



# An Observer's View on the Future of Asteroseismology

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Scientific research is a continuous process, and the speed of future progress can be estimated by the pace of finding explanations for previous research questions. In this observer's based view of stellar pulsation and asteroseismology, we start with the earliest observations of variable stars and the techniques used to observe them. The earliest variable stars were large amplitude, radial pulsators but were followed by other classes of pulsating stars. As the field matured, we outline some cornerstones of research into pulsating star research with an emphasis on changes in observational techniques. Improvements from photographs, to photometry, CCDs, and space telescopes allowed researchers to separate out pulsating stars from other stars with light variations, recognize radial and non-radial pulsation courtesy of increased measurement precision, and then use non-radial pulsations to look inside the stars, which cannot be done any other way. We follow several highlighted problems to show that even with excellent space data, there still may not be quick theoretical explanations. As the result of technical changes, the structure of international organizations devoted to pulsating stars has changed, and an increasing number of conferences specialized to space missions or themes are held. Although there are still many unsolved problems, such as mode identification in non-asymptotic pulsating stars, the large amount of data with unprecedented precision provided by space missions (MOST, CoRoT, Kepler) and upcoming missions allow us to use asteroseismology to its full potential. However, the enormous flow of data will require new techniques to extract the science before the next missions. The future of asteroseismology will be successful if we learn from the past and improve with improved techniques, space missions, and a properly educated new generation.

**Keywords:** variable stars, pulsation, non-radial modes, space missions, mode identification, asteroseismology

## 1. INTRODUCTION

Let me start with ancient times to show how slow was the progress over centuries without serious technical devices. The stars of the night sky, especially the brighter ones, have always been part of the life of people. Initially, the most prominent objects whose celestial movement was perceptible were planets that were considered to be gods who had a direct impact on their lives. The fixed stars were formed into constellations that depicted mythical figures. Over the centuries, however, individual observations had accumulated and founded the science of astronomy. Although stars still occupied a special place in the lives of people, the Sun and the distant stars were no longer considered gods and myths, but simple cosmic objects. With these few sentences, I have described

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centuries, first, those years when stars were only seen with naked eyes, and those when telescopes were already built, but observations were recorded only by drawings, such as spots on the Sun or phases of the planets. Then the development and appearance of the photographic technique in the observation of stars allowed us to capture their current status, how bright or dim they are. Finally, the research of variable stars began.

In this article I would like to show how the separation of stars have developed into independent groups as a result of technical progress (increasing precision) and how the actual technique (photographic, photoelectric, or CCD) influenced which problems (group of stars or individual stars connected to the field of view of the actual instrument) were examined. I also present how scientific results (not properly resolved and biased frequencies) and requirements (continuous, long observations compared to the pulsation periods) have led to the need for spacecraft. I do not intend to provide a detailed and complete overview of the scientific results of the last 60–70 years, but I want to highlight the dominant directions of research in a given decade up to the space era. The results and raised questions of a given decade turned out to be the base of the research lines of the next decade. From decade to decade, unresolved issues have shown what the hot lines of scientific research in the era of space telescopes will be and what the future of astroseismology holds. I do not intend to give a complete theoretical overview, I only want to emphasize and show that there can be no substantial progress without theoretical interpretation.

## 2. PRE-HISTORY OF ASTEROSEISMOLOGY

In the last centuries naturally the largest light variations of the brightest stars were discovered first. Mira (*o Ceti*) was the first to be discovered, with observations dating back to the 1600s<sup>1</sup>. A detailed historical summary of the observation of Mira was given by Hoffleit (1997) for the 400 year anniversary of the discovery. The light variability of  $\delta$  Cep was discovered in the eighteenth century (Goodricke, 1786). The variability of RR Lyrae, along with 64 additional newly discovered variable stars, was announced 40 years later (Pickering et al., 1901). The radial velocity variation of  $\beta$  Cephei was noticed by Frost (1906). The date of the first discovery of a  $\delta$  Scuti type variation is more difficult to determine. The change of  $\delta$  Scuti itself was announced by Fath (1935), and radial velocity measurements were also published in that year (Colacevich, 1935). However,  $\delta$  Scuti type stars as a new group were identified only after another 20 years (Eggen, 1956). The process is clear, we are talking about a new group if we have found more stars with a similar variation. The criteria include the degree of variation and the star's location on Hertzsprung-Russell diagram. In the subsequent years and decades several new groups of variable stars were discovered and identified. I will follow how the knowledge of the groups improved from decade to decade at first for the early recognized groups and later for the newly identified groups, too.

<sup>1</sup><https://www.aavso.org>

Of course, the light variability of stars aroused the interest of theoretical physicists. Many of Eddington's works dealt with the theory of pulsation, which he summarized in a book (Eddington, 1926). He predicted that the light variability generated by the pulsation of the stars would provide information about the inner structure that otherwise we cannot acquire. Asteroseismology is exactly the method in which the inversion of the star's light variability, getting at first their frequency content, leads to the physical parameters inside stars, i.e., temperature, pressure, density, speed of sound, and chemical composition along the radius. The method, called helioseismology, has worked successfully in the case of the Sun. On the other hand distant stars do not easily share their secrets with us. We have determined the frequency content of many stars and their global physical parameters, but inversion has not been achieved so far for most kinds of pulsating stars, so the dependence of the physical parameters on the radius of the star has not yet been determined, except for the Sun and compact stars.

In the following I show how we have come closer to our goal from decade to decade, and how much the technical development of the given age and the related accuracy of the measurement influenced what problems were investigated by previous researchers. I am convinced that knowing the work of predecessors can have a profitable impact on today's research. This article is not a complete review of each field of pulsating stars that would require a more regular structure of the paper. I decided to use my life as a guideline when I was invited to present my view on the future of asteroseismology (another personal review). I decided to begin the summary at the epoch when I was born and the science field started to attract more attention.

## 3. RESULTS BETWEEN 1950-1960

From the point of view of technical development, the middle decade of the 20th century was particularly impressive and productive. The *photographic technique* was still used; moreover, Cuffey (1954) designed and built a new photometer at the beginning of this decade. One of the two beams came directly from a control lamp while the other led to an oscilloscope via the iris and the photographic plate. Matching the two rays provided the star's brightness. The photometer produced 0.003–0.13 mag accuracy on the Mt Wilson 100-inch telescope, depending on the brightness of the star and its position on the plate. The photometer proved to be so successful that I started working with such type of photometer in 1974 when I began my scientific career at Konkoly Observatory, Hungary. Of course, the accuracy was worse due to the use of a smaller telescope, but the error of the finally accepted physical parameters were seemingly reduced by averaging many plates obtained on the same field. The enormous advantage of the photographic photometry was the large area covered with wide-angle telescopes. The most well-known project was the all-sky survey of the 48-inch Palomar Schmidt camera resulting in the Palomar catalog. Of course, this technique was most advantageous for the discovery of stellar variability and for the investigation of stellar clusters as well as galaxies.

Naturally, there was the need to achieve greater precision for individual stars, which called for a new technical solution. *Photoelectric photometers* started to be produced in the leading astronomical observatories/institutes. A photoelectric photometer generally consisted of an aperture in the focal plane of the telescope to isolate the light from a single star. The light then (usually) passed through a filter of known passband to a photomultiplier which converted photons to pulses of electrons which could be measured as a weak current or, better, counted as a series of pulses. Photometry using such device consisted of pointing the telescope alternatively at a variable star, a comparison star and piece of sky without visible stars (to measure the sky background). This inevitably put a heavy burden on the observer when he/she had to work as quickly as possible, as long as possible on many nights one after another to answer certain questions of the star which was being investigated. It was Walraven (1952) who designed a photoelectric photometer which removed the human efforts by rendering the actions otherwise performed by the observer automatic. It was attached to the 16-inch Rockefeller telescope of the Leiden Station of Johannesburg. However, it took some time for photoelectric photometers to appear in the observatories all over the world. Scientists of communist countries, for example, suffered restrictions on high-tech electronic devices due to political concerns. I myself started to work with a normal photometer in 1980 at Konkoly Observatory (moving the telescope by hand from variable, to comparison and to background), when I changed my interest from photographic to photoelectric photometry, since I was delighted by the higher precision. The photoelectric photometer was built in our observatory by Géza Virághalmly using a photomultiplier tube which was personally donated, without any official permission, to the director of Konkoly Observatory, to László Detre by Th. Walraven when he visited Hungary. Both photographic and photoelectric photometry used filters in different wavelength to get more information on the stars in general, and on the characteristics of the pulsation. The two basic photometric systems, Johnson UB<sub>V</sub> (Johnson, 1955) and Strömberg ubv (Strömberg, 1954) were established during this decade.

The development of *spectroscopy* had gone through a similar process. In the past, only an objective prism was employed for the simultaneous photography of the spectra of large numbers of faint stars. After World War II, Wood (1946) reported that it was possible to construct transmission gratings which throw as much as ninety percent of the light into a single spectrum. In the next years, the technical development accelerated. In 10 years Harrison (1955) reported that echelle spectrographs had been produced in six forms. Some years later an electronic camera was developed by Lallemand and Duchesne and was installed at the focus of Coudé spectrograph of the 120-inch reflector at Lick Observatory (Lallemand et al., 1960). The sensitivity of the photocathode was 10-20 % instead of 0.1 % of the photographic emulsion, which meant a gain in speed by a factor of about 100. The 2-dimensional classification of stellar spectra, the Morgan-Keenan system, was also established in this decade (Keenan and Morgan, 1951; Johnson and Morgan, 1953).

The higher precision of the photoelectric technique and the higher sensitivity of spectroscopy led to the discovery of more and more variable stars of lower amplitude and shorter period. Groups of similar stars were recognized, such as the Cepheids, RR Lyrae, cluster variables, dwarf cepheids, short period  $\delta$  Scuti,  $\beta$  CMa and  $\beta$  Cephei variables. There was no clear-cut separation between the groups, but the nomenclature changed when more information was collected on the groups. The research field was in the data collection phase. On the Harvard patrol plates Payne-Gaposchkin (1954) discovered 51 RR Lyrae stars, 135 classical Cepheids and nine variables of a similar period that belonged to Population II. The two groups of stars, Pop I and Pop II were recognized by Baade (1944). Pop I stars are younger and are located in the spiral arms, while the Pop II stars are older and are located in globular clusters. Later, different metallicities were found for the groups. In the M3 globular cluster the RR Lyrae stars and those non-variable stars were measured which border the variable ones on the HR diagram (Roberts and Sandage, 1954). The resulting color-magnitude diagram showed that all the cluster-type variables fell in a distinct region which was not occupied by non-variable stars. So, there was a sharp separation between variable stars and non-variable stars. The basic question whether there are non-variable stars in the instability strip was raised for the first time, and has been investigated up to now. If the answer is yes, then what is the physical reason that some stars with similar physical parameters (temperature and surface gravity) show pulsation, while the others do not? This is one of the issues that we can follow from decade to decade to see how fast we can provide an answer to a question, if we can manage it at all.

All the available technical possibilities were used in the *data collection* for RR Lyrae stars during this decade. For the end of the decade photoelectric observations in *V* and *B* were collected for nine RR Lyrae stars (Spinrad, 1959). Preston (1959) got spectra of low dispersion (430 Å/mm at  $H_{\gamma}$ ) for hundreds of RR Lyrae stars. He derived the  $\Delta s$  index to characterize the metal content of the stars at minimum light. This way a new possibility was opened for comparing the stars according to their evolutionary status. Additionally, the discovery and analysis of 49 Cepheids in the Small Magellanic Cloud (Arp, 1958) opened the new question of whether, at a given period, the Cepheids in the galaxy and SMC had the same luminosity, mass or chemical composition. Period-luminosity (P-L) relation for Cepheid variables had been exclusively used to find distances to nearby galaxies, since its discovery by Miss Leavitt (Leavitt and Pickering, 1912). However, the precise photometry of Arp (1955) pointed out that the scatter in the P-L relation was real, and not due to the photometric uncertainty. According to Sandage (1958), there was good evidence that Cepheids in the globular cluster obeyed a mean P-L relation, which was at least 1.5 mag fainter than the P-L relation for classical Cepheids. Both types of population and pulsation mode seemed to have an influence on the P-L relation. Although the Population I and II Cepheids were identified (Payne-Gaposchkin, 1954), the type of pulsation modes was not clearly determined.

For other type of variables less information was obtained, which, however, were compared to each other. In the early years

of this decade, before the identification of the group of  $\delta$  Scuti stars (Eggen, 1956),  $\delta$  Scuti itself was compared to classical Cepheids, to cluster-type variables, and to  $\beta$  Canis Majoris stars. Similarities or differences were searched for. The maximum brightness of  $\delta$  Scuti occurred very close to the time of minimum radial velocity (Struve, 1953), as in the classical Cepheids and in cluster-type variables. A range of about 0.005 magnitude in color was found, and the star proved to be bluer at maximum light, as were the Cepheids and certain  $\beta$  CMa stars. By the end of the decade seven members of the  $\delta$  Scuti group were confirmed. Both fundamental and first overtone modes were reported observationally (Fitch, 1959). The  $\beta$  CMa and  $\beta$  Cephei stars were compared to determine whether they belonged to the same group or not (Struve et al., 1953). The possible members displayed similarities and differences concerning the number of periods, the variation in the line profile, the difference in luminosity and sudden change in the main period. Definitely more data were needed to determine the real nature of these types. However, the amount of knowledge collected for Cepheids seemed to be so convincing that in 1954 the Irish Astronomical Journal presented news based on the paper of Grandjean and Ledoux (1954) that "the theory of internal structure and pulsation of Cepheids as well as the structure of their atmospheres, is now based on solid ground". The statement was absolutely truthful in that decade, but we will see how much new information was collected for Cepheids in the next decades. This case teaches us that our current knowledge serves only as the base for the next improvements, although we might feel at each epoch that we have found the truth.

#### 4. RESULTS BETWEEN 1960-1970

There was no dominant technical development in 1960's. Everything was available, both photographic and photoelectric photometry as well as spectroscopy for collecting more information on pulsating stars. The photographic technique allowed us to investigate larger structures of stars (clusters and galaxies) with less accuracy, while the photoelectric technique was used to get measurements of higher precision for individual stars. I emphasize here the importance of the interaction of observation and theoretical interpretation. The observations collected in the previous decade inspired much *theoretical work*. According to King and Cox (1968) the theoretical study of pulsating variable stars had been considerably advanced in the previous 10 years. The progress was attributed in large part to the availability of modern electronic computers, which made it possible to treat the equations appropriate to radial pulsations in their fully non-linear form. They emphasized that the most important and far-reaching result of Eddington was the well-known period-mean density relation,  $P(\rho/\rho_{\odot})^{1/2}=Q$ , where  $Q$  was a constant. Zhevakin (1963) was the first who found that the interaction of the He II ionization with pulsation led to a sufficiently strong unstabilizing force that could overcome damping and drive pulsation. The evolutionary path to the main sequence was calculated by Iben (1965a), and later in many papers he presented the evolutionary path from the

main sequence through core helium burning for stars of different masses (Iben, 1965b). As a major result, a theoretical period-luminosity relation was derived by Hofmeister (1967) in an evolutionary calculation of Cepheids. Compared with the observational data, a good match was found for the fundamental mode. The period-luminosity relation has been used more carefully since then. Stars at a different evolutionary stage served as good distance indicators to the spiral arms and the younger parts of the Galaxy (Pop I classical Cepheids), while the RR Lyrae and Pop II Cepheids (W Virginis) stars that range from intermediate to old age provided an important clue to the kinematics and chemical history of the Galaxy. Wesselink (1963) raised a quite relevant question whether Pop I RR Lyrae variables exist. There was no answer for this question at that time. Although, Pop I RR Lyrae stars were not found in the next decades, the field RR Lyrae stars of higher metallicity were discovered. Combining the period-density law and the expressions for density and luminosity, the pulsation constant ( $Q$ ) could be calculated from photometric observables (absolute magnitude, effective temperature, surface gravity and the pulsation period) (Danziger and Dickens, 1967). The theoretical model of Christy (1966) for RR Lyrae resulted in the pulsation constant for the fundamental and some overtone modes. The transition period [ $P_{tr} = 0.057(L/L_{\odot})^{0.6}$ ], where the fundamental pulsation changed to the first overtone depended only on the luminosity and was independent of mass and composition. Following this a model for classical Cepheids was produced by Stobie (1969). Theoretical models were inevitable to interpret the observational data for the different type of variables. The pulsation constant and the period ratios became an important tool for determining the type of pulsation in pulsating stars.

