Progress in Physics of the Sun and Stars: A New Era in Helio- and Asteroseismology

Held under the auspices of the Fujihara Foundation of Science

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Hakone, November 25-29 2012

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List of contributions

I. Impacts on seismic investigations on solar/stellar physics

What aspects of stellar physics are we trying to understand through seismic investigations?

Arlette Noels
University of Liège

Asteroseismology is a very powerful tool that must be added to our other tools, such as spectroscopy, photometry, interferometry, ..., to constrain and improve stellar theoretical models and in such a process help us discover new aspects of stellar physics. The open questions are extremely numerous. I shall try to address some of them in various types of stars, from solar-like to massive main sequence stars, and from unevolved stars to red giants, and show how a detailed asteroseismic analysis of individual stars can reveal some fine structural aspects of these stars while a less ambitious but extraordinary rich seismic analysis of stellar populations can serve as a guide towards drawing a detailed chart of the Galaxy and even writing down its chemical history.

Progress in global mode helioseismology

Jesper Schou*, M. F. Woodard, C. S. Baldner, and T. P. Larson
*Stanford University

While global mode helioseismology has been around for decades and has contributed some of the most significant results in solar physics, systematic errors persist and we continue to make progress. In this talk I will describe some of the recent progress in global mode seismology, including ridge fitting. In particular I will describe progress in fitting for meridional circulation by exploiting the distortion of normal mode eigenfunctions. I will also discuss possible sources of the remaining systematic errors, such as the effect of flows on the phase of the eigenfunctions.

Energetic balance of the Sun and stars

Sylvaine Turck-Chièze
CEA, Saclay

Helioseismology and asteroseismology have allowed unprecedented views on the solar and stellar interiors that we have not anticipated twenty years ago. After two decades of detailed measurements, accompanied by impressive progress on solar neutrino detections, it is interesting to discuss the different observations, their coherence or their inconsistence at the light of initial hypotheses still well alive 20 years ago.

It is also interesting to try to interpret the present discrepancies or new results using the most recent progress done in different disciplines (astrophysics and fundamental physics).

This talk will question some of the most believed knowledge on energetic balance, transfer of energy, particle physics or dynamo not only for the Sun but also for massive stars to suggest some possible solutions that could orientate future developments and observations and could help our progress on the internal dynamical aspects of stars.

An overview of white dwarf stars

Gilles Fontaine
Université de Montréal

I will present a brief summary of what is currently known about white dwarf stars, with an emphasis on their evolutionary and internal properties. As is well known, white dwarfs represent the end products of stellar evolution for the vast majority of stars and, as such, bear the signatures of past events (such as mass loss, mixing phases, loss and redistribution of angular momentum, and thermonuclear burning) that are of essential importance in the evolution of stars in general. In addition, white dwarf stars represent ideal testbeds for our understanding of matter under extreme conditions, and work on their constitutive physics (neutrino production rates, conductive and radiative opacities, interior liquid/solid equations of state, partially ionized and partially degenerate envelope equations of state, diffusion coefficients, line broadening mechanisms) is still being actively pursued. Given a set of constitutive physics, cooling white dwarfs can be used advantageously as cosmochronometers. Moreover, the field has been blessed by the existence of five distinct families of pulsating white dwarfs, each mapping a different evolutionary phase, and this allows the application of the asteroseismological method to probe and test their internal structure and evolutionary state. I will discuss briefly some of the properties of pulsating white dwarfs.

Asteroseismic constraints on rotation of a Sun-like star

Laurent Gizon and the *CoRoT* collaboration
Max-Planck-Institut für Sonnensystemforschung
and
Georg-August-Universität Göttingen

Rotation is thought to drive cyclic magnetic activity in the Sun and Sun-like stars. Stellar dynamos, however, are poorly understood owing to the scarcity of observations of rotation and magnetic fields in stars. In this presentation, inferences are drawn on the internal rotation of a distant Sun-like star by studying its global modes of oscillation. We report asteroseismic constraints imposed on the rotation rate and the inclination of the spin axis of a *CoRoT* prime target known to host a planetary companion. These seismic inferences are remarkably consistent with an independent spectroscopic observation (rotational line broadening) and with the rotation period of starspots. Further, asteroseismic constraints on the mass of exoplanet are presented.

Constraints on the stellar parameters of white dwarf stars from asteroseismology

Gerard Vauclair
Université de Toulouse

Asteroseismology has proved to be a powerful tool to infer the internal structure of white dwarf stars at different evolutionary stages along their cooling sequence. As white dwarf stars are the final evolutionary stage of most of the stars, their detailed structure gives interesting constraints on physical processes occurring either during previous phases of stellar evolution or during their evolution along the cooling sequence. I will show on some examples how fundamental parameters can be inferred and discuss some challenging issues which need theoretical developments and observational efforts.

Convective cores and stellar ages as revealed by Kepler: what do we know?

Victor Silva Aguirre
Aarhus University

It has long been known that reproducing the observed hook-like feature in the CMD of intermediate-age clusters requires stars at the turn-off phase which possessed a convective core during their main-sequence lifetime. However, the appearance or not of a convective core in stellar models at the limiting mass of $\sim 1.2\,M_{\odot}$ is extremely dependent on the input physics, as well as its total extent that is controlled by an efficiency parameter calibrated to reproduce observations of clusters. Thus, we currently lack a reliable estimation of the size a convective core has in main-sequence stars, if it does indeed exist. An exciting approach comes from the possibility of using asteroseismology to obtain information about stellar cores, where suitable combinations of frequencies have shown to be sensitive to the deep layers of stars. I present the current status on our research based on two $Kepler$ targets with the aim of discriminate between existence or not of convective cores, and analyze the caveats and uncertainties in current asteroseismic modelling techniques.

Asteroseismic twins

Nesibe Ozel
Université de Liège

The *CoRoT* short asteroseismic runs give us the opportunity to observe a large variety of late-type stars through their solar-like oscillations. Our aim is to define a method able to extract as much information as possible from a low signal-to-noise ratio (SNR) power density spectrum, benefiting from the comparison to a reference star. We propose a differential approach which consists in using a well-known star as a reference star to characterize a neighboring star with a low SNR oscillation spectrum. This method is based on scaling relations and benefits from the comparison to a star with similar seismic and fundamental parameters and with a precise modeling derived from high signal-to-noise ratio asteroseismic measurement.This method is not just useful to characterize the lower SNR targets. It can can also be applied to the well-constrained stars. In this case, it would give a very precise determination of the structural differences between nearby stars. The importance of the differential method here is that the results will be less sensitive to the systematic errors coming from both the modeling and the data analysis method.

II. New observational findings and other enigmatic phenomena

Highlights of recent CoRoT results and their impacts on stellar astrophysics

Annie Baglin
Observatoire de Paris

CoRoT is now being extended for 3 more years. A few major highlights of the first 6 years will be presented. A new scientific program will be performed during the extension, based on the *CoRoT* "niches", and the complementarity with *Kepler*. The specific topics of the stellar part will be described in more details. It focusses on hot and young stars and clusters, bright solar like stars, and the mapping the different regions of the galaxy with red giants.

Observing dynamical effects on solar-like stars with CoRoT and Kepler

Rafael García
CEA, Saclay

High quality time series provided by space instrumentation such as *CoRoT* and *Kepler*, allow us to measure changes in the surface of stars related to rotation and activity. Therefore, we are able to infer the surface (differential) rotation rate as well as cyclic effects related to activity cycles. Moreover, thanks to the long continuous photometric observations (high frequency resolution) we are now able to extract the rotational splitting of the p and mixed modes of several stars opening the study of the internal radial rotation.

G-mode oscillations in hot B subdwarf stars

Stéphane Charpinet
Université de Toulouse

Observations from space with *CoRoT* and *Kepler* have contributed to reveal the very rich pulsation spectrum in the long period hot B subdwarf (sdB) pulsators of the V1093 Her type. These evolved and compact helium core burning stars can develop low amplitude oscillations with periods in the range ∼ 1-4 hours that correspond to low degree, mid/high order g-modes. These modes have the property to probe deep inside the star, down to boundary of the central convective core, and are extremely interesting asteroseismic probes. However, correct interpretations of the observed oscillation spectra requires a good knowledge of the properties of these modes. I will review how the g-modes behave in sdB stars and discuss how to interpret space data obtained on the long period pulsators.

Pulsation amplitude variations in hot subdwarf stars

Anthony Lynas-Gray
University of Oxford

Hot subdwarfs which pulsate are not easily distinguishable by their chemical element abundances, effective temperatures and surface gravities from their non-pulsating counterparts. An apparent characteristic of pulsating hot subdwarfs is that they exhibit pulsation amplitude variations suggesting that pulsation in these objects may be a transient phenomenon. Alternative interpretations are discussed in the context of pulsation amplitude variations found in other pulsating stars.

