Probing the core of the Sun and the stars

Response to a call for proposals for International Science Teams from the International Space Science Institute (ISSI)

To be held at ISSI-Bern

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Abstract

The structure and dynamics of the energy-generating core of the Sun and other stars remain poorly constrained, and poorly understood, in spite of their fundamental role in determining the overall structure and evolution of stars.

The detection of solar normal modes of pressure oscillations (p modes) permitted the development of helioseismology, which has allowed us to accurately describe the internal structure and dynamics of the solar outer radiative and convective zones. The recent tentative detection of buoyancy or gravity modes (g modes) in the Sun as well as the impact of the detection of mixed (p and g) modes in low-mass evolved stars have rejuvenated the quest for understanding the central zone of the stars: the stellar core.

The aim of this series of workshops is to understand the impact of the inferences about the structure and dynamics of stellar cores for solar and stellar evolution, of the solar g-mode detection on spatially resolved inversions of the Sun's core rotation and subsequently for the detection potential of other data sets of solar and stellar g modes. All of these should have an important, direct impact on our understanding of solar and stellar structure and evolution.

Scientific rationale of the project and its timeliness

Since the beginnings of global helioseismology in the late 1970s, the search for g modes has been a major quest. The detection of g modes is key to the understanding of the internal structure and dynamics of the solar core (Christensen-Dalsgaard, 2002a), as much as the p modes are key to that of the structure of the outer radiative and convective zones (Christensen-Dalsgaard, 2002b).

The quest for solar g modes was a major driver in the design of very precise and sensitive instrumentation harboured by spacecraft such as the *Solar and Heliospheric Observatory*[1]. Aboard SoHO, there are three instruments dedicated to helioseismology all aiming at detecting g modes. A few years after the launch of SoHO at the end of 1995, it was realized that g modes would not be easily detected with these instruments. In 1997, a consortium of helioseismologists, belonging to the SoHO consortia and to ground-based networks, was formed with the ambitious, yet simple, goal of "detecting g modes". Under the auspices of ISSI, the consortium met several times in Bern, and delivered a review paper on solar g modes (Appourchaux et al., 2010). In that paper, there were several claims of g-mode detections of which none has yet been confirmed. In the same paper, many different techniques for g-mode detection were developed, but did not lead to *undisputed* g-mode detection.

Recently, Fossat et al. (2017) claimed to have detected solar g modes using a novel technique based on measuring the travel time of a packet of p modes. The detection suggests a rapid rotation of the solar core, about 3.8 faster than that of the radiative envelope, which confirms the faster core rotation rate previously inferred by García et al. (2007) analysing the g-mode asymptotic properties. Mixed modes with g-mode character were successfully applied to study the properties of the core in red giants (Bedding et al. 2011).

Despite the lack of confirmation of solar g-mode detection between 2007 and 2017, mixed modes, which share the dual character of being both g modes (deep inside the star) and p modes (in the stellar envelope), have been clearly detected in other stars with observations from the CoRoT and *Kepler* missions (Bedding et al., 2011; Deheuvels and Michel, 2011; Beck et al., 2011; Deheuvels et al., 2012). The detection of such mixed modes in red giants has enabled us to understand better how our stellar models might reproduce the evolution of these stars (Hekker and Christensen-Dalsgaard, 2017) as well as to better understand the rotation of the core of these giants (Mosser et al., 2012; Gehan et al., 2018). Similar work has been done for a few subgiants: Deheuvels et al. (2014) were able to infer that the core rotation rate of 6 subgiants or early red giants is between 3 and 20 times faster than their envelope rotation. Pure g modes still remain to be detected in these stars but these results demonstrate the powerful insights that a successful detection of g modes would provide for Sun-like stars.