Despite the great improvement in the theory, there remained questions: what is the limiting amplitude and what is the mechanism behind it? Or what is the effect of convection on pulsation stability? It seemed that a definite theory of time-dependent convective transfer was missing. In some types of pulsating stars even the cause of the exciting mechanism was not known (Mira variables and other type of red variables). According to Christy (1966), there was no indication that the  $\beta$  Cephei variables could be accounted for by the mechanism responsible for RR Lyrae and Cepheid pulsation. The role of the non-radial oscillations of the stars was not explained. New observations were urgently needed to step further in theoretical explanations. On the issues of the amplitude limitation and the convection also show how long a time span and how much observational effort is needed to solve the basic problem of pulsation.

Apparently, sufficient numbers of *Cepheids* were known in the 60's, because there were only a few surveys initiated and mostly in extragalactic systems. Gaposchkin (1962) found 223 variables in the Andromeda Nebula. 59 percent of the variables turned out to be Cepheids, 28 percent were reddish and red irregular variables and five percent eclipsing binaries. Michałowska-Smak and Smak (1965) obtained UBV photometry for eight Population II Cepheids. Kraft (1967) summarized the importance of the spectral lines in the atmospheres of Cepheids, which were



able to give information on the chemical composition and on the velocity of ordered motion of the gases constituting the atmosphere. The physical problems were discussed in connection with the atmosphere of a pulsating star. An obvious additional effect was the broadening of the spectral lines due to pulsation. The reasons were not only the geometrical effect, and a phase dependent velocity gradient, but also a possible change in the velocity parameters usually associated with the phenomenon called “turbulence.”

There was such an urgent need to produce time-dependent convection instead of the mixing-length theory (Böhm-Vitense, 1958) that three serious attempts were published in the 60's (Gough, 1967; Unno, 1967; Castor, 1968). (The treatment of convection is definitely going to be a critical topic for asteroseismology in the space era.) It is connected to the recognized problem that the red edge of the instability strip is determined by convection, which was noticed in the RR Lyrae model of Baker and Kippenhahn (1965).

For *RR Lyrae stars* there were some surveys and all techniques were used during this decade. 62 RR Lyrae stars were found on the southern hemisphere (Clube et al., 1969), and 77 new RR Lyrae stars appeared in the Lick survey (Kinman et al., 1966). Sturch (1966) obtained UBV photoelectric photometry of more than one hundred stars to derive the color indices at minimum light. Paczyński (1966) used the Lallemand photomultiplier for getting three color photometry of RR Lyrae stars, while Preston et al. (1965) carried out simultaneous spectroscopic and photoelectric observations for the RR Lyrae itself. Babcock (1956) discovered a variable magnetic field in the spectrum of RR Lyrae.

The multi-periodicity of RR Lyrae stars had been known for years, where the long periodicity was always of the order of 100 times longer than the fundamental period. The modulation phenomena of RR Lyrae stars was named as the *Blazhko effect* in an ADS search only from 1959. A suggestion for possible cause of the long-period variability, the oblique rotator model of an eruptive variable with an oscillating field was presented by Balázs-Detre and Detre (1962). Despite the observations of long-period variability in RR Lyrae stars, Christy (1966) did not find a 41-day modulation in his RR Lyrae model. Basically, he regarded the modulation phenomenon as a superficial manifestation rather than a deep-seated deviation from his model. As we will see, trying to interpret the Blazhko modulation in RR Lyrae stars extends even to the present day using space data. The Blazhko effect (discovered by Blažko, 1907) is a valuable indicator, too, to track the speed of solution in science.

The observed position of classical Cepheids, RR Lyrae stars,  $\delta$  Scuti stars and dwarf Cepheids on the HR diagram formed a continuous sequence in the  $\log g$  vs.  $\log T_{\text{eff}}$  plane. It was not surprising that there was a confusion in naming. Fortunately, the confusion was settled in this decade. Wesselink (1963) declared that Cepheids with periods shorter than a day, which were often called “cluster” variables, were more suitably named after their prototype RR Lyrae. According to Bessell (1969b), the name of dwarf Cepheids was misleading and naming after of the prototype, AI Velorum was more appropriate. However, Breger (1969a) suggested that it was reasonable to define the dwarf Cepheids as low-mass  $\delta$  Scuti-like variable stars. Two subgroups

of  $\delta$  Scuti stars were suggested. The stars in one group had a mass of  $1.9 M_{\odot}$  (Bessell, 1969a), while the mass of the stars in the other group was  $0.5 M_{\odot}$  (Bessell, 1969b). However, the future will show that this was not the final grouping of  $\delta$  Scuti stars. Due to the overlap of the evolutionary paths from the main sequence to the later evolutionary stages, this part of the HR diagram is rather complex. To see the similarities or differences among the different type of variables, the relation between the amplitudes of the light and radial velocity curves were compared to each other (Leung, 1970). The slopes for the RR Lyrae and  $\delta$  Scuti were nearly the same, while the slope for the  $\beta$  Cepheid was substantially smaller. The light and radial velocity data were consistent with the interpretation that the variability of  $\delta$  Scuti stars arose from radial pulsation similar to the RR Lyrae and the  $\delta$  Cepheid stars. The different groups of pulsating stars being so closely located warns us that pulsation is very common at certain ages and it is only us who separate them into groups (that is, put them into categories).

After the definition as a group in the 50's, the  *$\delta$  Scuti stars* were intensively investigated in this decade. Millis (1967) obtained photoelectric photometry, while Danziger and Dickens (1967) carried out spectrophotometry for new short-period variables. Breger (1969a) tested 213 bright field stars for short-period variability based on photoelectric measurements. Nineteen new variables were found. Narrow-band (Strömgren) photometry and spectroscopic data were collected for most of the 39  $\delta$  Scuti variables published until then. The exponential frequency-amplitude distribution predicted that most stars should vary by a few thousandths of a magnitude with definite periods. The question also emerged in connection to  $\delta$  Scuti stars whether all the stars in the instability strip might really be variable or not. This question was raised in the 50's and this is still an open question in the space era. If we compare the time scale of this unsolved problem to the financial support of 3–5 years of a project, it is obvious that the solution of the basic problems need much more time than the duration of a project. It is even worse if the continuation of the same research projects are not supported in the next application. The empirical  $\delta$  Scuti instability strip and the period-luminosity-color relation were established (Breger, 1969b) in this decade. Actually, only slightly more than 20% of the stars showed regular variability larger than 0.010 magnitude. The physical parameters were derived and investigated in connection to the pulsation. In conclusion, the  $\delta$  Scuti stars had normal mass, but a wide range of metal abundances and rotational velocities. Metal abundance and binarity appeared to have no influence on the incidence of variability. Metallicity and rotation had no effect on the period. The small-amplitude variables shared the high rotational velocity of the non-variables, while the incidence of larger amplitudes depended critically on low rotational velocity. The classical Am stars were stable against the pulsation (Breger, 1970). There was a remarkable improvement in understanding the pulsation in this group in this decade.

The  $\beta$  CMa and  $\beta$  Cephei groups merged to a single group by this decade. 24 new  *$\beta$  Cephei stars* were found in a search by Hill (1967). Altogether there were 41 members of the group. The observations extended considerably the limits of spectral type,

luminosity class, absolute magnitude, periods, and rotational velocity. The  $\beta$  Cephei stars occupied no preferred position in relation to normal stars, i.e., many of the non-pulsating stars were at the same stage of evolution as the  $\beta$  Cephei stars. However, the driving mechanism of the excitation was still unknown.

Observationally it was evident that both  $\delta$  Scuti and  $\beta$  Cephei variables showed long-period modulation (Fitch, 1967) and beat phenomena (Breger, 1969b). Even the amplitude modulation of RR Lyrae stars was mentioned to be connected to this phenomenon. The various interpretations showed large variety: (1) a tidal deformation by a faint component, (2) two nearly equal periods excited by rotation, (3) simultaneous excitation of a large number of radial modes by resonant interactions, (4) rotational coupling of a purely radial and a purely non-radial oscillation modes, (5) oblique rotator, (6) the radial pulsation of a non-spherical star which rotates and presents different aspects of its non-spherical appearance during the course of the rotation period, and (7) pure non-radial pulsation (Ledoux, 1951). The task to answer the remaining questions raised by the theory and to step further in understanding the stars with 'light modulation' was obvious for the next decade.

## 5. RESULTS BETWEEN 1970-1980

Photoelectric photometers, beside the traditional photographic possibilities, spread world-wide in the smaller observatories/institutes, not only in the major astrophysical centers. Using photoelectric photometers we gained higher precision, but we lost the wide field of view of the photographic plates. The photoelectric photometer became perfect for observing a single star with high precision. However, the larger structures in the Galaxy, like open and globular clusters, could not be investigated as a whole, but only from star to star. There was a definite need for a new technology that mixed the precision of the photoelectric photometer and the wide view of photographic plates. That was when the CCD (Charge-Coupled Device) appeared in astronomy, but only at the largest astronomical centers. I myself started my scientific carrier in 1974 at Konkoly Observatory using a Schmidt telescope and photographic plates taking pictures of an open cluster and later fields of intermediate galactic latitudes to study their structure. The photoelectric photometer had already been in use then, but the CCD appeared in Konkoly Observatory two decades later than the 70's.

From this time the work on pulsating variable stars became fashionable. About nine times as many papers were published in this decade as in the previous one. An obvious advantage of a star's pulsation started to be applied. Pulsation was used to find out the physical parameters of the stars, and these were compared to the observations. The investigations of *Cepheids* were dedicated in the whole decade to interpret the differences between masses deduced in different ways. The determination of absolute magnitude, color, effective temperature, and gravity allowed scientists to determine the masses ( $\mathcal{M}_W$  - Wesselink mass) and evolutionary stages of variable stars. Using pulsation theory, three versions of the stellar masses could be derived: from

the pulsation constant ( $\mathcal{M}_Q$ ), for bump Cepheids ( $\mathcal{M}_{bump}$ ), and for beat Cepheids ( $\mathcal{M}_{beat}$ ). The evolutionary theory provided the evolutionary mass ( $\mathcal{M}_{ev}$ ). The masses derived in different ways were supposed to be equal. Stobie (1974) reported ratios as  $\mathcal{M}_Q/\mathcal{M}_{ev} = 0.70$  and  $\mathcal{M}_{bump}/\mathcal{M}_{ev} = 0.60$  which was not acceptable. From time to time different ideas were suggested to resolve the discrepancy. Fricke et al. (1971) argued that the plausible systematic errors in the interior opacity, the distance calibration, or the  $T_{eff}$  vs B-V relation could cause a substantial error in the derived masses. A possible mass loss was also mentioned by Stobie (1974) as a cause of the discrepancy. It was generally emphasized that an error in the pulsation model did not mean that the pulsation theory was incorrect, but rather that the error might be in the input physics. King et al. (1975) suggested that self-consistent masses might be obtained, if the color-temperature scale was used, which reduced the Cepheid's effective temperature by 300–500 K below that normally assumed. Iben and Tuggle (1975) excluded the significant mass loss in the extragalactic Cepheids. New opacities were calculated by Carson and Stothers (1976). Instead of the customarily used standard "hydrogenic" Cox-Stewart opacities, the new opacities were based on the hot "Thomas-Fermi" statistical model of all the elements heavier than hydrogen and helium. The mass anomalies were suggested to be solved by the realization of a very helium-rich convective zone (Cox and Hodson, 1978). The helium enrichment was supposed to be caused by a Cepheid wind which blows away more hydrogen than helium, just as in the solar wind. By the end of the decade the mass discrepancies were not completely resolved, but many of the discrepancies were been alleviated mostly by an increase in the Cepheid luminosity and a decrease in their surface temperature (Cox, 1980a). The pulsation mass  $\mathcal{M}_Q$  was in satisfactory agreement with evolutionary masses ( $\mathcal{M}_{ev}$ ) and the "Wesselink" masses ( $\mathcal{M}_W$ ) were also fairly satisfactory. Thus, only the "bump mass" ( $\mathcal{M}_{bump}$ ) and the "beat mass" ( $\mathcal{M}_{beat}$ ) were anomalous with regard to evolutionary theory (Cox, 1980b). Probably inspired by the mass discrepancies, Cepheids were searched for binarity. A binary system allows for a precise direct measurement of the mass of the members. 35 percent of a sample of 202 variables proved to be in a binary system (Madore and Fernie, 1980). The evolutionary theory predicted the change of the periods as the stars evolved. Classical Cepheids which were monitored for a long time for light variability allowed researchers to check the constancy or the change of the pulsation period. Fernie (1979) reported a linearly decreasing period at a rate of  $8.06 \times 10^{-6}$  d/d for SV Vul, instead of the erratic period change that had been previously thought. Similar investigations were continued for many stars in the next decade. The mass discrepancy of  $\delta$  Cepheids nicely shows that the observations are able to provide a guideline to improve the laboratory physics (opacity calculations). In addition, the changes of the parameters connected to pulsation (periods, amplitudes) have started to be investigated and which is a well-traceable method for the generation of space era.

The research on *RR Lyrae stars* concentrated on three main lines, although they were connected to each other: types of globular clusters, cause of the period changes and the Blazhko effect. The original conclusion of Oosterhoff (1939) claiming that

there were two types of clusters, was confirmed. In Oosterhoff I clusters  $\langle P_{ab} \rangle \approx 0.^d54$  (like M3, M5, M14), while for OoII type clusters ( $\omega$  Cen, M15) the mean period of RRab stars were  $\langle P_{ab} \rangle \approx 0.^d64$  (Stobie, 1971). According to the author, the RRab stars in  $\omega$  Cen were more massive by  $\Delta \log \mathcal{M} = 0.10$  or more helium rich by  $\Delta Y = 0.20$  than the variables in M3. A difference in the mass loss was assumed. The metal content of the two types were also different: OoI type was metal-rich  $\text{Fe}/\text{H} > -1.0$ , while OoII type was metal-poor with  $\text{Fe}/\text{H} < -1.0$  (Butler et al., 1978). van Albada and Baker (1973) suggested that the Oosterhoff dichotomy was caused by a dichotomy in the “transition period.” They argued that Christy’s theoretical relationship between the transition period and the luminosity could not be valid for clusters of different Oosterhoff groups. The mode of pulsation of a star in the transition region depended on whether it was evolving toward the left (OoI) or the right (OoII). Iben and Rood (1970) interpreted that stars in M3 (OoI) passed through the instability strip during the major phase of the core helium burning and hence had high  $Z$ , whereas stars in  $\omega$  Cen (OoII) passed the instability strip rapidly from blue to red toward the end of the core helium burning and hence had low  $Z$ .

Cluster variables, the RR Lyrae stars were investigated for long enough up to this decade to check the period changes of the variables in globular clusters of different type. In early studies it was thought that the O-C diagrams were simply accumulated evolutionary changes in the period (Szeidl, 1975). However, the observations revealed a large variety of period changes. Different distribution of period changes were found for the globular clusters of two types, namely more stars showed period decreasing in OoI clusters and more period increasing were found in OoII type clusters (Szeidl, 1973; Wehlau et al., 1975). In addition, Iben and Rood (1970) calculated the theoretical rate of the evolutionary period change to be some orders of magnitude slower than the rate of the period change observed for many of the cluster variables. They inferred that most of an observed rate of the period change was “noise,” confirming the suggestion of Balázs-Detre and Detre (1965) that some stochastic process was going on. Random mixing events occurring in the semiconvective zone that could produce the observed period changes were mentioned by Sweigart and Renzini (1979). In a review paper Szeidl (1975) came to the final conclusion that at that time it was impossible to attach any evolutionary significance to the observed period changes. The investigation of time dependence became a general approach for each type of pulsating star with a long enough time base. The optimistic hope was to find the evolutionary time scale for the stars. Despite the discrepancies, it was useful to compare the theoretical evolutionary time scale to the observed one.

Furthermore, many RR Lyrae stars were known to show the *Blazhko effect* (Szeidl, 1976). The observed period of this effect ranged from 12 to 537 days and a slow modulation on a time scale of 4 to 10 years was found. There were RR Lyrae stars known where the Blazhko effect entirely disappeared for many decades. The extreme 4 year variation in the 41-day Blazhko effect of RR Lyrae itself was supposed to be an intrinsic magnetic cycle in the stars. Beside the oblique magnetic rotator explanation (Balázs-Detre and Detre, 1962), double mode pulsation was suggested as

a cause of the Blazhko effect (Borkowski, 1980) through a mode coupling (Dziembowski, 1982) of the fundamental mode to the second or third overtones. A decade passed and huge efforts were devoted finding a solution for the mysterious Blazhko effect, but a consensus was not reached. If the funding policy of nowadays had been applied then, the investigation of Blazhko effect would have been stopped for a long time.

