Community paper „Star Formation and Interstellar Medium“

Prepared by Eva Schinnerer, Paola Caselli, Stefanie Walch and Sebastian Wolf with input from the German SF-ISM community

Executive summary

The research field of `Star formation and Interstellar Medium (ISM)’ has seen a tremendous growth in Germany in the last 15 years. ISM and star formation research at German institutions is world-leading across the different research areas ranging from the high redshift universe to protostars to microphysical processes. This is due to the unique combination of (preferred) access to state-of-the-art observing facilities, excellent supercomputing infrastructure, world-class laboratory astrophysics and substantial funding support from outside the university and research institutes. To maintain the world-leading position it will be crucial to develop paths to sustain the personnel level while retaining expertise and knowledge. Continued access to state-of-the-art existing and future observatories (e.g. IRAM, ALMA, ELT, JWST, APEX, SOFIA, VLT/I) will be vital. In particular the lack of a planned major facility in the far-IR window, will need special care to avoid loss of unique world-class expertise and leadership in this critical window. The highly internationally recognized theoretical research heavily relies on good access to excellent large- and medium-scale supercomputing facilities. Fundamental data on physical and chemical reactions provided from the laboratory astrophysics groups remains key. To make significant progress in the next decade funding lines that allow for long-term initiatives in and across all research areas (here: observations, theory, instrumentation, laboratory astrophysics) will be highly beneficial.

1. Introduction

How stars form and how the interstellar medium (ISM) evolves are fundamental topics in astrophysics. The ISM is composed of (ionized, atomic, molecular) gas and dust, hot plasma and cosmic rays. On the one hand, understanding the star formation process and ISM physical/chemical conditions is essential to shed light onto galaxy formation and evolution. On the other hand, the star formation process elucidates how protostellar and, ultimately, protoplanetary disks form, thus providing information on the initial conditions for the assembly of planetary systems like our own.

Stars form from the contraction of interstellar material into dense pockets of gas and dust, where gravity overtakes counteracting forces such as thermal, turbulent and magnetic pressure. The physical and chemical properties of the ISM regulate the star formation process. At the same time, stars profoundly affect the evolution of the ISM via their energetic winds, radiation fields, and supernova explosions that shock and ionize their surrounding, and through chemical enrichment of the galaxies within which they form. Elements heavier than Helium (He) are produced in stellar centers, so stars are responsible for the production of elements such as C, O, Si, Mg, and Fe that are crucial for the production of dust, rocky planets, and, ultimately, life.

The study of the ISM and star formation spans many orders of magnitude in density, temperature, and size scales, from the tenuous and hot intergalactic medium, down to galactic warm and diffuse atomic clouds, which enshroud the cold and dense molecular clouds where fragmentation and star/planet formation takes place. This requires expertise in different fields of physics (such as hydro- and magneto-hydrodynamics, plasma physics, radiative transfer), chemistry (molecular plus atomic theoretical and experimental chemistry, spectroscopy, chemo-dynamics, dust formation and growth, interaction between gas and dust grains) and multiwavelength observational techniques, which allow us to probe the various phases of the ISM (from radio to (sub-)millimeter, (far-)infrared to near-infrared to optical to UV to X-rays and gamma rays). Thus, powerful telescopes, super-computers, and laboratory astrophysics are all needed to make substantial progress in this area, and indeed they have allowed the German community to excel in this field.

In the next sections, we will present key questions for the upcoming decade (with a focus on German community efforts) in Section 2, highlight selected key results from the German community in the previous decade (Section 3), and discuss the particular strengths of the German community (Section 4) and key infrastructures needed to maintain and/or relevant for achieving a (world-)leading role in the area of ‘Star Formation and Interstellar Medium’ (Section 5). We summarize and conclude in Section 6.

