Community paper „Stellar Parameters, Stellar Structure and Evolution“
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Executive summary

Stellar Astrophysics is not only one of the oldest branches of astronomy, but also the one with the most rapid and sustained information growth over decades. The success is due to the development of technologically more advanced telescopes, strong connections with the fundamental physical theory, and the fact that our understanding of any phenomenon in the Universe, from galaxy evolution and gamma-ray-bursts to exoplanets, neutrinos, and cosmic expansion is intricately linked to our understanding of stars. Recent advance in the field of stellar astrophysics is breathtaking. However, most fundamental (and, by implication, difficult) problems are yet to be solved. This requires not only new observations, which implies continuing support and development of new instrumentation for multi-wavelength studies, but also advances in the theoretical studies of stellar structure that provide the framework for the analysis of observations. The classes of unsolved problems are very broad; they range from planet-host stars, including the Sun, to the first stars in the Universe. With its exceptional contributions to stellar astronomy in the past decade, Germany is now well positioned to make fundamental contributions to these problems. It is important to maintain and strengthen this position, through continuous support of infrastructure, laboratory experiments, instrumentation, research collaborations, and development of multi-scale computing models that provide a realistic description of nature.

1. Introduction

Stellar astrophysics is about understanding what stars are made of, how they form, evolve, and die, how they impact their environment and how they influence the evolution of their host galaxies and of exoplanet systems forming around them.

One fundamental aspect of stellar astrophysics is observations, both through the studies of stellar spectra, and of integrated light together with its temporal variations. Figure 1 is a magnificent example of the complexity we expect to find when studying the radiation emitted from the majority of stars in the Universe. The spectra of stars like our Sun show numerous lines of metals in the ultra-violet (UV), while the forest of features becomes more diffuse as one looks in the red and infra-red (IR), probing progressively deeper layers of the star. At X-ray and radio frequencies, structures due to non-thermal gyrosynchrotron emission from stellar coronae are visible. In the μm range, one finds the contribution of circumstellar dust and water envelopes. This diversity provides many tools to study the physics of stellar radiation, and consequently, the physical conditions inside stars that lead to the observed starlight pattern.

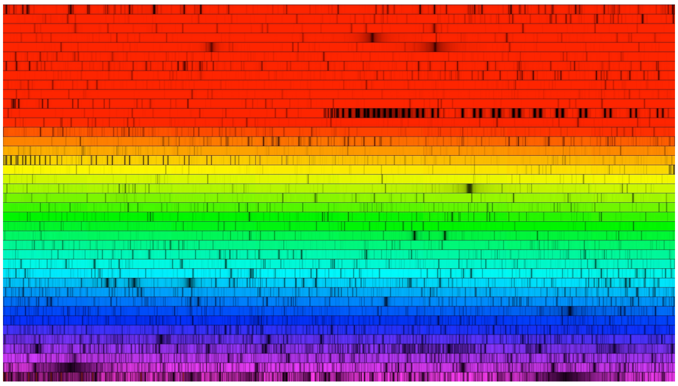

Figure 1: A solar twin star 18 Sco. The spectrum was taken with the PEPSI high-resolution spectrograph at Large Binocular Telescope (LBT).

The other fundamental aspect of stellar astrophysics is models that describe stellar structure as a function of mass and age – from pre-main-sequence to white dwarfs, neutron stars, and black holes, early and final stages of stellar evolution – from the birth stages to the violent explosive events, supernovae and hypernovae. The properties of all these classes of objects vary widely. Even inside the Sun, the gas density changes by 20 orders of magnitude (150 g/cm^3 in the core to 10^{-18} g/cm^3 in the corona). Therefore strong synergies with other branches of modern physics are needed to build sound stellar models: from physics of condensed matter, magnetised plasmas, and nuclear processes, to hydrodynamics, atomic physics, and energy transport.

Studies of the physics of stars have never been as important and crucial for astronomy as today. This is demonstrated by the fact that the fields of diagnostic spectroscopy, asteroseismology, stellar activity and magnetism, simulations of stellar explosions, and stellar populations have enjoyed a great deal of attention over the past decade. All these fields are strongly inter-linked. Moreover, there is a deep connection with solar physics, with planetary studies, galactic structure and evolution, stellar populations in galaxies.