The pulsating low-mass He-core white dwarfs

Alejandro H. Córsico*, L. G. Althaus, and A. D. Romero
*Universidad Nacional de La Plata

In the last years, many low-mass ($\lesssim 0.45\,M_\odot$) white dwarf stars expected to harbor He cores have been detected in the field of the Milky Way and in several galactic globular and open clusters. Recently, three pulsating objects of this kind have been discovered: SDSS J1840+6423 ($T_{\rm eff} =$ 9140 $\pm$ 170 K and $\log g =$ 6.22 $\pm$ 0.06), SDSS J1112+1117 ($T_{\rm eff} =$ 9400 $\pm$ 490 K and $\log g = 5.99 \pm 0.12$), and SDSS J1518+0658 ($T_{\rm eff} = 9810 \pm 320$ K and $\log g = 6.66 \pm 0.06$). Motivated by these very exciting findings, and in view of the valuable asteroseismological potential of these objects, we present here the first outcomes of a detailed theoretical study on the seismic properties of low-mass He-core white dwarfs based on fully evolutionary models representative of these objects. This study is aimed to provide a theoretical basis from which to interpret present and future observations of variable low-mass white dwarfs. Among other topics, we discuss here the plausibility of the ε-mechanism to destabilize pulsation modes in these stars.

The new white dwarf catalog and the implications therein for pulsating white dwarf research

Scot Kleinman
Gemini Observatory

Thanks to the Sloan Digital Sky Survey, we now have identified nearly an order of magnitude more white dwarf stars than were known before. In particular, we now have over a hundred DAV (ZZ Ceti), DBV (V777 Her) and DOV (PG 1159 / GW Vir) confirmed pulsators stars and hundreds more candidates pulsators. This new large sample is allowing us to study both class properties and unique aspect of these stars in ways we could not have done before. I present a brief overview of the new sample of stars and highlight some of the interesting work using them.

Comparing two mode identification techniques in a DB white dwarf

Atsuko Nitta
Gemini Observatory

Among various mode identification techniques used in white dwarf asteroseismology, the most successful one to date is what we call the "period distribution method". This method relies on period spacings and fine structure splittings of the pulsation modes to identify (k, ℓ, m) for each observed mode. Another method, less proven but potentially useful in stars that have only a few detectable modes where the period distribution method is not, is the "chromatic amplitude method". This method uses the fact that limb darkening and geometric cancellation result in different pulsation amplitude versus wavelength distributions for modes of different ℓ.

To evaluate whether or not both methods agree with each other, we applied both mode identification methods to the DBV, GD358, one of the best studied pulsating white dwarf stars. We observed GD358 simultaneously in the optical, with the Whole Earth Telescope (WET), and in the ultraviolet (UV) with the Hubble Space Telescope (HST). Our period distribution analysis resulted in the identification of both $\ell = 1$ and $\ell = 2$ modes in our data, the first time we have simultaneously seen identifiable $\ell = 1$ and $\ell = 2$ modes in this star, and fortunate for this particular study. The corresponding chromatic amplitude data very clearly separate the determined $\ell = 1$ modes from the $\ell = 2$ modes, although they do not quantitatively agree with theoretical predictions.

Decoding convection with white dwarf lightcurves

Judith Provencal
University of Delaware

Convection remains one of the largest sources of theoretical uncertainty in our understanding of stellar physics. Current studies of convective energy transport are based on the mixing length theory. Originally intended to depict turbulent flows in engineering situations, MLT enjoys moderate success in describing stellar convection. However, problems arising from MLT's incompleteness are apparent in studies ranging from determinations of the ages of massive stars, to understanding the structure F and early A stars, to predicting the pulsation periods of solar stars, to understanding the atmosphere of Titan. As an example for white dwarfs, Bergeron et al. (1995) show that model parameters such as flux, line profiles, energy distribution, color indices, and equivalent widths are extremely sensitive to the assumed MLT parameterization. The authors find systematic uncertainties ranging from 25% for effective temperatures to 11% for mass and radius. This is compelling, since we use our knowledge of white dwarf interiors to calibrate white dwarf cooling sequences, provide detailed estimates for the ages of individual white dwarfs, and calibrate the age of the Galactic disk. The WET is engaged in a long term project to empirically determine the physical properties of convection in the atmospheres of pulsating white dwarfs. The technique, outlined by Montgomery et al. (2010), uses information from nonlinear (non-sinusoidal) pulse shapes of the target star to empirically probe the physical properties of its convection zone. Approximately two thirds of all white dwarfs show nonlinear characteristics in their light curves. We present current results from WET targets in 2008-2012.

Decoding EC14012's rich pulsation spectrum

Agnès Bischoff-Kim
Georgia College & State University

EC14012-1446 (from hereon "EC14012") is a ZZ Ceti star (DAV) that was the object of a Whole Earth Telescope run in 2008. The extended coverage run provided a detailed and well resolved period spectrum for the star, confirming and revealing 19 independent modes of vibration, including 1 triplet and a few more incomplete triplets (doublets). The data and partial mode identification were published in Provencal et al. in 2012 (ApJ, 751, 91). With a large number of modes (for pulsating white dwarfs) and good clues for some of the mode identification from independent methods, EC14012 is a good candidate for high speed asteroseismology, were we try to infer interior structure based mainly on available data (spectroscopy and pulsation spectrum). With the asteroseismic analysis of EC14012 using this method, a consistent picture of its stellar properties and internal structure emerges. We also present preliminary results on the ZZ Ceti star that was discovered in the field of view of the *Kepler* satellite.

Oscillations of accretion disks in cataclysmic variable stars

Yoji Osaki
University of Tokyo

I discuss variability occurring in dwarf novae. Dwarf novae are eruptive variable stars showing quasi-periodic outbursts with amplitude 2-5 mag and a typical recurrence time of 10 to several ten days. They belong to a more general class of cataclysmic binaries in which a Roche-lobe filling red dwarf secondary star loses mass and a white dwarf primary star accretes it via an accretion disk. Variability in light curves of dwarf novae is now thought to be produced in accretion disks in these stars, such as a thermal limit cycle instability and tidal instability. One of the most interesting phenomena is an appearance of periodic humps called "superhump" in SU UMa type dwarf novae with a period slightly longer than the binary orbital period. The superhumps always appear when the star undergoes so-called "superoutburst", an outburst having an outburst amplitude 0.5 to 1 mag brighter and having longer duration by a factor 5 than those of the ordinary normal outburst. In 1989, I proposed a model to explain the superoutburst and superhump phenomenon, by coupling two kinds of intrinsic instabilities in accretion disks, the thermal instability and the tidal instability (the model now called "TTI" model). The TTI model has been well accepted as an explanation of the superoutburst and superhump phenomenon but some criticisms to this model still remained to be expressed from time to time.

The *Kepler* SC (short cadence) observations include light curves of two SU UMa stars, V344 Lyr and V1504 Cyg. We have studied the *Kepler* light curve of one of them, V1504 Cyg, by using two-dimensional power spectrum. The *Kepler* light curves have revealed many interesting phenomena, which seem basically to support the TTI model.

Stellar consequences of the accretion of stellar debris matter onto white dwarfs

M. Deal, S. Vauclair, and Gerard Vauclair*
*Université de Toulouse

Heavy elements are observed in the atmospheres of many DA and DB white dwarfs, and their presence is attributed to the accretion of matter coming from debris discs. Several authors have deduced accretion rates from the observed abundances, taking into account the mixing induced by the convective zones and the gravitational settling. The obtained values are different for DA and DB white dwarfs. Here we show that an important process was forgotten in all these computations: thermohaline mixing, induced by the inverse μ-gradient built during the accretion process. Taking this mixing into account leads to an increase of the derived accretion rates, specially for DA white dwarfs, and modifies the conclusions.

Progress in the detection of the p-mode spectra of roAp stars: Alpha Circini and Gamma Equulei

David E. Mkrtichian* and A. P. Hatzes

*National Astronomical Institute of Thailand

We present recent results on α Cir and γ Equ that are part of our program to detect the p-mode oscillation spectrum in roAp stars. For α Cir we have used a time series of precise radial velocity measurements made with the HARPS spectrograph of ESO's 3.6 m telescope at La Silla Observatory. These reveal a rich, low-amplitude p-mode spectrum of at least 36 modes that lie in the interval 2173-2641 μHz. The mode amplitudes range from 46 cm/s to 56 cm/s. The number and spacing of the modes indicate that we have detected, for the first time, the excited high-degree ($\ell > 3$) modes in a an roAp star.

In γ Equ we have discovered 4 new oscillation modes. This result is based on precise radial velocity measurements take with the Tull Spectrograph of the 2.7 m telescope at McDonald Observatory. The frequencies of these new modes, along with previously known modes, exhibit a well defined large spacing of 62.8 μHz. We conclude that consecutive overtones of even and odd modes are excited in γ Equ.

These discoveries have established new detection limits for asteroseismology of roAp stars and shows the need for updating theoretical pulsation models of magnetic stars.

Frequency regularities in Delta Scuti stars

Margit Paparó* and J. M. Benkő
*Konkoly Observatory

Mode identification is one of the most sensitive (critical) point of asteroseismology. In the asymptotic regime (solar type oscillation and white dwarfs) the regularities (patterns) help to identify the modes and to reach the level of real asteroseismology. However, over most part of the HR-diagram the pulsation is outside of the asymptotic regime. Especially the Delta Scuti stars exhibit a large discrepancy between the number of the observed and theoretically predicted modes, which points to the operation of a mode selection mechanism. Although we recognized that independent identification of modes is impossible in a large number of stars, there has always been a hope that longer and continuous observation will reveal the predicted but missing frequencies, or that we will find some kind of regularity amongst the larger number and lower amplitude modes. With $MOST$, $CoRoT$ and $Kepler$ space missions our dream has become reality.