Another way to probe the physics in the core of the stars is to detect neutrinos generated by the nuclear reactions there. The detection of solar neutrinos has helped a great deal to understand the reactions taking place at the heart of the Sun. Recently, Bellini et al. (2014) managed to directly measure the p-p neutrinos providing new constraints for the Standard Solar Model (SSM, Serenelli, 2016). Additional constraints from the lower solar metal abundances determined by Asplund et al. (2009) and Caffau et al. (2011) still result in large discrepancies with the helioseismic inferences of the solar sound speed (Serenelli, 2016). A potential solution to this disagreement may lie in the increase of Fe opacities recently obtained by Bailey et al. (2015) that could justify the lower solar abundance (Serenelli, 2016). Inversions for the solar metallicity

[1] *Solar and Heliospheric Observatory* (SoHO): a mission of international collaboration between the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA)

from helioseismic data favour a model with lower metallicity (Buldgen et al., 2017). The major discrepancy of the SSM with the helioseismic data is located at the base of the convection zone where iron is responsible for 25% of the opacity, which highlights even more the increasing need for accurate opacities in the solar models. Testing of stellar opacities using asteroseismic data is potentially a unique opportunity for understanding solar opacities (Ball, 2016).

With these recent developments and their implications for the structure and dynamics of solar and stellar cores, now is the time for advancing the field of stellar evolution by analysing data from space missions and from ground-based instruments in new ways. The primary goals of the team are to answer the following questions:

- What does the inferred structure of the stellar and solar cores tell us about stellar evolution?
- What is the potential to measure pure g modes in the Sun and Sun-like stars?
- How can the inversions within the core of the Sun and other stars be improved with g modes?

In addition to answering these scientific questions, based on existing observational programs, the team also aims to examine what kind of new approaches are required for confirming, and advancing, solar and stellar g-mode detection? What is the best strategy to perform new observations?

Expected output

Combining our expertise in stellar evolution, inversion techniques, and data analysis with new g-mode detection methods this team has the potential to significantly advance our knowledge of stellar evolution by placing constraints on the structure and dynamics of the cores of the Sun and solar-like stars. Our results will be published in high-quality peer-reviewed journals.

It is the intention of the group to produce at least 3 papers as a result of this team activity, related to i) the structure and dynamics of the solar and stellar cores, ii) the use of new detection techniques for g-mode discovery in the Sun and other stars with data from the SoHO and *Kepler* missions, and iii) the impact of the solar g-mode detection on spatially resolved inversions of the Sun's core rotation.

Why does ISSI qualify as preferred implementation site?

Given the controversial nature of some of the topics and the opposing views that we hope to bring together with this workshop, we feel that it is essential that this series of workshops be located in a neutral location, free from the influences of any specific institution. It is also essential that the workshop be located as far as practicable from the non-scientific duties of the participants. ISSI thus provides an optimal location in terms of scientific spirit. The members of the international collaboration are senior scientists having administrative institutional duties responsibilities that would pre-empt any of the team members' institutes from qualifying as a proper suitable location. The lack of constraints will allow the participants to freely talk to each other when needed and required. Face-to-face interaction is key to the success of these workshops. From this point of view, ISSI provides the necessary environment for a stimulating and productive collaboration.

The members of the team have various fields of expertise from building instrumentation, data analysis, data inversion and theoretical modelling. Each member usually has a capability of spanning at least 2 of these areas of expertise. The variety of fields of expertise is an essential part of the success of any workshop.

The two proposed workshops are likely to be supplemented by additional workshops not funded by ISSI. The workshops at ISSI will serve as a backbone for a larger collaboration involving the rest of the community interested in the issues laid out in this proposal.

List of confirmed participants

B. Andersen	Norwegian Space Centre, Norway
T. Appourchaux	Institut d'Astrophysique Spatiale (IAS), Orsay, France
S. Basu	Yale University, USA
K. Belkacem	Observatoire de Paris-Meudon, France
A.-M. Broomhall	University of Warwick, United Kingdom
T. Corbard	Observatoire de la Côte d'Azur, France
J. Christensen-Dalsgaard	Aarhus Universitet, Denmark
R.A. García	Commissariat à l'Energie Atomique et aux Energies alternatives (CEA), France
Y. Lebreton	Observatoire de Paris-Meudon and Université de Rennes, France
H. Schunker	Max Planck Institute for Solar System Research, Germany
T. Sekii	National Astronomical Observatory, Japan
M. Thompson	National Center for Atmospheric Research, USA

List of experts

E. Fossat	Observatoire de la Côte d'Azur, France
C. Fröhlich	Davos, Switzerland
J. Leibacher	National Solar Observatory, USA