Diagnostic stellar spectroscopy is the key method to determine fundamental stellar parameters and chemical composition of stars. It is currently possible to achieve the 10-20% accuracy of abundances for the majority of chemical elements, from CNO to gold and uranium. But the next big challenge is to bring the accuracy down to 1-5%, which is what is required to fully utilize the potential of very- and extremely-large telescopes (LBT, VLT, and the future E-ELT), but also space missions (such as PLATO and JWST). How do we achieve this accuracy?
Stars are difficult systems, and many physical ingredients are yet to be consistently included in the models of stellar atmospheres. In particular, modelling cool stars requires dust condensation and chromospheres, cloud formation, winds and pulsations, magnetic fields, 3D radiation hydrodynamics and convection (Fig. 2), non-local thermodynamic equilibrium (NLTE). However, these theoretical efforts will pay off.
With chemical abundances accurate to a few percent, we will be able to look for signatures of planet formation in the abundance distributions of solar-like stars – a path to biosignatures in the atmospheres of their exoplanets, to create realistic models of the formation of the Milky Way and other star-forming galaxies, to provide a convincing theory of cosmic nucleosynthesis, in particular for the origin of carbon and oxygen – the key elements for life, to find the truly „first" stars, and to use quantitative spectroscopy of light elements, Li and He, in the spectra of primordial stars to test the Big Bang nucleosynthesis and the physics of the standard cosmological model.

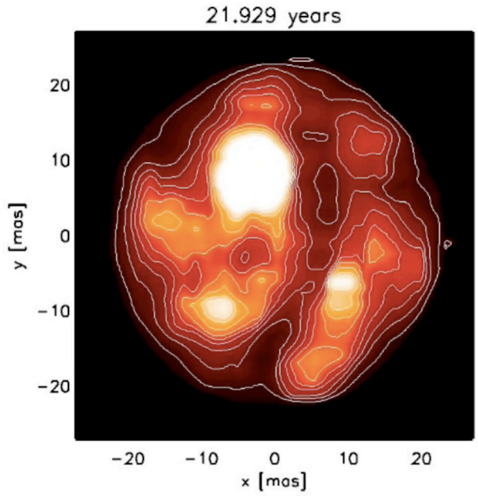

Figure 2: Surface convection simulation of a Red Supergiant star. The plot shows the G-band intensity at the surface, as seen with a 42-meter telescope (A. Chiavassa). The star is at a distance of ~200 pc.

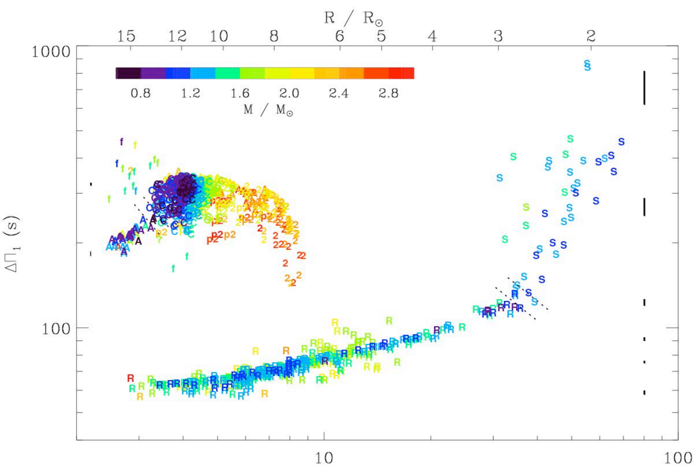

Figure 3: Seismic diagram showing the two loci, corresponding to the red clump and red giant branch stars (from Mosser et al. 2014).

Asteroseismology is a new technique that uses stellar oscillations to probe the internal structure of stars. Interest in the method was boosted by the advent of new ground-based observational campaigns, but, in particular, with the launch of two space missions, CoRoT and Kepler. While often credited with the discovery of a large numbers of stars with planets in the habitable zones, the two space missions also provided a wealth of new information about stars themselves, the key deliverables being estimates of stellar masses, radii, and evolutionary phases (Fig. 3). Currently, the main challenge for asteroseismology is to advance beyond the concept of "asteroseismic scaling relations", which are extrapolations of the relationships obtained from the standard solar model, and seek seismic diagnostics to determine the inner structure of stars at a far greater detail. This will also remove the main uncertainty in our understanding of extra-solar planet systems, namely the masses of their host stars.

Stellar Rotation, Activity, and Magnetism now play an important role in stellar astrophysics, providing new ways to characterize stars. The generation of magnetic fields in a stellar-size laboratory is an experiment that provides insight into aspects of physics that are inaccessible in any terrestrial setup.

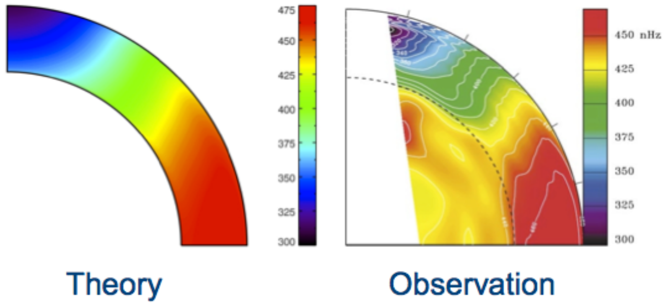

Figure 4: Differential rotation in the Sun. Left: Kueker et al. (2011). Right: Thompson et al. (2003).

