

in 2000. It lists the total of 2 539 913 stars, and includes 99% of all stars down to magnitude 11.

Besides the position and proper motion measurements, the major achievement of the HIPPARCOS mission was the discovery of a few thousand new periodically variable stars that have been reported in the *Catalogue of Periodic Variables* and another few thousand variables without a clear dominant periodicity, listed in the *Catalogue of Unsolved Variables*. Numerous new variables have been discovered with periods of the order of days. Such stars are difficult to find from ground. The results from the HIPPARCOS mission particularly impacted the studies of slowly pulsating B (SPB) stars, for which HIPPARCOS increased the number by a factor of ten (Waelkens et al., 1998), and it doubled the number of γ Dor stars (Handler, 1999). Moreover, HIPPARCOS also discovered 343 new eclipsing binaries and thus doubled their number (Söderhjelm, 2000).

The new catalogs of variable stars triggered extensive follow-up long-term ground-based photometric and spectroscopic campaigns. The brightest stars of each class were monitored to study their pulsational behavior and to derive the general properties of the objects.

4.2. Follow-up Surveys of Variable Stars

It took ten years after the end of the HIPPARCOS mission before the next satellite, dedicated to the observations of variable stars, was sent to space. An overview of all relevant space missions and their (actual or planned) duration periods is depicted in Figure 7.

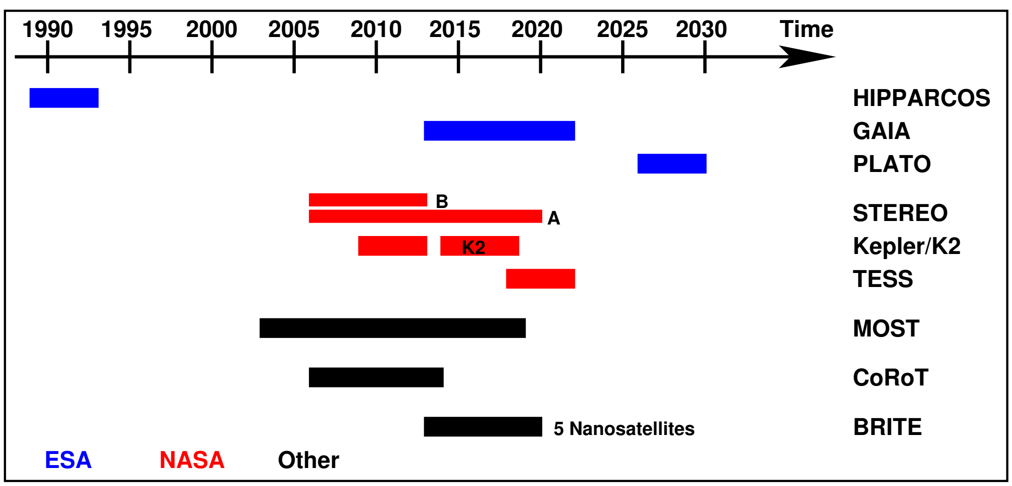

Figure 7. Space missions suitable for variable star research, even if their prime objective was sometimes quite different.

MOST The Canadians were the next to launch a satellite called Microvariability & Oscillations of Stars (MOST[6]). It was Canada's first space telescope,

[6]http://most.astro.ubc.ca//index.html

and the first spacecraft dedicated purely to the study of asteroseismology of a variety of pulsating objects.

MOST consisted of a visible-light dual-CCD camera, fed by a 15-cm aperture Maksutov telescope. One CCD observed the science target, while the other was used for star-tracking with a pointing accuracy better than $1''$. With its broadband (300 nm) filter centered at 525 nm, MOST performed ultra-high-precision photometry measuring brightness variations down to the mmag level.

With its suitcase size (65 cm $\times$ 65 cm $\times$ 30 cm) and a weight of just 54 kg, this microsatellite was given the nickname "Humble Space Telescope". It was launched in June 2003 and was intended to be a one-year mission to observe a total of ten bright ($V = 0.4 - 6.0$ mag) stars for a period up to 60 days. However, MOST succeeded to survive for more than 15 years and was in operation until March 2019. During this period it delivered precise data for more than 5000 objects.