Considerable progress had been made in determining the multiple-period structure of individual  $\delta$  Scuti stars and identifying the excited radial and non-radial modes through a variety of methods (Breger, 1980a). Several groups were working on the problem all over the world, in the US in Arizona (Fitch), in Texas (Breger), in Canada (Percy) and groups of Mexican, French, Italian and South African astronomers. By the end of the decade the observational efforts on individual  $\delta$  Scuti stars led to the conclusion that, like A-F stars in general, the  $\delta$  Scuti stars were not completely homogeneous (Breger, 1980b). The evolutionary status and the mass of the dwarf cepheids were determined. The dwarf cepheids were supposed to be Pop I stars with mass around  $2 M_{\odot}$  and a post main sequence evolutionary stage, while SX Phe had low metallicity (Pop II), high space motion and low luminosity. The  $\delta$  Scuti instability strip could be schematically separated for sectors: the stars of high amplitude and low radial velocity were found at the upper part, while the stars of low amplitude and faster rotation were at the lower part, on or near the main sequence. In classical Am (metallic line) stars pulsation was inhibited, however, examples were found for pulsating metallic-line giants, for the  $\delta$  Del stars by Kurtz (1979). According to the Q pulsation constant, the cool  $\delta$  Scuti stars (on the right side of the instability strip in the HR diagram) tended to pulsate in fundamental mode, while the hotter ones (on the left side) pulsated in higher (1st, 2nd) overtones (Breger and Bregman, 1975). The most outstanding example of the presence of the non-radial modes in the light variation of  $\delta$  Scuti stars was the case of 1 Mon, where modes with equidistant spacings were found and identified as rotationally split modes (Balona and Stobie, 1980). Period and/or amplitude variations were reported for some stars by Fesen (1973) and by Stobie et al. (1977) for 21 Mon. However, the most well-known and extreme period/amplitude variation from night to night was recognized by Stobie and Shobbrook (1976) in  $\theta$  Tuc. Although it was cited for years as a special type of  $\delta$  Scuti star, it was obvious that the co-existence of many non-radial modes could also cause an apparent period/amplitude variation. To distinguish the two cases, properly distributed long data sets were needed. Finally, Kurtz (1980) proved using an additional observation of 70 h over 21 nights that the amplitude of the main period was stable over 7 years, but not the others. My personal connection to  $\theta$  Tuc was that 20 years later, carrying out a three-site international campaign we could prove that there were nearly 1 c/d frequency differences among three modes which could not be resolved from single site observations (Paparó et al., 1996).

Concerning the modeling of  $\delta$  Scuti stars, it was Cox (1976) who summarized the difficulties. The non-radial pulsation seemed to be far more intricate than the corresponding theory of purely radial oscillation, for this reason it was in a considerably less-developed state. The fully non-linear,



non-radial, non-adiabatic calculation of stellar oscillations had not been attempted by anyone. The full set of non-linear, partial differential equations that describe the pulsation of stars had not been solved without significant approximations or special assumptions for any star or stellar system. In the theory of non-radial oscillations of a star it is customary to assume that each physical pulsation consists of the product of a purely “radial” part, a function of the radial distance alone, a spherical harmonic and an exponential time dependence. The order of the harmonic is given by the value of angular harmonic index  $\ell$ , which is positive integer or zero. Possible number of the other index  $m$ , are  $2\ell+1$ . The problem of mode identification (determination of the harmonic indices) for non-radial oscillations in realistic stellar models had proved to be very difficult. With such assumptions, a detailed linear survey of stellar models intending to represent dwarf cepheids and  $\delta$  Scuti stars was carried out by Stellingwerf (1979). Growth rates, periods, and other parameters for the first six radial modes were given. The non-adiabatic stellar modes indicated that non-radial modes were probably present as well (Stellingwerf, 1980). However, the author emphasized that some basic physical dissipation mechanism seemed to be missing. Due to the lack of the non-radial period ratios, the only possibility for identifying the non-radial modes was to compare the observed period ratios to the theoretically derived radial period ratios. If the observed period ratios did not agree with the theoretical radial period ratios, the modes were identified as non-radial modes. This was reacting to the physics of the model. Hard efforts have been made to solve the problem of mode identification. Dziembowski (1977) derived formulas for the light and radial velocity variations of non-radially oscillating stars in the case of linear approximation. The author showed that the Wesselink technique, similarly to the case of radial pulsation, might also be used to determine the radius of a star, if the spherical harmonic order of the oscillation is known, or alternatively to determine the spherical harmonic order, if the radius is known. Balona and Stobie (1979) extended Dziembowski's idea and formulated the practical application of the Wesselink technique for this purpose.

Investigations in this decade resulted in the belief that pulsation and especially non-radial pulsation were ubiquitous among the stars. They occurred in  $\beta$  Cep stars, variable line profile B stars,  $\delta$  Scuti stars, the white dwarf components of some cataclysmic variables, the Sun, and the ZZ Ceti stars. Huge efforts were invested to know more about their pulsational behavior.

Ledoux (1951) showed that free radial oscillations could explain some of the observed properties of the puzzling class of  $\beta$  Cepheids, however, he did not consider what the cause of such oscillations were. Observations in UBV from the ground (Jerzykiewicz, 1971) and in the far ultraviolet from different satellites (Hutchings and Hill, 1980) were carried out to know more on the pulsation behavior, however, the cause of the oscillations remained unknown. Osaki (1974) suggested a resonance between the non-radial oscillation of the whole star and the overstable convection in the rotating inner core. Aizenman et al. (1975) found a nuclear driven vibrational instability in some of the lower  $g^+$  modes. Non-linear coupling was suggested as a mechanism by which this instability might

excite the shorter-period  $f$  or  $p$ , or perhaps radial harmonic modes which were supposed to be observed in the  $\beta$  Cephei stars. However, the final conclusion by the end of this decade was that no viable instability mechanism had been found for their pulsation (Lesh and Aizenman, 1978).

To complicate our understanding of B stars, Smith (1977) found pronounced changes in the line profile of *53 Persei*, which was located far from the classical  $\beta$  Cephei region. In the same year Percy and Lane (1977) reported small, but significant light variations for *53 Persei*. This star, the prototype of a new group, was the first star to show both photometric and spectroscopic variations that could be best explained in the framework of non-radial pulsations (Buta and Smith, 1979). Definitely much work will be done on these stars in the next decades. I joined a multi-site photometric campaign on *53 Persei* 20 years later to resolve the full frequency spectrum that could not be acquired from single site observations (Huang et al., 1994).

After the discovery of the first pulsating *DA white dwarf (ZZ Ceti stars)* by Landolt (1968) during systematic surveys in broad range of colors, it soon became clear that the ZZ Ceti variability was caused by pulsation. The instability strip was then defined and it was established that the ZZ Ceti stars were otherwise normal white dwarfs. The variability was an evolutionary effect and all DA stars passed through the temperature range in which the variables occurred (McGraw, 1980). The improvement of our knowledge on pulsating white dwarfs was fast because we can observe many pulsations of a ZZ Ceti star per night. A great improvement in the realistic modeling of ZZ Ceti stars was also expected in the following decade. The investigation of the 5-min oscillation of the Sun became a distinct field, called helioseismology.

## 6. RESULTS BETWEEN 1980-1990

The new observational tool, the CCD, was slowly appearing in the smaller observatories/institutes. New instrumentation was developed only on specific request, like a multi-channel photoelectric photometer for doing fast photometry for compact objects, or a multi-slit photoelectric magnetometer for measuring the circular polarization of 230 spectral lines simultaneously. The CORAVEL (CORelation-RADial-VELocites) instrument started to operate at La Silla in 1981. Space instruments started to be used mostly in the far ultraviolet (International Ultraviolet Explorer, IAU, 1978) and in the infrared (Infrared Astronomical Satellite, IRAS, 1983), which cannot be observed from the ground, due to the atmosphere of the Earth. The Hubble Space Telescope (HST) was launched in 1990, but due to technical problems it started the science mission only in 1993 after servicing.

In this decade not only the classical radially pulsating groups (RR Lyraes, Cepheids), but the non-radially pulsating groups ( $\delta$  Scuti, white dwarfs) were intensively investigated, not only observationally, but the new observations immediately inspired extended theoretical work. Less improvement was achieved for  $\beta$  Cep stars, but the research status of a new group, the Long Period Variables (LPVs) is also mentioned in this decade.



The research of the *RR Lyrae stars* in this decade started with two exciting papers based on new observations. The first was still connected to the Oosterhoff types of globular cluster. Sandage et al. (1981) compared the period-amplitude, the period-rise time, the period-color, and the color-amplitude relations for M3 (OoI) and M15 (OoII) type clusters and recognized that all correlations of the parameters that involved the periods were shifted by  $\Delta \log P = 0.055$  toward longer periods in OoII type globular cluster, whereas the other relations of the two cluster coincided. The only consistent explanation was that the horizontal branch of M15 was brighter than that in M3 by  $\Delta \log L_{HB} = 0.090$ . As Smith (1984) summarized the series of Sandage's papers, the period of an individual cluster RR Lyrae star at a particular effective temperature decreased with increasing metal abundance. RR Lyrae stars are intrinsically fainter in metal-rich clusters than in metal-poor clusters. The RR Lyrae stars of different metallicity might also have different luminosity. Of course, huge efforts were put into determining the metallicity of individual RR Lyrae stars. Smith (1984) used the  $\Delta s$  method which was a means of determining the metal abundances from low-resolution spectroscopy. It was hoped that if photometry of high accuracy was available, the metal abundance of individual RR Lyrae stars could be determined from just their light curve. Definitely the space data of unprecedented accuracy offer the possibility to follow this suggestion and get the determination of metallicity for numerous RR Lyrae stars. The statistical approach might reveal some, up to now hidden, structural connections. Nevertheless, in the light of these results the question seems to be reasonable: are RR Lyrae stars good standard candles?

The second interesting paper reported the discovery of ten double mode RR Lyrae stars in the M15 (OoII) globular cluster (Cox et al., 1983). The period ratio of the fundamental and first overtone resulted in  $(\Pi_1/\Pi_0) = 0.746$ . Surprisingly, the period ratio of RR Lyrae stars gave a reasonable mass, compared to the double mode Cepheids, where the mass based on the period ratio was very low. Many clusters were checked for double mode RR Lyrae stars and about three dozen were found by 1987. However, in the  $\omega$  Cen cluster no doubly periodic RR Lyrae star was found (Nemec et al., 1986), suggesting that the number of double mode RR Lyrae is connected to the metallicity or the actual brightness of the horizontal branch.

Significant observational discoveries inspire immediate theoretical reactions, as we saw in the previous decades. Of course, there was a large interest in modeling the double mode pulsation in RR Lyrae stars. It was shown that based on the simultaneous effect of resonant mode coupling, the 2:1 resonance between one of the two linearly unstable modes and a higher frequency mode caused double mode (fundamental and first overtone) pulsation (Dziembowski and Kovacs, 1984). According to the authors, the resonant mode interaction might be an effective amplitude limiting mechanism in oscillating stars. Stothers (1987) concluded that second overtone pulsators probably did not exist among RR Lyrae stars. Finally, stable multimode pulsations were shown to be possible in state-of-the-art RR Lyrae models, but did not have periods close to those observed in beat RR Lyrae stars (Kovacs and Buchler, 1988). The simultaneous effects of the resonant mode coupling

and the non-linear saturation of the driving mechanism were also studied by Moskalik (1986). Under certain conditions the only stable solution was a limit cycle in the form of a slow periodic modulation of the amplitudes. In the case of RR Lyrae stars the 2:1 resonance between the fundamental and the 3rd overtone was the most likely cause of such behavior. Upon a reasonable choice of parameters one could reproduce observed periods of the Blazhko effect. A strong suggestion was that the amplitude-modulated stars might be closely related to  $RR_d$  stars and the same mechanism might be responsible for both phenomena. A new cornerstone in the explanation of amplitude limiting mechanisms and the Blazhko effect is the idea of the resonant mode coupling.

A different observational/theoretical approach also appeared. Fourier decomposition was employed to compare the light curves of RR Lyrae stars with those emerging from the hydrodynamical models. The  $\phi_{21}$ ,  $R_{21}$  and  $\phi_{31}$  were plotted against the period. The general definitions of the time-dependent phase difference between the fundamental mode and the harmonics and the amplitude ratio are given as:  $\phi_{k1} = \phi_k - k\phi_1$  and  $R_{k1} = A_k/A_1$ . The  $RR_c$  type pulsators stand out from the  $RR_{ab}$  stars, particularly on the  $R_{21}$  plot which was found to be a more sensitive discriminator of Bailey a, b, and c type stars (Bailey, 1902) than the traditionally employed amplitude-period diagram (Simon and Teays, 1982). Such kinds of investigations will be definitely even more effective on space data. A very good agreement was obtained between theory and observation for the  $RR_c$ , but there were significant discrepancies in the Fourier phase quantities  $\phi_{21}$ , and  $\phi_{31}$  for  $RR_{ab}$  (Simon, 1985). The calculated values were considerably larger than the values determined from observed stars. It was not clear how drastic a change would be necessary in the models to get an agreement. According to Simon, a new series of hydrodynamic calculations was needed to answer the remaining questions. In an effort to explain the discrepancy of period ratios for Cepheids, Simon (1982) showed that arbitrarily increasing the opacity by a factor of 2–3 would solve the discrepancy. The new opacity code, OPAL, using an improved treatment of the atomic physics significantly increased the Rosseland mean opacity of metals in astrophysical mixtures (Iglesias et al., 1987). The new opacities confirmed what had been outlined as a need by observations over the previous decade. This is another data point to establish the time scale of the progress in pulsating stars.

Additional efforts were carried out in this decade for solving the mass discrepancy of *Cepheid variables* from both an observational and a theoretical point of view. The new P-L-C relation was obtained by Schmidt (1984), which revealed a discrepancy in the absolute magnitude as much as 0.4–0.6 magnitude. A new set of homogeneous Wesselink masses was obtained for 101 classical Cepheids (Gieren, 1989). Theoretical models of normal Pop II type Cepheids in the period range of 1–10 days were constructed with the Carson opacities (Carson et al., 1981). The derived masses closely agreed with masses determined directly from atmospheric analyses and indirectly from stellar evolution theory. The theoretical luminosities predicted from the standard evolutionary tracks had to be increased by 0.5 mag, but they were entirely consistent with the modern evolutionary tracks that included some degree

of convective core overshooting (Carson and Stothers, 1988). Observations of Cepheids in local and distant galaxies comprised one of the Key Projects approved for the Hubble Space Telescope in the first cycle (Simon, 1990). Unfortunately HST was properly working only from 1993. The main goal was to pin down the Hubble constant to an accuracy of  $\pm 10\%$  to determine the correct distance scale. The non-linear pulsational behavior of several sequences of Cepheid models was computed with a numerical hydrodynamic code (Moskalik and Buchler, 1990). These sequences exhibited a period doubling, as the control parameter, the effective temperature, was changed. The period doubling was caused by the resonance of the type  $(2n+1)\omega_o \approx 2\omega_k$  ( $n$  is an integer), and it turned out to be different for Pop I (single doubling) and Pop II (a cascade of period doubling or chaos) Cepheids. The period doubling is a phenomenon which becomes more important in the future.

More and more additional details made our view of Cepheids colorful, however, in most cases there was no consensus in their interpretation. Much attention was paid to the so-called s-Cepheids as well which were classified as low amplitude pulsators with short period and sinusoidal light curves. They were Pop I Cepheids that did not follow the Hertzsprung progression of the classical Cepheids, but had a progression of their own (Antonello et al., 1990). In the  $\phi_{21}$ -P plane they exhibited separate sequences. The short period group with  $p < 3d$  had high  $\phi_{21}$  values, while the long period group with  $p > 3d$  had low  $\phi_{21}$  values. According to Antonello et al. (1990), both groups were pulsating in the first overtone and they attributed the apparent sharp break in the  $\phi_{21}$  diagram near  $3d$  to a resonance between the first overtone and a higher normal mode. However, Gieren et al. (1990) argued that the low  $\phi_{21}$  value represented fundamental mode pulsation as was predicted by theory, only the light curves for some reason differed from those of the stars along the classical fundamental mode sequence. The periods of the long period region essentially coincided with the observed range of classical double-mode Cepheids (Simon, 1990). As a result a far-reaching precedent started in the well-defined  $\delta$  Cep stars and when new details appeared, apparently new subclasses were created. So, instead of unification we divided the HR diagram into smaller and smaller boxes.

