Postdoc Fellowships for non-EU researchers

Final Report

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Selection	Postdoc fellowships to non-EU researchers
Host institution	Institute of Astronomy, KU Leuven
Supervisor	Prof. Dr. Conny Aerts
Period covered by this report	From 01/01/2014 to 30/06/2015
Title	Asteroseismology of OB-type Supergiant Stars

1. Objectives of the Fellowship

The objectives of the proposed project were to design and implement an evolutionary grid of models adapted to massive stars, and to compute the adiabatic and non-adiabatic oscillation properties of each input model. For that, we have put together the latest physics input relevant for massive stars into the stellar structure and evolution code MESA (Paxton et al. 2011, 2013, 2015; www.mesa.sourceforge.net). In order to get acquainted with this state-of-the-art code prior to the Belspo fellowship, the applicant attended the 2nd MESA Summerschool in August 2013. In the course of the Belspo fellowship, we have computed a grid of non-rotating massive stars with the standard mixture of Galactic B stars. In this basic grid, we have picked four basic parameters that largely influence the evolution of stars, i.e., the initial mass (M=4 to 20 $M_{\odot}$), initial metallicity (Z=0.010 to 0.020), width of the overshooting zone on top of the convective core (f_{ov}=0.0 to 0.03), and stellar age. The equilibrium structure models starting from the zero-age-main-sequence up to the core helium depletion was stored in the grid. The computation of the grid for the Galactic metallicity Z=0.014 was completed during the first year of the fellowship and was used in several publications, both published and in preparation. The main-sequence part of our grid fully covers the Slowly Pulsating B Stars and Beta Cephei stars instability strips, where we expect the massive stars to undergo radial and/or nonradial oscillations.

As a second global step of our research, the output from the MESA evolution code served as input to the adiabatic oscillation code GYRE (Townsend and Teitler, 2013; https://bitbucket.org/rhdtownsend/gyre/wiki/Home). We have computed the adiabatic eigenfrequencies of radial (l=0), dipole (l=1) and quadrupole (l=2) modes for the whole range of models in our grid.

The combination of our evolutionary and pulsation grids allows its confrontation with high-precision space based and/or ground based observations of massive pulsating stars. With such a forward modelling approach, we are simultaneously able to constrain the global observed properties of stars – coming e.g. from ground-based spectroscopy – and the well identified pulsation modes from space based photometry with CoRoT, *Kepler* and now K2 missions. This led to estimates of the global and internal structure parameters with an order of magnitude better precision compared to the case where no seismic data is available.

2. Methodology in a nutshell

As already mentioned, our grid computations depended heavily on two state-of-the-art open-source codes, one for the computation of stellar structure and evolution models (MESA, Paxton et al. 2011, 2013, 2015) and another one for the computation of adiabatic and non-adiabatic oscillation frequencies (GYRE, Townsend & Teitler, 2013). The fellow has developed several tools to compute multi-dimensional grids of models, in addition to their asteroseismic properties (such as low-degree radial and non-radial moe frequencies). Furthermore, he has developed several user interfaces to carry out such extensive computations on the institute's local computing cluster, and on the VSC (Vlaams Supercomputer Centrum). These tools are now also used by other colleagues at the Institute of Astronomy at KU Leuven, who are in need to carry out similar computations for their own research.

Our grids are parameterized by four key input parameters, i.e., the initial mass, metallicity, core overshoot parameter and extra diffusive mixing in the envelope. The life time of the star is the fifth dimension, expressing the temporal evolution of the models. These parameters are input parameters at the initialization of each evolutionary track, and uniquely specify every evolutionary model that is stored per each track. For massive stars, there is no initial value for these four structure parameters, hence we have to compute and scan a large input grid, consisting of several million input models, to achieve meaningful forward seismic modelling in the era of the Kepler data revealing numerous oscillation frequencies.

All these input models are subsequently fed into the pulsation code, GYRE, for which the adiabatic low-degree ($0 \leq l \leq 2$) frequencies of low- to high radial-order ($-80 \leq n_{pg} \leq 10$) pressure and gravity modes are computed and stored. The list of frequencies create a massive database to scan for the best match between model frequencies and observed frequencies of well-identified modes. For the latter confrontation step, we employ a reduced-χ^2 scheme for fitting individual frequencies. The parameters of the those models that have the lowest χ^2 scores correspond to the best (even degenerate) set(s) of model(s) that reproduce the observed seismic properties of the stars, given the uncertainties in the measurements. This forward asteroseismic modelling is thoroughly explained in Aerts (2013, EAS conf. proceeding) and was applied for the first time to a new Slowly Pulsating B star disovered in the Kepler data in the two refereed papers published by Papics et al. (2014) and Moravveji et al. (2015) by the KU Leuven team.