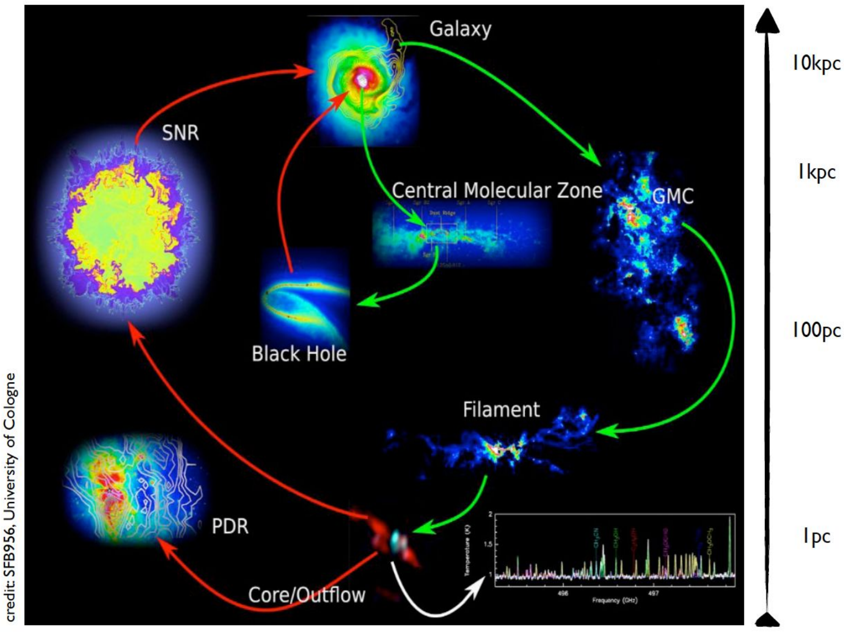

Figure 1: The cycle of interstellar matter spans a large range of spatial scales. From the diffuse to the dense and star-forming ISM in galactic spiral arms or the centers of galaxies, which is arranged in molecular clouds that have a turbulent, filamentary substructure. The forming stars provide feedback in the form of protostellar outflows, ionising radiation, stellar winds, and supernovae, which disrupt the dense clouds and launch galactic outflows. The combination of multi-wavelength observations, theoretical modeling, and laboratory astrophysics provides key insights into the different evolutionary states (figure taken from SFB 956 “Conditions and impact of star formation” , a collaborative project between the University of Cologne, the University of Bonn, and the MPIfR in Bonn).

2. Key Questions for the Upcoming Decade

The main themes in the research area of `Star Formation and Interstellar Medium (ISM)’ range from probing the cosmic evolution of galaxies to understanding the microphysical and astrochemical processes underlying this evolution. Given the recent and future advances in technology, instrumentation and computation, we foresee substantial to transformational progress in the following key areas. Figure 1 highlights the different fields of astrophysical research that are impacted by the key topics of star formation and ISM. These govern for example how much gas is converted into stars, how the turbulent, multi-phase ISM is formed and maintained, how galactic outflows are launched and driven from normal star-forming galaxies to Active Galactic Nuclei (AGN), how radiation from stars impacts galaxy evolution (from the epoch of reionization to present-day star forming regions in the Milky Way), and how these processes can be observed with present and upcoming ground- and space-based observatories.

2.1 Cosmic Evolution of ISM Properties

Observations using the IRAM NOrthern Extended Millimeter Array (NOEMA) and the fully operational Atacama Large Millimeter/ Submillimeter Array (ALMA) will revolutionize this field in the next decade. These arrays will provide measurements of the total neutral, molecular and/or ionized gas for hundreds to thousands of galaxies from the local universe well into the epoch of reionization (at z>6), allowing for the first time a precise determination of the evolution of the cosmic molecular gas mass density. These data will provide essential insights into the mechanisms of stellar mass build-up as a function of galaxy type, redshift and environment. In conjunction with new advanced simulations, there is a good chance that our current understanding of the star formation process will evolve from fragmentary to physical in the next decade. In particular, we will improve our knowledge of the gas mass budget in galaxies that ranges from gas accretion to gas consumption and loss, e.g. via outflows driven by highly energetic phenomena such as star formation feedback or AGN. The formation of cosmic dust and its evolution over time is currently highly debated as its presence is critical for ISM cooling. Finally, the role of cosmic rays and magnetic fields in the heating/cooling processes of the ISM over redshift is currently ill-defined and requires a concerted effort from observations and theory.

2.2 ISM Cycle on Small and Large Scales

Our understanding of the coupling and interplay between the different ISM components (gas, dust, cosmic rays) and their multiple phases is still in its infancy. A combined effort of different observatories, theory/simulations, and laboratory research will be required to understand how dust grows and molecules form, how galactic or (proto-)stellar environments affect the ISM's physical and chemical evolution including the formation of prebiotic molecules. ISM properties and phase transitions depend on multiple environmental parameters (e.g. gravity, radiation, turbulence/pressure) and need a thorough investigation to identify the main responsible ones. Unlike stars, the ISM responds quickly to energy input, thus its capability and ability to cool needs further investigations to develop a full picture on how far different energy sources impact and alter the ISM. Similar efforts are needed to decipher the plasma structure and its impact on other ISM components and to characterize the mass and physical state of gas that is being accreted from the intergalactic medium. In this context, combining multi-wavelength observations (from the radio to the X-ray) will be essential to understand the interplay of the different ISM phases.

2.3 Physics of Star Formation from Small to Global Scales

One of the key questions in the next decade that tightly connects this research field to other fields, is how and where do stars form: Answering this fundamental question will dramatically impact our view on galaxy formation and evolution and provide the critical boundary conditions for stellar studies as well as planet formation. We need to characterize the necessary and sufficient conditions for star formation to occur, how star formation proceeds on small scales within a molecular cloud and on large scales within a galaxy. The role of the different ISM phases (hot and warm ionised gas, warm and cold atomic gas, and cold, molecular gas) in the star formation process needs to be clarified. Similarly the importance of magnetic fields, cosmic rays, plasma physics and turbulence in the different phases of the star formation process are not well understood. There is still no consensus if the mechanism for star formation is a universal one or if actors on different spatial scales play equally important roles depending on galaxy type and cosmic time.