The unusual Cepheid HR 7308, with the shortest known period was extensively investigated (Breger, 1981). The long-term follow up revealed that the amplitude varied by over a factor of 5 with a period of about 1210 days. The amplitude variation suggested a Blazhko effect (observed in RR Lyrae variables, but not in Cepheids) or that an evolutionary event was taking place. Radial velocity variation was monitored during 3 years with the spectrophotometer CORAVEL, confirming the same periodicities as in the light curve (Burki et al., 1982). The type of the excited mode was doubtful. According to Fernie (1982) HR 7308 was not an overtone pulsator. In contrast, an intercontinental simultaneous survey revealed that HR 7308 was a classical Cepheid pulsating in the second (or higher) overtone. However, the possibility that the star was a Pop II Cepheid and/or that it was pulsating in the fundamental mode or the first overtone could not be ruled out definitively (Burki et al., 1986).

More and more precise rates of period change were obtained as the time baseline increased. Secular period changes of 100 northern Cepheids were investigated with the help of O-C diagrams (Szabados, 1983). The rates of the period changes were in good agreement with those determined from stellar evolutionary theory. The frequency of binary stars among the Cepheids was as high as 25%. Most of the companions of Cepheids were B-type stars (Szabados, 1982).

Of course, the  $\delta$  Scuti stars being in the childhood of their investigation and, due to their having shorter periods than the classical Cepheids, attracted more interest observationally. Individual  $\delta$  Scuti stars were intensively investigated. Different pulsational behaviors were reported: (i) a single sinusoidal component which did not agree with the fundamental mode (Bossi et al., 1983), (ii) a mixture of radial and non-radial modes (Bossi et al., 1982), (iii) monoprotic pulsation in the second overtone (Pena and Gonzalez-Bedolla, 1981), (iv) pure radial pulsation in first and second overtones or fundamental and first overtone with He depletion (Cox et al., 1984), (v) mode switching (McNamara and Horan, 1984; Paparó and Kovacs, 1984), (vi) multiple close frequencies (Breger et al., 1987), (vii) an amplitude variability on a time scale of years (Breger et al., 1990), which was compared to the Blazhko effect of RR Lyrae stars, and (viii) a period decrease (Breger, 1990; Guzik and Cox, 1990). The metallicity and the pulsation connection in  $\delta$  Scuti stars got a new aspect. Pulsation was also found in a classical Am star (Kurtz, 1989). Even the discovery of a new class of variable stars, the rapidly oscillating Ap (roAp) stars was announced (Kurtz, 1982). The amplitudes of oscillations were modulated with the same period and phase as the magnetic strength. This fact suggested that the excitation mechanism of the oscillation in Ap stars was somehow related to the strong magnetic field. All Ap stars were located in the  $\delta$  Scuti instability strip, therefore some physical connection between the pulsation of  $\delta$  Scuti stars and those of Ap stars was suggested (Shibahashi, 1987). Despite the huge effort in investigation of  $\delta$  Scuti stars, Kurtz (1986) called the attention to collaborative contemporaneous observations of multi-periodic  $\delta$  Scuti stars from more than one observatory. He claimed this was needed much more than the discovery of new  $\delta$  Scuti stars or incomplete frequency solutions for many stars.

Concerning the theoretical work, a basic step was done by Fitch (1981). He used a full stellar model and calculated linear adiabatic periods for all models. He presented 489 Q values for 35 modes. The survey was complete for the range  $0 < \ell < 3$ . For double mode  $\delta$  Scuti stars the period ratio resulted in a serious discrepancy between the theoretical and the observed values. According to Andreasen and Petersen (1988), a helium depleted outer zone with a relatively low mean molecular weight due to inward He diffusion might be the correct explanation for the observed  $\Pi_1/\Pi_o \approx 0.77$ . However, there was a great discrepancy between the number of observed and theoretically excited frequencies. Different concepts were checked for getting an appropriate mechanism for the amplitude limitation and mode selection. The effect of the parametric resonance on the development of acoustic mode instability in a model of Zero-Age Main-Sequence, ZAMS  $\delta$  Scuti stars was first discussed (Dziembowski and Krolikowska, 1985). Later

amplitude equations were derived describing the three-mode coupling in the presence of rotation (Dziembowski et al., 1988). For the evolved  $\delta$  Scuti stars with very dense non-radial frequency spectra the phenomenon of mode trapping was investigated as a possible mode selection mechanism (Dziembowski and Krolikowska, 1990). There was evidence that this effect, rather than saturation of the opacity mechanism, determined the mode amplitudes. However, the non-linear theory of stellar non-radial oscillation had not reached the level to enable the calculation of the amplitude of the unstable modes. In any case, the prospect of asteroseismology rests on our ability to connect measured frequencies to specific eigenmodes of stellar oscillations. This would mean the possibility for mode identification which would be an important step in the asteroseismology of  $\delta$  Scuti stars. Mode trapping as a mode selection mechanism was first mentioned in this decade, but later we will find this explanation in connection with other type of pulsating stars.

New efforts were made in the determination of the spherical harmonic degree  $\ell$  and the azimuthal order  $m$  of a mode from observations. Balona (1986a) proposed a simple method of analyzing spectral line profiles in non-radially oscillating, rotating stars avoiding the profile modeling. What was more, an algorithm was presented which allowed a completely objective determination of all parameters for line profile variation in a non-radially oscillating star (Balona, 1986b). Watson (1988) presented histograms as a function of  $\ell$ , among them was the amplitude ratio vs. phase difference plane ( $A_{col}/A_{\lambda 1}$ ,  $\Phi_{col}-\Phi_{\lambda 1}$ ). Compared with the model predictions, the light and color data seemed to assist in mode discrimination for low  $\ell$ . Garrido et al. (1990) calculated the six possible discrimination diagrams from the four Strömgren filters, and they found that the diagrams v-y and b-y were discriminant between radial and low order non-radial pulsations, irrespective of the physical parameters such as temperature, gravity, or pulsational constant for the  $\delta$  Scuti models considered. Although seemingly many ways of mode identification were available, only a few modes in a few  $\delta$  Scuti stars were identified. It was predicted by theoreticians that data sets that were long and continuous were the missing cornerstone of the massive mode identification in  $\delta$  Scuti stars. Observers in my generation often heard the following sentence: “go to the telescope and observe more and the problem will be solved.” We will see that it is not easy to identify modes in the non-asymptotic regime (p modes), especially for fast rotating stars, even from the much longer, more continuous space data that we only dreamed about in this decade. Mode identification in stars pulsating in the non-asymptotic region is also a good indicator of the speed of progress. The problem was theoretically discussed in the last decade, but reliable practical applications are presented here. It will be followed also in the next decades.

The most impressive improvement was achieved in the field of *white dwarfs* along the lines of doing real asteroseismology. From the observational side, partly they were ideal targets for single site ground-based observations (Kawaler and Hansen, 1989), and the new astronomical instrument, the Whole Earth Telescope (WET, Nather et al., 1990) concentrated the efforts of existing telescopes distributed in longitude to measure designated targets. The details of the pulsational features grew incredibly

quickly. The theoretical studies of ZZ Ceti (DAV) stars led to the prediction that the DBV white dwarfs should also pulsate driven by helium partial ionization zone. The same team discovered the first DB pulsator, GD 358 (Winget et al., 1982). Soon, groups of different ages were recognized: PNNV ( $10^4$  yr), DOV ( $10^5$  yr), DBV ( $10^7$  yr), and DAV (ZZ Ceti,  $10^9$  yr) (Winget, 1988). According to the rate of the period change ( $9.9 \times 10^{-15}$  s/s), a ZZ Ceti star (G117-B15A) proved to be one of the most stable clocks of any kind in the sky (Kepler et al., 1988), which was equivalent to a  $6.9 \times 10^8$  year evolutionary cooling time scale. For the prototype of the hot group, PG 1159-035, the rate resulted in  $dP/dt = -1.2 \times 10^{-11}$  s/s, and a faster evolutionary time scale,  $\tau \approx 1.4 \times 10^6$  yr (Winget et al., 1985). Impressively, evolutionary changes could have been detected in one to two decades using stellar pulsation.

Mostly multi-periodic oscillations were observed, but mono-periodic pulsation (and its harmonics) was found in a DBV star (PG 1351+489, Winget et al., 1987) that was both unanticipated and unexplained. In addition, a significant pulsation frequency near  $3/2 \nu_0$  was localized, not only in this DBV star, but in DAV white dwarfs, one of which was GD 154. Let me include a personal connection to GD 154. In the frame of an educational project for MA students I initiated the observation of GD 154 at Konkoly Observatory over a whole observational season (about 6 months) in 2006 (G. Fontaine suggested the star, due to the large amplitude). We confirmed the surprising finding of Robinson et al. (1978), that on the last night the  $3/2 \nu_0$  became the dominant mode. In 2006 GD 154 showed multimode pulsation, except at the end of the observing run, when the pulsation switched to monoperiodic pulsation (Paparó et al., 2013). Alternating high and low amplitude cycles and temporarily increased amplitudes of some cycles (about 30 % more pulsational energy) were presented in a poster even earlier, but the revulsion of the editor concerning the content led to the withdrawal of the poster paper from the proceeding. Years later (suggested by P. Bradley), though, we did finally get these unusual behaviors published in the aforementioned paper. We will see that space data revealed similar effects, such as alternative cycles-period doubling for RR Lyrae stars and outbursts for white dwarfs. It is definitely a great advantage for the present generation that they do not have to fight for the acceptance of the observed data. Comparative analyses of the observation of the subsequent years for GD 154 revealed that the star not only varied its pulsational behavior between a “simple” multi-periodic and a quasi mono-periodic phase with harmonic and subharmonic peaks, but there were differences between the visibility of the near-subharmonics in the latter phase (Bognár et al., 2019). GD 154 will be a target of TESS (private communication by Zs. Bognár). GD 154 epitomizes the situation that Winget (1988) summarized in his white dwarf review: “we will find little that we do expect and much that we would never expect.” I think this statement will be extremely valid in the space era.

Nevertheless, there were other exciting results in this decade in which nobody doubted. Two statistically mean period intervals, “characteristic period spacing” of  $21.0 \pm 0.3$  or  $8.8 \pm 0.1$  s were derived from observation for the hot white dwarf star PG 1159-035. A very good agreement with the theoretically derived



period intervals resulted in the determination of the mass ( $0.6 M_{\odot}$ ) and the identification of the modes as  $\ell = 1$  or  $3$ , or both (Kawaler, 1988). The determination of the physical parameters of white dwarfs meant that the modeling of the groups of white dwarfs was also a great success in this decade. The model had a simple stellar structure, C/O core, thin layers of helium and/or hydrogen depending on the group. For the hotter groups (PNN and DOV) the partial ionization of C and O were also taken into consideration. However, the problem of the selection mechanism also occurred here. The resonance of a certain  $g$  mode to the thickness of the surface composition layers meant that mode trapping could be a possible filtering mechanism (Winget, 1988; Kawaler and Weiss, 1990). Convective blocking was reported as another candidate for a spatial filter in ZZ Ceti stars (Pesnell, 1987). Color observations confirmed the theoretical expectation that white dwarfs evolve at constant gravity (Fontaine et al., 1985). The instability strip was narrow and all the white dwarfs showed pulsation as they crossed the instability strip along their evolution. The research level of white dwarfs was so advanced that Winget (1988) was able to raise the question that we wanted only to guess at the beginning of the space era: can we reach the asteroseismological level? He gave two possible answers, a pessimistic and an optimistic one. The pessimistic was that asteroseismology will never work, but the optimistic one was that it would give us the age of the Universe. Let us hope that the space data will take us to the optimistic solution. Despite the success of white dwarfs Winget (1988) suggested that non-linear non-radial calculations were highly needed. Although these calculations are complex, supercomputers were improving, but a basic step was real progress in understanding convection. He called it the “Holy Grail” of hydrodynamics, since it was important in all helio- and asteroseismology. White dwarfs are discussed in detail as an excellent example to show how important the ratio between the length of the pulsation period and the time base of the observations are. Due to the shorter pulsation period the progress is accelerated compared to the time dependence of progress in the classical pulsating stars or in the non-asymptotic pulsators. Mode trapping became an obvious explanation for mode selection in white dwarfs.

For many decades it was supposed that the  $\beta$  Cep variables were the only pulsating B stars (Balona, 1990). The discovery of the 53 Per stars, the moving bump of  $\zeta$  Oph and the periodic light and line profile variations of many Be stars confused the picture. Although the theoretical problems in  $\beta$  Cep stars were still existent (Cox, 1987), many observers moved to the observation of new features instead. Although 150 stars were classified as  $\beta$  Cep candidates, even their definition as a group was not clear based on the type of pulsation (Sterken and Jerzykiewicz, 1990). However, according to the observational H-R diagram, all  $\beta$  Cep stars were confined to a very narrow spectral range from B0.5 to B2. Their evolutionary stage could be close to the end of the core hydrogen-burning, the second contraction or the shell-hydrogen burning phase. The most prevalent view was that practically all B stars were unstable to radial or non-radial pulsations and that the  $\beta$  Cep stars represented merely an island of short (possibly p-mode) pulsations in an ocean of long-period g-mode pulsation (Balona, 1990).

Advances in our knowledge of the details of long-period variability have been gained rather slowly due to the extended nature of the atmosphere and the dominance of the convective energy transport in the interiors (Wood, 1987). The LPVs occurred at a very interesting phase in the life of all the stars independently of mass, when they were most luminous and gave insight into their evolutionary mass loss. The old LPVs belonged to a kinematic system which had a systematic velocity that was indistinguishable from that of the H I gas (Bessell et al., 1986). Because of their great brightness and the existence of the P-L relation, these stars might be a useful group of extra-galactic indicators (Wood and Bessell, 1985).

## 7. RESULTS BETWEEN 1990-2006, BEFORE THE SPACE ERA

Though data collection mostly continued in traditional ways, different approaches were followed to obtain more and more adequate data-sets for solving specific problems. The success of the WET organization in the research of pulsating white dwarfs had a great influence on getting more appropriate data for other pulsating stars, too. Some low-amplitude  $\delta$  Scuti and roAp stars were also observed by the WET organization. On the other hand, coordinated multi-site international campaigns were more and more often organized to get as continuous data as possible for  $\delta$  Scuti stars,  $\beta$  Cep stars, especially for  $\gamma$  Doradus and SPB stars, where the determination of the characteristic periods of the pulsation were highly disturbed by the daily gaps. Most of these campaigns were organized by different individuals from time to time. However, there were two permanent networks, the Delta Scuti Network (DSN) and STEPPI for solving the problems of  $\delta$  Scuti stars. Some hundreds of hours of data were collected and analyzed together. Another advantageous option appeared for the variable star research in this decade when telescopes dedicated to special problems started to work. SDSS (Ivezić et al., 2000) was a multi-color survey which aimed at providing a 3-D map of the Universe over a large part of the sky. The other projects, MACHO (Alcock et al., 1997), OGLE (Paczynski and Udalski, 1994), OGLE II (Udalski et al., 1997), EROS (Beaulieu et al., 1995), MOA (Bond, 2001) photometrically monitored tens of millions of stars in different parts of the sky to search for dark matter with microlensing phenomena. These surveys happened to include variable stars, too. The new efforts led to new results, adding new mosaics to the general knowledge. These surveys have extended archived databases, that could be also important in connection to the space data for checking time dependence on longer time scales.