3. Results

The pulsating massive stars are the "hot" testbeds of the physical mechanisms that operate in the upper Hertzsprung-Russell diagram (HRD). While a general understanding of the stellar structure and evolution was established since long, important details are missing and hence still subject of intense research. This prevented the derivation of global and interior stellar parameters with high precision.

Now that we are in the era of high-precision space photometry, this poor situation can be remedied. During this fellowship, we mainly made use of Kepler space data. For the low-mass stars, different stellar structure and evolution codes agreeably succeeded to explain the morphology of evolutionary tracks, and the seismic properties of solar-type main sequence stars, as well as red giants (see Figs. 16 to 19 in Paxton et al. 2013 as an example). In contrast, our understanding of the physical properties of massive stars is poor. A perfect manifestation of this is given in Figs. 28 and 32 in Paxton et al. (2013), where the evolution and internal structure of 25 $\mathrm{M}_{¤}$ and 40 $\mathrm{M}_{¤}$ MESA models are compared with those relying on the STERN code. The disagreement between the two is huge and serves as an illustration of the poor level of stellar evolution theory of massive stars. Two key sources of such ambiguities are the extent of core overshooting (Maeder 2009), and extra diffusive mixing in the core (Heger et al. 2000, 2005, Maeder et al. 2013).

Fortunately, asteroseismology is very sensitive to the detailed treatment of mixing in massive stars, and offers for the first time a quantitative tool to indirectly measure mixing in such stars (Miglio et al. 2008). Therefore, careful asteroseismic modelling of massive stars have the potential to provide tests of input physics and a testbed to gauge the validity of different physical assumptions used so far in an uncalibrated way, by lack of observational data to confront them with. The procedure we discussed above and developed in the framework of the Belspo fellowship allows us to iteratively revisit the treatment of various physical ingredients of our models (e.g. rotation, nuclear burnings, opacities, convective and non-convective mixings, chemical diffusion etc.), and to provide improved models of massive stars. For this purpose, we have carefully selected the unique richest Slowly Pulsating B Star (SPB) to conduct tests of different input physics tuned to its seismic properties deduced from a Kepler data set assembled during the full duration of the mission.

KIC 10526294 (B8V) was observed for the whole (~ 4-year) duration of the *Kepler* mission. This star was initially proposed and later analysed by Pápics et al. (2014). These authors discovered 19 triplet structures in the low-frequency regime in the Fourier power spectrum of the light curve of this star, which unambiguously identifies all of them as dipole (*l*=1) g-modes. The surface rotation period of this star is almost 188 days (~ 5 times longer than the Sun), which is rare-to-find for B-type stars. The stunning feature of this series of g-modes is that their periods are almost equally spaced, with a deviation of ~7% from the mean period spacing. This did provide a clear signature of mode trapping in chemically inhomogeneous layers of this star (Miglio et al. 2008, Cunha et al. 2015), in the so called μ-gradient layers. Therefore, we employed this observed series of well-identified modes for the purpose of different theoretical experiments:
(a) to test if extra diffusive mixing in the radiative envelope – beyond the overshooting layer – is required,
(b) to constrain the extra diffusive mixing in the core, and overshooting mixing from the convective core,
(c) to test if the extra diffusive mixing and overshoot parameter depend on the assumed mixing and opacity tables,
(d) to test whether overshooting mixing has radial dependence.
Below, we address each of these experiments in the light of our detailed seismic tests tailored only to KIC 10526294. We stress that the methodology to perform forward seismic modelling of massive stars has taken a big step ahead compared to the setup that was available before. Indeed, the modelling done in the timeframe of the CoRoT space mission was limited to manual work, while our grid methodology is far more extensive and the only way to correctly interpret the data from the NASA Kepler mission, as explained below.