CoRoT The next mission, initiated and led by the French Space Agency (CNES) in conjunction with ESA and other international partners, was entitled Convection, Rotation and planetary Transits (CoRoT[7]). It was designed to investigate stellar pulsations and to search for exoplanets.

The telescope was equipped with a 27 cm diameter lens and a wide-field camera observing in visible light and with a field of view of 7 square degrees. The camera had 4 CCD detectors with 2000×2000 pixels. For its asteroseismic goals the satellite operated in two modes: long runs of 150 days (central program) devoted to a small number of ($\sim$ 50) selected main-sequence targets brighter than magnitude 9, and short runs of 20 days (exploratory program) inserted in between two long runs dedicated to a variety of stars across the whole HR diagram from spectral type B to K. For the exoplanet hunting, the targets were red dwarfs (F to M) with magnitudes between 12 and 15.5.

The satellite was launched on 27 December 2006 and it terminated its operation in June 2014. During this 7.5-year mission, CoRoT discovered several hundred exoplanet candidates and collected light curves for about 160 000 variable stars.

Kepler Space Telescope Another satellite, dedicated primarily to the search for Earth-size planets, was NASA's Kepler Mission[8]. Kepler was a 0.95-m aperture Schmidt telescope equipped with a photometer that operated at 430–890 nm and continually monitored the brightness of approximately 150 000 main sequence stars in a fixed field of view of 105 square degrees ($\sim$12 degree diameter). The focal plane consisted of an array of 42 CCDs pointing to one field, read-out every 3 seconds for stars brighter than $R \sim 16$ mag and integrated over 30 min. For uninterrupted observations, the field of view had to be out of the ecliptic plane, and to maximize the number of stars in the field, it pointed towards a region in the constellations Cygnus and Lyra.

The satellite was launched in March 2009, and the mission's lifetime was initially planned to 3.5 years. This lifetime has been extended, because the data

[7] https://corot.cnes.fr/en/COROT/index.htm

[8] https://www.nasa.gov/mission_pages/kepler/overview/index.html

had higher than expected noise which required longer integration (hence longer duration) for a successful completion of the planned mission. In 2012, one of the spacecraft's four reaction wheels used for pointing the spacecraft stopped turning, and in May 2013 the second wheel failed. This was the end of the main mission.

A new concept for the satellite has been developed, which allowed a restart of observations relying only on the remaining two reaction wheels. This so-called "Second Light" of Kepler was dubbed the K2 mission and was in operation from 2014 until the spacecraft ran out of fuel in 2018. To cope with the satellite's limitations, the new observing mode was a series of sequential fields distributed around the ecliptic plane with a length of 80 days each.

In total, Kepler observed 530 506 stars and discovered 2 662 exoplanets over its lifetime. Despite its major goal of exoplanet research, Kepler observed many more stars as a side product, and in fact, the number of publications based on Kepler and K2 data in other fields of astrophysics became even higher than the one dealing with exoplanets, showing that other scientific branches can greatly benefit from missions that are not directly related to their fields.

STEREO How stellar astrophysics can benefit from missions other than their own is impressively demonstrated by another NASA mission called Solar TErrestrial RElations Observatory (STEREO[9]). This mission consists of two nearly identical satellites orbiting the sun at 1 AU distance equipped with white light coronagraphs. The prime goal of that mission was to provide the first-ever stereoscopic measurements to study the sun and space weather, and to construct a 3D structure of the sun and of coronal mass ejections. Nevertheless, the satellites imaged also stars in the vicinity of the sun. These are monitored each year for a period of about 20 days and the images can be used to extract light-curves of the objects.

The mission was launched in October 2006. While the STEREO B satellite died in 2014, STEREO A still continues to deliver data which can also be used for asteroseismic studies of variable stars.

BRITE A mission dedicated solely to the monitoring of objects with V-band magnitudes brighter than 6 is provided by the constellation of nanosatellites, each of them being a BRIght Target Explorer (BRITE[10]). The first two have been provided by Austria (BRITE-AUSTRIA and UniBRITE) and were launched on February 25, 2013. These have been followed by two Polish BRITEs, BRITE-Lem launched on November 21, 2013, and BRITE-Heweliusz, launched on August 19, 2014. Finally the Canadians launched two more BRITES (BRITE-Toronto and BRITE-Montreal) together on June 19, 2014. Unfortunately, BRITE-Montreal is not operating, so that the final constellation consists of just 5 nanosatellites.