The long-standing unsolved problem of the Blazhko modulation remained a central issue, but on a higher level. The dedicated telescopes improved the database and new concepts appeared. Amazing efforts were devoted to the interpretation of the Blazhko effect in *RR Lyrae stars*. Both an extensive multi-site photometric observation over a 421-day interval in 2003-2004 (Kolenberg et al., 2006) and spectroscopic coverage over an entire Blazhko cycle (Chadid and Chapellier, 2006)



of RR Lyrae itself were carried out to make a choice between the two possible explanations. According to the resonant model, the non-linear resonant coupling of the dominant radial mode and the non-radial modes predicted a triple frequency structure with side lobes of similar amplitudes which were expected to be symmetrically placed. The magnetic model predicted a quintuplet structure; however, in certain geometric configuration only a triplet structure could have been expected. Both photometric and spectroscopic campaigns resulted in a triplet structure in the frequency content, and there was no sign of the quintuplet structure. It was hoped that high-quality and continuous space data will decide between the two possible explanations. Furthermore, the MACHO project (Alcock et al., 1992) incidentally gathered data for many Blazhko-type RR Lyrae stars. It became clear that the Blazhko effect had a different appearance. There were Blazhko RRab stars with pure amplitude modulation or with both amplitude and phase modulation, or abrupt period changes could occur. The Blazhko effect was found not only in RR<sub>ab</sub> stars, but in RR<sub>c</sub> stars (Kurtz et al., 2000) as well. The existence of non-radial pulsation in a “pure” radial pulsator had always been questionable. Finally, non-radial pulsation was reported in three RR<sub>c</sub> stars in the M55 globular cluster (Olech et al., 1999). The theoretical calculations also clearly showed that low-degree non-radial modes could be excited (Van Hoolst et al., 1998). A large number of unstable modes in the vicinity of radial modes were partially trapped and presumably most likely to be excited. However, their routine observations needed excellent photometric coverage, e.g., uninterrupted continuous space data. The available high-quality ground-based data that had been accumulated for many RR Lyrae stars allowed the establishment of a relation between the metallicity parameter, Fe/H and the Fourier parameters, most importantly  $\phi_{31}$ . It became possible to derive physical parameters based on the morphology of the light curves for both RR<sub>ab</sub> (Jurcsik and Kovacs, 1996) and RR<sub>c</sub> stars (Simon and Clement, 1993). A comparison of the Blazhko-type and non-modulated RR<sub>ab</sub> stars yielded the conclusion that there was no Blazhko phase that seemed to be well-matched with that of non-modulated RR<sub>ab</sub> stars (Jurcsik et al., 2002). Definitely the RR Lyrae research was waiting for the space missions. The longer expected time base of the space data compared to the length of the pulsation period or, more importantly, to the length of the period of the Blazhko effect, was expected to give remarkable improvement for the explanations.

The research for *Cepheids* partly used the most advanced techniques and dedicated telescopes in getting more sophisticated data, at the same time advanced theoretical investigations were carried out. Much progress was made in determining the fundamental properties of Cepheids. The indirect determination of Cepheid masses seemed now to be in agreement with the direct mass and the evolutionary masses due to the new opacities as it was summarized by Percy (1993). The calibration of the zero point of the Cepheid P-L relation was still a challenge, but CHARA and AMBER gave a good chance for the precise determination of the stellar diameters and the related physical parameters (Moskalik and Gorynya, 2006). The Hubble Space Telescope contributed to the binary Cepheids with a new discovery. Some previous binary systems were revealed

to be in fact members of a triple system. At least 44 percent of the Cepheids was thought to be in a triple system (Evans et al., 2005). For many years AC And (Fitch and Szeidl, 1976) was the only triple-mode radial pulsator. Recently, two Cepheids were discovered by OGLE in the Large Magellanic Cloud that were pulsating in three radial modes (Moskalik and Dziembowski, 2005). From the theoretical side, strange modes were localized in radiative classical Cepheids and RR Lyrae models (Buchler and Kolláth, 2001). These were surface modes predominantly trapped in the outer region of the star due to a very sharp and enormously high potential barrier in the partial ionization zone. The typical modal number of a strange mode falls between the 7 and 12th overtone with a mmag amplitude level which could be observed in the space era. These stars could be the “strange Cepheids” or the “strange RR Lyraes.” The discovery of “anomalous” Cepheids (ACs), which had low metallicity but did not follow the P-L relation of Pop II Cepheids created some confusion in the identification of Cepheids. The new grid of evolutionary model by Fiorentino et al. (2006) led to the conclusion that the ACs were the normal extension of Pop I classical Cepheids to lower metal content and smaller masses. Hopefully, with more precise space data there will not be more and more separate subgroups, but that a unified explanation will be reached. Comparing the different groups we can notice that mode trapping appeared in RR Lyrae and  $\delta$  Cepheids, too, not only in white dwarfs. Once I was talking to a friend, who is a theoretician, about the similarities of the different type of pulsating stars, but at present independent codes are used for each type of pulsating stars. He immediately asked me whether I was talking about a unified pulsation code, where the different types of pulsating stars meant only different input parameters. I am an observer, so I may dream, although I know it is an extremely hard task. Definitely the first step would be a code for the non-linear treatment of non-radial pulsation.

The  $\delta$  Scuti research field was in the intensive data collection phase, during which up to that time unexplained characteristics were recognized. The effect of the chemical peculiarity on the pulsation got a new aspect, and the pre-main sequence  $\delta$  Scuti stars joined the company of the pulsating stars. Modeling of time-dependent convection in  $\delta$  Scuti stars had been started. Much new data were collected for a great number of  $\delta$  Scuti stars in this decade by coordinated multisite campaigns, although two permanent organizations were the really successful ones. These were the Delta Scuti Network (DSN) founded by M. Breger, and STEllar PHotometry International (STEPHI) headed by E. Michel as the coordinator. However, individual organizations were also successful (Paparó et al., 1996; Paparó and Sterken, 2000 for  $\theta$  Tuc, and Paparó et al., 2018 for 38 Eri, based on a multisite campaign from 1998 and MOST observation from 2011). The ground-based campaigns collected data in at least two colors, hoping for the possibility of mode identification. In the best cases, simultaneous spectroscopic observations were also carried out. FG Vir, 4 CVn, and XX Pyc became the most famous and best-studied  $\delta$  Scuti stars in this decade. From 435 h of observation 25 frequencies were derived for FG Vir in the last campaign (Breger et al., 1998). Although the asymptotic relations did not apply exactly to  $\delta$  Scuti stars, and the regularities were

also invaded by g modes and rotational splitting, regularities were searched for in FG Vir by the histogram method (Breger et al., 1999b). XX Pyx was observed not only with DSN, but the WET, which happened to discover its pulsations. A different method, the Fourier Transform method was used for finding any regularity among the frequencies (Handler et al., 2000). For 4 CVn an additional instrument, the Automatic Photoelectric Telescope (APT) was also used over the years beside the DSN and WET runs (Breger and Hiesberger, 1999). Amplitude variability was found on the time scale of years. In the majority of the well-studied  $\delta$  Scuti stars frequency pairs with less than 0.06 c/d (0.7  $\mu$ Hz) frequency separation, as well as amplitude variability were recognized (Breger and Bischof, 2002). Mixed modes, trapped modes, mode coupling, small spacing or rotational splitting were mentioned as explanations, but the real reason was unknown. I participated in many DSN campaigns (Breger et al., 1993, 1994, 1997, 1999a), but I was also involved in a STEPHEI campaign on BS and BT Cancri (Hernandez et al., 1998). To add more confusion in our view of the pulsation in the  $\delta$  Scuti instability strip, it was found that the chemically peculiar  $\lambda$  Bootis stars pulsated with high overtone modes (Paunzen et al., 2002). A multi-site campaign was organized for a pre-main sequence  $\delta$  Scuti star (Ripepi et al., 2006) to discriminate between the pre-main sequence and the post-main sequence evolutionary stage. The frequency distribution in the low frequency range seemed to be a good criterion. A promising step in the theory was that the red edge of the  $\delta$  Scuti instability strip for non-radial modes was obtained for the first time, using time-dependent convection (TDC) (Dupret et al., 2004). The investigation of  $\delta$  Scuti stars could have or at least is expected to have faster progress using space data.

A new class of pulsating stars, the  $\gamma$  Doradus stars were announced by Balona et al. (1994b). Very intensive observational efforts were dedicated to find the connection between the new group and the chemically peculiar (Am,  $\lambda$  Bootis) and  $\delta$  Scuti stars (King et al., 2006; Rodríguez et al., 2006). Especially the number of multi-site campaigns increased, since the long period light variation made uninterrupted data necessary to determine unambiguous periods. I also joined some campaigns as a contributor (Zerbi et al., 1997, 1999). A variety of explanations appeared: some mentioned non-radial pulsation, others talked about star-spots or quasi-stochastic amplitude modulation. Circumstellar dust shells were found around Gamma Doradus itself (Balona et al., 1994a). The description of  $\gamma$  Doradus stars as a group was given by Kaye et al. (1999). The stars typically had 1 to 5 periods ranging from 0.4 to 3 days with photometric amplitudes up to 0.1 mag in Johnson V. The consensus of the light variation was a high-order, low-degree, non-radial gravity mode pulsation. After discovering 70 new  $\gamma$  Dor candidates from the Hipparcos photometry it became clear that the location of the  $\gamma$  Dor stars on the HR diagram overlapped with the instability strip of  $\delta$  Scuti stars (Handler, 1999). The first convincing hybrid pulsator, pulsating in both p- and g-modes, were reported by Henry and Fekel (2005). The reason of the excitation was reported soon after the identification of the group. The pulsations were found to be driven by the modulation of the radiative flux by convection of the base of a deep envelope convective zone

(Guzik et al., 2000). The long period of pulsation biased by the alias structure of the ground-based observation pointed toward the need of space observation.

This period was a great decade concerning the improvement of our knowledge of B stars from both theoretical and observation respects. The long-standing problem of the source of the excitation had been finally solved. The new opacities (Rogers and Iglesias, 1992a,b) with the enhancement of heavy element opacity by a factor of 2 to 5 over the Los Alamos opacity due to a large number of iron lines at the temperature of around  $T \approx 2 \times 10^5$  degree highly contributed to finding the excitation mechanism in B stars (Osaki, 1993). Three groups were simultaneously working on the modeling of  $\beta$  Cep pulsation (Cox et al., 1992; Kiriakidis et al., 1992; Moskalik and Dziembowski, 1992) and showed that the  $\kappa$  mechanism acting in the partially ionized zone of the elements of the iron group could account for the pulsation of both radial fundamental and low-degree non-radial modes. Gautschy and Saio (1993) confirmed the excitation of g-modes in stellar models appropriate for early-type variables. Moreover, Pamyatnykh (1999) found that both short-period (low-order acoustic and gravity modes) and long-period (high-order gravity modes) oscillations were excited in the same stellar model of proper physical parameters. Observationally the confusion on B stars of light and line profile variability became less serious. The  $\beta$  Cep stars were accepted to pulsate in low-order p-modes in accordance with many multi-site international campaigns (e.g., Handler et al. (2004, 2006) that I also contributed to). At the same time, a part of the 53 Per stars that surrounded the instability zone of the  $\beta$  Cep was found to belong to an independent group of pulsating stars, named as *Slowly Pulsating B stars (SPB)* (Waelkens, 1991). The multi-periodicity and amplitude behavior unambiguously pointed toward pulsation in high radial-order of g-modes (n). [The low spherical harmonic degree (l) of these modes was given later (De Cat et al., 2004)]. Even 53 Per, the prototype of the line profile variables was reported to be an SPB star (Chapellier et al., 1998). The multi-frequency pulsation of  $\zeta$  Oph and its possible relation to  $\beta$  Cephei variables was concluded from the long and high precision photometry obtained by the Canadian satellite, MOST (Microvariability and Oscillations of Stars, Walker et al., 2003; Matthews, 2004) and ground-based spectroscopy (Walker et al., 2005). However, the distinct separation of the groups changed soon. One of the so-called "classical"  $\beta$  Cep stars turned out to be a  $\beta$  Cep/SPB hybrid pulsator, showing both low-order acoustic and high-order gravity modes that was predicted by Pamyatnykh (1999). The word "hybrid" started to appear more and more often in stellar pulsation. It predicts that the traditional groups of pulsating stars are not as distinct as we thought. Maybe we are moving to a unification of some, up to now separate groups. The case of B stars shows that the progress of research highly depends on the advanced theoretical background.

*Long-Period Variables* had been reported very briefly in this review, however, at the end of the last century Barthes and Luri (1999) highlighted that the theoretical treatment of the structure, the pulsation and the evolution of Long-Period Variables (LPVs) was still imperfect. The efforts to improve it suffered both from the complexity of the involved phenomena (strong convection

coupled to non-linear pulsation, thermal pulses, dredge-up of heavy elements, mixing, non-LTE, molecules, grains, shockwaves, high mass-loss etc), and from the basic problem that the physical parameters were not known. However, the gravitational microlensing surveys (MACHO, OGLE, OGLE II, EROS, MOA) revolutionized this field partly because their strategy of observing a large collection of stars at large distances let us estimate the luminosity of these stars (Fraser et al., 2006). It became well-established that pulsating red giants were located on a series of up to six parallel Period-Luminosity (P-L) sequences (Wood, 2000). LPVs first pulsated in overtone mode (1st to 3rd) and switched to fundamental mode pulsation when having crossed some luminosity limit. For the first time the measurement of the masses of AGB stars had shown that mass loss of the order of  $0.3 M_{\odot}$  occurred on the RGB and AGB (Lebzelter and Wood, 2006).

It would be hard to separate the observational and theoretical results for the *white dwarfs*, since the unprecedented progress in the development of white dwarf interior structure models allowed researchers to fit them immediately to the available observations (Metcalfe, 2005). This rapid improvement in the understanding has been most evident for the DBV white dwarfs, where the physical conditions were ripe for asteroseismic investigations. It became clear that the detailed core C/O profile and a double-step helium were the most important features for quantitative asteroseismology of the DBV white dwarfs (Dehner and Kawaler, 1995). The seismic study of the interiors of white dwarfs fed back into the theory of stellar evolution (Kawaler, 1998). Hot white dwarfs were also mature examples of active asteroseismology with such a great importance that in their interiors their prior evolutionary history, especially the story of their last nuclear evolutionary stage had been locked. Seismological data had demonstrated the action of gravitational settling in white dwarf envelopes and provided measurements and important upper limits to the cooling rates of white dwarf stars (Córscico and Althaus, 2004). The observed cooling rate of DAV stars proved to be in good agreement with the theoretical predictions (Kepler et al., 2005), however, in other types of white dwarfs, (DOV and DBV) the observed period changes were faster than the theoretically predicted values whose reason was unknown.

Exciting results for white dwarfs included determinations of stellar masses, distance, rotation rates (both surface and interior) and internal stratification of composition were reported. Kawaler and Bradley (1994) derived that the constant period spacing was primarily determined by the mass of the star, which allowed mass determination. Regular departures from uniformity could have been regarded as a result of mode trapping by a surface composition discontinuity (Kawaler, 1998) allowing the determination of the mass of the H and He layers. Rotation could be deduced by identifying the equal frequency split in the pulsation spectrum. Different amount of rotational split from multiplet to multiplet suggested the departure of the interior from solid-body rotation. The observed splits in GD 358 (DBV type) indicated that the outer layers of this star rotated much faster (by a factor of nearly 2) than the inner regions (Winget et al., 1994). Kawaler et al. (1999) explored the possibility to estimate the whole internal rotation profile. This has been one of the final goals of asteroseismology. The possibility of the

crystallization in the core of white dwarfs had been discussed. The discovery of a DAV lying near the red edge of the instability strip and having characteristic long periods, but anomalously low amplitudes provided the first opportunity to search for the observational signature of crystallization in an individual star (Kanaan et al., 1992, 2005). Montgomery and Winget (1999) suggested that the core of this star might be up to 90 percent crystallized, depending on its mass and internal composition. The crystallization process led to one of the largest sources of uncertainty in the ages of cool white dwarfs (Segretain et al., 1994). In an optical spectroscopy approach two ZZ Ceti (DAV) stars were discovered (Fontaine et al., 2003a), which brought the number of known ZZ Ceti stars to a total of 34. They concluded that the instability strip was pure, in which no non-variable star was found. A pure instability strip was mentioned at the first time for a group of pulsating stars. The number of discovered non-radially pulsating white dwarfs in cataclysmic variables was rapidly increasing by the aid of SDSS (Nilsson et al., 2006). It is worthwhile to emphasize that the phenomenon of mode trapping became a useful method in determining the physical parameters of white dwarfs, in not more than one or one and a half decades.