Ground-based observation of 44 Tauri revealed that more than one radial period sequence exists (Poretti et al. 1992). Modelling (Lenz et al. 2008, 2010) confirmed that non-radial trapped modes around the radial modes are responsible for the sequences. The $CoRoT$ Delta Scuti star, 102749568 shows high level regularities between the frequencies, such as systematic spacings (including the large separation) and radial period ratio sequencies (Paparó et al. 2013, before submission). In this presentation we check a large sample of Delta Scuti stars (using both ground-based and space data) on how general the appearance of the radial period ratios or sequences is and how effective the mode trapping in the mode selection is.

Directions for the future of the ground-based follow-up for the Kepler space mission

Joanna Molenda-Żakowicz
University of Wrocław

The NASA space mission *Kepler* has been providing high-precision time-series photometry in a single, broad-band filter for thousands of stars since March 2009. During that time, the *Kepler* data allowed to discover more than 70 exoplanets, and to study new or already known but poorly investigated astrophysical phenomena in stars of different kinds. In April 2012 NASA approved the extension of the *Kepler* mission and its observations will be continued for another four years.

In order to make a full use of those space-born data, an enormous ground-based observational effort has been undertaken aiming at deriving fundamental atmospheric parameters of the *Kepler* targets, and detecting new targets for *Kepler*.

In this contributions, give an account of the present state of the photometric and spectroscopic monitoring of the *Kepler* field, discuss the results which have been already obtained, outline the progress of the on-going work, and show the directions for the future research. Then, I specify the areas of the scientific research that need further development, and the limitations which must be removed in order to take full advantage of the opportunities offered by the exquisite quality of the *Kepler* data.

Low-frequency variations of unknown origin in the A-type star KIC 5988140

Patricia Lampens* et al.

*Royal Observatory of Belgium

At first sight, the *Kepler* data of the A-type star KIC 5988140 resemble the light curve of an eclipsing binary system with superposed short-period variability of type δ Scuti (e.g. Uytterhoeven et al. 2011). It has thus been attributed by the Kepler Asteroseismic Science Consortium to the Working Group on "Pulsations in eclipsing binaries", where we picked it up. We used the high-quality *Kepler* photometry supplemented by new high-resolution spectra to investigate the cause of the variability of this late A-type target. We considered three different scenarios: binarity, co-existence of both γ Doradus and δ Scuti pulsations (the hybrid case) and rotation of the stellar surface with an axisymmetric intensity distribution. However, none of these scenarios is capable of explaining all of the characteristics of the observed variations. We confirm the occurrence of multiple pressure modes of type δ Scuti, but argue that the cause of the remaining light and radial velocity variations is presently unexplained by any of the three considered physical processes.

Asteroseismic study of the CoRoT target HD 169392

Savita Mathur* et al.
*High Altitude Observatory

After five year of observation, the satellite $CoRoT$ (Convection, Rotation, and Transits) is still providing high-quality data. We will show here the results of the asteroseismic analysis and modeling of the solar-like star, HD 169392A, the main component of a binary system. This analysis was complemented by spectroscopic observations obtained by HARPS.

Oscillation and surface rotation of more than 400 red giants observed by Kepler

C. Hedges, Savita Mathur*, and M. J. Thompson
*High Altitude Observatory

More than 15000 red giants observed by *Kepler* during almost one year have become public beginning of this year. We analyzed a subsample of 416 stars to determine the global properties of acoustic modes (mean large separation and frequency of maximum power). Using the effective temperature from the *Kepler* Input catalog, we derived a first estimation of the masses and radii of these stars. Finally, we applied the wavelets to look for signature of surface rotation, which relies on the presence of spots crossing the stellar visible disk.

Red giants in the field and open clusters observed by Kepler

Dennis Stello
University of Sydney

In this talk I will present recent observational and theoretical results on the asteroseismology of red giant stars. I will focus on results arising from *Kepler* observations of the open star clusters and the more than 10,000 field red giants in its field of view.

Red giants in eclipsing binary systems: Analysis of 53 lightcurves from Kepler data

Patrick Gaulme
New Mexico State University

The objective of the present work is to list a set a potentially precious targets to test theories of stellar evolution: it consist of red giants belonging to eclipsing binary systems. Indeed, if we can estimate the stellar parameters with both transit fitting and asteroseismology they may become the most accurately studied stars. *Kepler* has detected about 14000 red giants and 2200 eclipsing binaries (Slawson et al. 2011). From the combination of eclipsing binary and red giant catalogs, we identified 53 red giants possibly belonging to eclipsing binary systems, of which 33 present clear global modes. Mean properties of global modes are used to infer red giant masses and radii. We then discuss whether the oscillating red giants do belong to the eclipsing binaries they are associated with, to deduce that 8 red giants possibly belong to eclipsing systems and 8 more to triple systems.

Spectroscopic mode identification in Gamma Doradus stars

Karen Pollard
University of Canterbury

I outline the observational programme we are undertaking at the Mt John University Observatory in New Zealand to obtain long time-base high-resolution spectra of selected γ Doradus, and related, stars. We have investigated various methods to successfully analyse these observations to obtain reliable mode-identifications in order to constrain the theoretical models of γ Dor stars. In particular we are looking at the way that g-modes differ from p-mode pulsations in the mode-identification methods and the effects of rotation in these stars.

Line-profile variations of the primary of Epsilon Aurigae eclipsing binary system

Eiji Kambe*, K. Sadakane, O. Hashimoto, S. Honda, and B. Sato
*National Astronomical Observatory

Epsilon Aurigae is a single-line spectroscopic eclipsing binary system with an orbital period of about 27.1 year. The duration of its eclipse of about two years is quite long. It consists of an F0 supergiant primary and an unseen secondary surrounded by a very large and half-opaque disk that causes such a long eclipse. The mass and evolutionary status of the primary has been disputed over years. We have monitored the binary since October 2008 by high dispersion spectrographs attached to Okayama 1.88-m telescope and Gunma 1.5-m telescope, covering its total eclipse around the summer in 2010. We have found that lines of the primary show complicated variations with time scale of tens to a hundred days which may be caused by stellar pulsations in addition to the occulting disk. We have made period analysis of the line-profile variations of the primary spectra and detected at least six periods ranging from about 50 days to 160 days. The wavelength dependence of the variations depends on the periodicity. We will discuss the pulsation modes excited in the primary and natures of this enigmatic eclipsing binary system.

Understanding helioseismic observables

Kaori Nagashima
Max-Planck-Institut für Sonnensystemforschung

In order to interpret measurements in global and local helioseismology, it is important to be able to model the observables (filtergrams and Dopplergrams). Here by using numerical simulations we study the possibility of measuring Doppler velocity at two different heights using a set of 6 filtergrams obtained by SDO/HMI. One potential application that is particularly interesting is to search for the upward propagating waves caused by individual acoustic events. Understanding helioseismic observables is important also, for example, in interpreting center-to-limb effects in local helioseismology and in exploiting multi-wavelength analyses.

III. New techniques for helio- and asteroseismology

FM stars: a Fourier view of pulsating binary stars

Hiromoto Shibahashi* and D. W. Kurtz
*University of Tokyo

Some pulsating stars are good clocks. When they are found in binary stars, the frequencies of their luminosity variations are modulated by the Doppler effect caused by orbital motion. For each pulsation frequency this manifests itself as a multiplet separated by the orbital frequency in the Fourier transform of the light curve of the star. We derive the theoretical relations to exploit data from the Fourier transform to derive all the parameters of a binary system traditionally extracted from spectroscopic radial velocities, including the mass function which is easily derived from the amplitude ratio of the first orbital sidelobes to the central frequency for each pulsation frequency. This is a new technique that yields radial velocities from the Doppler shift of a pulsation frequency, thus eliminates the need to obtain spectra. For binary stars with pulsating components, an orbital solution can be obtained from the light curve alone. We give a complete derivation of this and demonstrate it both with artificial data, and with a case of a hierarchical eclipsing binary with $Kepler$ mission data, KIC 4150611 (HD 181469). We show that it is possible to detect Jupiter-mass planets orbiting δ Sct and other pulsating stars with our technique. We also show how to distinguish orbital frequency multiplets from potentially similar non-radial m-mode multiplets and from oblique pulsation multiplets.

Super-Nyquist asteroseismology

Don Kurtz*, S. J. Murphy, and H. Shibahashi
*University of Central Lancashire

Barycentric corrections made to the timing of *Kepler* observations break the regular time-sampling of the data. The Nyquist frequency is therefore periodically modulated. A consequence is that Nyquist aliases are split into multiplets that can be identified by their shape. Real pulsation frequencies are distinguishable from these aliases and their frequencies are completely recoverable, even in the super-Nyquist regime, that is, when the sampling interval is longer than half the pulsation period. We provide an analytical derivation of the phenomenon, alongside demonstrations with simulated and real *Kepler* data for δ Sct, roAp, and sdBV stars. For *Kepler* data sets spanning more than one *Kepler* orbital period (372.5 d), there are no Nyquist ambiguities on the determination of pulsation frequencies, which are the fundamental data of asteroseismology.