2.4 Impact of Highly Energetic Phenomena

The energy output of AGN (Active Galactic Nuclei), stars, and supernovae can have dramatic effects on the surrounding ISM. The energy can be in the form of radiation (e.g. photons, X-rays, cosmic rays) and winds (leading to mechanical shocks). The complex, hierarchical internal structure of the ISM makes it difficult to develop a clear picture of how these alter the chemical and physical properties of the ISM, as it is difficult to decouple chemical from physical processes. Exact knowledge of the processes changing the ISM properties is required to understand how mechanical and radiative feedback works and can impact, for example, galaxy evolution. To make significant progress in this field, detailed high resolution case studies as well as studies of large samples at different cosmic times will be required to capture the interplay of physics and chemistry.

2.5 Origin of the Initial Mass Function (IMF)

The stellar initial mass function is a key parameter for our parametrization of the star formation history of galaxies and our interpretation of the fossil record of early star forming epochs. Current open questions include how does the fragmentation of molecular clouds into molecular cores relate to the final emergence of the IMF, how do very small scale processes such as outflows and jets from protostars affect the IMF and is the IMF the same in a stellar cluster and in the field across the different environments from disk to center. Related to this is the still uncertain fraction of binary stars. Recent reports of different IMFs in, e.g., elliptical galaxies challenge the picture of a universal IMF across cosmic time and require further investigation.

2.6 Proto-stellar Disks

The next decade will see a giant leap in our understanding of the formation and evolution of protostellar disks due to a combination of very high resolution imaging from ALMA, NOEMA and new theoretical work that includes better physical descriptions for turbulence and viscosity. Further, our understanding of the importance of dust sublimation and the role of magnetic fields in shaping protostellar disks is just at the beginning. Many open questions pertain to the mass gain and loss during the formation of the central stars and how these processes affect the mass and size of its disk. Insights gained in this area will have an immediate impact for our understanding of planet formation and properties of exoplanets as proto-stellar disks provide the boundary conditions for planet formation and evolution.

2.7 Microphysical Processes and Astrochemistry

Much of our understanding of the ISM in a larger context relies on good knowledge of the underlying microphysical processes. In particular, laboratory experiments that help identify the emission and/or absorption features of dust particles and molecules will be essential for the interpretation of the wealth of data collected with Herschel and coming from ALMA, NOEMA, IRAM 30m, APEX and SOFIA in the next years and the ELT in the next decade. To ensure significant progress in this area of research, theorists need reliable information on reaction rate coefficients to develop the next state-of-the-art chemical networks and on collisional coefficients to include in radiative transfer codes, which in turn allow for the interpretation of the multitude of molecular lines observed. Further progress in our understanding of the dust composition and grain growth will be required in conjunction with a better handling of the radiative transfer in the ISM gas phase.

3. Key Results of the Previous Decade

Interstellar medium and star formation physics are relevant over an impressively large range of spatial and dynamical scales at nearly all redshifts. For this reason the study of this field in Germany is diverse and covers a broad range of topics, from the cosmic evolution of the ISM properties on galactic scales to microphysical processes and astrochemistry. In the following we highlight some of the major achievements and contributions from Germany that have been made within the past decade.

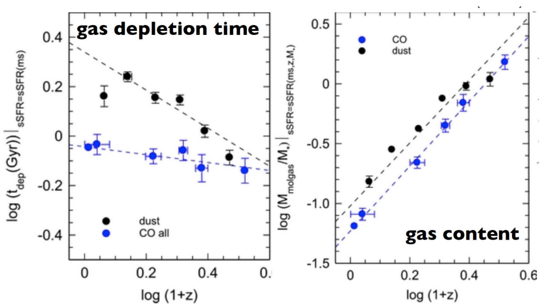

Figure 2: Evolution of the gas depletion time (*left*) and gas content or fraction (*right*) with redshift. The gas depletion time is a measure of the time it takes to exhaust the available gas reservoir at the current star formation rate, while the gas fraction is the ratio between the cold gas mass and the amount of stellar mass. Both quantities have been obtained for the largest sample of typical star forming galaxies via direct detections of molecular line emission as part of the PHiBBS surveys and using the continuum emission of dust as a proxy. (credit: MPE Garching, Genzel et al., 2015)

3.1 Cosmic evolution of ISM properties

Recent discoveries of molecular gas in high-redshift galaxies out to z~7 show that a fundamental understanding of the multi-phase structure of the ISM is required for galaxy evolution at all epochs. Complementary tracers for molecular gas are being explored as the CO-to-H2 conversion factor depends on, e.g., metallicity and cosmic ray ionization rate. The most comprehensive survey of gas properties out to z~2 has been jointly done by groups at Garching, Bonn, and Heidelberg institutes using both IRAM instruments: A strong increase of both molecular gas fraction and star formation efficiency with increasing redshift has been found in massive star forming galaxies. At the same time the feasibility of blind molecular gas surveys has been demonstrated using IRAM PdBI by a team from Heidelberg and Bonn institutes. The cold molecular gas sets the stage for efficient star formation, though theoretical work by Heidelberg-U shows that molecule formation appears to coincide with star formation rather than cause it.