The second new group of pulsating stars in this decade, the *pulsating subdwarf B (sdB) stars* were discovered in a surprising way, allowing a new field for doing asteroseismology. In the frame of the Edinburgh-Cape (EC) Blue Object Survey a small-amplitude, very rapid light variation was discovered in the sdB binary, EC 14026-2647 (Kilkenny et al., 1997). It was regarded as a prototype of a completely new class of variables which was referred to as EC 14026 stars (also called sdBV<sub>r</sub> or V361 Hya stars). The main period was 144 s with a semi-amplitude of  $\approx 0.012$  mag with a possible second period near 134 s. The variations were more obvious at U than at V which was a strong indicator that variation originated in the hot sdB star rather than in the cooler component, a main sequence F or early G type companion. Kilkenny's discovery inspired a search for other stars of this kind. EC 14026 sdBV stars were found with six periodicities (Koen et al., 1997), with periods showing evidence of a variable amplitude (Stobie et al., 1997) and with evidence for period/phase changes in the main period (O'Donoghue et al., 1997). Interestingly, at the same epoch, the existence of pulsating sdB stars was independently predicted from theoretical considerations based on the identification of an efficient driving mechanism for the pulsation (Charpinet et al., 1996). The driving mechanism was due to an opacity bump associated with heavy-element ionization. It was found that the models showed low radial order unstable modes; and both radial and non-radial (p, f, and g) pulsations were excited. They felt confident enough to risk the prediction that some subdwarf B stars showed luminosity variations resulting from pulsational instability. This was one of the best examples when inductive (observation) and deductive (theoretical) investigations met! However, the sequence of the discoveries was not finished with the short-period hot sdB stars. During the course of an ongoing CCD monitoring program a new class of low-amplitude, multi-mode sdB pulsation with periods of the order of an hour was discovered (Green et al., 2003) and named originally *lpsdB* (or sdBV<sub>s</sub> or V1093 Her stars in the new nomenclature, Charpinet et al., 2011) as a group. The



periods were more than a factor of 10 longer than those of EC 14026 stars implying that they were due to gravity modes rather than pressure modes and they were located on the cooler part of the Extended Horizontal Branch (EHB). The same  $\kappa$  mechanism successfully explained the presence of longer periods, however, radiative levitation was needed to boost the iron abundance in the driving region and modes with  $\ell = 3$  and/or 4 were excited, not the "more visible"  $\ell=1$  and/or 2 modes (Fontaine et al., 2003b). Almost naturally, examples of the hybrid hot and cool sdB stars, pulsating both in short and long periods, were discovered (Oreiro et al., 2005; Schuh et al., 2006). In addition, pulsation was discovered in a He-rich subdwarf B (*He-sdB*) star. According to the periods, the pulsation was more likely due to a high order, non-radial g-mode than to radial or non-radial p-modes (Ahmad and Jeffery, 2005). Using thirteen simultaneously excited periods in a hot sdB led to the first asteroseismological determination of the fundamental parameters, such as the star's temperature, its surface gravity (with a greatly improved accuracy), its total mass, and the mass of its H-rich envelope (Brassard et al., 2001). The first hot pulsating *sdO* star was discovered by Woudt et al. (2006). The relatively rapid discovery of many new pulsating groups required a systematic order in the nomenclature (Kilkenny et al., 2010). A summary of the names is given in a table, but the basic concept of the changes is that rapid, slow, and hybrid pulsations are marked by "r, s, and rs." Asteroseismology can be applied in the future in a new part of the HR diagram. Could new changes in the opacity lead to discovery of new groups of pulsating stars? There seems to be not much space for new groups on the HR diagram. Started from the classical instability strip, almost all part of the HR diagram is covered now by pulsating stars, except for the coldest part of the main sequence, the M and brown dwarfs, and the most luminous part of the HR diagram.

## 8. NEWEST RESULTS OF THE SPACE ERA, 2006-2018

Space-borne instruments are the new generation of the technical developments. The Canadian MOST (Microvariability and Oscillation of Stars, launched in 2003, ended in 2014) space telescope was the first spacecraft dedicated entirely to the study of asteroseismology (Matthews, 2003; Walker et al., 2003). In the last few years the research field of variable stars has benefited more and more from the operation of space telescopes, although their primary goal was the detection of exoplanets. The French-led CoRoT (Convection, Rotation and planetary Transit, launched in 2006, ended in 2013) and the NASA-built Kepler telescope (launched in 2009, ended 2012, but operated as the K2 mission between 2013-2018) were joint missions for planetary and stellar research (Baglin et al., 2006; Borucki et al., 2010). Searching for exoplanets, a huge amount of data was gathered together for the stars that were located in the fields of view. The newest American space telescope, TESS (Transiting Exoplanet Survey Satellite, launched in 2018) produces the first-ever spaceborne all-sky transit survey to detect small planets with bright host stars in the solar neighborhood (Ricker et al., 2015). The upcoming ESA telescope, PLATO (PLANetary Transits and

Oscillations of stars, with a planned launch in 2024) will devoted to figuring out under what conditions planets form and whether those conditions are favorable for life (Rauer et al., 2016) or not. The Swiss-led ESA mission, CHEOPS (Characterizing ExOPlanet Satellite), which is ready to be launched in 2019, is planned for the study of the formation of extrasolar planets (Rando et al., 2018). With so many dedicated instruments, it is not surprising that planetary science has become as fashionable nowadays as variable star research used to be some decades ago. However, one has to admit that variable star research also benefits from the purely exoplanet-oriented projects. Beside the exoplanet missions, a basic space telescope, the GAIA, was launched in 2013 which was designed to measure the position and distances of stars with unprecedented precision (Eyer et al., 2013). The Gaia data release 2 was recently published (Gaia Collaboration et al., 2018). Definitely the greatest advantage of space telescopes for the presently active generation of scientists is that they do not have to suffer for collecting data on individual objects from night to night. In addition, space-based data are continuous with different lengths (6 months for CoRoT and 4 years for the Kepler mission) and the precision is now at the unprecedented ppm level. There is good hope to answer some, many, or all the questions that have been asked in the last decades. Due to the fact that the data are more easily available, and there is publication pressure for getting financial support, the number of published papers has increased enormously. International teams are organized for working on the data of a given mission and the same teams migrate from one space mission to the next one. The structure of the national institutes seems to have been loosened and scientific connections with colleagues outside of those permanent teams have been reduced/or vanished. The whole research field has been revolutionized, which is not a disadvantage in itself. However, here are some thoughtful points. The results of certain space missions are presented in specialized conferences (CoRoT weeks, KASC, TASC, and BRITE meetings). I am sure that in the future we will have TESS, GAIA, CHEOPS, and PLATO meetings, too. On the other hand, thematically highly specialized meetings are organized more and more often (RR Lyrae, white dwarf and sdB meetings, although white dwarf meetings are not only for pulsating white dwarfs, but for the whole community who are working on white dwarfs in any respect.) Smaller workshops are also organized for mostly the international teams. Such a great change in the policy of presenting the scientific results compared to the fewer IAU supported general meetings in every 3 years may have some unplanned consequences. Although we still have the IAU supporting more general meetings, unfortunately the financial support is not enough to attend both the general and the specialized meetings. The knowledge of the experts is getting deeper, but concerns a more and more narrow field, especially if we consider the flood of published papers. There is no time to properly follow the whole field of pulsating stars, only a smaller and smaller section of the general knowledge. So, another important question for the space era is whether we are able to synthesize/assimilate such a large flood of data. Do we have enough time and energy to theoretically interpret the new discoveries, beside the very convenient task of data treatment? The future will tell.



It is impossible to cover all results obtained from space data up to now, rather I intend to give a taste of what we could answer from the previous questions, what we still have to solve or what the new fine details are that appeared in connection with pulsating stars.

The past shows that temporary confusion seems to appear when new data are obtained, especially if we do not immediately have guiding principles. The advanced ground-based instruments, the space data of long time base and of unprecedented precision questioned the constancy of the observable parameters of the pulsation in *Cepheids*. Just to name a few, amplitude irregularities, period fluctuations, doubled periods, non-radial pulsations and multimode radial pulsations were found. Although the Irish Astronomical Journal based on the paper of Grandjean and Ledoux (1954) reported that the “structure of the atmosphere of the Cepheids is on solid ground”, a program on the secret life of Cepheids (SLiC) is nowadays going on in which the aspects and behavior of classical Cepheids, which are still regarded as unclear, were planned to be studied (Engle et al., 2014). Observations were obtained both from the ground and space. Due to the application of space instruments (HST Cosmic Origins Spectrograph in UV and XMM-Newton, the X-ray Multi-Mirror Mission) and the improvement in precision, even the prototype of the classical Cepheids,  $\delta$  Cephei, surprised us. For example, high temperature plasma ( $10^3$ – $10^7$  K) was detected above the Cepheid photosphere with variable X-ray activity which was attributed to pulsation-driven shocks propagating through the Cepheids’ outer atmosphere and giving rise to mass-loss through a stellar wind. The HI 21 cm line observations with the Very Large Array (VLA) directly determined a mass of circumstellar atomic hydrogen  $M_{HI} \approx 0.07 M_{\odot}$  with a mass-loss rate of  $dM/dt \approx (1.0 \pm 0.8) \times 10^{-6} M_{\odot} \text{ yr}^{-1}$  (Matthews et al., 2012). Modeling showed that the combination of moderate convective core overshooting and pulsation-driven mass loss could solve the Cepheid mass discrepancy (Neilson et al., 2011). In addition, the  $\delta$  Cephei proved to be a spectroscopic binary based on measurements of high-precision radial velocities (Anderson et al., 2015). Using all available data, the orbital period was 2201 day, the eccentricity,  $e = 0.647$ , and the companion mass was constrained within  $0.2 M_{\odot} \leq M_2 \leq 1.2 M_{\odot}$ . The close pericenter approach of the two stars has far-reaching consequences for the explanation of the observed circumstellar environment of  $\delta$  Cephei. The MOST photometric measurements revealed low-amplitude irregularities in Cepheid stars. The nearly continuous high-precision photometry also revealed alternations in the amplitudes, the first case of a period doubling detected in a classical Cepheid. The period doubling led to the appearance of half integer frequencies (Molnár et al., 2017a). The Kepler data disclosed significant cycle-to-cycle fluctuations in the pulsation period, indicating that classical Cepheids might not be as accurate astrophysical clocks as commonly believed (Derekas et al., 2012). However, this statement does not seem to be valid overall. Using MOST data, a fundamental mode pulsator had a light curve that repeated precisely, an overtone pulsator on the other hand showed light curve variation from cycle to cycle (Evans et al., 2015). Concerning the type of pulsation, CoRoT

light curves of Galactic Cepheids did not show any convincing evidence of excitation of non-radial modes (Poretti et al., 2015). However, in the Large Magellanic Cloud additional variability was discovered by the OLGE team for Cepheids with period ratios in the  $P/P_0 = (0.60, 0.65)$  range. A power excess at half the frequency of the additional variability was also reported (Smolec and Śniegowska, 2016). In addition, two triple mode classical Cepheids pulsating simultaneously in the first three radial overtones were also discovered (Moskalik and Kołaczkowski, 2009). Hopefully, the details will sooner or later be combined into an overall explanation.

The staunchest community of astronomers are those who have been working from decade to decade to solve the mystery of the Blazhko effect. Huge efforts have been devoted to getting ground-based data. The Konkoly Blazhko Survey (Jurcsik et al., 2009), the Antarctica project (Chadid et al., 2014), the OGLE project (Smolec et al., 2015), and the Catalina Sky Survey (Torrealba et al., 2015) represented such successful ground-based efforts, while the CoRoT, the Kepler and the GAIA space missions have provided a larger and larger contribution to the improved knowledge on *RR Lyrae* stars. The number of stars showing RR Lyrae characteristics has increased incredibly, and definitely surprising statistical results have been predicted in connection with the evolution of stars and the structure of our galaxy. However, at present our picture has become much more confusing compared to the simple categorization of  $RR_{ab}$ ,  $RR_c$ ,  $RR_d$  subtypes that we used to have in earlier decades. The discovery of additional low-amplitude modes blurred the line between the three main groups (Molnár et al., 2016). Since the first discovery of the additional frequencies that did not belong to the classical multiplet structure of a Blazhko-type RR Lyrae and was interpreted as a non-radial mode with a ratio of  $f_0/f_{add} = 0.6965$  (Chadid et al., 2010), all unusual frequencies were called additional frequencies. Nevertheless, these additional frequencies could have different types, as well as definitely different physical origins, although most of them were explained by some kind of resonance of the higher-order radial modes. The period doubling phenomenon was first detected in Kepler  $RR_{ab}$  stars (Kolenberg et al., 2010; Szabó et al., 2010) and later in CoRoT RR Lyrae stars, (Szabó et al., 2014). The period doubling manifested itself as alternating maxima and minima of the pulsational cycles in the light curve, as well as through the appearance of half-integer frequencies located halfway between the main pulsation period and its harmonics in the frequency spectra. According to the theoretical explanation, the period doubling was caused by 9:2 resonance between the fundamental mode and the 9th-order radial overtone showing strange-mode characteristics due to mode trapping (Kolláth et al., 2011). This was one type of additional mode. The phrase “additional modes” was used for frequencies which could have been identified as the second radial overtone, but the excitation of the second overtone was not theoretically expected (Benkő et al., 2010; Poretti et al., 2010). In this case, the group of  $RR_d$  stars could be extended with stars where not the fundamental and first overtone, but the fundamental and the second overtone were simultaneously excited. Without any knowledge on the amplitude of non-radial modes, these additional modes could be simply regarded as a

non-radial mode excited near the second radial overtone, where excitation was theoretically predicted. This was the second type of “additional modes.” An additional frequency was reported as early as 2007 (Gruberbauer et al., 2007) in an  $RR_d$  star. The  $f_0/f_i = 0.9272$  ratio suggested that the additional mode was a member of the second type. The third type of additional modes were the  $f_x$  or 0.61-type (for the frequency ratio) modes which were strongly connected to the first overtone and could be detected in both first overtone ( $RR_c$ ) and double-mode ( $RR_d$ ) RR Lyrae stars (Moskalik et al., 2015; Netzel et al., 2015). Such modes occurred in Cepheids, too, with a slightly different frequency ratio (0.60–0.64), as it was mentioned earlier. According to the theoretical explanation, the additional periodicities arose from the harmonics of non-radial f-modes effectively trapped in the outer part of the envelope (Dziembowski, 2016). In Cepheids the modes had angular degrees from  $\ell = 7$  to 9, in RR Lyrae only  $\ell = 8$  and 9. It seems that all cases represent the fact that non-radial modes were discovered in the traditional radial pulsators, the Cepheid and RR Lyrae stars. Unfortunately, the approaches do not agree on the definition of the old/new subtypes. Molnár et al. (2017b) kept the traditional categories, but colored them by the non-radial modes, while Netzel et al. (2015) kept the traditional radial pulsation categories and created a new category for the radial-non-radial-mode pulsators. Hopefully, the picture will become clearer in the future, but the final solution can only be given by a non-linear non-radial pulsation code which can provide the amplitude ratio of the radial and non-radial modes. The non-linear, non-radial code was already urged as early as 1988 by D. Winget in connection with white dwarfs (Winget, 1988). The successful progress of the asteroseismology of the different types of non-radially pulsating stars (and as we see the classical radial pulsators also belong to them) requires further steps in modeling. The newest results for  $\delta$  Cep and RR Lyrae stars show that the space data will discover many new details on the classical radial pulsators, partly suggesting that they also belong to the non-radially pulsating stars, and only the amplitude ratio of the radial and non-radial modes are different compared to the rest of the non-pulsating stars. It strongly points toward the need to know more about the amplitude of the excited modes. The half integer frequencies, the period doubling, and the trapped modes echoes the case of white dwarfs.

There has been no consensus on the reason of the *Blazhko type* modulation of the RR Lyrae stars either, but the number of possible causes has been much reduced. A possible suggestion was that the Blazhko effect is caused by the combined effect of the fundamental and first overtone shocks on the atmosphere (Gillet, 2013). A beat mechanism in double mode RR Lyrae stars were also suggested (Bryant, 2015). The more widely accepted explanation was the resonant model (Buchler and Kolláth, 2011). The suggested reason was the 9:2 resonance of the fundamental mode and the high-order (9th) radial overtone, as in the case of the period doubling. The amplitude equation formalism showed not only the period doubling, but also that the amplitudes were modulated, and that in a broad range of parameters the modulations were irregular. Observations showed that the Blazhko cycles did not repeat regularly (Guggenberger et al., 2011; Kolenberg et al., 2011) and the Blazhko modulation

was multiperiodic (Sódor et al., 2011; Benkő et al., 2014). In a remarkable case, two different modulation periods were identified with a similar strength and a different period ratio from season (5:4) to season (4:3) (Sódor et al., 2011). One of the most important recent observational findings was the limited modulation in the K band (Jurcsik et al., 2018). They showed that the Blazhko modulation was primarily driven by changes in the temperature variation and the radius variation played only a marginal role. This empirical fact alone drastically reduced the possible mechanism that could be responsible for the modulation. That was the first observational evidence that the Blazhko phenomenon was strongly related to the top of the atmospheric layers of the stars that was predicted by Christy in 1966 (Christy, 1966). Kolláth (2018) checked the aforementioned models and Stothers (2006) model vs. the constraints. According to the conclusion, there was no existing model which satisfied all the observational constraints of the Blazhko modulation exactly. However, the 9:2 resonance hypotheses of the fundamental to 9th overtone at least did not contradict any of the observational facts. An overview of explanations of the Blazhko effect for the past 60 years has been presented. The space data and the huge ground-based efforts led to more details, but there is no theoretical explanation that is accepted by everybody. This is the longest that a problem has not been solved in stellar pulsation.