Connections between quasi-periodicity and modulation in pulsating stars

József M. Benkő* and M. Paparó
*Konkoly Observatory

The observations of the photometric space telescopes *CoRoT* and *Kepler* show numerous Blazhko RR Lyrae stars which have non-repetitive modulation cycles. The phenomenon can be explained by multiperiodic, stochastic or chaotic processes. From mathematical point of view, almost periodic functions describe all of them. We assumed band-limited almost periodic functions either for the light curves of the main pulsation or for the modulation functions. The resulted light curves were examined both by analytically and numerical simulations. This presentation is a part of our systematic study on the modulation of pulsating stars (Benkő et al. 2009, 2011, 2012).

We checked two fundamentally different options: (1) almost periodic pulsation alone and (2) simultaneous pulsation and modulation where (at least) one of them is almost periodic. Option (1) produces light curves with amplitude and frequency variation but significant differences appear compared to the observed light curves (shape of Blazhko envelope curve, lack of modulation peak in the Fourier spectra). Option (2) yields completely analogous light curves with the observed data. Probably all discrepancies mentioned by Szeidl et al. (2012) can be eliminated using almost periodic functions for the Blazhko RR Lyrae stars.

IV. Impact of the revised solar abundances on astrophysics

“Old” solar abundances? Time to stop using them!

Nicolas Grevesse
University of Liège

We follow the evolution of the abundances of the elements in the solar photosphere since 1989. We describe how the largely used high metallicity mixtures ($Z = 0.02$ to 0.017) of Anders and Grevesse (1989), Grevesse and Noels (1993) and Grevesse and Sauval (1998) have been obtained and explain why these mixtures should not be used anymore. They are to be replaced by the more recent mixture of Asplund, Grevesse, Sauval and Scott (2009) which results from the first comprehensive and homogeneous analysis since many decades. We describe the main characteristics of this work and discuss the most important impacts of this low Z ($Z = 0.0134$) mixture. We also comment on another recent analysis by Caffau et al. (2011) that leads to somewhat larger abundances of O and C. Finally, future progress in the field of solar abundances from new MHD models will be suggested.

The solar abundance and stellar astrophysics

Joyce Guzik
Los Alamos National Laboratory

Solar models calculated with element abundances derived after 2005 (Asplund et al.) do not give as good agreement with helioseismic inferences as do the older abundances. I will discuss inclusion of early mass loss, modified electron screening based on molecular dynamics simulations, and dark matter on solar structure and how these may improve helioseismic agreement given the new abundances. Clues to resolving the abundance problem may also come from asteroseismology. I will show, for example, how the oscillation spectrum of stars at the boundary between solar-like oscillators and γ Doradus g-mode pulsators, such as the bright star θ Cygni observed by the *Kepler* spacecraft, may show a sensitivity to interior abundances. Predictions for variability in slowly-pulsating B stars and β Cephei stars are also affected by opacities and abundances, and can be tested by asteroseismic data. Photospheric abundances may not be representative of the stellar interior because of diffusive settling, radiative levitation, mixing, accretion, or mass transfer. After the talk I would like to have a discussion of possible asteroseismic tests of stellar abundances and opacities.

Solar heavy element abundance and the equation of state

Vladimir A. Baturin* and S. V. Ayukov
*Lomonosov Moscow State University

We consider a physical background of the equation of state used in solar modeling, focusing of our attention on the adiabatic solar convection zone. Geometry of equation of state is described as a Hamiltonian flow defined by the adiabatic exponents as a vector field. A variety of possible profiles of the adiabatic exponent Γ_1 in the ionization region of heavy elements predicted by OPAL and SAHA-S Equation of state is considered. Basic (uncertain) factors contributing to Γ_1 are the Coulomb correction, which increases Γ_1, and heavy elements ionization, which reduces it. Contributions of each element into Γ_1 may be found and correlated with locations of consequent ionization stages in the temperature scale. As a result, the profile of Γ_1 (and its gradient) is appeared to be directly connected with the heavy elements content, provided that the Coulomb corrections are the same in different EOS's, what can be checked by comparison of $Z = 0$ profiles. Modern EOS indicates consistently on the lower (about twice smaller than standard one) value of Z, when helioseismic calibration of the envelope is applied.

V. Chemical stratification in the Sun and stars

Atomic diffusion, mixing and element abundances

Sylvie Vauclair
Université de Toulouse

Atomic diffusion is now recognized as a "standard process" working in stars, and gravitational settling is introduced in most stellar evolution codes. Helioseismology proved the importance of the downward diffusion of helium and heavy elements below the solar convective zone. However, in more massive stars, the effect of the selective radiative accelerations cannot be neglected. It has been known for a long time that the resulting atomic levitation may, in some cases, lead to abundance variations in stellar atmospheres, as observed in the so-called chemically peculiar stars. But this was only part of the story. We now discovered that, when acting on important elements like iron or nickel, radiative levitation may also lead to global macroscopic effects inside stars, like extra convective zones, wave excitation by kappa mechanism, double-diffusive mixing processes (thermohaline), etc. I will discuss the links between these processes and their consequences.

Clouds of chemical elements in high atmospheric layers of ApBp stars

Georges Alecian
Observatoire de Paris

Models that include atomic diffusion in chemically peculiar stars have considered mostly internal layers and usual line-forming layers in atmospheres. Indeed, main observable effects of diffusion processes (and of the subsequent abundance stratifications) are expected to come from these layers. However, recent progresses in modeling, and new observations, allow a better comprehension of the richness of phenomena that may be related to atomic diffusion in high atmospheric layers (above $\tau \approx 10^{-4}$). Clouds/spots of chemical elements may form in those layers, even in stars considered as non-magnetic (HgMn). In HgMn stars, such spots could be due to weak magnetic fields, and will be situated above a background of homogeneous element stratifications that cause the usual and well-known overabundances of, for instance, iron peak elements. According to current models, the effects of such inhomogeneities are compatible, not only with peculiarities observed in spectra, but also with peculiar variabilities due to waves propagating in these inhomogeneous media.

VI. Constraints from helio- and asteroseismology

Seismic diagnostics of the equation of state and chemical composition in the solar convective envelope

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We address the diagnostic potential of solar p-mode frequencies inferred from Doppler-velocity measurements of SOHO MDI "medium-ℓ" programme to explore the accuracy of different versions of the equation of state, and the chemical composition in the solar envelope. We examine solar models constructed with four different modern versions of the equation of state (two versions of OPAL, and two versions of SAHA-S equation of state). We use two diagnostic techniques, which supplement each other: (1) direct calibration with using grids of envelope models which differ in chemical composition (parameterized by helium abundance Y and heavy-element abundance Z) and in the specific entropy in the adiabatically-stratified part of the solar convective envelope, and (2) a constrained structural helioseismic inversion. The best agreement with seismic data is allowed by the recently developed SAHA-S3 equation of state. The maximum-likelihood estimates of composition parameters Y and Z depend on the implemented version of the equation of state, and may also be distorted by systematic errors in solar frequency measurements. The estimates obtained in this study are in the range of $Y = 0.240 - 0.255$ and $Z = 0.008 - 0.013$. All our results bring a strong evidence in favour of low Z values, reported from recent spectroscopic measurements.

New approach to the solar evolutionary model with helioseismic constraints

Sergey V. Ayukov* and V. A. Baturin
*Lomonosov Moscow State University

Classic procedure of modelling the solar evolution is in adjusting a value of convective adiabate and initial hydrogen content to obtain model with given radius and luminosity at specified age. Standard solar model does not incorporate helioseismic data (convection zone depth $R_{\rm cz}$, helium abundance in the envelope $Y_{\rm cz}$ and specific entropy in the adiabatic part of the convection zone $S_{\rm cz}$) as boundary conditions. Modern standard models of the Sun with diffusion settling have $R_{\rm cz}$ and $Y_{\rm cz}$ rather close to the helioseismic values. However detailed analysis of eigenfrequencies requires exact values of $Y_{\rm cz}$ and especially $R_{\rm cz}$ in solar models. This work proposes a method to calculate models with specified convection zone parameters. Target calibration values are chosen from the set of $R_{\rm cz}$, $Y_{\rm cz}$, $Z_{\rm cz}$ and $S_{\rm cz}$ (alternatively, mass parameter can be used instead of entropy). The method utilizes local and global opacity modifications. Global modification allows to adjust $Y_{\rm cz}$, change in the radiative zone mainly affects $S_{\rm cz}$. Convection zone depth depends on $Y_{\rm cz}$, $Z_{\rm cz}$, $S_{\rm cz}$ or can be independently adjusted via local opacity correction. Proposed method introduces new class of solar models which strictly adhere to helioseismic data. We consider sound speed profile in the constructed models and compare with inversion results; it was found that models which conform to helioseismic value of $S_{\rm cz}$ cannot reproduce helioseismic sound speed profile. The consequences of this controversy remain to be investigated.