3.2 ISM Cycle on Large and Small Scales

In the last decade the following picture has emerged: the ISM in star forming disk galaxies is replenished by gas infall into the dark matter halo. This gas settles towards the midplane, cools, condenses, and partly forms stars. Stellar feedback then disperses the cold molecular clouds and possibly launches galactic fountains and outflows back into the halo (see Fig. 1). German researchers from Heidelberg, Garching/Munich, Berlin, Cologne, Bonn and Potsdam have substantially contributed to the emergence of this picture via observations and theoretical simulations. A fraction of the gas must be able to leave the halo in order to match the observed cosmic star formation rate density. The recent detection of molecular gas entrained in galactic outflows using Herschel and IRAM instruments by researchers from Garching and Bonn consolidates the multi-phase nature of the ISM outside the disk midplane and supports the picture of ISM cycling between disk and halo. The role of cosmic rays in driving these galactic outflows has recently received attention as a viable mechanism to boost the mass loading as shown by work from researchers in Heidelberg and Munich/Garching.

3.3 Physics of Star Formation from Small to Global Scales

The tight relation between the star formation rate surface density and the molecular gas surface density observed globally, also holds when looking at kpc-scales as shown by the IRAM Large Programme HERACLES led by Heidelberg researchers. Dependencies on galaxies properties have been found by the IRAM Large Programme COLDGASS survey led by a team from Garching. This fundamental relation breaks down on scales smaller ~200 pc, i.e. close to the scale of the units of star formation. The IRAM Large Programme PAWS led by researchers from Heidelberg provided first intriguing evidence that the properties of the ISM and its star forming units, i.e. Giant Molecular Clouds (GMCs), are shaped by galactic structure. The Galactic Plane survey ATLASGAL on APEX by Bonn researchers and the significant contribution of research groups from Bonn, Cologne and Heidelberg to various Herschel Key Programmes, resulted in the discovery and quantitative analysis of the filamentary structure of molecular clouds. Follow-up ISM studies, e.g. with SOFIA, investigate the viability of other dense gas and star formation tracers and deliver important follow-up work on the warm (e.g. C+), cold (e.g. atomic carbon), and molecular ISM (CO) as well as PDR (Photon Dominated Region) emission associated with molecular cloud formation and stellar feedback. Simulations by groups from Cologne, Heidelberg, and Garching/Munich have investigated different scenarios, e.g. the turbulent ISM, colliding flows, the impact of flow magnetization or the role of chemistry and cooling. The question if molecular clouds inherit their structure from gravitational collapse or supersonic turbulence is still hotly debated. The formation of individual stars themselves is the focus of several strong groups in Bonn, Cologne, Garching/Munich, Heidelberg, and Kiel, and ranges from low-mass to high-mass star formation at solar metallicity to the first stars in the early Universe.

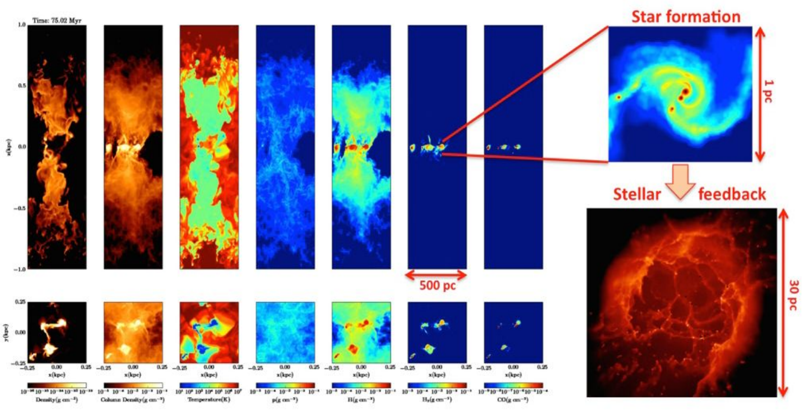

Figure 3: Energetic stellar feedback processes originate from small scales but affect the structure of the whole galaxy. Radiation, the associated radiation pressure, stellar winds, and supernovae heat and disperse the gas in molecular clouds and launch galactic outflows from the disk (credit: Walch, Cologne-U)