Schedule of the project

The workshops will preferably take place during university breaks, in order to allow the members with faculty positions to attend. We shall hold two one-week meetings over a period of 18 months. The first meeting will be devoted to stellar models and inversion techniques incorporating g-mode detections. A paper on the impact of g modes on solar core rotation inferences will result, as well as allocating tasks for a paper on the structure and dynamics of solar and stellar cores. The second meeting will be devoted to the detection of solar and stellar g modes in the SoHO and *Kepler* data sets, and the impact of these findings on mode physics. A paper on the use of new detection techniques for g-mode discovery in the Sun and Sun-like stars will result. Of course, the group will also interact/work in between the ISSI sessions as required to prepare the data, the coordination and the final talks. Monthly teleconference meetings will be organized to keep track of progress.

Facilities requested

During the meeting, we would like access to the usual sorts of facilities: meeting room with a projector, internet connections, occasional access to printers. We shall need a meeting room with a beamer. It would be nice (but not essential) if the projector could be conveniently located and controlled from any of our connected laptops. Internet access to NASA's Astronomical Data Service is useful, as is access to peer-reviewed scientific journals such as *Astronomy and Astrophysics*, *Monthly Notices Royal Astronomical Society*, *Astrophysical Journal*, *Nature*, and *Science*; however, members' access through VPN to their institutions' subscriptions is always possible.

Financial support from ISSI and available funding sources.

For the two meetings, we request a total per-diem of 24 person-weeks (2 times 12 person-weeks, with 5 days a week). The travel for the Team Leader should not be more than 2 k€. Team members' institutions will cover their travel costs.

Additional financial support will come from institutional funding that will cover additional activities based at ISSI or elsewhere.

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Serenelli, A., 2016, *European Physical Journal A*, **52**, 8

Annexes

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Role in the project: Coordinator. Data analysis, g-mode research, and instrumentation.

Current position: 2004-Present: Directeur de Recherches 1ère classe du CNRS, IAS

Former Position(s): 1988-2004: Staff Scientist, ESA, Noordwijk, The Netherlands
1986-1987: Post-doc, John Hopkins University Applied Physics Laboratory
1984-1988: Post-doc Service d'Aéronomie, Verrières-le-Buisson

Education: 2000: Habilitation à Diriger des Recherches (HDR), Université de Nice
1984: PhD in Physics at Université Pierre et Marie Curie

Services in National and/or International Committees (last ones):

2016 – Present: Member of the Steering committee of the NASA's TESS Asteroseismic Science Consortium (TASC) Working group 2: Solar-like Stars

2010 – Present: Leader of the ESA M3 PLATO activities at IAS. Responsible of the Stellar Analysis System of the PLATO Data Center and for the calibration of 10 Flight cameras.

2008 – Present: Member of the Steering committee of NASA's *Kepler* Asteroseismic Science Consortium (KASC) Working group 1

2008 – Present: Scientific coordinator of the IAS contribution to the payload of Solar Orbiter. Former Co-PI of the Extreme Ultraviolet Imager. Lead Co-Investigator of the Polarimetric and Helioseismic Instrument for the provision of the Filtergraph sub-system. Co-Investigator of SPICE.

Selected Publications:

Appourchaux, T., Antia, H.M., Ball, W., Creevey, O., Lebreton, Y., Verma, K., Vorontsov, S., Campante, T.L., Davies, G.R., Gaulme, P., Régulo, C., Horch, E., Howell, S., Everett, M., Ciardi, D., Fossati, L., Miglio, A., Montalban, J., Chaplin, W.J., Garcia, R.A. et Gizon, L., 2015, "A seismic and gravitationally-bound double star. Implication for the presence of a convective core", *A&A*, **582**, A25

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NAME, First Name: ANDERSEN, Bo

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Role in the project: Searchs for g-modes experience

Current position: Director General (from June 1, 2018 International Director)

Former Position(s): Research Director NSC, Staff ESA, Research fellow UiO

Education: Doctorate Astrophysics in Solar Physics

Services in National and/or International Committees (last ones): Head ESA Council Delegation, Head Norwegian Polar Research and Space Science Committees, Head of ESA SPC and ESA Council.