Constraint on the axion-photon coupling constant using helioseismic solar models

Kazuhiro Maeda* and H. Shibahashi
*University of Tokyo

The axion is a hypothetical elementary particle and a candidate of dark matter. Its property is described mostly by its mass. If the mass is high enough, a photon can be converted into an axion in stellar cores. This is known as the Primakoff effect.

We aim at setting constraints on the axion-photon coupling constant from helioseismology and solar neutrino fluxes. First, we have constructed a helioseismic solar model which is exactly consistent with the sound-speed profile determined by helioseismology. Next, we have taken the Primakoff effect into account in modeling a series of such helioseismic solar models by introducing a free parameter $g_{a\gamma}$ for the axion-photon coupling. Comparison of the neutrino fluxes estimated from our models with observations enables us to set an upper limit on the axion-photon coupling constant $g_{a\gamma}$.

Current version of SAHA-S equation of state: improvement and perspective

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Modern version (SAHA-S3) of the equation of state proposed for solar modeling is presented. Basic improvement in the version is a detailed description of excited states of ions of 10 elements. The physical assumptions in the EOS and main contributions to the Γ_1-profile along an adiabate (typical in solar condition) are described. Adiabatic Γ_1-profiles are shown for different values of adiabate as well as for different helium and heavy elements contents. Distributions of ionic abundances and contributions of every elements to Γ_1-profile are plotted. The SAHA-S3 EOS is used in the calibration of solar envelope and inversion of Γ_1 in the solar convection zone. The results shows the certain advantages of SAHA-S3 over other EOS (e.g. OPAL2005 EOS) and consistently indicates on a low Z in the convective zone of the Sun.

VII. Oscillations and excitation mechanisms

Strange mode instability for the pulsation of blue supergiants

Hideyuki Saio
Tohoku University

Many blue supergiants show light variations probably caused by radial/nonradial pulsations. We discuss the strange mode instability to explain the excitation of radial/nonradial pulsations in blue supergiants. It is found that the mechanism works if these stars had spent sometime in the red supergiant region and had lost substantial mass. We argue that such an evolution actually occurs if substantial rotational mixing occurs in the radiative layers during the main-sequence stage.

Dipole low-order g-mode instability of metal-poor main-sequence stars due to the epsilon-mechanism

Takafumi Sonoi* and H. Shibahashi
*University of Tokyo

The vibrational instability of low-degree, low-order g-modes due to the ε-mechanism has been proposed as a possible solution to the solar neutrino problem, and the detailed numerical calculations of linear stability analyses by several groups demonstrated that such instability is likely to occur in a certain early evolutionary stage of the sun and solar-like stars. The presence of convective envelope, which occupies the outer 20-30 per cent in the case of Population I low-mass stars, however, has made it hard to reach a definite conclusion about the vibrational instability.

The situation is different in the case of metal-poor stars. Since the outer convection zone is limited only to the very outer layer, its effect on vibrational stability is expected to become small. This is favorable to see whether or not the vibrational instability is indeed induced.

We carried out the fully nonadiabatic analysis of the ε-mechanism instability against low-degree, low-order g-modes for metal-free, -poor stars. We restricted our analysis to stars having very thin convective envelopes ($M \gtrsim 1M_{\odot}$). We first analysed Population III stars, and found that the ε-mechanism instability appears for $M \lesssim 13M_{\odot}$, for which the hydrogen burning proceeds with the pp-chain around the ZAMS stage. The more massive stars, on the other hand, is not favorable for this kind of instability, since the CNO cycle burning keeps a substantial size of the convective core, and prevents gravity waves from propagating in the nuclear burning core.

Next, we analyzed Population II stars with different metallicities. As the metallicity increases, the CNO cycle becomes to dominate over the pp-chain for less massive stars, and then the upper limit stellar mass of the instability goes down. We found the ε-mechanism instablity for $Z \lesssim 6 \times 10^{-4}$ without the uncertainty due to convection.

The newly discovered pulsating low mass white dwarfs: an extension of the ZZ Ceti instability strip

Valerie Van Grootel*, G. Fontaine, P. Brassard, and M.-A. Dupret
University of Liège

In the light of the exciting discovery of g-mode pulsations in extremely low mass, He-core DA white dwarfs, we report on the results of a detailed stability survey aimed at explaining the existence of these new pulsators as well as their location in the spectroscopic Hertzsprung-Russell diagram. To this aim, we calculated some 28 evolutionary sequences of DA models with various masses and chemical layering. These models are characterized by the so-called ML2/α=1.0 convective efficiency and take into account the important feedback effect of convection on the atmospheric structure. We pulsated the models with the nonadiabatic code MAD, which incorporates a detailed treatment of time-dependent convection. On the other hand, given the failure of all nonadiabatic codes to account properly for the red edge of the strip, including MAD, we resurrect the idea that the red edge is due to energy leakage through the atmosphere. We thus estimated the location of that edge by requiring that the thermal timescale in the driving region — located at the base of the H convection zone — be equal to the critical period beyond which $\ell = 1$ g-modes cease to exist. With this approach, we find that our theoretical ZZ Ceti instability strip accounts remarkably well for the boundaries of the empirical strip, including the low-gravity, low-temperature regime where the three new pulsators are found. We also account for the relatively long observed periods in these stars, and thus conclude that they are true ZZ Ceti stars, but with low masses.

Constraining radiative damping, mode inertia and non-adiabatic effects in evolved solar-like stars

Othman Benomar
University of Sydney

Recent observations for the $CoRoT$ and $Kepler$ space-borne instruments revealed a large population of solar-like stars showing mixed modes that arise from a coupling between p and g modes. Measuring the properties of these modes allows us to better constrain the internal structure of stars, as they are very are sensitive to core properties contrary to pure p modes (e.g., Metcalfe et al. (2010), Deheuvels & Michel (2011), Benomar et al. (2012)). Interestingly, as shown by Dupret et al. (2009) the mixing does not affect only the frequencies but also heights, amplitudes and widths of the modes. Therefore, their measure, give a direct insight on the radiative damping, the modes inertia and on non-adiabatic effects, which could provide new constrains on stellar models. Using a global power spectrum fitting approach, involving an MCMC algorithm, we recently measured precisely all modes individual parameters of several sub giants and red giants. During this talk, we will present our results on the measure of heights, amplitudes and widths and compare them to recent theoretical predictions.

Damping rates of oscillations in red giants and main-sequence stars (observed with Corot and Kepler)

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Y. Elsworth, S. Hekker, T. Kallinger, B. Mosser, and D. Stello
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The detection of solar-like oscillations in red giants greatly enlarged the domain where seismology provides constraints on stellar physics. Oscillation frequencies are not the only parameter bringing constraints: the mode linewidths also provide valuable information since they are a measure of the damping rate of oscillations due to different mechanisms related to the physics inside the star (such as radiative losses, convection-pulsation coupling...). We will present damping rates in red giants from observations made with $CoRoT$ and $Kepler$. We will also consider them in a larger view including results from main-sequence stars. Finally, we will compare these observed damping rates with modelled ones and include a discussion of the level of agreement between observations and modelling.

On the relation between the frequency of the maximum amplitude and the cut-off frequency

Kevin Belkacem
Observatoire de Paris

Scaling relations between asteroseismic quantities and stellar parameters are becoming essential tools to study stellar structure and evolution thanks to the $CoRoT$ and $Kepler$ space-borne missions. Those relations are based on physical mechanisms that are still to be fully investigated.

We will address the issue of the relation between the frequency of the maximum in the power spectrum of solar-like oscillations and the cut-off frequency. We will show that the basic physical picture is grasped and that departure from the observed relation arises from the complexity of non-adiabatic processes involving time-dependent treatment of convection. This will be further discussed on the basis of a set of 3D hydrodynamical simulation of surface convection.

Evolution of theoretical power spectrum of solar-like oscillations during the ascending phase on the red giant branch

Mathieu Grosjean*, M. A. Dupret, K. Belkacem, J. Montalban, A. Noels, and R. Samadi
*Université de Liège

$CoRoT$ and $Kepler$ observations of red giants reveal rich spectra of non-radial solar-like oscillations allowing to probe their internal structure. An important question comes from the observation of mixed modes : When during the star's ascension on the RGB are mixed-modes more likely to be detectable ? We follow the evolution of a star on the RGB and investigate the effect of its ascension on theoretical power spectrum. Equilibrium models (computed with the code ATON) represent four different stages of a star on the RGB. The mass of the star ($1.5\,M_\odot$) is in the typical mass range of stars observed by $CoRoT$ and $Kepler$. We used a non-radial non-adiabatic code to compute the theoretical solar-like oscillations of these models. An important output of these calculations is the theoretical lifetimes of the modes. Then we computed the oscillation amplitudes through a stochastic excitation model. These computations allow us to draw theoretical power spectrum and discuss the possibility to observe mixed-modes at different evolutionary stages on the RGB. We found that structure modifications in a star ascending the RGB have an important impact on theoretical power spectrum of solar-like oscillations. Efficiencies of trapping and lifetimes of mixed modes are indeed strongly affected by this evolution.