Space data increased our knowledge on the pulsation of  $\delta$  Scuti stars remarkably and let us answer many long-standing questions, but the validity of the new information changed from year to year, as more and more data were processed. The  $\delta$  Scuti instability strip seemed to contain both pulsating and non-pulsating stars in about equal fractions. The amplitude distribution of the frequencies did not support the suggestion that all stars pulsated with amplitude of low level (Balona and Dziembowski, 2011). However, a different sample and other aspects led to a conclusion that the instability strip was pure, unless pulsation was shut down by diffusion or another mechanism, such as interaction with a binary component (Murphy et al., 2015). In a different vein, the precise GAIA luminosities allowed the instability strip of  $\delta$  Scuti and  $\gamma$  Dor stars to be redetermined, which partly proved that less than half of the stars pulsate and that the two instability strips overlap (Balona, 2018). However, the question why there are non-pulsating stars with roughly similar parameters in the instability strip remains open. New theoretical calculations confirmed the overlap of the two instability strips and suggested that there was no essential difference between the  $\delta$  Scuti and  $\gamma$  Dor stars, they were only two, a p-mode and g-mode, subgroups of one boarder type of pulsating stars below the Cepheid instability strip, and most of the variables were hybrids (Xiong et al., 2016). Consequently, it was not surprising that low frequencies were present in at least 98 % of  $\delta$  Scuti stars (Balona, 2018) and it was meaningless to continue to call them as  $\delta$  Sct/ $\gamma$  Dor hybrid stars (Balona et al., 2015b). However, it had been reported that pure  $\delta$  Scuti stars with no significant frequencies in the  $\gamma$  Dor region (below  $5 d^{-1}$ ) did, albeit rarely, exist (Bowman and Kurtz, 2018). Although the largest part of two instability strips overlapped both observationally and theoretically, the red and blue edges did not perfectly agree (Balona, 2018). In the

$\delta$  Scuti instability strip several peculiar types of pulsators were located. According to the precise luminosities, Balona (2018) concluded that *High Amplitude Delta Scuti (HADS) stars* were normal  $\delta$  Scuti stars and not transition objects and SX Phe stars were also located well inside the instability strip. Surprisingly, the roAp stars also exhibited  $\delta$  Scuti and  $\gamma$  Dor pulsation (Balona et al., 2011a). Part of the low frequencies in  $\delta$  Scuti stars were attributed to different co-rotating surface features. Most of the Am stars had light characteristics of rotational modulation due to spots (Balona et al., 2015a). Flares were also detected in about two percent of Kepler A stars (Balona, 2013). The surface metal enrichment in the peculiar stars was explained as the result of diffusion and gravitational settling in the absence of a magnetic field. Two spectropolarimetric measurements revealed a clear magnetic structure in the Stokes profile in a Kepler  $\delta$  Sct/ $\gamma$  Dor hybrid candidate (Neiner and Lampens, 2015). This was the first magnetic main sequence  $\delta$  Scuti star. A weak magnetic field was also detected in 1 Mon, the famous multi-periodic high-amplitude  $\delta$  Scuti star (Baklanova et al., 2017). The interaction of diffusion-pulsation and the physics of the stellar envelopes should be re-examined to see how a magnetic field could be generated in A stars (Balona et al., 2015a). Investigating Kepler  $\delta$  Scuti stars, 603 stars exhibited at least one pulsation mode that varied significantly in amplitude over 4 years (Bowman et al., 2016). In more general, amplitude and/or frequency variations had been found among nearly all types of non-stochastically excited pulsators (Guzik et al., 2015). The long-term follow-up of the famous  $\delta$  Scuti star, 4 CVn, showed that most pulsation modes exhibited a systematic significant period and amplitude changes on a timescale of decades (Breger et al., 2017). The reasons of the period and amplitude variability will definitely be investigated as space data on a longer and longer time base will be available in the future. Two kinds of anomalous pulsators seemed to exist between the blue edge of the  $\delta$  Scuti and the cool edge of the  $\beta$  Cep instability strip (Maia variables) and between the cool edge of the SPB and the blue edge of the  $\gamma$  Dor instability strips (hot  $\gamma$  Dor variables) (Balona et al., 2016). The current models did not predict pulsation in this region of the HR diagram. Nevertheless, a large population (36 stars) was found in this region in a young open cluster (Mowlavi et al., 2013) and 17 similar stars were also identified in another young open cluster (Lata et al., 2014). Both the rapid rotation and a revision of the opacities were mentioned as a possible solution for these anomalous pulsators. It seems that explanations of the many new discoveries need serious theoretical work on the different parts of the input physics. Despite the space data of unprecedented precision the question of why some stars with the same atmospheric and physical parameters pulsate and others do not, has been still an unexplained issue for 60 years. Presumably this problem is also connected to the amplitude limiting mechanism, which also remains unsolved.

Mode identification in  $\delta$  Scuti stars was still an unsolved problem, due to the lack of simple, easily identifiable frequency patterns; especially for fast rotating stars, it was a formidable challenge (Reese et al., 2018). Nevertheless, we might say that remarkable improvement had been achieved in the last decade. Great effort has been put into the establishment of the pulsational

model of fast rotating stars (Roxburgh, 2006; Lignières and Georgeot, 2008, 2009). Reese et al. (2008) suggested a new asymptotic formula for the island modes which were later confirmed and for which theoretical echelle diagrams were built (Ouazzani et al., 2015). Realistic multi-color mode visibilities were calculated for possible mode identification (Reese et al., 2017) and were applied for BRITe data (Reese et al., 2018). The mode identification needed data at least in 3 photometric bands and also required a large number of acoustic modes, preferably in the asymptotic regime. Unfortunately, it is hard to satisfy these requirements for the bulk of  $\delta$  Scuti stars. From an observational side, a quasi-periodic pattern was found in  $\delta$  Scuti stars at first for CoRoT data, and a spacing periodicity around 52  $\mu$ Hz was derived (García Hernández et al., 2009). Calibrated for  $\delta$  Scuti stars in eclipsing binaries, a scaling relation ( $\Delta\nu$ - $\rho_{mean}$ ) was established between the frequency spacing obtained from the pattern in the star and its mean density (García Hernández et al., 2015). This relation was theoretically derived by Suárez et al. (2014). Later the scaling relation was used to get the precise surface gravity without any constraints from spectroscopy or binary analysis (García Hernández et al., 2017). The scaling relation could lead to the possibility of a massive statistical investigation of  $\delta$  Scuti stars. Not only the determination of the spacing, but the identification of independent modes were aimed at searching for sequences of quasi-regularly distributed modes, allowing for a tolerance level in the exact spacing (Paparó et al., 2016a). Echelle diagrams were constructed for 90 CoRoT  $\delta$  Scuti stars and the characteristic spacings were derived (Paparó et al., 2016b). Unfortunately, a test investigation revealed that the echelle diagrams could be built not only for the consecutive radial orders of a certain  $\ell$  degree mode, but for the combination of eigenmodes and rotationally split modes, producing sometimes more than one spacing value. We could not disentangle the normal eigenmodes from rotational splitting. However, a new observable, the shift between the sequences was derived. The fact that some shifts between the sequences were integer multiples of the rotational split might suggest a possible resonance effect between eigenmodes and rotation as a selection mechanism (Paparó et al., 2018). Using 1860 CoRoT  $\delta$  Scuti stars, a common regular pattern was found in agreement with island modes featured by theoretical non-perturbative treatment of fast rotation (Michel et al., 2017). Regularities in the amplitude spectra of these stars produced ridge-like structures with a spacing of order of a few tens of  $\mu$ Hz (of order a few  $d^{-1}$ ) which was consistent with the consecutive radial order pulsation modes. The  $f_{min}$  and  $f_{max}$ , as well as the large separation values might be used as seismic indices to characterize stars, which opens the perspective for ensemble seismology using  $\delta$  Scuti stars. The space data introduced progress in the identification of modes in the non-asymptotic regime, but there is room for the next generation to work on this field.

Although the  $\gamma$  Doradus stars were newly identified, the interpretation of their pulsation seemed to be an easy task. Spectacular improvement was achieved on the asteroseismology of g-mode pulsators on the main sequence, both on  $\gamma$  Dor and SPB stars, as well as on the hybrid stars. The asymptotic theory predicted regular period spacing patterns which was evinced



both in CoRoT and Kepler stars. A series of g-modes of the same  $\ell$ -degree and different radial orders  $n$  consisting of 24 frequencies were found in a  $\gamma$  Dor/ $\delta$  Scuti hybrid (Chapellier et al., 2012). In addition, strong coupling of the g-modes to the radial fundamental mode was also manifested. Rotationally split g-mode triplets and surface p-mode triplets were discovered in a Kepler star (Kurtz et al., 2014). This gave the first robust determination of the rotation of the deep core and the surface of a main-sequence A star. They showed with high confidence that the surface rotated slightly faster than the core. Period spacings were determined and echelle diagrams were constructed for several  $\gamma$  Dor stars (Bedding et al., 2015). Small deviations from regular period spacing were found that arose from the gradient in the chemical composition just outside the convective core. Van Reeth et al. (2018) presented an extended theoretical overview on the restoring forces for rotating stars. The simple, exactly regular period spacing predicted by the asymptotic theory is valid only for a non-rotating chemically homogeneous star. The real manifestation of the period spacing depends on the rate of the stellar rotation and in consequence, on the type of the restoring force (buoyancy, Coriolis or both). For slowly pulsating stars (buoyancy) the g-modes split into triplets, however, for moderate to fast rotators (the rotation rate is 20 % or more of the critical rotation rate) purely internal pulsation such as r-modes (Coriolis force), or gravito-internal pulsation modes appear (both type of forces are acting). For stars pulsating in gravito-internal modes the period spacing has a positive or negative slope depending on the sign of the azimuthal number,  $m$  (retrograde or prograde). In the frame of ensemble modeling of  $\gamma$  Dor stars near-core rotation rates were determined from the observed period spacing pattern (Van Reeth et al., 2016). For most stars gravity or gravito-internal modes were identified, but for the first time Rossby modes were also found. A new observable, the slope of the period spacing when plotted as a function of the period was derived which was uniquely related to the internal rotation (Ouazzani et al., 2017). The global Rossby waves (r-modes) were found to be present in many  $\gamma$  Dor stars, spotted stars and heartbeat stars (highly eccentric binary stars), and even in a frequently outbursting Be star. The common feature of r-modes in the amplitude spectra was the presence of broad humps that appeared immediately below the rotational frequency (Saio et al., 2018).

The SPB variables were also identified as a separate group only in the last decade, they shared the remarkable success of the  $\gamma$  Dor stars along the way to asteroseismology due to the g-mode pulsations. The detection of numerous gravity modes in a young star was reported from CoRoT data (Degroote et al., 2010). The mean period spacing allowed researchers to estimate the extent of the convective core, and the clear periodic deviation from the mean constrained the location of the chemical transition zone to be about 10 % of the radius. The first detailed asteroseismic analyses of a cool SPB star, showing a series of 19 quasi-equally spaced dipole modes, was reported from 4 years of Kepler photometry (Pápics et al., 2014). The amount of splitting showed an increasing trend toward longer periods which pointed toward a non-rigid internal rotation profile. Independent modeling was done by Moravveji et al. (2015) and Triana et al. (2015). In a next example, the longest unambiguous series of 36 gravity modes of

the same degree  $\ell$  with consecutive radial order  $n$ , which carried clear signatures of chemical mixing and rotation was discovered (Pápics et al., 2015). According to the authors, this star should be considered as the Rosetta stone of SPBs for future modeling. Over the years of the Kepler era the number of in-depth analyzed SPB stars in the original Kepler field doubled from four to eight, and the number of SPB with an observed period spacing from four to nine; seven of these are from Kepler (Pápics et al., 2017). Simultaneously, it had been shown that the period series were not only common, but they dominated the frequency spectrum of SPB stars. Both the  $\gamma$  Dor and SPB variables show that the results of high level observations can be straightforwardly interpreted if the theoretical background is available (the asymptotic theory).

The impact of MOST, CoRoT, and Kepler and K2 missions on seismology of  $\beta$  Cephei stars was rather modest, because few of these stars were observed and because one color photometry alone allowed mode identification only through the recognition of eventual patterns in the stellar pulsation (Handler, 2017). Several bright stars of  $\beta$  Cep-type were observed by the WIRE satellite tracker, several by MOST and only one by CoRoT (Degroote et al., 2009). The largest impact on the number of known  $\beta$  Cephei stars came from the All Sky Automated Survey (ASAS) (Pigulski and Pojmański, 2009). The BRITe Constellation (BRITe Target Explorer) was designed for asteroseismic studies of  $\beta$  Cep stars. Despite the observational disadvantage, some results were obtained both on  $\beta$  Cep and  $\beta$  Cep/SPB hybrids by combining space and ground-based data. One hybrid pulsator had a sufficiently large number of high-order g-modes and low-order pressure (p) and mixed modes were detected to be usable for in-depth modeling (Handler et al., 2009). In a triple system with two massive fast rotating early B-type components, both components proved to be  $\beta$  Cep/SPB hybrids. In addition, the system's secondary star had a measurable magnetic field (Pigulski et al., 2016). In a  $\beta$  Cep star 40 periodic signals were detected intrinsic to the star with some of the previously known pressure and mixed modes and some newly found gravity modes. Temporal changes in the amplitudes were also detected. The disagreement of the observed and the theoretically predicted amplitude behavior might lead to incorrect identification, if using data in optical filters only (Handler et al., 2017). Kepler data showed that there were non-pulsating stars in the  $\beta$  Cep and SPB instability strip (Balona et al., 2011b). Magnetic fields seemed to not be common in SPB,  $\beta$  Cep and Be stars, although there were some magnetic B pulsators (Silvester et al., 2009). A huge effort was dedicated to getting precise physical parameters of pulsating stars with LAMOST (Large Sky Area Multi-Object Fiber Spectroscopy Telescope) (De Cat et al., 2015). Despite the massive efforts, the models calculated with standard opacity tables could not explain the observed oscillation spectra (Briquet et al., 2011; Handler et al., 2012). An opacity increase of a factor 2 at the depth at which nickel had a significant contribution would solve the discrepancies between the observed low-frequencies and the theoretical high-order g modes (Daszyńska-Daszkiewicz et al., 2017). Does it mean that we still need to increase the opacity for getting a reliable model for  $\beta$  Cep variables? The results obtained on space data for both  $\beta$  Cep and  $\delta$  Scuti stars point toward



the urgent need for theoretical improvement of non-asymptotic pulsations. It is an extremely hard problem for the upcoming generation. However, they have to step further, otherwise the space data will be only described, but remain unexplained from a theoretical point of view.