Selected Publications:

Andreassen Ø, **Andersen B.N.**, Wassberg C.E., "Gravity Waves and Convection Interaction in the Solar Interior", 1992, *A&A*, **257**, 763-769.

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Role in the project: Theorist/Modeller

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Former Position(s):
2011-2016 Director of Graduate Admissions, Department of Astronomy, Yale University
2005- Professor, Department of Astronomy, Yale University
2004-2005 Associate Professor, Department of Astronomy, Yale University
2002-2007 Director of Graduate Studies, Department of Astronomy, Yale University
2000-2004 Assistant Professor, Department of Astronomy, Yale University
1997-1999 Member, Institute for Advance Study, Princeton, NJ, USA
1994-1997 Post Doc. Researcher, Theoretical Astrophysics Center, Univ. of Aarhus, DK
1993-1994 Post Doctoral Researcher, Queen Mary & Westfield College, London, U.K.

Education:
1993 Ph.D. in Physics, Tata Institute of Fundamental Research, Mumbai, India
1988 M.Sc. in Physics, University of Poona, Pune, India
1986 B.Sc. in Physics, Women's Christian College, Chennai, India

Services in National and/or International Committees (last ones):
2018 Member, Scientific Organizing Committee, 20th Cambridge Cool Stars Meeting, Boston, 2018
2017-present Member, Editorial Board, Solar Physics
2015-present Member, Board of the TESS Asteroseismic Science Consortium
2014-present Member, Board of Directors, Association of Universities for Research in Astronomy (AURA)

Honors:
2018: The George Ellery Hale Prize of the Solar Physics Division of the American Astronomical Society
2015: Fellow of the American Association for the Advancement of Science
2002: Hellman Family Faculty Fellowship, Yale University
1996: The M.K. Vainu Bappu Gold Medal of the Astronomical Society of India.

Selected Publications:
All publications can be accessed from http://bit.ly/sarbani_basu_papers

Bellinger, E.P., Basu, S., Hekker, S., & Ball,W. H. 2017 "Model-independent Measurement of Internal Stellar Structure in 16 Cygni A and B ", *ApJ*, **851**, 80
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Affiliation: LESIA – Observatoire de Paris

Role in the project: Theoretician in stellar modelling and asteroseismology

Current position: Full-time research position at CNRS (Chargé de recherché CNRS)

Former Position(s):

- CNES post-doctoral fellow at IAS (Université Paris-Sud) – 2010 - 2011
- Post-doctoral fellow at University of Liège – 2008 - 2010

Education:

- PhD thesis at Paris observatory – 2008
- Master of Astronomy and Astrophysics at Observatoire de Paris - 2005

Services in National and/or International Committees (last ones):

- Member of the French national council of astronomers (CNAP)
- Member of the scientific council of the Paris observatory

Honors:

- Prize of the French society of Astronomy and Astrophysics (2013)
- Richelieu prize of the Chancellerie des Universités de Paris (2009)

Selected Publications:

Pinçon, C., **Belkacem, K.**, Goupil, M. J. and Marques, J. P., 2017, Can plume-induced internal gravity waves regulate the core rotation of subgiant stars?, *A&A*, **605**, A31, 2017

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Role in the project: Data analysis and instrumentation

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Former Positions:

2012 – 2017 Global Research Fellow
Institute of Advanced Study/Centre for Fusion, Space, and Astrophysics, Department of Physics, University of Warwick, UK

2008 – 2012 Post-doctoral research fellow
Department of Physics & Astronomy, University of Birmingham, UK

Education:

2008 PhD: 'The hunt for low-frequency modes of oscillation of the Sun: application of statistical techniques and instrumentation modelling.' School of Physics and Astronomy, University of Birmingham, UK

2004 MMATH (Hons) Mathematics and Astronomy (First Class)
University of Sheffield, UK

Selected Publications:

Broomhall, A.-M., 2017, A Helioseismic Perspective on the Depth of the Minimum Between Solar Cycles 23 and 24, *Sol. Phys.*, accepted.

