Open Discussion

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Abstract During the last morning of the conference, a one-hour open discussion allowed the participants to debate some of the “hot” topics presented all along the meeting as well as on some of the key issues in the field mostly related with the work Prof. Michael J. Thompson studied during his carrier. The discussion covered theory and methods, current and future modeling efforts, observations, and future instrumentation. At the end, Dr. Robin Thompson discussed about the use of inversion methods in his current research, of particular interest these days, about the control of infectious disease outbreaks.

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1 Theory and Methods

1.1 Inversions

The discussion started with one of Michael's seminal works: Solar and stellar inversions. One of the current problems while inverting real data is the proper treatment of jumps, whether it is in space or in time. This is one of the current challenges that scientists must face to extract the best of the internal structure and dynamics. We need to find a way to deal with the inversions as a whole. A solution could be to make custom target kernels, which could allow us to deal with jumps for instance, or a clever way to place the nodes. Sharp changes like the tachocline or near the core are one of the most complicated features to deal with and the community expressed the need to improve their treatment.

Another important "worry" concerns the systematic errors in the input data and how they can be solved. Indeed their treatment is very important and they have a larger influence on some of the methods, in particular, for the optimally localized averaging (OLA) inversion technique. Moreover, the way in which over-resolution can be used properly and a better way to improve the real data prior to make the inversions are still open issues. A-priory information should not be used to force any given inversion.

One objective of the community is to move towards 3D inversions where the new dimension could be not only space but rather time. The question is how to do it.

What we are looking for is a quantitative response from the inversions and not a subjective one. Indeed, in general the inversion techniques usually assume a smooth profile, in particular when no information at different depths is available. A trade-off needs to be reached between data-driven inversions and our own prejudice.

Finally, and mostly for the solar case, it was pointed out that better high-frequency modes are required. The community is facing this issue and several groups are currently working to extract better high-frequency modes but we need to wait until this is done. These high-frequency modes imply that non-adiabatic calculations should also be improved on the theoretical side. This path has already been taken with averaged 3D Radiative Hydrodynamical simulations of the stellar surface (e.g. [7]) that can replace standard near-surface layers in 1D stellar structure models.

1.2 Surface Effects: From Machine Learning Tools to Open-Source Codes

This brings us to the (in)famous surface effects. The key point is how to extract them from simulations. The good news is that several groups are working on it but there are still important problems to solve and we need to know them. For example, in the tachocline, is there a dynamo operating there? Can the highly turbulent convective zones build activity? Maybe not in the way we want. . . We also do not know how boundary layers work and how they affect the surface effects and the dynamics below them. We also need to understand how magnetism impacts surface effects and move from studying snapshots towards a continuous time evolution of the different physical effects in play.

Can Machine Learning (ML) techniques contribute to better understand surface effects? A hot and animated debate followed this last question and got far beyond the framework of surface effects. Indeed, ML techniques are more and more often implemented in all disciplines and helio- and astero-seismology also follow this trend. ML techniques can be considered as highly non-linear mapping. So, they seem to be well adapted to the surface effect problem. However, it is important to not use these ML techniques for problems that can be solved by classical methods. ML are tools that should be better understood and we need to learn to interpret them in the best possible way. There is a balance to be found.

This discussion opened a second hot topic about open-source codes. The astronomy community in general is adopting these codes very fast but the seismic community is lagging behind. It is true that there are some codes such as the Modules for Experiments in Stellar Astrophysics (MESA, [5]) or several global seismic pipelines available but they are just exceptions and not the norm. The debate concerned the use of these programs as a "black box" with some examples of publications that contain important errors due to the bad use of these packages. Of course it has been pointed out that good open-source codes need good support behind and there is often a lack of funding by the institutions to give that to the community. Fortunately, there are a few people deeply involved on this path and more support is required from the community as well as feedback to the developers in order to improve the codes.

2 Current and Future Modeling

The general feeling of the community is that we need to go beyond the standard 1-D stellar evolution codes and generalize the use of 2-D codes, such as the Evolution STellaire en Rotation (ESTER, [2]), or even 3-D codes.