VIII. Solar and stellar activity

Helioseismic constraints and paradigm shift in solar dynamo

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*Stanford University

Helioseismology provides important constraints for the solar dynamo problem. However, the basic properties and even the depth of the dynamo process, which operates also in other stars, are unknown. Most of the dynamo models suggest that the toroidal magnetic field that emerges on the surface and forms sunspots is generated near the bottom of the convection zone, in the tachocline. However, there is a number of theoretical and observational problems with justifying the deep-seated dynamo models. This leads to the idea that the subsurface angular velocity shear may play an important role in the solar dynamo. Using a model of the internal rotation derived from helioseismology, we develop a mean-field MHD model of dynamo distributed in the bulk of the convection zone but shaped in a near-surface layer. We show that if the boundary conditions at the top of the dynamo region allow the large-scale toroidal magnetic fields to penetrate into the surface, then the dynamo wave propagates along the iso-surface of angular velocity in the subsurface shear layer, forming the butterfly diagram in agreement with the Yoshimura rule and solar-cycle observations. We compare this model with inferences of variations of the interior structure, differential rotation, and meridional flows from SOHO/MDI and SDO/HMI helioseismology data.

Oscillation power in sunspots and quiet Sun from Hankel analysis on SDO/HMI and SDO/AIA data

Sebastien Couvidat
Stanford University

We analyzed data from the Helioseismic and Magnetic Imager (HMI) and the Atmospheric Imaging Assembly (AIA) instruments onboard the Solar Dynamics Observatory satellite: Doppler velocity and continuum intensity at 6173 Å as well as intensity maps at 1600 and 1700 Å. Fourteen datasets of active regions and four datasets of the quiet Sun were used for helioseismic studies at different heights in the solar photosphere. An Hankel-Fourier analysis was performed in an annulus centered around the regions of interest, to estimate the power reduction and phase differences of waves crossing them. There is a dependence of power-reduction coefficients on measurement height in the photosphere: Sunspots reduce the power of outgoing waves with frequencies lower than about 4.5 mHz at all heights, but enhance the power of acoustic waves in the range 4.5-5.5 mHz toward chromospheric heights, which is likely the signature of acoustic glories (halos). Maximum power reduction seems to occur near the continuum level and to decrease with altitude. Sunspots also impact the frequencies of outgoing waves in an altitude-dependent fashion. The ingoing-outgoing phase differences appear relatively unaffected by the measurement height. The quiet Sun is shown to behave like a strong power reducer for outgoing f and p-modes at the continuum level, with a power reduction of about 15-20%, and like a weak power enhancer for p-modes higher in the atmosphere. It is speculated that the surprising power reduction at the continuum level is related to granulation. In Doppler-velocity data, and unlike in intensity data, the quiet Sun behaves like a strong power reducer for granular flows.

The wavefunctions of solar acoustic waves scattered by sunspots

Dean-Yi Chou
National Tsing Hua University

Solar acoustic waves are scattered by sunspots because of the interaction between the acoustic waves and sunspots. The interaction can be viewed as that the sunspot, excited by the incident wave, generates the scattered wave, and the scattered wave is added to the incident wave to form the total wave around the sunspot. We use a deconvolution scheme to obtain the wavefunction of the wave on the solar surface at various times from cross-correlation functions computed between the incident wave and the signals at other points on the surface. The wavefunction of the scattered wave is obtained by subtracting the wavefunction of the incident wave from that of the total wave. We use the incident waves of radial order $n = 0$ - 5 to measure the scattered waves from n to n and from n to n'. The ultimate goal is to measure the scattered waves from a mode (n, k_x, k_y) to another mode (n', k'_x, k'_y), namely the elements of the scattering matrix, which provides information on the interaction of waves with sunspots.

Helioseismology challenges models of solar convection

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Solar turbulent convection is notoriously difficult to model across the entire convection zone, where the density spans many orders of magnitude. Recently, Hanasoge et al. (2012) used helioseismic observations from SDO/HMI to derive stringent empirical constraints on the amplitude of large-scale convective velocities in the solar interior. This upper limit is far smaller than predicted by the ASH hydrodynamic numerical simulation. In this poster, we provide further comparisons with surface observations using granulation tracking, other simulations of solar convection, and a theoretical lower limit from Miesch et al. (2012).

Excitation of solar and stellar oscillations by flares

Alexander G. Kosovichev
Stanford University

Observations of solar flares revealed "sunquake" events representing helioseismic response caused by strong localized impacts in the low atmosphere during the flare impulsive phase. Several mechanisms of the impact have been debated, but there is no clear understanding of how energy and momentum are transported from the magnetic energy release site (presumably located in the higher atmosphere) to the solar surface. It is also puzzling why some moderate class flares produce sunquakes, while significantly more powerful flares do not. Observations with SDO have substantially improved our ability to investigate details of the helioseismic response and the impact source properties and dynamics, providing data with high spatial and temporal resolutions, as well as spectro-polarimetric properties. I will present new results on several sunquake events observed with the HMI and AIA instruments and discuss the basic properties of the helioseismic waves, their interaction with active regions, the source dynamics and its relation to the amplitude and direction of the waves. The observations also reveal interesting relationships between the sunquake impacts, X-ray and white-light emissions and magnetic field changes in solar flares. I will compare the observational results with the physical models of sunquakes (thick-target model, McClymont jerk, backwarming, mass eruption), and discuss model constraints from the new observations. The solar observations allow us to put the upper limit on the energy and momentum the flare-excited waves, estimate amplitude of the global oscillation modes, and make predictions of such oscillations on flaring stars.

Rotation, magnetism, binarity, and chemical peculiarities in A-type stars

Gautier Mathys
ESO

In recent years, growing evidence has been collected for the existence of a number of dependences between rotation rate, magnetic field strength and structure, and binary orbital properties, of magnetic chemically peculiar stars of spectral type A (Ap stars). One of the most recent and intriguing results suggests the existence of a connection between rotation and orbital periods in Ap binaries. I shall discuss the nature of this connection and its potential implications for the origin of the magnetic fields of Ap stars.

Activity in A-type stars

Luis A. Balona
South African Astronomical Observatory

Using all available *Kepler* data, we find clear indications of variability due to starspots in about 40 percent of A-type stars. In most of these stars one can detect the harmonic of the rotation frequency, as expected for a starspot. The distribution of the derived equatorial velocities is in agreement with the distribution for A-type stars obtained from a catalogue of projected rotational velocities. In a substantial fraction of spotted stars we find a distinctive pattern of peaks for which we have no explanation. We find that differential rotation in A-type stars does not exceed 15 percent and that there are indications of a starspot cycle similar to the solar cycle. About 1 percent of A-type stars show superflares which are unlikely to be due to a cool companion and suggests magnetic fields much stronger than actually observed. It would seem that stellar activity, so prevalent in late-type stars, continues through the A-type stars and perhaps even into the B stars. Inspection of the light curves shows that the low-frequency variability in A-type stars can be explained as solely due to starspots. However, this is not the case in A-type δ Scuti stars in which multiple low-frequency peaks are nearly always visible. At present, this cannot be explained by the current pulsation mechanisms. We also find some stars which would normally be classified as γ Dor pulsators except that they are too hot. Finally, we are puzzled by the fact that the amplitude distribution of A-type over-contact binaries found in our sample peaks at zero amplitude, which is not expected if the orbital axes have random orientations.

Constraining magnetic fields in stars exhibiting solar-like oscillations with seismology

Savita Mathur
High Altitude Observatory

Many studies devoted to the study of the magnetic activity cycle of the Sun have been done and led to the development of different dynamo models. The current models do not predict the solar activity cycles yet. With the increasing power of the supercomputers, we can push further the limits of 3D models. The understanding and knowledge of the solar magnetic activity can be improved thanks to the observation of other stars like the Sun.

We know that the magnetic activity results from the interaction between the rotation/ convection/ magnetic field. With the precise and continuous data provided in a large amount by missions such as $CoRoT$ and $Kepler$, we can start to study the magnetism of solar-like stars thanks to asteroseismology. Indeed, we can get constraints on the surface rotation, on the structure of the stars and on the magnetic activity. We will show what asteroseismology is telling us about magnetism of stars with some example stars.

IX. Hydrodynamics

Differential rotation and angular momentum transport caused by thermal convection in rotating spherical shell

Shin'ichi Takehiro
Kyoto University

We review generation mechanisms of differential rotation and angular momentum transport caused by Boussinesq thermal convection in rotating spherical shells based on weakly and fully nonlinear numerical calculations.

When the Prandtl number (the ratio of viscosity to thermal diffusivity) is larger than order unity, the nonlinear thermal effect dominates the nonlinear momentum effects and equatorial outer region becomes retrograde due to thermal wind balance or angular momentum transport by thermally induced mean meridional circulation. The distribution of differential rotation in this parameter regime is not consistent with the observation of the sun, where equatorial prograde is observed at the surface.