Elsworth, Y., **Broomhall, A.-M.**, Gosain, S., et al., 2015, The Importance of Long-Term Synoptic Observations and Data Sets for Solar Physics and Helioseismology, *Space Science Reviews*, **196**, 137

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Role in the project: Theoretician (solar modelling, inversion)

Current position: Professor, Aarhus University, head of SAC

Former Position(s): Associate Professor, Aarhus University, 1984 – 1996
Visiting Scientist, NORDITA, Copenhagen, 1983 – 1984
Postdoctoral Fellow, High Altitude Observatory, 1980 – 1983

Education: PhD, Cambridge University, UK, 1978
MSc, Aarhus University, Denmark, 1975

Services in National and/or International Committees (last ones):
Danish Delegate, ESA SPC, 2007 – 2017 (chair, 2016 – 2017)
Head, Danish Space Advisory Board, 2010 – 2017
Member of ESA SSAC, 2001 - 2003

Honors:
Honorary Fellow of Royal Astronomical Society, since 2016
Annual Carlsberg Foundation Research Prize in Natural Sciences, 2013
Danish Knighthood, 2007

Selected Publications:
Christensen-Dalsgaard, J., 2002. Helioseismology. *Rev. Mod. Phys.*, **74**, 1073 – 1129.
Christensen-Dalsgaard, J., 2004. Physics of solar-like oscillations. *Solar Phys.*, **220**, 137 – 168.
Christensen-Dalsgaard, J., Di Mauro, M. P., Schlattl, H. & Weiss, A., 2005. On helioseismic tests of basic physics. *MNRAS*, **356**, 587 – 595.
Howe, R., **Christensen-Dalsgaard, J.**, Hill, F., Komm, R., Schou, J. & Thompson, M. J., 2009. A note on the torsional oscillation at solar minimum. *ApJ*, **701**, L87 – L90.
Houdek, G., Trampedach, R., Aarslev, M. J. & **Christensen-Dalsgaard, J.**, 2017. On the surface physics affecting solar oscillation frequencies. *MNRAS*, **464**, L124 - L128.

NAME, First Name: CORBARD, Thierry

Affiliation: Observatoire de la Côte d'Azur, Laboratoire Lagrange CNRS UMR 7293, Nice, France

Role in the project: Data scientist: time series analysis and inverse theory.

Current position: Associate Astronomer at Côte d'Azur observatory since 2003

Former Position(s): Data Scientist, Global Oscillation Network Group, Tucson, AZ

Education:

- 2016 Habilitation à Diriger des Recherches "Hélosismologie et astrométrie solaire à haute resolution", Nice Sophia-Antipolis University.
- 1998 PhD thesis "Inversion de mesures héliosismiques: la rotation interne du Soleil", Nice Sophia-Antipolis University
- 1994 Diplôme d'Études Approfondies "Imagerie en sciences de l'Univers", Nice-Sophia Antipolis University.

Services in National and/or International Committees (last ones):

- Member of the Sun-Earth national program Scientific Council since 2010
- Member of the Users Committee of the Multi Experiment Data & Operation Center (MEDOC) since 2010

Selected Publications:

Fossat, E., Boumier, P., **Corbard, T.**, Provost, J., Salabert, D., Schmider, F. X., Gabriel, A. H., Grec, G., Renaud, C., Robillot, J. M., Roca-Cortés, T., Turck-Chièze, S., Ulrich, R. K. and Lazrek, M. "Asymptotic g modes: Evidence for a rapid rotation of the solar core", 2017, *A&A*, **604**, A40

Zaatri, A., Provost, J., **Corbard, T.** and Roth, M. "Sensitivity of the sub-photospheric flow fields inferred from ring-diagram analysis to the change on the solar model", 2010, *Astrophysics and Space Science*, **328**, 135-138

Corbard, T., Boumier, P., Appourchaux, T., Jiménez-Reyes, S. J., Gelly, B. and the PICARD team "Helioseismology program for the PICARD satellite", 2008, *Astronomische Nachrichten*, **329**, 508-516

Garcia, R. A., **Corbard, T.**, Chaplin, W. et al. "About the solar radiative rotation", 2004, *Solar Physics*, **220**, 269

Couvidat, S., Garcia, R. A., Turck-Chièze, S., **Corbard, T.**, Henney, C. J. and Jiménez-Reyes, S. J. "The rotation of the deep solar layers", 2003, *ApJ*, **597**, L77

NAME, First Name: GARCIA, Rafael A.

