The Art of Modeling Stars in the 21st Century
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Conference summary

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To summarize 54 mostly excellent and innovative talks, plus 57 interesting posters, is an impossible task, which I will not even try. This the more as the focus of this meeting was extraordinarily broad. We discussed many different processes in stars, from mixing to pulsations and mass transfer. And we discussed the whole spectrum of stellar types, up an down the main sequence, including the Sun, and into many branches of evolved states of single and binary stars. As we are all working on more or less particular niches in the field of stellar physics, this meant an extraordinary learning experience for most of us. Indeed, this conference offered a stellar physics course at the highest level, which can not be obtained in any other way.

Of course, there is a price to everything. In contrast to more specialized meetings, we could cover basically none of the topics which we discussed thoroughly. Furthermore, we had to leave out many interesting subjects of stellar physics entirely. The retained mix of depths and topics was, however, very interesting for most of us, and the (intended) theoretical inclination of most talks helped us to discuss in a common language, and with mutual interest. In fact this mix turned out to be extremely stimulating, and helped many of us to develop new ideas on things related to our fields of specialization.

In the following, I will go through the conference ordered by topic, and convey my subjective view of what struck me as most relevant. For simplicity, I will not mention any names, as the reader my easily find the details of the mentioned issues in these proceedings.

1. Micro-physics

It was quite impressive to see that the micro-physical functions which are required for any theoretical consideration of stellar structure, stellar atmospheres or stellar pulsations are being more and more refined and tested, and include more and more physical components.

We have seen that stellar opacities are now available for a very wide range of parameters, i.e. temperatures, densities and chemical compositions. In fact, stellar modelers are running out of excuses to *not* update their input opacities to the most appropriate data. Also molecules and dust are incorporated in modern opacity compilations, where local thermodynamic equilibrium is assumed to compute their occurrence. This really is a sufficient prescription for a vast spectrum of applications, while a discussion of the extra dimension of time dependent molecule and dust formation and destruction, which is important for many fields as well, has not been mentioned much at our meeting.

For the important issue of the equation of state (EOS), where two groups have made large progress in the last ten or so years, we heard that we have the choice between imperfect results from a mathematical exact approach, and results from a more pragmatic approach which may capture more of the relevant physics. It was fascinating to see how the adiabatic part of the Solar convection zone can be used as a laboratory to test the accuracy whatever EOS is used in a solar model, and it was reassuring to hear that the EOS is no major source of uncertainty for the modeling of non-degenerate stars, except if it gets to the level of accuracy required for studies of stellar pulsations.

The third topic under the heading of this section is the initial composition of stars, which relates most notably to the chemical composition of our Sun. It may, at first glance, be surprising that for our Sun, which is so close and bright, the surface composition is still uncertain. While the difficulty to determine the Solar helium abundance is acknowledged since a long time, it turns out that measuring even the most abundant metal in the Sun, oxygen, is also far from trivial. While radiation-hydrodynamic modeling of the solar atmosphere, as now routinely performed by several groups, provides a method of abundance determination which is in principle parameter-free, some parameters which describe unknown micro-physical processes – like the strength of an unknown nickel blend to an oxygen line, or collisional excitation of hydrogen – slip back in through the backdoor. We have seen furthermore that presumably simple issues as an equivalent width measurement add to the ambiguity of the Solar oxygen determination. Still, there was agreement at this meeting that there is less oxygen in the Sun than we thought about five years ago — which is good, as it makes the Sun more normal compared to the chemistry in the Solar neighborhood, and which is bad, as it destroys the nice agreement between observed and modeled solar oscillations (cf. below).

2. Mixing in stars

In the stellar interior, a wealth of different (magneto-) hydrodynamic instabilities may occur and lead to the transport of heat, chemical elements or angular momentum. Mixing! We heard many talks on this issue! And there was generally no consensus on the efficiency and consequences of any of these instabilities, while the interaction of more than one of them has not even been addressed give very few exceptions.