3.4 Impact of Highly Energetic Phenomena

The impact of energetic phenomena on the evolution of the multi-phase ISM and star formation has been studied by groups in Garching, Berlin, Bochum, Bonn, Cologne, Heidelberg and Potsdam. On galactic scales, the role of feedback by supernovae, stellar winds, ionizing radiation, radiation pressure, and cosmic rays for regulating the ISM structure and driving galactic outflows has been studied (see Fig. 3 for one example). On small scales within molecular clouds, the role of jets and outflows from young stars is investigated. Furthermore, concerning the efficiency of star formation as a function of halo mass, the picture emerged that AGN feedback dominates the evolution of massive galaxies, while supernova feedback is efficient enough to suppress star formation in dwarf galaxies. Further, groups in Germany also play a major role in developing the protostellar evolution, stellar wind, and supernova explosion models, which are the indispensable input to study the impact of these processes on their environment on larger scales. Multi-wavelength studies, combining data from the radio to the X-ray and gamma ray regime, are key to assess the impact of supernovae and cosmic rays but these are challenging.

3.5 Origin of the Initial Mass Function (IMF)

It seems that the correct shape of the present-day stellar initial mass function (IMF) can be reproduced if feedback physics (accretion/outflows/radiation) is included in star formation models as shown by researchers from Cologne and Garching/Munich. However, the universality of the IMF has been recently challenged. Observational studies have reported both, bottom-heavy (e.g. in elliptical galaxies) as well as top-heavy IMFs (at high redshift galaxies). This important ingredient for the interpretation of observational data at all redshifts needs to be further investigated.

3.6 Proto-stellar Disks

Protostellar disks have been observed already in the earliest phase in the formation of protostars. The first hints towards the presence of disks in deeply embedded envelopes and towards protostellar multiplicity of young stellar objects have strengthened the scenario of turbulent sub-structure in collapsing prestellar cores. In addition, the impact of magnetic fields during this evolutionary stage needs further theoretical and observational investigations. Disks around more evolved systems have recently been studied with ALMA. An impressive example is the resolved disk around HL Tau, which shows a number of cleared rings that could hint towards the presence of young planets. Groups in Bonn, Garching and Heidelberg have significantly contributed to an impressive gain in knowledge in particular via the IRAM PdBI Large Programmes CORE, SOLIS and W43 HERO on the observational side, while the theoretical effort has been mainly pursued by groups in Heidelberg, Kiel and Tübingen. One noteworthy example is the simulation of a protostellar disk that has been used as the posterchild for the expected ALMA capabilities for almost a decade.

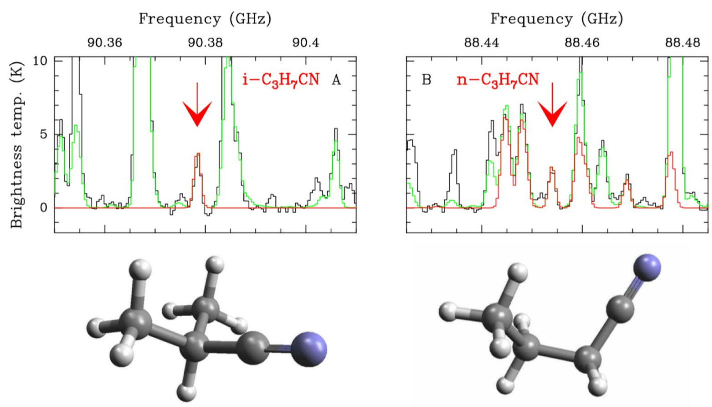

Figure 4: Prebiotic molecules detected with ALMA toward the star forming region Sgr B2(N) (credit: Belloche et al. 2014). The identification of the two molecules in the rich ALMA spectra was possible thanks to the laboratory work at the University of Cologne (red lines; Müller et al. 2011).

3.7 Microphysical Processes and Astrochemistry

The many detections of complex organic molecules with IRAM telescopes and the first detection of a branched-carbon chain molecule in star forming regions with ALMA led by researchers from Bonn have clearly shown that a rich prebiotic chemistry is present during star formation and was only possible via previous lab identification from the Cologne group (see Fig. 4). Moreover, the discovery of complex molecules, water, and hydrides in Galactic and extragalactic environments with Herschel, IRAM, ALMA, APEX, SOFIA, and their confirmation in the lab sheds new light on the chemistry cycle of the ISM. At the same time, this demonstrates how lab and space astrophysics go hand in hand to achieve an in-depth understanding of chemical gas ingredients. In this way, molecules can be used as powerful diagnostic tools of the ISM dynamical evolution. This world-leading effort is mainly done by research groups in Bonn, Cologne, Garching, Heidelberg, and Jena. The incorporation of small chemical networks in complex 3D simulations allows us to trace the history of the chemical composition and ionisation structure (crucial for magnetised clouds) on the fly, while complex networks are used in post-processing to understand the details of PDR emission and the abundances of more complex molecules, e.g. in pre- and protostellar envelopes as well as in protoplanetary disks. The development of such world-class chemical networks is pursued by researchers in Heidelberg and Garching.