Affiliation: Astrophysics Department (DAp), CEA-Saclay, France

Role in the project: Expert in data analysis, g-mode research, and stellar dynamics including effects of rotation and magnetism.

Current position: 2013–Now: Director of research at CEA-Saclay

Former Position(s): 1998-2013: Staff scientist at the DAp, CEA-Saclay
1996-1998: Post-doctoral position at the DAp, CEA-Saclay

Education: 2012: Habilitation à Diriger des Recherches (HDR), Université Paris 7
1996: PhD in Physics at Universidad de La Laguna and Instituto de Astrofísica de Canarias (IAC)

Services in National and/or International Committees (last ones):

2016 – Present: Member of the Steering committee of the NASA's TESS Asteroseismic Science Consortium (TASC) Working group 2: Solar-like Stars
2014 – Present: Member of the expert's committee of the Laboratoire d'excellence Physique des 2 Infinis et des Origines (P2IO). Chair of the stellar physics division. Université Paris-Saclay.
2014 – Present: Responsible of the ESA M3 PLATO activities at the SAp/CEA. Responsible of three Working Packages of this mission.
2012 – Present: Member of the Core Science Team of APOKASC (APOGEE: SDSS III Survey) on *Kepler* & K2 Targets

Selected Publications:

García, R.A., Turck-Chièze, S., Jiménez-Reyes, S.J., et al., "*Tracking solar gravity modes: the dynamics of the solar core*", 2007, *Science*, **316**, 1591

García, R.A., Mathur, S., Salabert, D., et al., "*CoRoT Reveals a Magnetic Activity Cycle in a Sun-Like Star*", 2010, *Science*, **329**, 1023

García, R.A., Ceillier, T., Salabert, D., et al., "*Rotation and magnetism of Kepler pulsating S-L stars. Towards asteroseismically calibrated age-rotation relations*", 2014, *A&A*, **572**, A34

Beck, P.G., Bedding, T.R., Mosser, B., Stello, D., **García, R.A.**, et al., "*Kepler Detected Gravity-Mode Period Spacings in a Red Giant Star*", 2011, *Science*, **332**, 205

Bedding, T.R., Mosser, B., Huber, D et al., "*Gravity modes as a way to distinguish between hydrogen- and helium-burning red*", 2011, *Nature*, **471**, 608

Beck, P.G., Montalban J., Kallinger, T., et al., "*Fast core rotation in RG stars as revealed by g-dominated mixed modes*", 2012, *Nature*, **481**, 55

Deheuvels, S., García, R.A., Chaplin, W.J., et al., "Seismic Evidence for a Rapidly Rotating Core in a Lower-giant-branch Star Observed with Kepler", 2012, *ApJ*, **756**, 19

Fuller, J., Cantiello, M., Stello, D., **García, R.A.**, Bildsten, L., "*Asteroseismology can reveal strong internal magnetic fields in red giant stars*", 2015, *Science*, **350**, 423

NAME, First Name: LEBRETON Yveline

Affiliation: LESIA, Paris Observatory and University of Rennes, France.

Role in the project: theoretician (modeler)
- Stellar structure and evolution modeling in 1D: microscopic and macroscopic physics.
- Determination of the properties of stars (mass, radius, age…) using stellar models and observational constraints (asteroseismology, astrometry and photometry, spectroscopy).
- Collect and select classical stellar parameters (Gaia CU8 Astrophysical parameters).

Current position:
Researcher, Paris Meudon Observatory, and Professor, University of Rennes 1, France.

Education:
2002 Habilitation à diriger les recherches, University of Paris 7, Denis Diderot, France.
1986 PhD, University of Paris 7, France & Geneva Observatory, Switzerland.

