Community paper „Laboratory Astrophysics of Molecular Systems and Dust“

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Executive summary

Light detected by telescopes carries information about matter from distant places in the universe. The physical conditions in the envelope of stars, in molecular clouds or the atmospheres of exoplanets are derived from these observations. In all cases the analysis is based on results of **laboratory experiments** and **theoretical models** which simulate the gas and dust in the respective astrophysical environment. This is the prime target of most observations. Therefore, the interpretation and understanding of astronomical observations becomes possible only in close collaboration with laboratory research. This research has a long tradition in Germany, and as a result many research groups are organized in the laboratory astrophysics community. In this paper the scientific background and the relevance of laboratory work for the interpretation of astronomical observations are outlined and some of the German laboratory astrophysics centers are introduced.

1. Introduction

The information provided by experimental research and extensive theoretical modelling comprises above all spectroscopic data on **atoms, molecules, dust** and **ices** present in the various environments. As an example in the life cycle of stars (Fig. 1) from diffuse through dense clouds to protostellar objects, stars and aging red giants various molecules are key tracers of this temporal evolution. The analysis of emission spectra of the corresponding molecules recorded with radio telescopes depends on the availability of laboratory spectra.

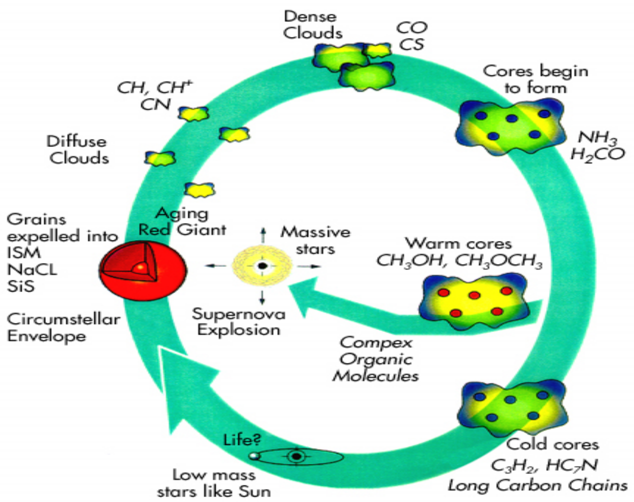

Figure 1: *The life cycle of stars depicted in this simple graph is accompanied by the presence of rather different molecules. Their identification is based on extensive laboratory spectra. These molecules are important tracers of the physical conditions such as temperature and density of the corresponding astrophysical environment. Their abundances are derived from the intensities of the observed emission lines. [http://herschel.jpl.nasa.gov]*

The great sensitivity of today’s telescopes like ALMA, NOEMA, IRAM 30 m, APEX or SOFIA provides astronomers with a tremendous amount of data at very high spectral and angular resolution. As a result broad band spectra at a resolution of better than 10^{-6} for hundreds of molecules at different temperatures are needed in order to exploit the exceptional wealth of the available astronomical data. Without the corresponding laboratory data valuable information from the very expensive telescopes is just thrown away. Therefore the success of astrophysics is tightly connected to the continuous development of laboratory astrophysics in order to match the observational needs.

Information on molecular spectroscopy is but one pressing example where the need of laboratory data is most obvious. Besides spectra of the most abundant molecules, these spectra need to be available as a function of temperature, for many isotopologues whose abundance in space is often vastly different from the terrestrial values. Therefore the remote spectroscopy of these species gives insight into the isotope abundances and potential chemical enrichment processes of certain isotopologues. This information is needed to unravel the chemical history of the various astrophysical environments. Laboratory spectra are also needed for vibrationally **excited species** as well as for **radicals** and **ions**. Therefore dedicated laboratory instruments are needed to prepare these **transient species** which are not abundant under typical conditions on Earth.

Most of the fundamental research in this field is funded by DFG as regular research projects. However, as explained exemplarily for molecular spectroscopy much more data is needed for astrophysical interpretation. Often measurement series are required to obtain complete data sets which are not important for fundamental research but urgently needed for comparison with astronomical observations. Therefore such **community service** and the compilation of the relevant data in **data bases** for astrophysical use has to be funded as **supporting science and infrastructure** of current astrophysics.