Clearly, the most important process in this context is convection, and it was impressive to see how much progress there has been obtained at all levels of sophistication! We have heard about new analytical formulations which include the key physical ingredients of convection, namely buoyancy, shear and vorticity, and which not only describe the transport of heat but also of angular momentum, and which will supersede the Mixing Length Theory eventually. We also heard about innovative methods to describe convection in 1-dimensional grid based calculations which still capture the asymmetry of the upflow and the downdrafts observed in multi-dimensional calculations, and which is thought to have important applications for the modeling of Cepheid pulsations. And finally, we have seen results from ground-braking 2D- and 3D-hydro modeling, which is nowadays applied to many different phases of stellar evolution. From those models we have seen that the interaction of convection and rotation may lead to a variety of rotation laws, which are mostly far from the simple case of rigid rotation. And we could see that convection driven by helium core- or shell flashes, even though hindered by mean molecular weight barriers, may propagate through gravity waves, as well as through inherently multi-dimensional entrainment processes.

In relation to convection, we have seen at lease seven talks which dealt with convective overshooting, where it was quite noticeable that the terminology in the community is not yet coherent. Terms like penetration, entrainment and wave propagation have been used in this context. And while a description of overshooting which is valid in general terms seems rather difficult right now, there was consensus on one result: overshooting is *diverse*, i.e. one can not expect the same efficiency in different situations. And while quite clearly the effects of overshooting may play a role all the way to the bitter end of stellar evolution, many questions may have no satisfactory answer yet. E.g., is significant overshooting always present in hydro-simulations, and if so, why? Is it true that convection zones never have boundaries? Just think of oil floating on water.

We also had many talks on rotationally induced mixing in stars. This topic is also quite complex since rotation may trigger a whole bunch of different instabilities, depending on the conditions inside the star, i.e., the shear instability, Eddington-Sweet circulations, the baroclinic instability, to name just the most important ones. It was interesting to see that evidence for rotational mixing seems to be present throughout the stellar mass spectrum on the main sequence. However, at low mass, where rotational mixing seems required to explain why the surface composition of most A to F-type stars is not affected by, e.g., gravitational settling, only very shallow mixing is needed. At high mass, where nitrogen enrichment is observed in some main sequence stars, deep mixing is required to obtain it. Also, in low mass stars, some shear needs to be generated in order for rotational mixing to become efficient, while in massive stars shear may help, but the Eddington-Sweet circulations may be efficient even in rigid rotators. Rotationally induced mixing may also have an important role in post-main sequence stars, e.g. in the context of the cool bottom processing of low mass red giant stars, or during the s-process nucleosynthesis in thermally pulsing AGB stars.

However, all the mentioned processes are not enough. There is ample observational evidence for the need of further transport processes! The signatures of gravitational settling and radiative levitation in Am/Fm stars are overwhelming, and the settling of helium is likely important for understanding the Sun. These processes may further be important for the so called lithium dip on the lower main sequence, and it may help explain the high enrichment factors seen in the carbon-enhanced metal-poor (CEMP-) halo stars. Angular momentum transport through gravity waves has been put forward as an explanation of the slow rotation of the Solar core. This very complicated mechanism clearly deserves further studies, e.g. to find out whether it has any direct effect on chemical mixing. A future cooperation with oceanographers seems most helpful in this case, who already studied this process in much more detail than astronomers. Thermohaline mixing and semiconvection, both thermally driven instabilities, are also clearly important in stars. While the former appears to very well account for surface abundances in low mass red giants, the latter, again studied in detail in the ocean, is predicted to occur in stars of almost any mass. Finally, rotationally induced magnetic fields may lead to the transport of matter and angular momentum, where the second appears to be required to understand the spins of young neutron stars and white dwarfs.

The problem is of course that none of the available theoretical prescriptions of the mentioned processes allows to make quantitative predictions without involving uncertain parameters. There is little predictive power in explaining one given phenomenon with one given mixing process by calibrating the parameters involved so that the observed phenomenon is reproduced. I feel that we are still struggling to understand for many of the mentioned processes whether they are fundamentally important or not! In particular, we have seen various examples at this meeting where the *same* observation (the Solar core rotation, the lithium dip, increased main sequence core masses, ...) could be explained by combinations of *different* mixing processes! We clearly have difficulties to cope with the inventiveness of Nature which produces so many ways to mix a star! And it may be of key important for future progress, besides increasing our analytical and modeling efforts, to design key observations which can cleanly serve to test one instability and not simultaneously a few others.