Services in National and/or International Committees (last ones):
President of the French National Program of Stellar Physics of INSU/CNRS (2014-2018).
Member of the Conseil National des Universités, France (2015-2019).
Co-chair and member of the Panel D4 of the OPC of ESO (P87-88, 2011-2012).
Member of the Gaia DPAC since 1997 (leader of WP S825 2005-2001 and then Co-I).
Member of the CoRoT SWG (1998-2012, co-leader of ESTA project, 2002-2010).
Member of the KASC (Kepler Asteroseismic Science Consortium (2009-…).
Member of the TASC (TESS Asteroseismic Science Consortium, 2016-…).
Member of the PLATO SPM (leader of WP 121100 'stellar models', 2009-…).
2013-…, SOC/LOC member of 3 international colloquia and 5 schools, (co-)editor of 4.

Honors:
Pol and Christiane Swings Price of Royal Academy of Belgium, 1993.

Selected Publications:
Lebreton, Y., Goupil M.-J. and Montalban, J : How accurate are stellar ages based on stellar models? I. The impact of stellar model uncertainties. 2014, *EAS Publ. Series.*, **65**, 99-176,
Lebreton, Y., Goupil M.-J. and Montalban, J : How accurate are stellar ages based on stellar models? II. The impact of asteroseismology. 2014, *EAS Publ. Series.*, **65**, 177-223,
Lebreton, Y., Goupil M.-J, Seismic signature of envelope penetrative convection: the CoRoT star HD 52265. 2012, *A&A Letters*, **544**, L13.
Lebreton, Y., Stellar structure and Evolution: deductions from Hipparcos, 2000, *ARA&A*, **38**, 35-77
Lebreton, Y., Maeder, A. Stellar evolution with turbulent diffusion mixing. VI - The solar model, surface Li-7, and He-3 abundances, solar neutrinos and oscillations, 1987, *A&A*, **175**, 99-112.

NAME, First Name: SEKII, Takashi

Affiliation: Division of Solar and Plasma Astrophysics, NAOJ, Mitaka, Tokyo 181-8588, Japan

Role in the project: Expert in Global- and local-helioseismology, asteroseismology, inverse theory

Current position: 2000-present Associate Professor, Division of Solar and Plasma Astrophysics and Hinode Science Center, National Astronomical Observatory of Japan/National Institutes of Natural Sciences and Vice Chair, Department of Astronomical Science, School of Physical Sciences, SOKENDAI(Graduate University for Advanced Studies)

Former Position(s): 1990-2000 Research Associate, Institute of Astronomy, University of Cambridge

Education: University of Tokyo, B.A. 1985, M.Sc. 1987, PhD 1990

Services in National and/or International Committees (last ones): 2017-2018 Joint-Research Oversight Committee, Institute for Space-Earth Environmental Research, Nagoya University

Selected Publications:

Gizon, L., **Sekii, T.**, Takata, M. et al., 2016, "Shape of a slowly rotating star measured by asteroseismology", *Science Advances*, **2**, e1601777

Nagashima, K., **Sekii, T.**, Gizon, L., and Birch, A.C., 2016, "Statistics of the two-point cross-covariance function of solar oscillations", *A&A*, **593**, A41

Sekii, T., Appourchaux, T., Fleck, B., and Turck-Chièze, S., 2015, "Future Mission Concepts for Helioseismology", *Space Science Reviews*, **196**, 285

Toriumi, S., Ilonidis, S., **Sekii, T.**, and Yokoyama, T., 2013, "Probing the Shallow Convection Zone: Rising Motion of Subsurface Magnetic Fields in the Solar Active Region", *ApJ*, **770**, L11

Nagashima, K., Zhao, J., Kosovichev, A.G., and **Sekii, T.**, 2011, "Detection of Supergranulation Alignment in Polar Regions of the Sun by Helioseismology", *ApJ*, **726**, L17

Zhao, J., Kosovichev, A. G., and **Sekii, T.**, 2010, "High-Resolution Helioseismic Imaging of Subsurface Structures and Flows of a Solar Active Region Observed by Hinode", *ApJ*, **708**, 304

Nagashima, K., **Sekii, T.**, Kosovichev, A.G., Zhao, J., and Tarbell, T.D., 2009, "Helioseismic Signature of Chromospheric Downflows in Acoustic Travel-Time Measurements From Hinode", *ApJ*, **694**, L115