Among the top themes for the next decade will be the understanding of the origin of magnetic fields in stars, the evolution of magnetic field configuration(s) during stellar evolution, and the organization of dynamos on large scales. The next decade will also provide large numbers of rotation periods (enabling the derivation of stellar ages) and of stellar differential rotation (Fig. 4), and bring a wealth of data about stellar surface structure from high-resolution spectroscopy (PEPSI, Carmenes), Doppler imaging (e.g. PEPSI, STELLA), and Zeeman Doppler Imaging using polarimetry (PEPSI, STELLA), asteroseismology and photometry (PLATO, TESS, CHEOPS), see Fig. 5. High-resolution instruments (e.g HARPS at VLT) will provide an unprecedented new view of stellar magnetism.

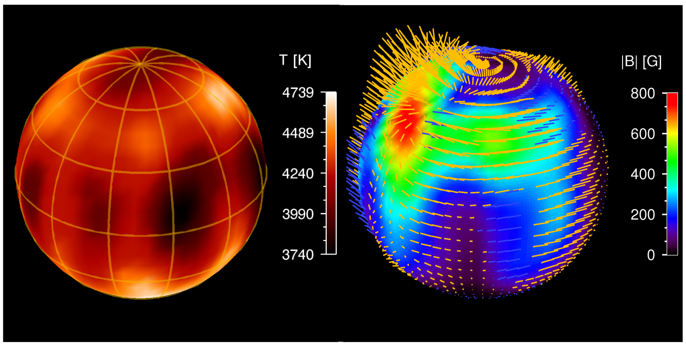

Figure 5: The surface temperature (left) and magnetic field (right) distribution of a subgiant II Peg (from Carroll et al. 2007).

How is angular momentum transported in stars? While the rotation profile for the Sun is mostly known, the models of stellar evolution are less than satisfactory in describing the evolution of angular momentum in stars. Intriguingly, evolved stars show cores and envelopes rotating at substantially different rates. There is also evidence that some massive stars may have counter-rotating cores and envelopes. The development of models, that consistently include stellar rotation and its impact on stellar evolution will be a fundamental achievement for the next decade.

Stellar explosions

The past decade has seen a major step forward in our understanding of how stars end their lives in violent explosions, known as supernovae. This has been possible through the development of 3D hydrodynamical simulations of core collapse in massive stars and thermonuclear explosions of white dwarfs (Fig. 6). The key challenge for the next decade is to understand the stellar evolution towards explosion, i.e. the last phases of evolution of massive stars and interaction of stars in binary systems.

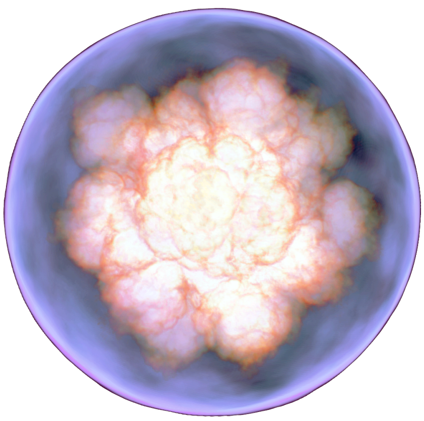
Figure 6: A thermonuclear supernova explosion model. (c) F. Roepke

We are now on the verge of a new era in observational studies of stellar explosions through the data made available by the Palomar Transient Factory, the Supernova Factory, the Spectroscopic Survey of Transient Objects (ESO), and other future surveys (e.g. on LSST). A completely new window has just been opened by detecting gravitational waves from merging black holes; mergers of compact objects and exploding massive stars will be observed with facilities like Advanced LIGO. These signals allow to conclude on the equation-of-state at supernuclear densities. For all these efforts, it is essential to produce consistent supernovae models to make robust statements about the ultimate fate of stars and thus to predict the key observables, such as the neutrino and gravitational wave signals.

Stellar Populations in the Local Group of Galaxies

Currently, the number of observed stars in the Local Universe is skyrocketing, owing to the new generation of Multi-Object-Spectroscopy (MOS) facilities, such as the MUSE[1] and KMOS instruments at the VLT, and MOSFIRE at the 10-meter Keck telescope. As a result, *data-driven models* are becoming one of the major instruments for the analysis of observations. In the future, 4MOST alone will revolutionise stellar astronomy by providing spectra of 25 million stars. The main focus of the Gaia space mission (ESA's prime mission in Cosmic Visions) is to observe 1.000.000.000 stars in the Milky Way. Besides large populations of normal stars, many among them hosting exoplanets, those projects will discover significant numbers of faint, rare and exotic objects, such as extremely metal-poor old stars, and binaries with common envelopes. Gaia will also provide, for the first time, masses and radii of millions of wide binary systems as well as light curves of millions of eclipsing and variable close binary stars. The revolutionary observed datasets will provide an unprecedented new view of the local and distant worlds, from brown dwarfs in the solar neighbourhood to extremely luminous massive stars in other galaxies.