(a) Extra diffusive mixing is needed in B stars

As the convective core in B stars recedes, it leaves behind the outcomes of CNO-burning process from the core in the radiative region of the star. At the same time, the hydrogen and helium profiles vary steeply at the core boundary. This develops a rapid local change in the chemical stratification on top of the convective core, which is known in the literature as the μ-gradient layer. Here, μ represents the mean molecular weight of the stellar material. The immediate consequence of this is that the spatial gradient of μ – which is designated by ∇_μ - is locally nonzero, and contributes effectively to the Brunt-Väisälä (or buoyancy) frequency in this region. It is well known that such structural changes immediately modifies the morphology of the deviations from asymptotic period spacing and avoided crossings, because g-modes that propagate in the entire radiative interior are very sensitive to such subtle changes in the μ-gradient layer. This is theoretically shown by Miglio et al. (2008) and Cunha et al. (2015), and observationally established for the first time by Degroote et al. (2010) for the case of the CoRoT B-type pulsator HD 50230. Having a rich g-mode pulsator like KIC 10526294 immediately calls for testing whether or not adding extra diffusive mixing in the envelope is needed from an asteroseismic point of view. It is noteworthy to mention that the theory of stellar structure and evolution predicts a non-exhaustive list of rotating and non-rotating causes of mixing in massive stars. They are well summarised and explained in Heger et al. (2000, 2005) and in the monograph by Maeder (2009). However, such theoretical predictions have been poorly confronted with observations. The main exception is the rotational mixing which is used to try to explain the surface Nitrogen excess in LMC B stars (Hunter et al. 2007, 2008a, 2008b, 2009, Brott et al. 2011, Maeder et al. 201). However, the large size of error bars and unknown binary nature among target stars prohibit a solid conclusion if rotational mixing is the only cause of Nitrogen excess in such stars. Aerts et al. (2014) proposed that pulsation is also related to the Nitrogen excess, and even more profoundly than rotation, in an ensemble of well-studied slowly-rotating Galactic B stars. Therefore, it is quite valid to explore whether or not extra mixing in non-rotating models is needed to explain the observed pulsation frequency of a very slowly-rotating B8V star.

To achieve this, we computed two independent huge asteroseismic grids of models, one with and one without extra diffusive mixing in the envelope. As explained in Section 2, the frequency lists within each grid were confronted with the observed list of frequencies, and a χ^2 score was assigned to each model. Then, from each grid, the best model that has the minimum χ^2 score was selected and compared. We found that the χ^2 for the model that includes extra diffusive mixing is about 11 times smaller than the one without extra mixing. The reason is that the extra diffusive mixing modifies the shape of the ∇_μ profile in the model, and allows a perfect trapping of the modes in this region, leading to an improved frequency match between the model and the observation.

As a result, we believe the seismic model of KIC 10526294 as well as that of HD 50230 (Degroote et al. 2010, Moravveji & Aerts 2015, in preparation) significantly favour the inclusion of extra diffusive mixing outside the overshooting layer in the input equilibrium models. Given the fact that HD 50230 is also a very slowly rotating star, the source of such extra diffusive mixing beyond the convective core and overshooting layer that probably does not stem from rotational sources are interesting. The investigation of the sources of such mixing mechanisms is a dedicated study by itself and is planned for our future studies in the framework of the Marie Curie Postdoctoral Fellowship obtained by the fellow.

Constraints on extra diffusive mixing and core overshooting parameters

As explained above, we strongly favour the inclusion of extra diffusive mixing in the models, so the rest of this discussion is based on the grid of models that includes extra mixing. In this grid, $\log D_{mix}$ is varied from 0.25 dex to 6.0 dex in tiny steps of 0.25 dex, to ensure that we cover this parameter range fine and broad enough for an appropriate resolution. Instantaneously, the overshooting mixing from the top of convective core D_{over} is also varied with the exponentially decaying or step-function overshoot with reasonable fine steps (the comparison between the two prescriptions is explained below). Since overshooting is stronger than the extra mixing in the envelope, it dominates as the only source of mixing on top of the core, and then changes into D_{mix} as soon as D_{over} drops below D_{mix}. In our forward seismic modelling (also explained in Aerts 2013), all possible combinations of overshoot and extra mixing are covered, ranging from negligible mixing to strong mixing for D_{mix} and D_{over}. As a result, our frequency fitting approach (with χ^2 minimisation) should in principle find a value which lies in the middle of the parameter space. In other words, the range for each parameter must be broad enough that the best model lies somewhere in the middle of the (multi-dimensional) grid.