To achieve their goal of investigating the stellar structure and evolution of the brightest stars in the sky, the camera exposure times range from 1 to 5 seconds, collected about 3-4 times per minute and for 15-35 minutes per orbit. The observing run for each field is limited to about 180 days. The satellites are

[9] https://www.nasa.gov/mission_pages/stereo/main/index.html

[10] https://brite-constellation.at/

equipped with an instrument sensitive either in a red bandpass (550 – 700 nm; UniBRITE, BRITE-Toronto, and BRITE-Heweliusz) or in a blue one (390 – 460 nm; BRITE-Austria and BRITE-Lem). The field of view of both the red and the blue version of the camera is about 24 degrees in diameter allowing for the observation of about 15 bright targets per field at the time.

Gaia ESA's next big mission was Gaia[11]. As a follow-up of the HIPPARCOS mission, Gaia has the ultimate goal to measure the positions, distances and space motions of about one billion stars. On board are two identical telescopes that point in different directions with a separation angle of 106.5 degrees. Three instruments collect the light coming from the two telescopes and merged into a common path. The astrometric instrument measures the stellar positions on the sky. By the end of the mission, the global astrometry will be measured for all one billion stars down to $G \sim 20\,\mathrm{mag}$ down to micro-arcsecond precision. The two photometers, one operating in the blue (330 – 680 nm) and one in the red (640 – 1050 nm), collect low-resolution spectra and provide color information of the stars that will allow to derive stellar parameters such as temperature, mass and chemical composition. The radial velocity spectrometer measures the stars' radial velocity at medium resolution ($R \sim 11\,500$) based on absorption lines in the red part (845 – 872 nm) of the spectrum.

Gaia is observing since July 2014. It is expected that throughout the mission, many thousands of extra-solar planets will be discovered (from both their astrometric wobble and from photometric transits) and that their detailed orbits and masses will be determined. During its 5-year mission, a sky-averaged number of 70 photometric measurements is expected from the astrometric field and from the blue and red photometers. Moreover, variability on short (seconds) to long (of order 5 years) time scales can be detected.

TESS A further mission, primarily devoted to the discovery of transiting exoplanets, is NASA's Transiting Exoplanet Survey Satellite (TESS[12]). The satellite is equipped with four identical, highly optimized, red-sensitive (600 – 1000 nm bandpass) wide-field cameras, each with a 24 deg by 24 deg field of view so that together they can monitor a 24 deg by 90 deg strip of the sky. Each strip is observed for a total of 27 days so that almost the full sky is mapped within a period of 2 years. The first year of its operation TESS scanned the southern sky, and in the second year the northern one. The CCDs read out continuously at 2-second intervals, and the data are stacked to the length of the chosen cadence. During the 2-year run, a selected number of 200 000 brightest stars were observed with 2-minute cadence and provided with postage stamp sizes (usually 10×10 pixels), whereas full-frame images had a cadence of 30 minutes. All data become public four months after observations, providing an unprecedented pool of high-quality light curves for all types of variable stars.

TESS is in operation since 2018 July 25 and finished its 2-year prime monitoring mission on 2020 July 5. Right after, the TESS extended mission started, which will last for another 27 months, beginning again with the southern sky

[11]https://www.cosmos.esa.int/web/gaia/home

[12]https://tess.mit.edu/

and focusing on those targets that fell into gaps between sectors during the first monitoring period. During the extended mission, about 20 000 objects will be monitored per sector at 2-minute cadence as during the prime mission. However, a sample of up to 1000 targets per sector will be read out with a 20 s cadence, whereas the full-frame image cadence has been reduced from 30 to 10 min to broaden the range of scientific investigations.

PLATO Finally, it is worth mentioning that ESA is currently preparing a new mission called PLAnetary Transits and Oscillations of stars (PLATO[13]). The launch of this satellite is scheduled for 2026 with an intended 4 years of operation.