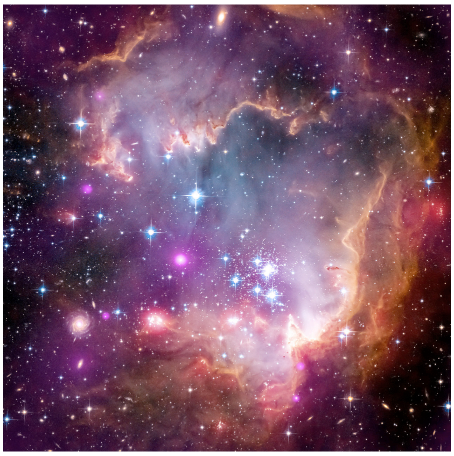

Figure 7: X-Ray emission from young solar-type stars in the "Wing" of the Small Magellanic Cloud. (c) X-Ray: NASA/CXC/Univ. Potsdam/L.Oskinova et al. Optical: ESA, NASA/STScl; Infrared: NASA/JPL-Caltech

With those samples we will be able to extend to more remote galaxies the science that has been possible in the local neigbourhood only, such as the observation of populations of low-mass and massive stars in different environments, their parental clusters through chemical tagging, and starburst regions (Fig. 7). By diagnostic spectroscopy we will learn how the feedback from massive stars shapes and carves their environment, triggers and terminates star formation. Even with existing instruments, such as KMOS and MOSFIRE, resolved stellar populations and individual stars, e.g. luminous Red Giants and Red Supergiants, can be probed out to distances of the Virgo Cluster, at 10 Mpc. With instruments like IRMS at the TMT and MOSAIC at the E-ELT, as well as JWST, it would be possible to measure abundances of chemical elements in individual stars out to the enormous distance of 70 Mpc, allowing detailed studies of the structure of star-forming galaxies and their chemical and dynamical evolution.

2. Key Questions for the Upcoming Decade

Our assessment is that transformational results in stellar physics, which have the potential for major impact in all fields of modern astronomy can be achieved by pursuing the efforts along the following five directions:

- Stellar evolution and asteroseismology
- Diagnostic spectroscopy and spectropolarimetry
- Numerical simulations and observations of stellar explosions
- Stellar rotation, activity, and magnetism
- Populations in the Local Group of Galaxies

[1] With novel source extraction one can get 2000-5000 spectra in about one minute exposure from galactic clusters in a range of about 10 kpc – 20 kpc.

Within each of these broad and complementary topics, we identify the following key problems that will arguably attract major attention in the coming decade:

1.1 Stellar Evolution and asteroseismology

1.1.1 Can we construct a standard model of stellar evolution that applies to the majority of stars and does not assume that stars are 1-dimensional quasi-static objects?

1.1.2 How does dark matter interact with stellar plasma and does it influence stellar evolution?

1.1.3 Since all chemical elements in nature beyond Li are produced in stellar furnaces, will the new stellar models imply a paradigm shift for the theory of stellar nucleosynthesis, the theory that was recognised by the Nobel prize for physics in 1983?

1.1.4 What is the role of 3D hydrodynamics, rotation, diffusion, and magnetic fields? Is our understanding of micro-physics of stellar plasma sufficient to explain the observations?

1.1.5 What can we learn from asteroseismology, besides mass and radius? Can we improve the asteroseismic diagnostics to determine the nuclear ages of stars with the accuracy, that allows using this diagnostic in such sensitive domains as, e.g. the search for solar-like planet host stars or constraining the age of the Universe?

1.1.6 Can we understand and model the properties and significance of binary stars?

1.2 Diagnostic stellar spectroscopy

1.2.1 What is the impact of 3D convection, non-local thermodynamic equilibrium (NLTE) physics and non-equilibrium chemistry on stellar spectra and, thus, on fundamental stellar parameters?

1.2.2 Can we learn about stellar magnetism, winds, pulsations, formation of clouds, dust shells, from stellar spectra?

1.2.3 Are signatures of planet formation in the chemical abundance distributions of solar-like stars real? If yes, can we use stellar spectra in the quest for exoplanet-host stars?

1.2.4 Where and how can we find the truly first stars, and what are their properties (age, chemical composition)?

1.2.5 Will it be possible to determine Li and He abundances in the oldest stars with sufficient accuracy to constrain the physics of the standard cosmological model?

1.3 Simulations and observations of stellar explosions

1.3.1 What type of stars end in what type of explosion? What is their chemical and hydrodynamical structure? How do they interact with binary companions?

1.3.2 How do instabilities in stellar evolution towards explosion make the stellar structure diverge from spherical symmetry?

1.3.3 Can we find observational evidence to confirm the progenitor systems of Type Ia SNe?

1.3.4 What is the 3-dimensional structure of massive stars, the progenitors of core collapse SNe?

1.3.5 How do explosion properties connect to the structure of the remnant?

1.3.6 What are the key observables from supernova explosions (multi-wavelength observations, neutrinos, gravitational waves, heavy elements)?