3. Pulsations

The field of stellar pulsations is rapidly progressing, with new space missions providing unprecedented high-quality data, and analytical and numerical methods becoming evermore sophisticated. The unrivaled star in the field is of course our Sun, where incredibly accurate data (1000σ error bars!) provide tough constraints to stellar modelers. This led in fact to a crisis, as there seems to be no possible Solar model which fulfills the seismic constraints when the new, lower Solar oxygen abundance is used. The gravitational settling of helium is helpful, but is unlikely to be stronger than already applied in the current models. Perhaps, the oxygen abundance is not quite *as* low? In fact, based on the observed oscillation frequency splittings, we have seen that one can derive the opacity which is required to lead to a consistent Solar model, which leads to a required metallicity of $Z = 0.017$. Is then perhaps the neon abundance larger than we think? It would help, but there is no clear evidence for this. For the Sun, we furthermore await the first undisputed detection of gravity modes, which will certainly pin down the core properties of the Sun in great detail.

The observations of p-modes in the sun and Solar-type stars have been shown to provide a powerful method to age-date these stars. The Solar age comes out as 4.68 Gyr, which is not a perfect match but demonstrates the capabilities of the method, which will be soon applied to many bright stars in the sky. It was further exciting to see that oscillation data combined with interferometry can not only provide accurate stellar ages, but also masses and radii.

Of course, pulsations provide the most promising window to look inside the stars, and to this respect we have seen already, and will see many more exciting results. A nice example at this conference was provided by the analysis of pulsations in PG 1159 post-AGB stars, which showed that in principle one might measure their rate of evolution by determining the change of their oscillation frequency with time, which then might provide the strongest observational constraints on the neutrino cooling which constitutes the dominant energy loss mechanism in these stars.

4. Stellar atmospheres, winds, mass loss

Having our Sun as an example, it clearly provides the test case for the best radiation-hydrodynamic model atmospheres so far, which indeed can reproduce the Sun's atmosphere in very great detail. Atmosphere models of this kind are helpful to derive accurate surface abundances, as mentioned above. But even in these models, further improvements are desirable, i.e. on the level of the micro-physics input, but also regarding turbulence e.g. induced by shear.

For hot stars, the state of the art are 1D-model atmospheres, which now routinely include the elements from hydrogen to nickel in non-LTE, and which keep leading to extraordinary discoveries, e.g., the detection of a fluorine overabundance by a factor of 100 in PG 1159 stars. In luminous hot stars, stellar winds are important, which can now be modeled simultaneously with the stellar atmosphere. As these winds are driven by photon scattering in metal lines, a metallicity dependence is predicted and observed which has important consequences for the the evolution of massive stars. The theoretical challenge today comes from the evidence that hot star winds are not smooth but clumpy outflows. The origin as well as the effects of this clumpiness are not yet well understood.

The atmospheres and winds of red giants and supergiants are even more complex than those of their hot counterparts. The self-consistent modeling is very difficult, and the wind driving in 1D models is only recovered for carbon-rich AGB stars with effective temperatures below 3200 K. The observed large wind anisotropy and the dynamic dust formation processes need to be considered to obtain more realistic AGB winds. On the other hand, we have seen that one may use statistical properties of observed samples of AGB stars to severely constrain the AGB mass loss rates.

And finally we have seen that we need models for what happens beyond the edge of the star, i.e. in its circumstellar environment, to be able to address the effects of feedback of star formation on the dynamical and chemical evolution of galaxies. All stars eject a significant fraction of their mass during their lives, which transports chemical elements, but also energy and momentum into their surroundings. While the low mass stars produce planetary nebulae, we learned that the definition of such a thing is a non-trivial matter. We were surprised by evidence for more than 90% of all planetary nebulae to be bipolar in the wider sense, making spherical planetary nebulae exceptional. The cause of that seems still unclear, except for indications that the shaping process already starts in the proto-planetary nebula phase. For the massive stars, it was shown that their wind bubbles and circumstellar shells may play a key role in the picture of self-regulated star formation. It turns out that multi-D simulations of these structures are necessary in order to correctly predict their energy deposition rate in the circumstellar medium, which may be as low as 1%.

5. Evolution

We heard many talks on stellar evolution modeling, which made clear that this task needs all of the above. The right micro-physics input is essential, and internal mixing needs to be considered. Pulsations may be needed to understand the mass loss process, or provide hard observational constraints to stellar models. And the atmosphere models provide the chemical composition for the onset of the evolution as well as for advanced stages, and the mass loss rates for the hot stars.