The *emission B (Be) stars* were not well-studied in the last decade. However, all space missions also observed Be stars, partly in dedicated runs, such as the MOST mission, but mostly as a by-product of their observing strategies (such as the CoRoT, Kepler, and also the solar mission SMEI - Solar Mass Ejection Imager). To date MOST has observed five Be stars, for several weeks each, Kepler has observed three stars for 4 years, CoRoT has observed 40 Be stars for between a few weeks and half a year, and SMEI almost 130 stars over 9 years (Rivinius et al., 2017). From a stellar pulsation perspective, Be stars are rapidly rotating SPB stars, that is, they pulsate in low-order g-modes (Rivinius et al., 2016) (precisely in low degree (l) and high order (n) g-modes, De Cat et al., 2004). The BRITE and SMEI joint data revealed that next to rapid rotation, non-radial pulsation seemed to be the most common property of a known Be star. Four large amplitude frequencies were exhibited. Two of them were closely spaced frequencies of spectroscopically confirmed g-modes near  $1.5 \text{ d}^{-1}$ , one slightly lower (about 10 %) exophotospheric (Stefl) frequency, and at  $0.05 \text{ d}^{-1}$  the difference frequency between the two non-radial g-modes (Baade et al., 2018). The circumstellar (Stefl) frequency did not seem to be affected by the frequency difference, which underwent large amplitude variations. Its variability seemed to be the main reason for the modulation of the star-to-disk mass transfer. When a circumstellar disk was present in a Be star, the power spectra were complicated by both cyclic, or periodic and aperiodic circumstellar phenomena, possibly even dominating the power spectrum (Rivinius et al., 2016). Depending on the spectral type, four categories of variability were distinguished, namely, (1) stochastic (Neiner et al., 2012), (2) bursting and (3) cleanly pulsating (Semaan et al., 2013), and (4) almost harmonics (Diago et al., 2009). Optical light curves for 160 Be stars obtained by the KELT (Kilodegree Extremely Little Telescope) and simultaneous infrared and visible spectroscopy were analyzed to study the disk creation process and to monitor the evolution and demise of these disks once formed (Labadie-Bartz et al., 2018). The duration of disk build up and dissipation phases were measured for 70 outbursts showing that the average outburst took about twice as long to dissipate as it did to build up in optical photometry.

Progress in the field of *white dwarfs and sdB stars* was even more impressive in the space era than the last decades. New versions of the stellar/binary evolutionary endpoints were recognized as a new type of white dwarfs. The *extremely low-mass (ELM) white dwarfs* having five pulsating members for the time of space era (Hermes et al., 2013), represented a new group of white dwarfs with their  $0.18\text{--}0.2 M_{\odot}$  mass as opposed to normal white dwarfs with a mass of  $\approx 0.6 M_{\odot}$  and massive white dwarfs with a mass of  $\geq 0.8 M_{\odot}$ . Binary evolution was the most likely origin in the process of which they harbored very thick H envelopes and were able to sustain residual H nuclear burning via a pp-chain, leading to a markedly longer evolutionary timescale (Córscico et al., 2016). An ELM white dwarf was shown to be in a compact,

5.9-h orbit binary with a fainter, more massive WD companion, and the system exhibited both primary and secondary eclipses in the light curve (Hermes et al., 2014). The discovery of other new group, several white dwarfs with atmospheres primarily composed of carbon with little or no trace of hydrogen or helium, was reported (Dufour et al., 2007). The first pulsating member in the hot *DQ group*, as the new group was named, was revealed by Montgomery et al. (2008).

Extended ground-based surveys were performed to find white dwarfs and sdB stars in the Kepler field, and finally the surveys were successful. 42 white dwarfs were discovered in the original Kepler field (Greiss et al., 2016), and 27 white dwarfs were measured through the K2 mission (Hermes et al., 2017b). The most surprising results in the DA white dwarfs were the detection of a new phenomenon, the large-amplitude outbursts at timescales of much longer than the pulsation period (Hermes et al., 2015), which was first reported on the 1.5-year long light curves of the first ZZ Ceti star discovered by Kepler (Bell et al., 2015). As the number of similar cases increased, it was established that only the coolest pulsating white dwarfs within a small temperature range near the cool, red edge of the DA instability strip exhibited the outbursts (Bell et al., 2016). There was discrepancy between the theoretically and observationally determined locations of the red edge of the DA instability strip (Van Grootel et al., 2012). The outbursts recurred stochastically on days-to-weeks timescales and could brighten a white dwarf by more than 40 % for several hours (Hermes et al., 2017a). In addition, the fastest rotational rate ( $1.13 \pm 0.02 \text{ h}$ ) of any isolated pulsating white dwarf known to date was found in K2 data. The highest mass ( $0.87 \pm 0.03 M_{\odot}$ ) that was measured for any pulsating WD with known rotation suggested a possible link between high mass and fast rotation. The mean flux increase corresponded to nearly  $750 \text{ }^{\circ}\text{K}$  (Hermes et al., 2017d). As soon as a DB white dwarf was found in the surveys, it was immediately submitted for follow-up space observation. Five modes roughly equally spaced in period were found with a mean spacing of 37 s. The three strongest modes showed a triplet with a mean splitting of  $3.3 \text{ } \mu\text{Hz}$  (Østensen et al., 2011). In an other DBV, clear signatures of non-linear effects were found that could be attributed to a resonant mode coupling mechanism, which might motivate further theoretical work to develop the non-linear stellar pulsation theory (Zong et al., 2016). The hottest helium-atmosphere white dwarf known to pulsate exhibited a rich oscillation spectrum of low-order g-modes with clear patterns of rotational splitting from consecutive sequences of dipole and quadrupole modes. These modes were able to probe the rotation rate with depth in this highly evolved stellar remnant. A bright spot was also recognized and used for the measurement of the surface rotation rate (10.17 h) (Hermes et al., 2017c). The space era has been a very productive data collection phase for white dwarfs. Hopefully, immediate theoretical work will be inspired to incorporate the newly observed phenomenon into the white dwarf models.

The search for members of the new instability strip on the Extreme Horizontal Branch (EHB) continued and five *sdO pulsators* were discovered in  $\omega$  Cen (Randall et al., 2011, 2016). A very rapidly pulsating sdO star was discovered in the

Edinburgh-Cape (EC) survey with strongly variable amplitude, which may be a field analog of the  $\omega$  Cen sdO variables (Kilkenny et al., 2017). The harvest for the *sdB stars* based on space data started with the clear identification of nine compact pulsators and a number of interesting binary stars (Østensen et al., 2010). Using only 30.5 d of nearly continuous time series from Kepler, more than ten independent pulsation modes were found in a short-period pulsator, and one longer periodicity showing that this sdB might be the hottest member of the hybrid sdB stars. Additional periodic changes suggested that a significant number of additional pulsation frequencies might be present (Kawaler et al., 2010). A statistical investigation was done for 13 sdB stars concerning the nearly equally spaced periods. It was concluded that period spacings could be easily or readily detected and they are useful for mode identification. Most of the stars indicated modes with  $\ell = 1$  and some showed modes with both  $\ell = 1$  and 2 degree (Reed et al., 2011). It was amazing that a 2.75-year Kepler observation with a 93.8 % duty cycle containing 1.4 million measurements and resulting in  $0.017 \mu\text{Hz}$  resolution was obtained for the most slowly rotating sdB star ( $88 \pm 8$  day). Back then it was not surprising that 278 periodicities were found in which 59 % had been associated with low-degree ( $\ell \leq 2$ ) pulsation modes. According to the authors, this star represents a “solved” sdB pulsator (Reed et al., 2014). We could not have issued such a statement before the space era! More fascinating results were obtained: (i) the clear indication of mode trapping in a stratified envelope (Østensen et al., 2014b), and (ii) modes without long-term coherency showing the stochastic characteristic of these modes beside the two normal pulsation modes (Østensen et al., 2014a). Such solar-like pulsations, although suspected in sdB stars, have never been observed before. Extremely complex systems were also found. The near-continuous 2.88 year Kepler light curves revealed that one sdB star had an unseen white-dwarf companion with an orbital period of 14.2 days. A rich g-mode frequency spectrum with a few p modes at short periods was also found. The g-mode multiplet splittings constrained the internal rotation period at the base of the envelope to 46–48 days as a first seismic result for this star. The few p-mode splittings might point to a slightly longer period further out in the envelope of the star, suggesting the possibility of radial differential rotation (Telting et al., 2014). The presence of two nearly Earth-sized bodies orbiting the post-red-giant hot sdB star was also reported (Charpinet et al., 2011). The distances from the star were 0.0060 and 0.0076 AU and the orbital periods were 5.7625 and 8.2293 h, respectively. They were interpreted as the dense cores of evaporated giant planets that were transported closer to the star during the engulfment. Maybe we are closer to the optimistic prediction of Don Winget (Winget, 1988) who said that with asteroseismology we might be able to provide the age of the Universe. Understandably, due to the physical limits of this publication, certain excellent results in the successful field of pulsating stars had to be omitted.

Despite the great improvement in the asteroseismology of white dwarfs,  $\gamma$  Dor and SPB stars showing pulsation in the asymptotic regime excited by  $\kappa$  mechanism on any kind of ionization zone, and even helioseismology, these cases represent only certain evolutionary stages. To have asteroseismology for

all evolutionary stages, we need improvement for the non-asymptotic regime and the non-linear treatment of the non-radial pulsation in any kind of pulsating variables, in Cepheids, RR Lyraes,  $\delta$  Scuti, and  $\beta$  Cep stars. We would need at least to reach the possibility for ensemble asteroseismology, to get more precise physical parameters and characteristic similarities for as many stars as possible to step further in seismic modeling. Space observations of *red giants* (RGB stars) present a worthy example.

In the stars on the main sequence that are similar to our Sun and also in the more evolved red giants, which represent the future of our Sun, small-amplitude oscillations are intrinsically damped and stochastically excited by the near-surface convection were predicted, which were sensitive to the physical processes governing their interiors (Brown and Gilliland, 1994; Christensen-Dalsgaard, 2004). Brown et al. (1991) suggested that the frequency of the maximum oscillation power ( $\nu_{max}$ ) might be expected to be a fixed fraction of the acoustic cut-off frequencies, which is a directly accessible seismic parameter. The spacing between the consecutive radial orders, e.g., the  $\Delta\nu$ , was related to the acoustic radius and therefore to the mean density. A scaling relation was derived by Kjeldsen and Bedding (1995). The first case of a star other than the Sun showing an unambiguous evidence of solar-like oscillations was published (Christensen-Dalsgaard et al., 1995; Kjeldsen et al., 1995). Several ground-based observations were carried out in getting radial velocity measurements (Frandsen et al., 2002; De Ridder et al., 2006) and photometry (Stello et al., 2007), which were followed by early space detections [WIRE - (Buzasi et al., 2000), HST - (Stello and Gilliland, 2009), MOST - (Barban et al., 2007), and SMEI - (Tarrant et al., 2007)]. The real harvest started when the unprecedented precision of the space data (CoRoT, Kepler) allowed for the detection of the low-amplitude light variations in red giants. De Ridder et al. (2009) presented the first study of 300 red giants observed by CoRoT showing that they exhibited non-radial oscillations with common patterns. Hekker et al. (2009) demonstrated that there was a tight relation between the large separation  $\Delta\nu$  and  $\nu_{max}$  for red giants as in the case of solar-like stars. This opened the possibility to study the characteristics of their oscillations in a statistical sense, unlike the traditional goal of asteroseismology where the accurate measurement of individual mode frequencies was compared to the model frequencies (Huber et al., 2010). Miglio et al. (2009) identified the signature of the red clump and were able to distinguish the stars of the red clump from the red giant branch (RGB) stars, which represent a different evolutionary stage. In the RGB stars helium burning has not started in the core, while in the red clump stars started burning helium in the core. This is a defining moment in the life of a star from an evolutionary point of view. Kallinger et al. (2010) exploited the possibility of measuring stellar masses and radii from asteroseismic measurements, even when the effective temperature was not accurately known. In the following years larger and larger samples were analyzed together, up to thousands of stars. The second cycle of the important discoveries was the measurement of core rotation rates in subgiants and red giants (Beck et al., 2012; Deheuvels et al., 2012). These rotation rates were slower than the current models predicted

(Marques et al., 2013). Another mechanism is needed that can transport the angular momentum between the core and the envelope (Belkacem et al., 2015a,b). Less success was found in fitting stellar models directly to the observed frequencies due to poor modeling of the near surface layers (Ball et al., 2018). Fine tuning was carried out on the scaling relations, namely, the empirical scaling relation was based on more refined theoretical assumptions (Kjeldsen and Bedding, 2011). What is more, the non-linearity of the scaling relation was also discussed (Kallinger et al., 2018). The astrometric distances provided by GAIA proved to be in excellent agreement with the asteroseismic distances (De Ridder et al., 2016). The overwhelming success of the seismic indices inspired the preparation of the Stellar Seismic Indices (SSI) database that intended to provide the scientific community with a homogeneous set of parameters characterizing solar-type pulsators observed by CoRoT and Kepler (de Assis Peralta et al., 2018). It is impossible to cite all the papers in a review with limited space which evidently has to lead to excluding certain scientific work. This review only intended to indicate that the research field has improved a lot owing to the appearance of space data and inspiring immediate theoretical interpretation, which is the ideal process of the scientific research.

## 9. CONCLUSION

In a review paper on the current status of asteroseismology Kjeldsen and Bedding (2001) predicted that "it is impossible to imagine that asteroseismology will ever reach a level similar to that in which we find helioseismology today concerning analysis techniques, data quality and the level of results." Maybe, thanks to space missions, the excellent data of high precision and the results obtained up to now, the future of asteroseismology is brighter than the vision was before the space missions. The data are easily available for everybody who is interested in the research field. However, for some space missions a priority phase is applied for those who financially supported the mission, before the data becomes public. It means a limitation for the countries which are financially not powerful. Of course, the easiest reachable results, discoveries and the predictions with prepared algorithms can be obtained first in the priority interval. To go deeper in the data requires a longer time and much more effort. As this overview shows, even in the past there was a delay of about 10–20 years from the technical point of view between scientists from different countries. Hopefully, enough members of an enthusiastic young generation will be ready to look for new aspects, and for new relations to give answers to the long-standing questions and to draw up new questions in the field of stellar pulsation beside the fashionable exoplanet research. The computing power and observational data are much more readily available worldwide now.

The present and forthcoming space missions will definitely give a strong base for statistical investigations concerning the spatial distribution of stars of a certain evolutionary status. The astrometric measurements will lead to a better understanding of how our galaxy was born and how it has evolved. The theoretical overview let us conclude that there are questions

which were raised up decades ago and are still unanswered. Other problems were solved over 1–2 decades. In any case the solution of theoretical issues requires a much longer period than the duration of the supports of the funding agencies. The past shows that new data always inspired theoretical improvements. Hopefully, the space data will accelerate work on the theoretical issues. The overview shows that many similar physical processes were localized in pulsating stars of different evolutionary status. Amplitude and/or period variations were found among nearly all types of non-stochastically excited variables. Period doubling was localized in RR Lyrae, Cepheids and white dwarfs. Mode trapping was used as an explanation in RR Lyrae, white dwarfs, and sdB stars. Non-linear coupling and resonance were mentioned in different types of stars as a possible explanation for the observed phenomenon. Outbursts were localized in Be stars and white dwarfs, although the mechanisms are different. Maybe the similar phenomenon obtained from stars of different evolutionary status will help us in find the physical cause and let us get closer to the general aspect of pulsation.

Nowadays, we do not expect to discover major new classes of pulsating variable stars, that would add drastically to our knowledge of pulsation, although there are still places for new groups on the HR diagram. As Kilkenney et al. (1997) concluded after the discovery of sdB stars, "serendipity appears to have a major role to play in research and we are forcibly reminded that if we only look for what we expect to find, we might well miss exciting new discoveries." Nevertheless, the greatest challenge is to step further in describing the physics of the stars. Cox (1976) summarized the difficulties connected to the non-radial pulsation of  $\delta$  Scuti stars reminding us that the fully non-linear, non-radial, non-adiabatic calculation of stellar oscillations has not been attempted by anyone. The theoretical framework and application in simplified situations will be needed to guide physical intuition first. The full set of non-linear partial differential equations that describe the pulsation of stars has not been solved without significant approximations or special assumptions for any star. Of course, since that time some special assumptions have been relaxed, but the homework is clear. If we cannot give a reliable description of a real star, not in average, but from single star to single star, then modeling is not mature enough to help the interpretation of the observed data. In "real" stars we are faced with not only pulsation, but different physical processes: rotation, diffusion, convection, magnetic field, outbursts, spots, flares, everything that we see in the case of our Sun. Space data provided this high level of knowledge.

Computer-minded and/or sensitive thinking young scientists are needed who are able to process and interpret the flood of space data. The need for computer-minded young scientists is because a larger and larger database is going to be treated and new pulsation codes are expected to be written to include more and more, up to now excluded, physical processes. In addition, new ways of looking at the data and the theory together are required compared to what was used in the past.

Maybe we cannot immediately give the age of the Universe, but the future of asteroseismology is definitely bright. It depends on us how open-minded we are to notice previously unpredicted (by theory) and unidentified (by observation) features of the Universe.



## AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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