The outcome of our grid search and χ^2 minimisation is that the best matching model has a mass 3.25 M¤, radius 2.215 R¤, and solar metallicity Z=0.014. The best overshooting free parameter (explained below) is $f_{ov} = 0.017$ and extra diffusive mixing is $D_{mix} \approx 55 \text{ to } 100 \text{ cm}^2 \text{ sec}^{-1}$. These values for both parameters certainly lie in the middle of the parameter range and we are confident about their validity. As a result of this, the size and mass of the convective core in our best model are 0.329 R¤ and 0.672 M¤, respectively. Similarly, the size and mass of the overshoot layer is 0.190 M¤ and 0.037 R¤, and the relative size and mass of the overshoot layer are 1.67% and 5.8%, respectively. Therefore, the observed frequency spectrum of KIC 10526294 allows to resolve the structure of the overshooting layer, which is below 2% of the spatial extent of the model. This is the first time ever this has been achieved, and our value of the mixing coefficient is the only one available thus far. We consider it a major result of the Belspo fellowship.

Robustness of the results against choices of initial mixture and opacity

To parameterize and expand a model, one should choose orthogonal axis (or principal components in statistics). If this is achieved, then the survey of the parameter space should always end up with unique and non-degenerate models to explain observations. This, however, is not trivial when modelling the stars, because of the vast number of key ingredients of the models. In our analysis, we chose initial mass, metallicity, core overshoot, and extra diffusive mixing as the independent parameters to distinguish each evolutionary track from another. The time is an additional axis, that comes for free.

The distribution of the final χ^2 scores on the parameter plane determines the possible orthogonality of the chosen axis (i.e. independent parameters). Fig. 5 in Moravveji et al. (2015) shows such a diagram for our specific modelling. Different panels show the possible correlation between different parameters around the best model. Obviously, mass and metallicity have a strong correlation, and are roughly linearly dependent, because one can almost compensate for the other. However, it is not possible to freeze metallicity, because we already know that the Galactic B stars can also have a spread in Z. Other parameters are either perfectly confined within a parameter interval, or exhibit a semi-linear correlation trend with a significant χ^2 dip. Indeed, this representation is always limited to the discretization of the parameter space. In conclusion, we regard our constraints on extra diffusive mixing D_{mix}, age and f_{ov} quite robust, since they are well confined in our multi-dimensional parameter space. Mass and metallicity are constrained les strictly, for the reasons explained above.

In addition to this, the choices of input physics like Equation-of-State tables, opacity tables, chemical mixture, etc. can also influence the individual frequencies. This is manifested in Fig. 3 in Moravveji et al. (2015) where dipole g-mode periods of 6 models from 6 possible combinations of two opacities and three mixtures are presented. Clearly, the higher-order g-modes show stronger sensitivity to the combined choices of mixture and opacity. This can question the robustness of our seismic inference of core overshooting and extra, since one speculates by changing the assumed mixture and/or opacity, the best model would have totally different values of D_{mix}, age and f_{ov}. To eradicate this, we computed five more extensive grids for the remaining combined choices of opacities and mixture, and repeated our χ^2 computation. The outcome of this test is that the best parameter values for our star from these newly computed models is very consistent with the first initial result. Therefore, we claim that our seismically derived age, core overshooting and extra diffusive mixing in the core depend weakly on the assumed mixture and opacity, and are considered robust. A comparison of all these tests is tabulated in Table 1 in Moravveji et al. (2015).

Step-function versus exponentially decaying overshoot

Convective overshooting is still one of the "Achilles heels" of the contemporary models of massive stars. From the first principles, we still lack the understanding of the thermal and chemical stratification of the overshooting layer on top of the convective core, mainly because of our simplistic and local treatment of convection, which is the Mixing Length Theory of Bohm-Vitense (1958). In fact, the core overshooting (or undershooting in case of convectively unstable stellar envelopes) are physically required, because at the boundary of the convective core, where, the acceleration of the convective eddies is zero, their net velocity is non-zero! Therefore, the convective plumes can penetrate into the radiatively stable regions, to carry and exchange entropy and momentum with their ambient environment; this give rise to a chemically inhomogeneous layer called the overshooting layer (Maeder 1975). Thus, it is hard to believe that no overshooting layer would form around convective medium, and zero-overshoot models should be excluded (unless in massive magnetic stars). This region is actually in charge of transferring fresh hydrogen fuel between the envelope and the core, as a result of which the cores of OBA-type stars in the presence of overshooting grows, and the main sequence lifetime of the models prolongs. However, we are still unsure about the exact thermal and chemical stratification in this layer, and over the past four decades, many authors have considered this from theoretical and observational perspectives. For instance, the width of the main sequence of stellar populations can be tuned to yield a *moderate* value of the overshoot, f_{ov} (α_{ov} is defined below). Moreover, the isochronal fit to the location of stars in binary systems consistently points at a moderate value of overshoot (Stancliffe et al. 2015).