When the Prandtl number is order unity or less and the rotation rate of the system is sufficiently large compared with the viscous effect (the Ekman number is smaller equal to $O(10^{-2})$), the Reynolds stress transports angular momentum from cylindrically inner region to the outer region, and produces equatorial surface prograde rotation rate, which seems to be consistent with the observed surface flows on the sun. However, the internal distribution of the rotation rate is uniform along the rotation axis due to the columnar thermal convection structure governed by the Taylor-Proudman theorem, which is inconsistent with observation of the solar interior by Helio-seismology.

On the other hand, when the Prandtl number is order unity or less and the rotation rate of the system is small (the Ekman number is larger than $O(10^{-2})$), the structure of thermal convection is not governed by the Taylor-Proudman theorem, and banana-type convection cells emerges, which are along with the spherical boundaries rather than the rotation axis. Due to the Coriolis effect, the velocity field associated with this type of convection cells induces the Reynolds stress which transports angular momentum from high-latitudes to the equatorial region horizontally, and produces equatorial prograde flows. The surface and internal distribution of differential rotation realized in this regime with small rotation rates is quite similar to that observed in the sun with Helioseismology.

These results may suggest that we should apply larger values of the eddy diffusivities than those believed so far when we use a low resolution numerical model for thermal convection in the solar interior.

Transport by internal waves in stellar interiors and consequences for solar-type and red giant stars evolution

Stéphane Mathis
CEA, Saclay

Internal waves are excited in stellar interiors by turbulent convective regions. Then, they propagate in stably stratified stellar radiation zones where they are able to deposit/extract angular momentum because of damping processes and corotation resonances. This thus modify the rotational evolution as well as the internal mixing in stars. In this review, I will present the state of the art for modelling such transport mechanisms with a peculiar focus on the most recent advances that has been achieved taking into account the influence of rotation and magnetic fields on internal waves. Next, I will discuss consequences for solar-type and red giant stars dynamical evolution and what can be learn from asteroseismology.

Be star outbursts: transport of angular momentum by waves

Coralie Neiner
Observatoire de Paris

The Be phenomenon, i.e. the ejection of matter from Be stars into a circumstellar disk, has been a long lasting mystery. In the last few years, the $CoRoT$ satellite brought clear evidences that Be outbursts are directly correlated to pulsations. It is the transport of angular momentum by waves/modes that brings the already rapid stellar rotation to its critical value at the surface and allows the star to eject material. The recent discovery of stochastically excited gravito-inertial modes by $CoRoT$ in a hot Be star confirms this scenario. I will present the $CoRoT$ observations and modelling of several Be stars and describe the new picture of the Be phenomenon which arose from these results.

Angular momentum transfer by non-adiabatic oscillations in weakly differentially rotating stars

Umin Lee
Tohoku University

We discuss the effects of weak differential rotation on the pulsational stability of low frequency modes of slowly pulsating B (SPB) stars. It is now well known that low frequency g- and r-modes of SPB stars are excited by the iron opacity bump mechanism. The main excitation of the low frequency modes takes place in the temperature region of $T \sim 2 \times 10^5$ K in the outer envelope close to the surface. Assuming the angular rotation frequency Ω gradually increase or decrease outward in the outer envelope, we examine the stability of the low frequency modes, where Ω is assumed to depend only on the radial distance r from the stellar centre. We find that only 10% increase or decrease in $\Omega(r)$ in the outer envelope is large enough to stabilize retrograde r-modes of $|m| \geq 2$ that are unstable in the case of uniform rotation. The effects on the g-modes are found rather unimportant.

Toward a proper seismic diagnostic for rotation of red giants

Rhita-Maria Ouazzani
University of Liège

The space missions $CoRoT$ and $Kepler$ provide high quality data that allow to test the transport of angular momentum in stars by the seismic determination of the internal rotation profile. Our aim is to test the validity of the seismic diagnostics for red giant rotation that are based on a perturbative method and to investigate the oscillation spectra when the validity does not hold. We use a non-perturbative approach implemented in the ACOR code (Ouazzani et al. 2012) that accounts for the effect of rotation on pulsations, and solves the pulsation eigen-problem directly for dipolar oscillation modes. We find that the limit of the perturbation to first order can be expressed in terms of the core rotation and the period separation between consecutive dipolar modes. Above this limit, each family of modes with different azimuthal symmetry, m, has to be considered apart. For rapidly rotating red giants, we propose a new seismic diagnostic for rotation: the differences between the period spacings associated with each m-family of modes.

Traditional approximation for low-frequency modes in rotating stars and a working hypothesis about episodic mass loss in Be stars

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Be stars eject their mass from the equatorial region quasi-periodically at intervals ranging from several years to some decades, and this mass forms a cool gas disc around them. The mechanism of the episodic mass loss in Be stars is, however, as yet unknown. Here we discuss the relation between nonradial oscillations and mass loss in Be stars from a point of view of oscillations in a rotating star. Actually, many Be stars are nonradial oscillators with long periods, and some Be stars are rotating very close to critical velocity. It should be noted first that the non-axisymmetric nonradial oscillations can transport angular momentum from the driving zone to the damping zone. If low-frequency prograde nonradial oscillations are selectively excited by the κ-mechanism of the iron bump, which seems to work in β Cep and SPB stars, angular momentum transported by nonradial oscillations is deposited near the surface due to dissipation. This will result in a gradual increase in the critical wavenumber, leading eventually to break the standing wave condition. Once nonradial oscillations start to leak out, the damping effect becomes large so that a big phase shift appears between the radial and azimuthal components of the oscillation velocity. This angular momentum transport is closely related to the mechanical energy flux of waves and, in the case of leaky waves, the angular momentum is transported by prograde waves outward. Therefore it is expected that the angular momentum is transported outward with increasing speed once the waves become leaky. On the other hand, the oscillation itself will be soon damped owing to kinetic energy loss overcoming the excitation mechanism. Also, once angular momentum is lost from the star, the envelope of the star spins down and then the standing wave condition is recovered. Hence angular momentum loss stops very soon. The star remains quiet until new nonradial oscillations are built up by the κ-mechanism to sufficient amplitude and a new episode begins. According to this scenario, the interval of episodic mass loss corresponds to the growth time of the oscillation. It is expected to be of the order of a decade or longer, and seems to be fairly in good agreement with observations.

Turbulent hydrodynamics and oscillations of moderate-mass stars

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The solar-type pulsators are characterized by acoustic oscillation modes excited by turbulent convection in the upper convective boundary layer. As the stellar mass increases the convection zone shrinks, the scale and intensity of the turbulent motions increases, providing more energy for excitation of acoustic modes. When the stellar mass reaches about 1.6 solar masses the upper convection zone consists of two very thin layers corresponding to H and He ionization, and in addition to the acoustic modes the stars show strong internal gravity modes. The thin convection zone is often considered insignificant for the stellar dynamics and variability. We use 3D numerical radiative hydrodynamics simulations to study convective and oscillation properties of main sequence stars from the solar-type stars to more massive stars. We presents the simulations results for some of the target stars selected for the Kepler GO project "Transition in variable stars: from solar-type stars to gamma-Doradus stars". For the moderate-mass (A-type) stars the simulations reveal supersonic granular-type convection of the scale significantly larger than the solar granulation, and strong overshooting plumes penetrating into the stable radiative zone, that can affect oscillation properties of these stars.

Direct numerical simulation of shear mixing in stellar radiative zones

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Rotation in stellar interiors is able to drive turbulent motions, and the related transport processes have a significant influence on the internal structure and the evolution of stars. Turbulent mixing in the radiative zones is currently taken into account in stellar evolution models through a set of diffusion coefficients that are generally poorly constrained. The purpose of our work is to constrain the form of one of them, the radial diffusion coefficient of chemical elements due to the turbulence driven by radial differential rotation, which has been firstly derived by Zahn (1974, 1992) on phenomenological grounds and largely used since. To do so, we perform local direct numerical simulations of stably-stratified homogeneous sheared turbulence in the Boussinesq approximation. The domain of high thermal diffusivities found in stellar interiors is currently inaccessible to numerical simulations without approximation. It is explored in our work thanks to a suitable asymptotic form of the Boussinesq equations. The turbulent transport of a passive scalar is then determined in statistical steady states. We are thus able to provide a first quantitative determination of the turbulent diffusion coefficient and find that the form proposed in Zahn (1974, 1992) is in good agreement with the results of the numerical simulations.

Shocking: coupling hydrodynamic and radiative transfer models to interpret the dynamic spectrum of the pulsating helium star V652 Her

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V652 Her is an extreme helium star which pulsates with a period of 0.108 d. A substantial period change (Kilkeny & Lynas-Gray 1982) has been identified with a secular contraction (Jeffery 1984) in radius and later interpreted in terms of the evolution of a post-white dwarf merger contracting to become a hot subdwarf (Saio & Jeffery 2000). The pulsations have allowed the mass and radius to be measured precisely (Hill et al. 1981, Jeffery et al. 2001), and are almost unique in that, for 90% of the pulsation cycle, the photosphere follows a near-ballistic trajectory punctuated by a short acceleration phase. Jeffery et al. (2001) found evidence of a high Mach-number shock moving outward through the photosphere during acceleration. To explore physics in the shock, we have obtained a superlative series of spectra at high time resolution with the high-resolution spectrograph of the Subaru telescope. A hydrodynamic model of the pulsation indicates how the shock propagates through the stellar envelope (Montañés Rodríguez & Jeffery 2002). New calculations will couple the hydro model with a radiative transfer model of the photosphere. With these tools, the unique combination of transparency in the helium atmosphere and the violence of the pulsation allow V652 Her to be used to explore the physics of pulsation-driven shock propagation within a stellar photosphere.