Moving up the main sequence, we have seen that we need more helium-rich stellar models of K and M dwarfs to understand the surprising different stellar populations in Galactic globular clusters. For the Galactic G dwarfs, understanding the distribution of observed lithium abundances is still a challenge; we have heard two very different explanation of the lithium gap. In the A and F type regime, we understand that we may need rotational mixing to keep the chemically normal stars as such, and we may require to consider mass loss to prevent the chemically anomalous Am/Fm stars from getting too extreme anomalies due to radiative levitation and gravitational settling. Finally, we may need rotational mixing to explain nitrogen enhancements in OB stars, and anisotropic mass loss may help to keep them rapidly rotating, which may lead to quasi-homogeneous evolution at low metallicity.

In the late evolutionary phases of stellar evolution, not only the uncertain processes discussed above play a role, but any mistakes in describing the earlier evolution may show effects as well. If then we extrapolate our knowledge to the low metallicity universe where we have little observational constraints, it may not be too surprising that our understanding becomes poorer. This may concern the so called super-AGB stars, which undergo core-carbon burning and thermal pulsing, and of which the most massive ones may undergo electron-capture induced core collapse and supernova explosions. This type of stars, which are largely neglected in most comprehensive compilations of stellar evolution models, occupy perhaps a very small initial mass range at solar metallicity; at low metallicity, however, they might be more abundant than any other supernova progenitor type. This rich site for nucleosynthesis is still largely unexplored. And perhaps equally uncertain is the role of very low metallicity intermediate mass stars in the pollution process of the carbon-enhanced metal-poor (CEMP-) halo stars. While binary models have often been used to explain some of their properties, we have seen that perhaps (dual) self-pollution can produce some of them as well.

And also for the massive stars, despite the local populations of main sequence stars are not well understood, much attention is give to their possible role in the early universe and at very low metallicity. This is motivated in part by an observed bias of long-duration gamma-ray bursts toward low metallicities, which may involve rotationally induced rotation as explanation. And at reduced mass loss rates, pair-creation supernovae appear possible at low metallicity, which is interesting in the context of very bright local supernovae, as well as for the potentially very massive stars of the first and second generation in the early universe.

6. Binaries

If it needed one more degree of physical complexity and modeling uncertainty: stellar binaries provide it. And to make the issue more severe: binaries are abundant! So they must play a role in any observed stellar population – and we have seen some examples of this – which means we have to try and model them!

Many classes of stars may exist only because there are binaries, and a prominent one which was discussed in this meeting are the sdB stars. Binary evolution models can explain their properties well, even though, of course, there are parameters involved. And for binaries to also affect the photometric properties of stellar populations, the explanation of the UV-upturn in the SED of elliptical galaxies being due to sdB stars may be one of the best examples. We have also seen that binaries may produce blue stragglers in star clusters, as well as the CEMP stars which were mentioned previously, where, again, fluorine may be the best discriminator between various possible progenitor evolution paths.

But some things get actually simpler in binaries, compared to single stars; E.g., the measurement of stellar masses. And it may also be that binary stars may provide the best constraints for uncertain mixing processes. We have seen that it is possible to put strong constrains on convective overshooting in main sequence stars by comparing models to suitable unevolved binaries. And in contrast to single stars, one thing seems rather clear in unevolved close binaries: the stars involved are not the product of a binary merger – which was shown to relate to 10% of all stars! – or Roche-lobe overflow. It was thus proposed that massive close binaries are the best test case for rotational mixing in single stars.

On the other extreme of evolution, in the supernova regime, binaries again play a clear and substantial role. We heard that the progenitor evolution of half of all core collapse supernovae is affected by a binary companion. And that can exert strong effects. E.g., even if single stars were to produce black holes above, say, $25\,M_{\odot}$, the mass donors in close binaries might produce neutron stars up to about $50\,M_{\odot}$. May be electron-capture induced supernovae (see above) occur preferentially in binaries, and explain X-ray binaries with low-eccentricity. And binaries are needed to explain Type Ia supernovae, short-duration gamma-ray bursts, but perhaps also long-duration gamma-ray bursts and even magnetars. So it is clearly worth investing into understanding binary evolution, and the observed populations of evolved binaries, like the Be-X-ray binaries, have been shown to provide essential clues on the uncertainties involved in the modeling process.

7. Final remarks

This meeting provided us with excellent reviews and contributions showing where we stand in our understanding of the essential processes acting inside stars, and in the art of modeling their evolution as single and binary stars. It was very useful to have no limit on the type of star we could discuss during this meeting, which lead to the identification of many cross links which could not have occurred in a more specialized meeting. This conference, and this proceedings book, will be a very useful tool to guide us into new directions for future research.

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