4. Particular Role/Strengths of Research Groups in Germany

Research groups in Germany have been at the forefront of the research on the interstellar medium and star formation since decades. Over 200 researchers (counting only PhD students and higher levels) work at 20 institutes at universities and research institutes of the Max Planck Society and Leibniz Association (in the following marked by 'U' and 'I'). The high quality of ISM and star formation research is also evident from the award of nine ERC (European Research Council) research groups located at universities and research institutions in the past years. The exceptional international standing is possible thanks to the broadest possible bandwidth of complementary approaches: (1) Theoretical and numerical studies, (2) observational studies, (3) laboratory studies, and (4) the development of new instruments and observatories largely devoted to this research:

A. Theory and numerical simulations shed light on physical processes and the importance of their combined effect on structuring the ISM and the driving of turbulence, while observations are the key to constrain theoretical models and provide insight into the structure of the ISM and its dependence on galactic environment. These studies strongly benefit from national computer centers (in particular in Garching and Jülich) which operate some of the world's largest supercomputers.
B. Germany has some of the worldwide best laboratories where studies are performed to provide the necessary quantitative constraints for molecular and ionic reactions as well as transition frequencies and data on dust physics, which are essential for the physical and chemical description of the ISM and development of chemical network models.
C. There are various large, ambitious observational projects led by researchers in Germany, fully exploiting the access to world-class, state-of-the-art ground- and space-based telescopes. At the same time, instrument development for these telescopes has a long, highly successful tradition in Germany.

Moreover, it is the tight connection and resulting interaction between these different approaches that provides the basis for a continuous successful development of the ISM and star formation community. Collaborations are present on various levels among the different groups at universities and research institutes. For example, the still ongoing DFG Priority Programme 1573 "Physics of the Interstellar Medium" represents a national effort (a) to combine the expertise of researchers in Germany who work on different aspects of ISM physics, (b) to investigate observationally and

theoretically how various physical processes interact with one another and shape the ISM, and (c) to construct a new model of the dynamical, non-linear, multi-phase ISM. The previous DFG Priority Programme 1177 “Witnesses of Cosmic History: Formation and Evolution of BHs, Galaxies and their Environments” provided already a solid foundation for the high redshift aspects of ISM and star forming research in Germany. Another success story is the DFG Collaborative Research Center 956 “Conditions and Impact of Star Formation – Astrophysics, Instrumentation and Laboratory Research” between Cologne-U, Bonn-U and Bonn-I that contributes to our fundamental understanding of star-forming processes and establishes an international interdisciplinary scientific network. Here, observational astrophysics and laboratory astrophysics, instrumentation, modeling, and high-resolution magneto-hydrodynamic (MHD) simulations are applied to explore conditions and impact of star formation by looking at the physical, chemical and dynamic state of the interstellar medium. The Heidelberg institutes profit similarly from the DFG Collaborative Research Center 881 “The Milky Way System” and focus on matter cycling and related feedback loops.
An excellent basis for the world-class research is furthermore provided by the Max Planck Society with dedicated research groups at its Max Planck Institutes in Bonn (MPIfR), Garching (MPE, MPA), and Heidelberg (MPIA).

Another important aspect are the strong instrumentation groups located in Bonn, Cologne, Garching/Munich, and Heidelberg that have been leading the instrumentation for Herschel PACS, several APEX instruments, SOFIA GREAT as well as instrumentation for ESO telescopes. These groups have also significantly contributed to other state-of-the-art (sub-)mm/IR instruments on Herschel and, recently, JWST. Close involvement in new instrumentation is critical as it allows for designing instruments that address the needs and interests of the German observer community, as well as to be on the fore-front of technology development (see community papers on FIR/sub-mm/mm and space instrumentation).

Numerical astrophysics is a highly successful field in Germany. Teams of researchers from Bonn, Cologne, Garching/Munich, Heidelberg, Kiel, and Tübingen, carry out state-of-the-art, high-resolution, massively parallel simulations of galaxy formation with gas dynamics, ISM evolution, star formation, and stellar feedback. These simulations are a necessity to understand the complex, non-linear interplay of the physical processes which govern the evolution of the ISM in galaxies and the physics of star formation.
Therefore, it is a necessity to develop and improve the employed numerical tools and algorithms and make them fit for exascale computing. To maintain the German position at the forefront of computational astrophysics, these tasks require interdisciplinary and novel research in terms of, e.g., software development, parallelization, memory management. Major code development is for instance carried out at the HITS in Heidelberg, where modern particle-based and moving mesh codes like Gadget-3 and Arepo are developed (see the community paper on computational astrophysics for further information).