1.4 Rotation, Activity, Magnetism

1.4.1 What is the origin of magnetic fields in stars?

1.4.2 How do magnetic field configurations evolve during stellar evolution?

1.4.3 How do dynamos organise on large scales?

1.4.4 Can we construct a model that describes the transport of angular momentum in stars?

1.4.5 How do rotation and magnetism interact, and how do they impact planetary habitability?

1.5 Stellar Populations in the Local Group Galaxies

1.5.1 What are the properties of populations of low-mass and massive stars in different environments? How do these properties correlate with the properties (and evolution) of the host galaxy?

1.5.2 Can we identify parental clusters of stars through chemical tagging?

1.5.3 How does feedback from massive stars shape their environment? How does it trigger and terminate star formation?

1.5.4 What can we learn about young star forming regions and starbursts in other galaxies?

3. Key Results of the Previous Decade

The past decade has seen a revolution in the quality and quantity of the observational data relevant to stellar physics and in the development of more realistic stellar models that describe different types of stars, different phases of stellar evolution, and different physical processes at the surface and in the interiors. Stellar models have supported and guided the design of new instrumental facilities and new observational programs on all scales, from small individual observing programs to major large-scale surveys, like the Gaia space mission and Sloan Digital Sky Survey (SDSS). The combination of the new observational information and models of stars has, in return, led to a number of prominent achievements and discoveries that have had an impact across all fields of astronomy. These achievements are briefly described below, focusing on particular efforts by the German community.

The arguably most fundamental result is the solution of the Solar Neutrino Problem, thanks to the confirmation of neutrino oscillations, a discovery crowned by the Nobel prize in 2015, that has made clear that our understanding of stellar structure is already impressively good. The Standard Solar Model, i.e. the evolutionary model that describes the evolution of the Sun from its formation until present, has been developed and has become a "golden reference" in astrophysics. German scientists have played an important role in these endeavours, not the least due to the development of the stellar evolution code Garstec (Garching). The lessons learned from the Standard Solar Model helped to improve models for other classes of stars, such as Cepheids and the tip red giants, both used as standard candles to measure cosmological distances and therefore to improve the accuracy of the local Hubble constant. The models were further improved by the results of geophysical experiments, such as thermohaline mixing in stars driven by molecular weight inversion, a process known from oceanography.

It has become possible to determine stellar parameters and the interior structure of stars from asteroseismology, a technique developed in close analogy to geophysics. The method has gained in popularity, now that helioseismology is remarkably consistent with the predictions of the Standard Solar Model. Asteroseismology, and in particular the advent of the Kepler and CoRoT space missions, has led to many discoveries, such as the radial differential rotation in stars, the determination of convective core sizes, the depth of outer convective layers, and the means to discriminate stars in different evolutionary stages. The technique has also made it possible to determine ages for a substantial number of stars.

Another breakthrough was brought about by new measurements of chemical abundances in the Sun (the Standard Solar Composition), carried out for the first time using realistic 3D radiative-hydrodynamics simulations of the solar convection (Fig. 8) and non-LTE by scientists at MPA in Garching and Heidelberg. These new data challenged ideas about the formation of stars and their planetary systems, but also about evolution of galaxies: the Milky Way is now a surprising stand-out among 20,000 galaxies in the fundamental mass-metallicity relationship of galaxies. The new abundances also created severe tension with the seismic model of the Sun, a fundamental problem that needs to be solved soon, and for which German researchers are well prepared due to their expertise in stellar evolution and stellar spectroscopy.

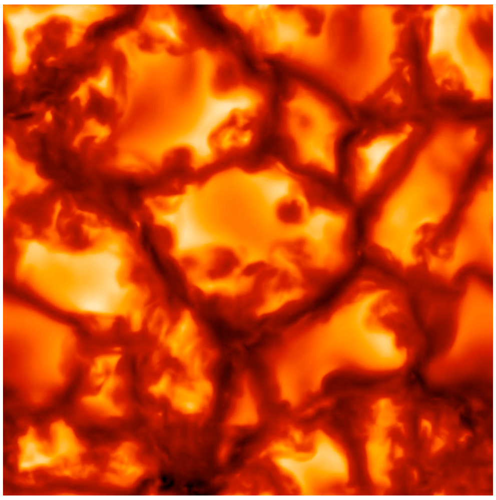

Figure 8: Simulated solar granulation. (c) R. Collet

Moreover, over the past 10 years, the art of computing 3D hydrodynamic and NLTE model atmospheres for cool stars has matured to a degree that allows their application to different types of stars, from Red SuperGiants to the smallest M dwarfs with dust and clouds. German groups have been leaders in this field, providing the first global (star-in-a-box) simulations of stellar convection, NLTE model atmospheres and spectra of stars (Munich, Heidelberg, Hamburg). With unique efforts by the Munich, Bonn, Potsdam groups, and Bamberg, the models of the atmospheres of hot massive stars and evolved low-mass stars (subdwarfs, white dwarfs, central stars of planetary nebulae) are now routinely computed with non-LTE and winds.