Fortunately, asteroseismology can also offer a quantitative measure of the extent of this layer (Dziembowski & Pamyatnykh 1991, Aerts et al. 2003, 2010 and Moravveji 2015) for individual stars, which agrees with the range inferred from other techniques (see above). However, the unprecedented quality of the space photometry provided by the *Kepler* satellite enables us to put a step forward, and investigate the details of the structure of the overshooting layer. This is made possible thanks to the high-order (long-period) dipole g-modes observed in KIC 10526294 (and other similar SPB stars), because the eigenfunctions of such modes are partially trapped in the overshooting zone, and are very sensible to the treatment of the overshooting zone therein. This is clearly manifested in Fig. 2 in Moravveji (2015, in press). As a result of this, we are able to make a further test of the input physics, considering the radial dependence of the mixing efficiency of the overshooting layer, by employing the long series of high-order g-modes of KIC 10526294.

Historically and physically, two distinct prescriptions for convective overshoot have been proposed: (a) step-function overshoot, and (b) exponentially decaying overshoot. The former primarily originates from the assumption that mixing by convective plumes even beyond the convective boundary is instantaneous, and it essentially extends the size of the fully mixed (thus adiabatic) core by $\alpha_{ov}H_p$ from the canonical boundary of the core, where α_{ov} is an adjustable free factor (that cannot be assessed from first principles). Here, H_p is the pressure scale height at the boundary of the convective zone. Thus, in this prescription and inside the overshooting zone, the convective mixing coefficient (coming mainly from Mixing Length Theory of Bohm-Vitense 1958) is adopted to describe the mixing efficiency, i.e. $D_{ov} = D_{conv}$. In the latter prescription, the diffusive overshooting mixing coefficient has spatial dependence and decays exponentially away from the convective boundaries, following the relation $D_{ov} = D_{conv}\exp\left[-2z/f_{ov}H_p\right]$. This prescription was first introduced by Freytag 1996 for shallow envelope convection in A-type stars, and was later employed by Herwig 2000 to describe convective core overshoot during the thermal pulses of Asymptotic Giant Branch stars (AGB). Recently, Viallet et al. (2015) proposed that the overshooting from the convective core during the core hydrogen-burning phase should be closer to step-function, since closer to the core, the convective eddies are able to transport entropy and chemical species, and further away the photon diffusion will dominate. However, we took a liberal position here, and try to test both scenarios as an input in our models.

We have computed two independent grids of models, where in one we use the step-function prescription for overshoot by varying α_{ov}, and in the other we use the exponentially decaying overshoot by varying f_{ov}. Needless to say that in each grid, we still vary the initial mass, metallicity and extra diffusive mixing around the best model formerly found (see above). As usual, we complement our seismic inference with a χ^2 goodness-of-fit estimate, and choose the best model from each of the two grids. The final result is that the best model with the exponentially decaying prescription outperforms its counterpart with a factor >2 in χ^2 sense. In other words, the radius-dependent exponentially decaying prescription for convective core overshoot is favoured over the classical step-function prescription. It is worthwhile to mention that this is only the first time such a test is conducted and the outcome should be generalized to the whole OB-type stars with great care. By the way, we are in the process of repeating the same exercise for HD 50230 (which is more than twice massive than our *Kepler* target) to add more evidence to this inference.

Results

The main message from our in-depth asteroseismic tests for a star – which we identify as a Rosetta Stone of the SPB class – is that the next generation of 1D stellar structure and evolution codes should include a minimum amount of extra diffusive mixing in the radiative envelope of OB-type stars with a rough amplitude of 10^2 to 10^4 [$\mathrm{cm}^2\ \mathrm{sec}^{-1}$] which has non-rotational origin. Moreover, different overshooting prescriptions for convective overshoot can be tested, thanks to the high-quality photometric data collected from *Kepler* and CoRoT space missions.

Future Work

Fortunately, there are still a handful of B stars that are observed with the nominal *Kepler* mission for which high-precision photometry is available, and they are not modelled in detail yet. One of the very recent case is the moderately rotating B8 star KIC 7760680 (Pápics et al. 2015), where 36 dipole g-modes are identified to form a long series of consecutive modes with linearly decreasing period spacing pattern due to the effect of rotation (Townsend 2000, 2003, 2005 and Bouabid et al. 2013). Our immediate goal is to conduct a thorough seismic modelling of this star, and keep testing the input physics of our 1D stellar structure and evolution codes to shed more light on our understanding of the physics of massive stars.