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Shocking remarks on stellar pulsation

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Smoothly varying sound waves steepen as they propagate, at a rate that increases with the amplitude of the wave. If they are not first absorbed or otherwise dissipated by diffusion, the waves eventually shock. One might expect, therefore, that the steepening process in the outwardly propagating component of a normal acoustic pulsation mode in a star might permit the wave to escape more easily into the atmosphere, thereby leaking energy in an amplitude-dependent manner. Is this the process that limits low-amplitude intrinsically overstable pulsations such as occur in roAp stars? Even if the waves do not shock below the location of the acoustic cutoff associated with the basic frequency of the wave, which is likely in low-amplitude pulsators, the transmitted component might shock subsequently, heating the atmosphere and perhaps even producing a chromosphere. There is observational evidence that shocks form in the atmospheres of some roAp stars, although an alternative mechanism has been proffered to explain the observations.

Self-organization of solar turbulent convection in magnetic field

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Observations of the solar surface show highly turbulent behavior of convection, which in presence of magnetic field leads to the formation of organized, coherent magnetic structures. We present results of realistic 3D MHD simulations of the solar surface and subsurface layers, which demonstrate the physical properties of magnetoconvection for various topology and strength of magnetic field. In particular, in strongly inclined almost horizontal magnetic field regions, the turbulent magnetoconvection forms long filamentary magnetic structures with a strong subsurface shear flow, providing a mechanism of the Evershed effect observed in sunspot penumbrae. In region with an initially uniform vertical magnetic field the magnetoconvection may lead to a spontaneous formation of compact self-organized structures with strong concentrations of magnetic field. These structures have characteristics of solar pores. A critical role in the formation of magnetic structures is played by turbulent vorticity. The simulation results explain a number of phenomena, observed by Hinode and SDO/HMI, and make predictions of the subsurface dynamics of magnetic regions, which can be verified by local helioseismology.

X. Development of theory of stellar oscillations

Semi-analytical solutions of regular p-modes in rapidly rotating stars

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An asymptotic theory of stellar oscillations based on the ray approximation and its applications to rapidly rotating star seismology are presented. Emphasis will be given to regular acoustic modes where semi-analytical asymptotic solutions have been obtained. These solutions explain the regular frequency spacings previously found through full numerical computations, relate these potential observables to internal properties of the star and should provide guidance to interpret the observed spectra of rapidly rotating pulsators like delta Scuti stars.

Validating observationally the evolved theory of oscillations in rapidly rotating stars

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The impact of rapid stellar rotation on stellar evolution is certainly important, but not well known as of today. In a recent work, F. Lignières and D. Reese presented an innovative theoretical approach, using tools developed in quantum chaos theory, to calculate oscillation modes of rapidly rotating stars. The results are significantly different to those predicted by the asymptotic theory, which cannot work anymore in that regime. In order to validate this new theory we searched for oscillations in the rapidly rotating and pole-on seen A0-star Vega; while periodic radial velocity variations have been identified with a very low amplitude level on more than 4500 Espadons/CFHT and Narval/TBL spectra, the confirmation and possibly clear attribution to a stellar origin is under process, based on the analysis of 2500 high resolution echelle spectra obtained with the ultra-stable spectrograph Sophie/OHP. However, only the equatorial zones of Vega are cold enough that a kappa-type excitation mecanism could occur, and perhaps only episodically; it is therefore important to extend this study to strong pulsators. A systematic asteroseismic observation and analysis of rapid rotators amongst delta-Scuti stars is proposed and could be performed with Espadons/CFHT, but also the highly stabilized instruments like Harps/ESO or Sophie/OHP. In a first step, the asteroseismic observations of one identified pulsating rapid rotator could allow us to demonstrate the asteroseismic behaviour of these stars and to validate the new theoretical approach.

Gravity modes in rapidly rotating stars

Jérôme Ballot*, F. Lignières, D. R. Reese, V. Prat, R. Benacquista, and M. Rieutord
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Thanks to the Two-dimensional Oscillation Program (TOP), we are able to explore the effects of rapid rotation on gravity modes in stars, including the Coriolis force and the centrifugal distortion. As a first step, we realised analyses in 2D distorted polytropic models. With these simplified models, we were able to determine the domains of validity of the perturbative methods and validate some properties derived from the traditional approximation. We also start to classify modes thanks to the ray theory developed by Prat et al. To conclude the talk I will show preliminary results about computations performed in realistic stellar structures.

The origin of rosette modes of oscillations in rotating stars

Masao Takata* and Hideyuki Saio
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We analyze unique axisymmetric eigenmodes of oscillations in rigidly rotating stars, which have been recently discovered in the frequency region of low-order gravity modes of the polytropic model with index 3, and named as rosette modes after their structure of the eigenfunctions (Ballot et al. 2012). We demonstrate that rosette modes appear in the presence of slow rotation due to a close degeneracy in the frequency among several eigenmodes. Regarding the effect of the Coriolis force on stellar oscillations as a small perturbation, and applying the quasi-degenerate perturbation theory, we can successfully reproduce the structure of rosette modes as a linear combination of several unperturbed eigenmodes, which have successive spherical degrees of the same parity. We discuss characteristics of rosette modes in detail.

Mode visibilities and frequency patterns in rapidly rotating stars

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One of the main obstacles in interpreting the pulsation spectra of rapidly rotating stars is mode identification. In order to address this issue, we generalise mode visibility calculations to rapidly rotating stars. These new calculations take into account gravity and limb darkening, as well as stellar deformation resulting from both the centrifugal force and the pulsation modes. Based on these new calculations, we produce synthetic pulsation spectra and study their statistical properties and the frequency patterns present within. These results are then compared with observations to see up to what extent they match. We then go on to discuss multicolour photometry and its potential for mode identification.

Should radial modes always be regarded as p modes?

Masao Takata
University of Tokyo

As standard textbooks of stellar oscillations say, the only restoring force of radial modes in spherically symmetric stars is the pressure (gradient), and there is no chance for the buoyancy force to operate because no horizontal inhomogeneity is generated by radial oscillations. This is the physical reason why all radial modes should be classified as p modes. In this presentation, however, we numerically demonstrate that unstable (adiabatic) radial modes should not be regraded as p modes. They should rather be closely related to f modes or g modes of nonradial oscillations.

Chaotic motions of pulsating stars with convective zones

Yasuo Tanaka
Ibaraki University

We have reported that the solutions of Stellingwerf equation (1986, ApJ, 303, 119) show period-doubling, chaotic, and long period oscillations in deep convective zones (Tanaka, 2011, PASJ, 63, L49). Introducing the convective luminosity, Stellingwerf had derived a simple Baker model with a convective zone. We have numerically solved the model of nonlinear and non-dimensional forms. I will present the results of simulations for deep convection and may introduce more recent results.

Synchronization model for pulsating variables

Saaya Takahashi* and M. Morikawa
*Ochanomizu University

We propose a simple model which describes a variety of stellar pulsations, from regular to irregular. In this model, a star is described as the integration of independent elements which interacts with each other. This interaction, which may be gravitational or hydrodynamic, promotes the synchronization of the elements to yield coherent mean field pulsation provided some conditions are satisfied.

In the case of Cepheids, the whole star is described as a coupling of many heat engines, interacting by the gravitation and the mean density of the star. We found the possibility that this parameter systematically describes the variety of pulsations. In the case of pulsating red giants, the whole star is described as a coupling of convection cells, interacting through their flow patterns. We describe the convection cells by the simple Lorentz model. Interactions of them lead to irregular and periodic light variations. Our model also describes that the light curve which shows semi-regular kind of variability also shows $1/f$ noise in its power spectrum. This is in agreement with the observations (Kiss et al., 2006). This new modeling method of "coupled elements" may provide a powerful description for the variety of stellar pulsations.

Avoided crossing and synchronization

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National Astronomical Observatory

The phenomenon of avoided crossing has been well known in stellar pulsation; when, as a result of varying certain parameters (e.g. spherical harmonic degree, stellar age) two mode frequencies of a single star approach, eventually they avoid each other. The only realistic examples known involve so-called mixed modes, with a p-mode cavity and a g-mode cavity present. Loosely put, this is about two frequencies repelling each other.

Then there is a phenomenon of synchronization/entrainment; when a pair of oscillators are interacting nonlinearly, then the two oscillators sometimes end up oscillating with the same (usually non-sinusoidal) frequency even if their intrinsic frequencies are different. Loosely put, this is about two frequencies attracting each other.

A natural question therefore is, if pulsations of a star in an avoided-crossing situation reach nonlinear regime, what would the two mode frequencies do — do they repel each other or do they attract each other. Or is this question meaningless?

We discuss if the question makes sense, or how it can be refined to a well-posed question, consider the issue using a simple mathematical model, and discuss how it can be related to real stellar pulsation problems.

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