Figure 9: Left: Experimental setup for the demonstration of a magneto-rotational instability (R. Arlt). Right: Isosurfaces of the expected vertical wave velocity (M. Gellert).

Equally impressive are the advances in the field of stellar activity and magnetism. Over the past decade, a large number of stellar rotation periods have been obtained, both from the ground and from space, and a relationship has been derived between the rotation periods, masses, and ages of cool stars (with active involvement of the Potsdam group), allowing the derivation of the age of field dwarfs from their rotation periods. Good progress has also been made in observing and explaining the surface differential rotation of stars. Stellar magnetic field measurements have become increasingly sensitive and reliable, permitting fruitful comparisons with theoretical work. A number of predictions of solar and stellar dynamo theory have become amenable to observational verification from measurements in stars, and key aspects, like the magneto-rotational instability (MRI), have also been verified from laboratory measurements (Fig. 9).

Regarding fundamental stellar parameters, the main success is firstly due to our understanding and numerical treatment of radiative transfer and atomic data, and secondly due to quantitative stellar spectroscopy that is used to verify or falsify the input physics. The realisation of large-area spectroscopic surveys, such as SDSS and Gaia-ESO, or RAVE lead by German astronomers (Potsdam) was another step forward. These data increased the samples of stars with known fundamental parameters by many orders of magnitude and have influenced new directions in areas where large statistics matter, in particular, studies of stellar populations and Galactic archaeology.
Thanks to these surveys, the number of observed peculiar objects, such as the „first“ stars or close binary systems has increased substantially. German astronomers have been among the first in searching for ultra metal-poor stars, the relics of the earliest epochs of the Universe. Their unique chemical abundance patterns generated great interest in the evolution of primordial (Population III) stars and their nucleosynthetic imprints. This development has had a profound influence on studies of star formation in the early Universe.

The discovery of a very high binary fraction for the most massive stars has shown that binary interactions play an extremely important role for their evolution. New classes of close binary stars were observed, among them evolved stars and stellar remnants. Those binaries include the closest systems known, binaries with substellar companions, candidates for SN Ia progenitors, and gravitational wave sources.

Impressive advances were achieved in the field of numerical simulations of stellar explosions. Consistent multi-dimensional models for both kinds of supernovae (core-collapse and thermonuclear) were developed by researchers at MPA in Garching, at Würzburg, and at Heidelberg. The models, for the first time, have provided solid predictions about various kinds of observables, and some of them have already been rigorously tested against observations. For SN Ia, these are light curves, spectra, gamma- and X-ray data, and nucleosynthesis yields. For SN II, the models have provided unique predictions of neutrino- and gravitational wave signals. All these model predictions will be tested on groundbreaking datasets soon expected from various facilities, like the advanced Laser Interferometer Gravitational-Wave Observatory (LIGO), the Dark Energy Survey (DES), Large Synoptic Survey Telescope (LSST), the James Webb Space Telescope (JWST), and, of course, the European facilities Gaia space mission, Euclid, and E-ELT.

4. Particular Role/Strengths of Research Groups in Germany

In the past decade, Germany has enjoyed a prominent standing in the international community, owing to its exceptionally strong theoretical school in stellar physics, continuous long-term involvement in international observational projects, and construction of world-class instrumentation for small-scale national facilities and large international facilities.

On the theoretical side, in the domain of stellar evolution, stellar atmospheres, and explosion simulations, three key factors have contributed to this success. Traditionally strong in theory, scientists in Germany have been involved in the development of new algorithms and their numerical implementation. Access to leading supercomputers (such as the Leibniz Rechenzentrum Garching, Jülich Supercomputing Centre, and the Höchstleistungsrechenzentrum Stuttgart) have allowed running codes taking advantage of massive parallel computation techniques. In contrast to observational studies, such projects normally take a decade to complete; thus the continuity of expertise and stability of funding in Germany, which did not require immediate pay off, was essential. This allowed not only to provide the community with unique codes for the interpretation of essentially any kind of observations, but also to influence new directions in planetary, stellar, and galactic astrophysics by providing a framework for carrying out feasibility tests and simulations of large international observing programs, such as the Gaia-ESO and RAVE[2] large spectroscopic surveys.

As a result, several powerful codes have been developed that are widely used in the followings areas of stellar astrophysics: radiation transport and diagnostic spectroscopy (Munich, Heidelberg, Kiel, Tübingen, Potsdam, Göttingen), magneto-hydrodynamic simulations of stellar convection, stellar dynamos, and magnetic field models (Potsdam, Goettingen, Heidelberg, and Hamburg), stellar evolution at all ranges of stellar mass (Garching, Bonn, Potsdam) and the hydrodynamical codes for simulations of stellar explosions (Garching, Würzburg, Heidelberg). Unique collaborations with the centres for experimental atomic and nuclear physics (e.g. Darmstadt GSI) facilitated the availability of critical nuclear and atomic data for stellar structure models.