4. Perspectives for future collaboration between units

The fellow meanwhile succeeded to receive a Marie Curie International Incoming mobility grant, which enabled him to pursue his collaborative research with the Institute of Astronomy, KU Leuven after the termination of the Belspo contract for another two years (until June 2017). This highly successful leverage building further on the Belspo fellowship implies an influx of European funds into Belgium.

The fellow is now well integrated into the educational and research workings of the Institute of Astronomy, and has found his unique position within the team, thanks to his modelling expertise and theoretical background. As a result of this, the recent observational findings of Pápics et al. (2014, A&A) and Pápics et al. (2015, ApJL) are complemented with the theoretical models he provided. Moreover, the basic input used for the inversion models of Triana et al. (2015, ApJ) were provided by the fellow, thanks to his thorough study of the very rich massive pulsating B star.

In addition to the research-related activities, the fellow is integrated into the educational tasks of the Institute of Astronomy by supervision of bachelor and master project courses. So far, six students have accomplished their “Research Project course” and orally present their results based on research topics that the fellow has proposed. Most importantly, as of 2015, the fellow assists Prof. Conny Aerts in teaching the master course “Stellar Structure and Evolution (SSE)”, where the professor presents the theoretical parts of the course, and the fellow offers the lab exercises as a complement to the course. The whole lab material, required physical knowledge, tools to solve the problems and analyse/visualize the data, and list of exercises with their thorough descriptions are made publically available through bitbucket:
https://bitbucket.org/ehsan_moravveji/ivs_sse
This ensures that the contents of the lab exercises, and all supplementary materials can be easily accessed and used in the future by anyone else, even in the absence of the fellow.

5. Valorisation/Diffusion (including Publications, Conferences, Seminars, Missions abroad...)

The main research results obtained by the fellow in the context of the Belspo 18 month fellowship are published in the three following papers:

- **Moravveji, E.** ; Aerts, C. ; Pápics, P. I. ; Triana, S. A. ; Vandoren, B. "*Tight asteroseismic constraints on core overshooting and diffusive mixing in the slowly rotating pulsating B8.3V star KIC 10526294*", Astronomy & Astrophysics, 2015, Volume 580, A27, 14 pp

- Triana, S. A.; **Moravveji, E.**; Pápics, P. I.; Aerts, C.; Kawaler, S. D.; Christensen-Dalsgaard, J.; "*The internal rotation profile of the B-type star KIC 10526294 from frequency inversion of its dipole gravity modes*", Astrophysical Journal, 2015, Volume 810, 16, 26 pp

- Pápics, P. I.; **Moravveji, E.**; Aerts, C.; Tkachenko, A.; Triana, S. A.; Bloemen, S.; Southworth, J. "*KIC 10526294: a slowly rotating B star with rotationally split, quasi-equally spaced gravity modes*", Astronomy & Astrophysics, 2014, Volume 570, id.A8, 21 pp

Furthermore, the results of our study were presented as invited and contributed oral talks in the following international symposia:

- [Invited] **Moravveji, E.** "*BRITE can improve the input physics of the upper HR diagram*", Science with BRITE-Constellation: initial results, 14 to 18 September 2015, Gdansk, Poland

- **Moravveji, E.** "*Tight asteroseismic constraints on core overshooting and diffusive mixing for massive stars*", in Solarnet III / HELAS VII / SpaceInn Conference, 31 August to 4 September 2015, Freiburg, Germany

- **Moravveji, E.** "*Lessons from asteroseismology of B-type dwarfs*", in Physics of Evolved Stars, a conference dedicated to the memory of Olivier Chesneau, 8 to 12 June 2015, Nice, France

- **Moravveji, E.** "*Semi-Convective Mixing in Massive Stars as seen by Asteroseismology*", in International Astronomical Union symposium 307, "*New Windows on Massive Stars*", 23 to 27 June 2014, Geneva, Switzerland

And the corresponding contribution papers have appeared as

- **Moravveji, E.** "*On the shape of core overshooting in stellar model computations, and asteroseismic tests*", 2015, to appear in the proceedings of "*Physics of Evolved Stars*", EAS publication series, in press

- **Moravveji, E.** "*Asteroseismic Diagnostics for Semi-Convection in B Stars in the Era of K2*", Contributed paper to appear in Proc. IAU307: New windows on massive stars: asteroseismology, interferometry, and spectropolarimetry, Editors: G. Meynet, C. Georgy, J.H. Groh & Ph. Stee, 2015, Volume 307, pp. 182-187

In addition, the fellow has actively contributed to the following list of publications during his fellowship:

- Pápics, P. I.; Tkachenko, A.; Aerts, C.; Van Reeth, T.; De Smedt, K.; Hillen, M.; Ostensen, R.; **Moravveji, E.** "*Asteroseismic fingerprints of rotation and mixing in the slowly pulsating B8V star KIC 7760680*", 2015, Astrophysical Journal Letters, Volume 803, Issue 2, article id. L25, 5pp

- Farrington, C. D.; ten Brummelaar, T. A.; Mason, B. D.; Hartkopf, W. I.; Mourard, D.; **Moravveji, E.**; McAlister, H. A.; Turner, N. H.; Sturmann, L.; Sturmann, J. "*Separated Fringe Packet Observations with the CHARA Array. II. ω Andromeda, HD 178911, and ξ Cephei*", The Astronomical Journal, 2014, Volume 148, Issue 3, article id. 48, pp. 1-8

- Zwintz, K.; Fossati, L.; Ryabchikova, T.; Guenther, D.; Aerts, C.; Barnes, T. G.; Themeßl, N.; Lorenz, D.; Cameron, C.; Kuschnig, R.; Pollack-Drs, S.; **Moravveji, E.**; Baglin, A.; Matthews, J. M.; Moffat, A. F. J.; Poretti, E.; Rainer, M.; Rucinski, S. M.; Sasselov, D.; Weiss, W. W. "*Echography of young stars reveals their evolution*", Science, 2014, Volume 345, Issue 6196, pp. 550-553

- Rauer, H.; Catala, C.; Aerts, C.; Appourchaux, T.; Benz, W.; Brandeker, A.; Christensen-Dalsgaard, J.; Deleuil, M.; Gizon, L.; Goupil, M.-J.; Güdel, M.; Janot-Pacheco, E.; Mas-Hesse, M.; Pagano, I.; Piotto, G.; Pollacco, D.; Santos, Ċ.; Smith, A.; Suárez, J.-C.; Szabó, R.; Udry, S.; Adibekyan, V.; Alibert, Y.; Almenara, J.-M.; Amaro-Seoane, P.; Ammer-von Eiff, M.; Asplund, M.; Antonello, E.; Barnes, S.; Baudin, F.; Belkacem, K.; Bergemann, M.; Bihain, G.; Birch, A. C.; Bonfils, X.; Boisse, I.; Bonomo, A. S.; Borsa, F.; Brandão, I. M.; Brocato, E.; Brun, S.; Burleigh, M.; Burston, R.; Cabrera, J.; Cassisi, S.; Chaplin, W.; Charpinet, S.; Chiappini, C.; Church, R. P.; Csizmadia, Sz.; Cunha, M.; Damasso, M.; Davies, M. B.; Deeg, H. J.; Díaz, R. F.; Dreizler, S.; Dreyer, C.; Eggenberger, P.; Ehrenreich, D.; Eigmüller, P.; Erikson, A.; Farmer, R.; Feltzing, S.; Oliveira Fialho, F. de; Figueira, P.; Forveille, T.; Fridlund, M.; García, R. A.; Giommi, P.; Giuffrida, G.; Godolt, M.; Gomes da Silva, J.; Granzer, T.; Grenfell, J. L.; Grotsch-Noels, A.; Günther, E.; Haswell, C. A.; Hatzes, A. P.; Hébrard, G.; Hekker, S.; Helled, R.; Heng, K.; Jenkins, J. M.; Johansen, A.; Khodachenko, M. L.; Kislyakova, K. G.; Kley, W.; Kolb, U.; Krivova, N.; Kupka, F.; Lammer, H.; Lanza, A. F.; Lebreton, Y.; Magrin, D.; Marcos-Arenal, P.; Marrese, P. M.; Marques, J. P.; Martins, J.; Mathis, S.; Mathur, S.; Messina, S.; Miglio, A.; Montalban, J.; Montalto, M.; Monteiro, M. J. P. F. G.; Moradi, H.; **Moravveji, E.**; Mordasini, C.; Morel, T.; Mortier, A.; Nascimbeni, V.; Nelson, R. P.; Nielsen, M. B.; Noack, L.; Norton, A. J.; Ofir, A.; Oshagh, M.; Ouazzani, R.-M.; Pápics, P.; Parro, V. C.; Petit, P.; Plez, B.; Poretti, E.; Quirrenbach, A.; Ragazzoni, R.; Raimondo, G.; Rainer, M.; Reese, D. R.; Redmer, R.; Reffert, S.; Rojas-Ayala, B.; Roxburgh, I. W.; Salmon, S.; Santerne, A.; Schneider, J.; Schou, J.; Schuh, S.; Schunker, H.; Silva-Valio, A.; Silvotti, R.; Skillen, I.; Snellen, I.; Sohl, F.; Sousa, S. G.; Sozzetti, A.; Stello, D.; Strassmeier, K. G.; Švanda, M.; Szabó, Gy. M.; Tkachenko, A.; Valencia, D.; Van Grootel, V.; Vauclair, S. D.; Ventura, P.; Wagner, F. W.; Walton, N. A.; Weingrill, J.; Werner, S. C.; Wheatley, P. J.; Zwintz, K. "*The PLATO 2.0 mission*", Experimental Astronomy, 2014, Vol. 38, pp. 249-300