A question was raised whether it is possible to do structure evolution and model convection in a 2-D code with the same time scales as evolution. Nowadays, 2-D convection models can be done for short time scales, too short compared to evolution. To go beyond that, a large effort should be undertaken towards a fully parallelization of the codes, which requires also a deep investment in manpower.

A final question was raised concerning the differences found between 2-D and 3-D convection models. This implies that the community needs to understand those differences first, before moving forward.

3 Observations

While modes located near the frequency of maximum power ($\nu_{\max}$) are "easy" to characterize, the current challenges for helio- and asteroseismic observations are to go lower in frequency. Because these modes have long lifetimes they are more precisely determined and because they are less affected by the surface effects and activity, they can be used in theory with less assumptions and are better suited to be compared with theoretical frequencies. As a consequence, they allow us to obtain better inversion results close or near the core.

In the solar case, a large effort is given to extract a larger number of precise high-degree modes to better probe the sub-surface layers of the Sun.

For astero-seismology, high-frequency modes are extremely important to properly define the surface effect correction. Moreover in many cases, it was pointed out that the *ultimate* precision cannot be reached for other stars because of a lack of high-precision spectroscopic observations. The community needs to make some extra effort in acquiring complementary parameters to properly feed the evolution codes. Moreover, a better understanding of the atmospheric spectrum is required to improve the precision and accuracy of the spectroscopic parameters measured. Combining seismology, spectroscopy, and astrometry with stellar evolution codes will provide this *ultimate* precision. The PLAnetary Transits and Oscillations of stars (PLATO, [6]) community is trying to face some of these challenges to get the maximum from this mission.

In main-sequence stars, including the Sun, the core is still inaccessible using p modes only. G modes are needed to progress in the understanding of the innermost layers of these stars. Only when this is achieved will we be able to start to answer some of the most burning questions regarding the angular momentum transport in the deep layers of a solar-like star as well as the existence and characterization of a magnetic field in the core.

Finally, the question about what is going on in the solar poles will be soon addressed thanks to the Solar Orbiter mission [4]. The Japanese Hinode mission [3] already provided some glimpse on it. On the stellar side, with hundreds of thousands of stars observed by space missions, we have in hand a broad range of inclination angles (of the rotation axis compared to the line-of-sight), meaning that we should have a non-negligible sample of stars observed from the poles. The community should take advantage of those observations to study stellar poles. However, the advantage of the solar observations is that the solar poles will be spatially resolved, giving more information than what can be obtained from other stars.

4 Future Instrumentation

A discussion was engaged on what would be the future missions that would lead us to make a quantum leap in our knowledge of solar and stellar physics, compared to what we have today or what is planned in the near future (e.g. Solar Orbiter, PLATO). A consensus was reached that this big step forward will come with a Stellar Imager in space (e.g. [1]). Even the observation of a handful of stars, pushing the degree of the modes would improve the resolution of the inversions not only close to the surface but also inside (e.g. the tachocline of stars) and better resolve internal kernels. Higher degree modes would also imply a much better latitudinal inversions.

For the Sun, it is necessary to think about new instrumentation capable of reducing the leakage of modes and move towards multi-band observations that could reduce the convective noise and increase the odds of detecting individual g modes with enough precision to be used in the inversions.

Finally all the audience agreed that an imperative requirement of future instrumentation for helio- and asteroseismic observations is to be able to provide decades monitoring for the former and as long as possible for the latter.

5 Concluding Remarks

To end the discussion on a different perspective a question was addressed to Dr. Robin Thompson, the son of Michael and his wife Kate, about the use of inversions in his research on epidemiology. Although this would be a very interesting technique to implement in such field, there are other issues to be addressed before. For example, there is a need in the current data sets to get to the origin of the pandemics. These data sets are in general noisy and come from multiple time series which complicates the modeling. One idea prior to use inversion techniques would be to do forward-backward modeling as it is also commonly done in solar and stellar physics.

At the time of writing this summary the world is facing the COVID-19 pandemic. Maybe in a few years from now, and using all the data sets that will be available, the inversions on this field will also be commonly used.

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