Continuous development and maintenance of stellar models, but also development and building of instrumentation (supported, e.g. by BMBF), has allowed German groups to compete successfully for observing time on major international facilities, such as Hubble Space Telescope, Chandra, and ESO facilities across the electromagnetic spectrum (optical, UV, X-rays, Infra-Red). Furthermore, German groups build and operate specialized ground-based telescopes (including robotic ones) and instrumentation (e.g. STELLA, GREGOR, Carmenes, Tautenburg) and contribute with instrumentation to space facilities (e.g. HST, Chandra, XMM, INTEGRAL, Herschel).

On the other hand, strong continuous involvement in international projects, both in design and operations, such as spectroscopic surveys (Germany-lead RAVE survey, but also SDSS and Gaia-ESO), supernova surveys (PESSTO), provided priority access to the critical observational data, giving German researchers a competitive advantage. Access to the large computer clusters made it possible for German astronomers to take the leadership in the data analysis.

In the next 15 years, Germany will be particularly visible internationally, thanks to its leading role in large-scale projects, 4MOST (4-meter Multi-Object Spectroscopic Telescope) and PLATO (PLAnetary Transits and Oscillations of stars). These projects involve the majority of German universities and research institutes, including Hamburg, Potsdam, Munich, Goettingen, and Heidelberg. 4MOST is a big player on the international arena, succeeding SDSS, arguably the most successful project in the history of astronomy[3]. 4MOST will provide unique spectroscopic observations of 25 million stars in the Galaxy, complementing the positions of stars from the Gaia space mission. In addition, for many thousands of these stars, PLATO will determine masses and ages. The 4MOST, PLATO, and Gaia legacy data will be one of the most powerful means of advancing stellar astronomy in the next decade, influencing all research directions from stellar habitability to planetary science and cosmology. To maximise the scientific return of these observations and to

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2 Radial Velocity Experiment (RAVE) , is one of the largest spectroscopic surveys of Milky Way stars available to the community presently.

3 Based on the number of papers published using the SDSS data and citations.

achieve the anticipated ground-breaking discoveries in stellar and Galactic astrophysics, scientists will need a grid of stellar model atmospheres including 3D hydrodynamics, extensive NLTE model atoms, contributions from chromospheres, and effects of diffusion and magnetic fields, covering a large fraction of the Hertzsprung–Russell diagram. Thanks to the traditional expertise in stellar physics, German researchers are now in the excellent position to take the lead in these calculations, providing a sound descriptive set of stellar models to be compared to observations. One of the highlight themes in the new decade is that of resolved stellar populations out to the Virgo Cluster. With the strong involvement of German institutes in a number of next-generation instruments, like MICADO and METIS and HIRES at E-ELT, NIRSpec at JWST, Germany is also visible and well positioned to make spectacular contributions to the field of stellar, galactic and extra-galactic archeology.

5. Key Infrastructures needed/relevant for Researchers in Germany

To maintain and strengthen the world-leading position of Germany in stellar physics, it is essential to provide and expand the following infrastructures.

First, the focus of stellar astronomy has now expanded from smaller-scale projects to large-scale international survey projects, such as the Gaia space mission, and future 4MOST, PLATO, and LSST. Other facilities, like PEPSI at the LBT, and in future HIRES at E-ELT, allow to observe individual stars with unprecedented spectral resolution and for the entire wave front (i.e. the full Stokes vector). Therefore, new additional resources are needed to build up the critical infrastructure, i.e. the software and new data analysis methods, to support the exploitation of the anticipated astrophysical datasets. This includes stable and guaranteed access to leading supercomputational resources (in particular, LRZ, SC Jülich, HLRS) and support by trained specialists in computer sciences, to assist researchers in building dedicated analysis software, in order to maximise the scientific exploitation of the data. Even more important is to provide training in numerical techniques to students, as well as longer-term employment perspectives for scientists working on the development of large codes – an effort that compares to the development and building of new instruments.

Secondly, we need a new strategy to ensure that all Universities and research institutes have an opportunity to participate in small- and large-scale projects (and facilities) run by international collaborations. Several institutes are operating their own small-size telescopes (Bochum, Bonn, Potsdam, Hamburg, Tautenburg, Göttingen, Heidelberg, Freiburg), which are science driven and are successful. However, there is currently no national plan for fully exploiting the medium-size (4-8 meter) telescopes other than abandoning them. Likewise, it is not easy for smaller institutes and Universities to join large international observing projects, which often require long-term financial contributions.

The community recognises there is a need for a collaborative research centre (e.g., Sonderforschungsbereich or Schwerpunktprogram), which focuses on stellar physics - on observations and on theory. Such a Centre for Stellar Astrophysics (CfSA) could carry out the core tasks from leading and organizing access of German institutions to the small- and mid-size telescope facilities, through multi-dimensional code development, to scientific exploitation of astrophysical data obtained by international experiments (in which Germany makes substantial investments). One of the core activities would be to put the community effort together the push the field of multi-D, MHD, and non-LTE computations with respect to stellar evolution and stellar atmospheres and link these developments properly to the observations. The medium-size facilities will offer a good complementary base for large-scale stellar science projects, which would not be possible on the large facilities such as E-ELT.