The prime goal of that mission is again to find and study a large number of extrasolar planetary systems. The emphasis is hereby on determining the properties of terrestrial planets in the habitable zone around solar-like stars and to investigate seismic activity for a precise characterization of the planet host stars. To achieve these goals, PLATO will perform high precision, long (months to years), uninterrupted photometric monitoring in the visible band of a very large sample of stars brighter than $V \sim 11\,\mathrm{mag}$.

In addition, many other objects will be observed, which fall outside PLATO's core science but are of high value for other branches in Astronomy dealing with stellar variability. These other aspects of astrophysics (e.g., binary and multiple stars, pulsating stars, magnetic stars, transient phenomena, stars with mass loss, etc. just to mention a few) are lumped together into what is called the PLATO Complementary Science (PLATO-CS[14]). The PLATO-CS will rely on the calibrated light curves provided by the PLATO mission. These light curves will be assembled in a variability catalog and will be offered to the scientific community for exploitation.

5. Ground-Based Photometric Surveys and Databases

For accessing photometric light curves and data from long-term monitoring one has not solely to rely on space missions, but can use products from their ground-based counterparts. Several large surveys have been carried out, not always with the prime goal to study stellar pulsations and not always performed by professional astronomers, but providing high-quality data that can be used for asteroseismological purposes. This section gives an overview of the diverse ground-based surveys and databases.

5.1. Missions Dedicated to Variable Stars

AAVSO The American Association of Variable Star Observers (AAVSO) is the world largest association of variable star observers. It was founded in 1911 to coordinate the variable star observations of mostly amateurs astronomers, and to foster collaboration between amateurs and professionals in the field of variable star research.

[13]https://sci.esa.int/web/plato

[14]https://fys.kuleuven.be/ster/research-projects/plato-cs

AAVSO's International Database[15] contains over 34 million variable star observations going back over one hundred years. It is the largest and most comprehensive digital variable star database in the world. To date, over 1 000 000 new variable star brightness measurements are added to the database every year by observers from all over the world. The database contains a diversity of photometric measurements in different bands, and the AAVSO webpage provides a light curve generator allowing the user to see and download the available data for a given object.

ASAS The All Sky Automated Survey (ASAS[16]) is a low-cost automated survey with the prime goal to detect any kind of photometric variability. ASAS consists of two observing stations, one at the Las Campanas Observatory in Chile (since 1997) and another one at Haleakala, Maui (since 2006). Both telescopes are equipped with two wide-field instruments that enable them to simultaneously observe in the V and I bands. The telescopes constantly monitor the whole available sky, meaning that they provide photometric data for about 10^7 stars which have magnitudes brighter than 14. The observations are converted to standard V and I magnitudes. They are collected in a variety of catalogs and can be accessed from the ASAS webpage.

5.2. Surveys Related to MACHOs

As for the space telescopes, there were also several ground-based missions not specifically targeted at variable stars, but providing data of variable stars as side-products. One of them was the search of MAssive Compact Halo Objects (MACHOs). These objects, which were considered to be mainly brown dwarfs and planets, have been proposed to constitute a significant fraction of the dark matter in the halo of the Milky Way. If they were detected, they could help explain parts of the missing dark matter in the Universe. To search for MACHOs, several large surveys were initiated in the early nineties. The idea was to discover these dark compact massive objects via microlensing events, in which the MACHOs would serve as gravitational lens passing in between us and a background light source, such as the stars of the Magellanic Clouds or of the Galactic Bulge. As such lensing events are extremely rare, long-time monitoring of a huge number of light sources with high precision photometry is required. Such monitoring naturally provides data for millions of stars as side-products and led to the discovery of many thousands of variable stars in the Magellanic Clouds and in the Galactic Bulge (e.g., Sarro et al., 2009). Based on these surveys, significant progress on the properties of large-amplitude oscillators, such as Cepheids, RR Lyrae stars, and red-giant and supergiant pulsators could be achieved. Here we list only the most important surveys related to the search for MACHOs.