Laboratory astrophysics in Germany is active and internationally recognized since many decades (see community paper on laboratory astrophysics). In Cologne laboratories, high resolution spectroscopy is carried out at Terahertz (THz) frequencies and Infrared (IR) wavelengths and, via sophisticated molecular modelling, model spectra can be predicted over the entire frequency range accessible by current and future telescopes. The Cologne group is home of the Cologne Database for Molecular Spectroscopy (CDMS), the largest database for molecular spectroscopy worldwide. The Max Planck Institute for Nuclear Physics has pioneered many of the now established techniques for electron recombination measurements and provided numerous rate coefficients and branching ratios for astrochemical databases and models. The recently established group at the Max Planck Institute for Extraterrestrial Physics is focusing on molecular spectroscopy and interstellar ice analogous. The Laboratory Astrophysics Group in Jena is measuring spectral data and performing experimental studies and laboratory simulations of condensation and processing of dust and dust-related molecules in various astrophysical environments. The Jena groups have significantly contributed to the Heidelberg-Jena-St.Petersburg Database of Optical Constants for Cosmic Dust (HJPDOC), one of the most widely used database for cosmic dust. The laboratories at the TU Braunschweig and University of Duisburg/Essen investigate processes that lead to the formation of the first macroscopic solid bodies in protoplanetary disks, the first steps toward comets, asteroids, moons and planets - an emerging research field in the next decade (see the community paper on exoplanets and protoplanetary disks).

However, the groundwork for this success of the German ISM and star formation community is the training of the next generation of excellent researchers, i.e. via a solid education in astrophysics and by bringing students in first contact with the research on ISM and star formation at various German Universities. In alphabetic order, these are primarily research groups at the Universities of Berlin, Bochum, Bonn, Cologne, Hamburg, Hannover, Heidelberg, Jena, Kassel, Kiel, Munich, Potsdam, and Tübingen. The broad selection of approaches to study the ISM and star formation is also represented here, both in terms of topics (e.g., cosmic evolution, ISM cycle, star formation, feedback mechanisms, initial mass function, protostellar disks, and microphysics) as well as in terms of techniques (theoretical, numerical, observational, laboratory studies, instrumentation development). There exists a vivid exchange and collaborations between these groups and the larger-scale research groups at Max Planck Institutes.

5. Key Infrastructures needed/relevant for Researchers in Germany

ISM and star formation studies require a multi-wavelength approach to properly probe the various phases of the ISM and of the star formation process in order to build a coherent picture.
The high density and cold phase of clouds on the verge of star formation is best traced by millimeter, sub-millimeter, and radio telescopes. In particular, the IRAM 30m telescope and NOEMA (NOrthern Extended Millimeter Array) are crucial for our community, as they allow us to probe large and small scales, respectively, while simultaneously observing broad frequency bands, thus many molecular species and transitions from which physical parameters and chemical content can be deduced. ALMA (Atacama Large Millimeter/sub-mm Array) is the most sensitive (sub-)mm interferometer ever built and will be revolutionising the whole field of star formation and ISM by providing exceptional angular resolution and sensitivity. APEX (the Atacama Pathfinder EXperiment) is crucial for the exploration of large scale structures in our Galaxy (not possible to observe with ALMA) and finding the most extreme star forming galaxies in the universe. It also provides access to the highest frequency part of the sub-millimeter window, where transitions from simple species and light hydrides (i.e. the building blocks of astrochemistry) reside. The support of the German community via the German ARC node has been critical for the success of proposers from German institutes. A more powerful large single dish sub-mm telescope at/near the ALMA site is under discussion in all three ALMA partner regions for large synergy effects with the ALMA interferometer (with CCAT prime as a potential pathfinder facility). Access to such a facility will be important for the German ISM and star formation community.
SOFIA (the Stratospheric Observatory For Infrared Astronomy) is currently the only facility for the mid- to far-IR window, not accessible from the ground, giving access to important coolants such as the C^+ line at 158 micron and tracers of the various phases of the ISM, from atomic to molecular in our Galaxy. JWST (to be launched in 2018) will probe molecular Hydrogen emission directly as well as emission from small dust grain, important for understanding the star and planet formation process. Future radio facilities such as SKA (the Square Kilometer Array) and/or ngVLA (Next Generation Very Large Array) will revolutionize access to the mm-window (> 4mm) where we can probe the evolution of the interstellar medium at cosmic dawn and study in more detail the origin and evolution of chemical complexity.

More energetic regions of the interstellar medium, for example those in proximity of young stellar objects or nearby supernova remnants, require observations at significantly shorter wavelengths, from near-IR, optical, X-rays and gamma rays. For this portion of the spectrum, the state of the art instrumentation resides in the ESO facilities, in particular the Very Large Telescope in Paranal (Chile), the flagship facility for European ground based astronomy, consisting of four 8m telescopes and four movable 1.8m telescopes. These telescopes can work together in the form of an interferometer (VLTI), which allows astronomers to study detailed structure at different stages during the process of star and planet formation. In the future, the ELT (the European Extremely Large Telescope) will enormously advance our understanding of star formation and its links to protoplanetary disks and ultimately exoplanet atmospheres. In the highest energy part of the electromagnetic spectrum, facilities such as XMM and INTEGRAL have provided important clues on the stellar feedback, thus closing the cycle of the interstellar medium life and evolution.