Sekii, T., Kosovichev, A.G., Zhao, J. et al, 2007, "Initial Helioseismic Observations by Hinode/SOT", *PASJ*, **59**, S637

Chaplin, W.J., **Sekii, T.**, Elsworth, Y., and Gough, D.O., 2004, "On the detectability of a rotation-rate gradient in the solar core", *MNRAS*, **355**, 535

NAME, First Name: SCHUNKER, Hannah

Affiliation: Max Planck Institute for Solar System Research

Role in the project: To provide expertise in new data analysis method to measure g modes in the Sun; methods to invert for the interior rotation of Sun-like stars; and time-series analysis

Current position: Project Scientist since 2012

Past position: Post-doctoral Research fellow at MPS (2006-2012)

Education: PhD, Monash University, Australia, 2007
Bachelor of Science at Adelaide University, Australia

Services in National and/or International Committees (last ones): International Astronomical Union member, Division E Sun and Heliosphere, Division G Stars and Stellar Physics

Selected Publications:

Birch, A.C., **Schunker, H.**, Braun, D. C., Cameron, R., Gizon, G., Löptien, B., and Rempel, M., 2016, "A low upper limit on the subsurface rise speed of solar active regions," *Science Advances*, **2**

Schunker, H., Schou, J. , Ball, W. H., Nielsen, M. B. and Gizon, L., 2016, "Asteroseismic inversions for radial differential rotation of Sun-like stars: ensemble fits", *A&A*, **586**, A79

Nielsen, M. B., **Schunker, H.**, Gizon, L. and Ball, W. H., 2015, "Constraining differential rotation of Sun-like stars from asteroseismic and starspot rotation periods", *A&A*, **582**, A10

Schunker, H. and Cally, P. S., 2006, "Magnetic field inclination and atmospheric oscillations above solar active regions", *MNRAS*, **372**, 551

NAME, First Name: THOMPSON, Michael J.

Affiliation: High Altitude Observatory, National Center for Atmospheric Research (NCAR)

Role in the project: Data analysis and theory, helioseismic inversions

Current position: NCAR Deputy Director; NCAR Senior Scientist

Former Position(s): Director, High Altitude Observatory (2010-14); Professor and Chair of School / Head of Department, University of Sheffield (2004-10); Professor, Imperial College London (2001-04); Lecturer and Reader, Queen Mary University of London (1990-2000).

Education: PhD, University of Cambridge (1988); MA, University of Cambridge (1985); BA, University of Cambridge (1981)

Services in National and/or International Committees (last ones): Max Planck Society Rapporteur for Chemistry, Biogeochemistry, Meteorology and Solar System Research (2017-18), NYU Abu Dhabi Center for Space Science External Reviewer (2017), University of Hawaii Institute for Astronomy Visiting Committee (2012), ISSI Science Committee (2009-13)

Honors: Honorary Fellow of the Royal Astronomical Society; Fellow of the American Geophysical Union; Tyson Medal.

Selected Publications:

Hanasoge, S., et al., 2015. Solar dynamics, rotation, convection and overshoot. *Space Sci. Rev.* **196**, 79

Toomre, J. & **Thompson, M.J.**, 2015. Prospects and challenges for helioseismology. *Space Sci. Rev.* **196**, 1

Thompson, M.J., 2014. Grand challenges in the physics of the Sun and sun-like stars, *Frontiers in Astronomy & Space Science* 1:1. doi: 10.3389/fspas.2014.00001

Broomhall, A.M., et al., 2014. The Sun's interior structure and dynamics, and the solar cycle. *Space Sci. Rev.* **186**, 191

Howe, R., et al., 2013. The high-latitude branch of the solar torsional oscillation in the rising phase of cycle 24. *ApJ*, **767**, L20

Reese, D.R., et al., 2012. Estimating stellar mean density through seismic inversions. *A&A,* **539**, id. A63

Christensen-Dalsgaard, J., et al., 2011. A more realistic representation of overshoot at the base of the solar convective envelope as seen by helioseismology. *MNRAS* **414**, 1158

Thompson, M.J., et al., 2003. The internal rotation of the Sun. *Ann. Rev. Astron. Astrophys.* **41**, 599