MACHO The MACHO Project[17] started in 1992. It has been carried out by a two channel system that employs eight CCDs, mounted on the 50 inch

[15]https://www.aavso.org/aavso-international-database-aid

[16]http://www.astrouw.edu.pl/asas/?page=main

[17]http://wwwmacho.anu.edu.au/

telescope at Mt. Stromlo for simultaneous imaging in two passbands, in the red (630 - 760 nm) and blue (450 - 630 nm) bands.

EROS In 1990 started the Expérience pour la Recherche d'Objets Sombres (EROS[18]) survey which consisted of two phases, EROS-I and EROS-II. This survey has been carried out based on a 40 cm telescope with a CCD camera, operated at the La Silla Observatory in Chile, and 1 meter Schmidt ESO telescope, with photographic plates, alternately with a blue and a red filter. In 1995, a 1.5-m telescope recuperated from French observatories replaced the 40 cm telescope. This was the start of the EROS-II era which ended in 2003. EROS monitored in total 90 million stars located in the Galactic Center and in the Magellanic Clouds.

OGLE The Optical Gravitational Lensing Experiment (OGLE[19]) started in 1992 with the first phase (OGLE-I) during which the 1-m Swope telescope at the Las Campanas Observatory in Chile has been utilized. The telescope was replaced in 1996 by the 1.3-m Warsaw Telescope, with which the second phase (OGLE-II) started in 1997. In 2001 OGLE-III started when a new CCD mosaic camera was installed covering a $35' \times 35'$ field of view. Finally a 32 chip mosaic camera with a total field of view of 1.4 square degrees has been installed in 2010, initiating the so far last phase, OGLE-IV, which is still ongoing. While during the phases OGLE-II and OGLE-III standard $UBVRI$ filters have been available, these have been replaced by standard VI interferometric filters.

5.3. Survey Related to Transiting Exoplanets

KELT The Kilodegree Extremely Little Telescope (KELT[20]) mission was a survey aimed at searching for transiting exoplanets around bright stars. The mission consisted of two fully robotic telescopes, one on each hemisphere. KELT-North is located at Winer Observatory in Arizona and went into operation in 2005. KELT-South followed in 2009. It is located at the Sutherland observing station of the South African Astronomical Observatory. Each telescope has a field of view of 26×26 degrees and observed multiple fields with between 50 000 and 200 000 stars per field. Their main focus was on stars with apparent visual magnitudes of $V = 8 - 11\,\mathrm{mag}$.

The KELT light curve data archive is publicly available via the NASA Exoplanet Archive (NEA[21]). It contains about 1.1 million light curves. The KELT transit search was concluded in March 2020. During its observing run, 26 planets have been discovered.

5.4. Future Ground-based Photometric Mission

To my knowledge, there is so far one large mission in preparation:

---

[18] http://eros.in2p3.fr/

[19] http://ogle.astrouw.edu.pl/

[20] https://keltsurvey.org/

[21] https://exoplanetarchive.ipac.caltech.edu/

LSST The Large Synoptic Survey Telescope (LSST[22], renamed into Rubin Observatory) is currently under construction on Cerro Pachón in Chile. It has a three mirror system and the world largest CCD. The 3.2 gigapixels camera will operate from the UV to the near-infrared in the spectral bands labeled u, g, r, i, z, & y. With its almost 10 square degrees field of view (corresponding to 40 times the size of the full moon), the LSST will survey the night sky for a period of 10 years. Each night, more than 800 panoramic wide-field images with 30 second exposures will be taken with this 8.4-m telescope, resulting in a recording of the entire visible sky twice per week, and a total of about 1000 visits for each object during the planned duration of the survey. The total data volume generated each night will be on the order of 20 Terabytes. Image data products will be made available daily, and data products resulting from coherent processing will be made available via yearly releases.

The scientific goal of this survey is to detect changes in brightness and position of objects as big as far-distant galaxy clusters and as small as near-by asteroids. The start of full science operations and the beginning of the survey is foreseen for the end of 2022.

5.5. Ground-based Spectroscopic Monitoring Facilities

The situation with observing missions dedicated to spectroscopic monitoring is much worse than the photometric possibilities. While many, especially national spectroscopic facilities exist and are used by individual research teams, there is to my knowledge only one coordinated network.