- Tkachenko, A.; Aerts, C.; Pavlovski, K.; Degroote, P.; Pápics, P. I.; **Moravveji, E.**; Lehmann, H.; Kolbas, V.; Clémer, K. "*Modelling of σ Scorpii, a high-mass binary with a β Cep variable primary component*", Monthly Notices of the Royal Astronomical Society, 2014, Volume 442, Issue 1, p.616-628

- Tkachenko, A.; Degroote, P.; Aerts, C.; Pavlovski, K.; Southworth, J.; Pápics, P. I.; **Moravveji, E.**; Kolbas, V.; Tsymbal, V.; Debosscher, J.; Clémer, K. "*The eccentric massive binary V380 Cyg: revised orbital elements and interpretation of the intrinsic variability of the primary component*", Monthly Notices of the Royal Astronomical Society, 2014, Volume 438, Issue 4, p.3093-3110

- Beck, P. G.; Kambe, E.; Hillen, M.; Corsaro, E.; Van Winckel, H.; **Moravveji, E.**; De Ridder, J.; Bloemen, S.; Saesen, S.; Mathias, P.; Degroote, P.; Kallinger, T.; Verhoelst, T.; Ando, H.; Carrier, F.; Acke, B.; Oreiro, R.; Miglio, A.; Eggenberger, P.; Sato, B.; Zwintz, K.; Pápics, P. I.; Marcos-Arenal, P.; Sans Fuentes, S. A.; Schmid, V. S.; Waelkens, C.; Østensen, R.; Matthews, J. M.; Yoshida, M.; Izumiura, H.; Koyano, H.; Nagayama, S.; Shimizu, Y.; Okada, N.; Okita, K.; Sakamoto, A.; Yamamuro, T.; Aerts, C. "*Detection of solar-like oscillations in the bright red giant stars γ Psc and ϑ^1 Tau from a 190-day high-precision spectroscopic multisite campaign*", Astronomy & Astrophysics, Volume 573, id.A138, 15 pp

6. Skills/Added value transferred to home institution abroad

The fellow is awarded a Marie Curie IIF fellowship from July 2015 to end of June 2017 to prolong his research stay at the Institute of Astronomy, KU Leuven. During his Belspo fellowship, he has received several trainings on high performance computation, Python, Fortran programming, and github code sharing and collaborative development from the KULeuven ICTS centre (and Vlaams Supercomputer Centrum), in addition to two weeks of observation experience with the Mercator Telescope (La Palma, Spain). He has also extended his working experience with the MESA stellar structure and evolution code.

Since the beginning of his fellowship at the Institute of Astronomy, he has tried to disseminate his knowledge among students and other colleagues, involving the asteroseismic modelling techniques. Moreover, he serves as the lab assistance for the graduate-level stellar structure and evolution course offered by Prof. Conny Aerts, where students use the MESA code to complement and solidify their theoretical education from the class with the numerical and practical exercises in the lab. Therefore, the fellow collaborates with Prof. Aerts in giving 50% of the final examination of this course. In this regard, the fellow is transferring his knowledge to the students and colleagues at the host institute, before returning back to his home country.

Since September 2014, he is co-supervising a PhD thesis of a student from Zanjan University, Iran, who is now visiting KULeuven for a duration of 9 months to work directly with the fellow and Prof. Aerts at the Institute of Astronomy. This has provided the fellow an opportunity to transfer his state-of-the-art knowledge to this Iranian student even before returning back to his home country.

The Belspo fellowship has successfully opened a crucial window in the fellow's career, and provided an opportunity to conduct his research in one of the best world-leading centres of Excellence in asteroseismology at KULeuven. He is looking forward to continue his close collaboration with the Leuven team as soon as he returns to his home country, and pursues the rest of his career there.