The leading position of the German computational astrophysics efforts (see section 4) can only be sustained if the existing high-performance computing (HPC) landscape with its multi-layered structure of computing centers with different sizes is maintained. Smaller scale centers (like RRZK in Cologne) are needed to test and develop codes, while large-scale centers are needed for high-resolution production runs, as the efforts of developing state-of-the-art code that is able to efficiently use the continuously improving computing infrastructure (e.g. GPU instead of CPU) has increased significantly within the past 10 years. These efforts will probably rise even more towards exascale (-aware) HPC architectures. Therefore it is essential to establish a funding scheme that can support code/software development, which is possibly carried out by a computer scientist rather than an astrophysicist. This type of funding is not accessible through existing schemes (mostly DFG for computational/theoretical projects) but desperately needed to support the excellent, ongoing computing efforts.

As described in section 4, key laboratory facilities are those of the University of Cologne, the Max Planck Institute for Nuclear Physics and the Laboratory Astrophysics Group in Jena for their long-standing world-class activities in molecular spectroscopy, gas phase reaction kinetics and dust. Other key laboratories are those of: Kassel, where spectra of high temperature tracers (e.g. metal oxides and refractory elements containing species) and other short lived astrophysically important molecules are recorded with high precision and sub-Doppler resolution; TU Braunschweig and University of Duisburg/Essen, where processes investigated are those that lead to the formation of the first macroscopic solid bodies in protoplanetary disks, the first steps toward comets, asteroids, moons and planets; the Center for Astrochemical Studies (CAS) at the Max Planck Institute for extraterrestrial Physics in Garching, where high resolution spectra of astrophysically important molecules from small molecular ions and isotopologues to small organics are obtained, and where the physico-chemical processes in which they participate within icy grain mantles are studied. Precise spectroscopic information is provided in particular for the frequency range of current and future radio telescope facilities.

Maintaining the leading position reached in the various areas of star formation/interstellar medium research will be only possible if the community is provided the means to preserve and to further develop the achieved broad expertise and world-class infrastructure. This requires to offer the best students in this field a reliable perspective via attractive tenured positions, strengthen the retention of knowledge and expertise in long-term projects, especially true for future instrumentation and simulation efforts via tenure-track mid-level positions at universities as well as adequate funding lines that acknowledge the long-term (>5yr) nature of such initiatives. A prime example are the first generation instruments for the ELT that approach timelines of space projects. While very well functioning collaborative networks already exist in certain areas, e.g. laboratory astrophysics, it seems that for full exploitation of the unique expertise landscape in Germany dedicated funding schemes (operating over long-terms) besides the current DFG schemes will be necessary. Another aspect is the lack of a mechanism to contribute to the operation costs of observatories and/or telescopes operated outside of ESO. A possible candidate for the need to contribute to operations costs is the large sub-mm single dish telescope at the ALMA site that is under discussion in all three ALMA partner regions.

6. Summary and Conclusion

The German research community working on `Star Formation and Interstellar Medium’ has currently a very high international standing as demonstrated by the award of nine ERC groups at German institutes in the last years. This is the result of an exceptional combination of (privileged) access to state-of-the-art research facilities (including special support), high-level supercomputing and laboratory astrophysics as well as substantial support from dedicated funding programs from the DFG (incl. priority programs, collaborative research centers) in the past decade. In order to ensure that the excellent standing of the German research community is maintained over the next decade, we make the following recommendations:

1. Continue providing (preferred) access to existing and planned world-class observatories, namely, ESO facilities (ALMA incl. up-grades, ELT, APEX, VLT/I), ESA missions (JWST) and IRAM facilities (NOEMA full up-grade).
2. Revive/maintain access to the full (far-)IR window via SOFIA or similar facilities such as a large sub-mm single dish telescope at/near ALMA site.
3. Gain access to the wavelength regime beyond 3mm via future radio facilities such as, e.g. ngVLA and SKA.
4. Provide access to excellent supercomputing facilities (local medium-scale, large-scale computing centers).
5. Provide means to obtain critical fundamental data on physical/chemical reactions (laboratory astrophysics network, databases, new measurements)
6. Develop a sustainable path to maintain personnel level to keep world-class/leading position (currently large contributions from outside funding).
7. Retain and preserve knowledge and expertise; provide financial support for long-term initiatives and/or projects (incl. code development/maintenance, facility support, instrumentation) via, e.g., long-term (> 3-5yr) funding lines and tenure-track mid-level positions.
8. Strengthen further collaborative networks via dedicated funding schemes for full exploitation of unique expertise landscape in Germany.
9. Finance university contributions to operations costs.