The top infrastructure priorities for stellar physics in the next decade are the 8-10 meter and forthcoming 30-40 meter optical/IR telescopes, in particular VLT, LBT, and E-ELT, and space missions, Gaia, JWST, PLATO, eRosita, and Athena. In addition, we identify two domains with exceptionally high scientific potential, where it is now crucial to design and build new facilities. Firstly, a medium-size space telescope with UV coverage. This facility will allow high-resolution spectroscopy with absolute flux continua, critical for studies of massive stars and the oldest stars in the early Universe. Secondly, there is a need for a dedicated 8-10 meter wide-field survey ground-based telescope that will allow massive spectroscopy of stellar fields in the Milky Way and other galaxies.

Third, the competition with the international community requires parallel efforts in theoretical stellar physics. Germany's excellence in stellar physics indeed relies on its traditionally strong focus on fundamental theory that has allowed individual researchers to successfully compete for observing time at international observatories. In the past, most hard-core theoretical developments took place at the level of individual departments thanks to a number of professorships in stellar physics. This guaranteed continuity of expertise over several generations of researchers, essential for the theoretical work. Strengthening the representation of stellar physics at German universities and research institutions[4] is therefore essential to remain internationally competitive and secure leadership in the field.

Finally, it is important to have resources to expand very promising directions, such as high-precision diagnostic spectroscopy, magneto-hydrodynamics, and asteroseismology, and to link these communities more thoroughly. These directions are currently at the forefront of stellar physics, as they combine the newest observational methods and theoretical techniques, having the largest potential for innovation and discovery in the near- and long-term future. Supporting these areas will avoid creating a critical gap in our capacity to exploit the forthcoming observational data, to remain internationally competitive, and provide influential and high-impact results. This also means that Germany will be well prepared for the era of new space missions and extremely large telescopes (ELTs) in 2020's.

6. Summary and Conclusion

Through spectroscopy, asteroseismology, and models of stars, stellar physics is one of the areas of astrophysics with the most rapid and sustained information growth in the next decade. The next 5-10 years will bring a major revolution in the volume of observational information about stars, triggered by the development of new ground-based instrument facilities and the successful launch and operation of several space missions, particularly Gaia. In the majority of these projects, Germany has been either an active participant or has co-led the efforts that allowed German scientists to maximise the scientific exploitation of the data and deliver groundbreaking results. With this experience, Germany is now in an excellent position to take advantage of the forthcoming astronomical facilities, in particular, the revolutionary projects, 4MOST and PLATO, led by the German institutes, but also LSST, JWST, and a number of dedicated facilities (STELLA, GREGOR, Carmenes). All these facilities provide unique information about stars, opening new windows to studies of stellar structure, planet formation and galactic archeology through high-precision spectroscopy and asteroseismology.

German scientists have a unique opportunity to maximise the impact of the data, through the development and application of sophisticated 3D magneto-hydrodynamic models and NLTE techniques that are a cornerstone of learning from observations and which provide a framework for developing new ideas and theories. In parallel to its exceptional endeavours in observational stellar astronomy, Germany must maintain its world-leading role in theoretical stellar physics by developing the fundamental directions of diagnostic spectroscopy, magneto-hydrodynamic simulations of stellar convection and dynamos, magnetic field modelling, stellar evolution at all ranges of stellar mass, and simulations of stellar explosions. Combined with new observations, this will facilitate addressing outstanding problems such as the origin of magnetic fields in stars and organisation of dynamos on large scales, the origin of chemical elements and cosmic nucleosynthesis, progenitors of supernovae, and looking for signatures of planet formation in abundances of their host stars, opening a new field – astrophysics of stellar habitability. They will also allow the prediction of the key observables, such as the neutrino and gravitational wave signals to be tested on groundbreaking datasets soon expected from the facilities like Advanced LIGO.

We suggest the following key priorities, that are needed to ensure that Germany maintains its leadership in stellar physics: access to the available and next-generation telescope facilities, continuous access to large supercomputers, a strategy for exploitation of medium-sized telescopes, strengthening the representation of stellar physics at German universities and institutes, support for astrophysical data exploitation, and instrument building. In particular, the two critical missing facilities for stellar physics are a medium-size space telescope with UV coverage and a dedicated wide-field 8-10 meter survey telescope. The scientific potential of these facilities is unique and

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[4] As in other Universities world-wide.

Germany has the capability of taking the lead in the design of these instruments, firmly establishing its role as the leader in all sectors of modern astrophysics – from instrumentation to hard-core theoretical research. This will also allow German scientists to benefit from international research environment, networking, and collaborations, opening far wider possibilities for astronomical research and training.