SONG This very promising project was launched in 2006 by the Stellar Observations Network Group (SONG[23]). Its ultimate goal is to construct a global network of six to eight small robotic telescopes distributed over the world to collect uninterrupted time series from ground for solar-type stars, and to search for and characterize planets.

Currently, only one 1-m telescope, located at the Teide Observatory in Tenerife, is in operation. It is equipped with a high-resolution echelle spectrograph with a resolution from 35 000 to 112 000 and a wavelength coverage of 440 – 690 nm. A second 0.7-m telescope is in its testing phase and will be located at the Delingha Observatory in China, and a further node is under development for Southern Queensland, Australia.

6. Conclusions

In this Chapter, the observational techniques for obtaining high-quality data in both photometry and spectroscopy and their adequacy, limitations, and benefits for investigating pulsating stars have been presented. To study all aspects of stellar pulsations concurrently, it would be most ideal to simultaneously monitor stars photometrically (preferentially from space to have continuous light curves) and spectroscopically (which is currently possible only from ground) utilizing

[22] https://www.lsst.org/lsst/

[23] https://phys.au.dk/song/

multiple, identical facilities distributed all over the world to minimize the losses due to day-time and bad weather, ideally with high cadence, excellent temporal resolution, high signal-to-noise and high spectral resolution. Obviously, this is wishful thinking and in reality the situation looks different from that.

For space photometry, many objects are very bright, meaning that the signal is polluted by read-out noise, or stars are saturated on the chip, if they are observed at all. Therefore, preference is often given to less bright objects.

For spectroscopy, many of the photometrically easily followed objects are too faint to monitor them with high cadence in high spectral resolution and high S/N. For this task, large 6-10 m-telescopes would be required, but monitoring campaigns at the big observatories have no or only little chance for getting time at their telescopes because of their low output but high costs. Therefore, such monitoring is usually performed with smaller, 1-2 m class telescopes. The advantage of these telescopes is that there is much lower pressure, but for the price of being limited to bright(er) or long-period objects, for which the needed coverage and data quality can be achieved.

These limitations mean that for each target a compromise needs to be made and for the observational setup a strategy has to be selected such that the specific science goal will be achieved. Nevertheless, despite these hindrances the field of asteroseismology has been steadily growing in the past decades. And considering all the currently available and newly planned instruments and missions for photometry and spectroscopy, I am confident that the future for research in variable and pulsating stars is bright.

Acknowledgments. I wish to thank the SOC and LOC for their fantastic job in organizing and implementing this interesting and pleasant Summer School. Most of the data and images shown have been collected with the Perek 2-m telescope at Ondřejov Observatory. The Astronomical Institute, Czech Academy of Sciences, is supported by the project RVO:67985815. This project has received funding from the Czech Science Foundation (GA ČR 20-00150S) and from the European Union's Framework Programme for Research and Innovation Horizon 2020 (2014-2020) under the Marie Skłodowska-Curie Grant Agreement No. 823734.

References

Aerts C., Christensen-Dalsgaard J., Kurtz D. W., 2010, *Asteroseismology*
Bessell M. S., 2005, *ARA&A*, **43(1)**, 293
Fukugita M., Ichikawa T., Gunn J. E., Doi M., Shimasaku K., Schneider D. P., 1996, *AJ*, **111**, 1748
Gies D. R., Kullavanijaya A., 1988, *ApJ*, **326**, 813
Handler G., 1999, *MNRAS*, **309(2)**, L19
Hardie R. H., 1964, *Photoelectric Reductions*, p. 178
Howell S. B., 2006, *Handbook of CCD Astronomy*, Vol. 5
Massey P., Hanson M. M., 2013, *Astronomical Spectroscopy*, p. 35
Sarro L. M., Debosscher J., López M., Aerts C., 2009, *A&A*, **494(2)**, 739
Söderhjelm S., 2000, *Astronomische Nachrichten*, **321(3)**, 165
Telting J. H., Aerts C., Mathias P., 1997, *A&A*, **322**, 493
Waelkens C., Aerts C., Kestens E., Grenon M., Eyer L., 1998, *A&A*, **330**, 215