The prime laboratory data needed for astrophysical interpretation are the optical properties of atoms, molecules, dust and ices. For quantum systems this comprises **quantum numbers**, **transition frequencies**, **intensities (Einstein coefficients)** and **partition functions**. For dust grains the **refractive index (real and imaginary part)** over an extremely broad frequency range, as a function of elemental composition, phase (crystalline/amorphous), over a wide range of temperatures are recorded and tabulated. Besides the optical information, directly linked to observations additional information is needed to put observations into the dynamical context of the respective environment. Namely, the solid grains including **refractory and icy grains** are continuously processed by the interstellar and stellar irradiation fields, shocks, and thermal treatment. Consequently, the composition and structure of the grains and therefore their optical properties are continuously modified. The understanding of the **chemical and structural evolution of grains** in different astrophysical environments is essential for synthesizing relevant dust analog materials in the laboratories and for the interpretation of observational results.

For atoms and molecules in the gas phase **reaction networks** have to be considered which are important for the temporal evolution of interstellar matter. Thermal **rate coefficients** are the figures which describe the reactivity of the involved species. Reaction **cross sections** as a function of collision energy are even more fundamental data needed for specific reactions, in particular when reactions are taking place under non-thermal conditions. Of particular interest are product **branching ratios** in reactions, a quantity directly linked to the observed intensities of the species in question. Equally important but well overlooked and hard to determine experimentally are rate coefficients or cross sections of **inelastic processes**.

The parameter space for dust opacities and dust evolution is even larger. Dust and gas are coming together at the interfaces where often **condensation** and **evaporation** have to be considered in detail. The efficient formation of **refractory silicate** and **carbonaceous material** in the icy mantles of interstellar dust grains has already been verified by laboratory studies but we are still far from a complete understanding of the interstellar dust formation. Moreover, the UV- and ion-induced erosion of dust at the interface between dust and molecular ice destroys interstellar grains but the additionally formed molecules can change the composition of the ice and participate in the chemical evolution of complex organic compounds. In addition, **molecular ices** and their complex organic chemistry play a crucial role in interstellar, protoplanetary, and planetary environments and has to be extensively investigated in the laboratory. The **catalytic role of dust surfaces** is still completely unknown and has to be addresses in upcoming laboratory studies.

Besides the strong activities to provide experimental data for most conditions prevailing in space, some conditions such as those in the atmospheres of stars are hard to meet in experiments. Most challenging tasks are the predictions of spectra of a) rare isotope enriched molecules found in stellar atmospheres and stellar mergers, b) high temperature molecular tracers in excited ro-vibronic states and c) strong non-linear Zeeman-splitting, probing conditions of stellar magnetospheres. For most of these cases present in astrophysical environments the standard approach of a rigid rotor Hamiltonian and the separation of fundamental vibration modes fails. Therefore the laboratory activities are accompanied by extensive **theoretical investigations** which allow to fill the gap between observational data and the available laboratory data. Most relevant are a) isotope invariant Dunham treatments, b) full nuclear kinetic energy approaches on semi-experimental potential energy surfaces (TROVE) and c) higher order magnetic coupling interactions treated by coupled-cluster calculations. It is the interplay of precise laboratory data and parametrized *ab initio* methods that allows to interpret the spectra of the extreme astrophysical environments and to reveal the prevailing physical conditions in all detail.

In addition, the wealth of observational data has to be matched by sophisticated analysis methods which make a link between e.g. the spectral and spatial information of astronomical observations. The development of these infrastructural tools is recognized as a separate branch of a technical infrastructure for the interpretation of astrophysics and is discussed in another chapter of this community paper. However, also the core fundamental laboratory data as described above has to be compiled in **data bases** in order to bring together all necessary information in one place for the respective use in astrophysical analysis tools. This is already going on for a long time and many achievements in astrophysics (see below) are based on the long time commitment on data bases by some laboratories.

2. Upcoming Facilities in the Coming Decade

Like astrophysics as a whole, laboratory astrophysics is driven by new technologies or the further development of existing instruments which pave the way for new data, let it be new systems which could not be studied before or instrumentation which provides higher quality and/or quantity data. Based on the existing working groups organized in the German community of laboratory astrophysics (see below) there are also emerging groups of young scientists who are going to establish new technologies. Together we open the door to new facilities which provide data for the analysis of current and future astronomical facilities. Below we briefly describe upcoming laboratory facilities dedicated for the service in laboratory astrophysics. When laboratory astrophysics topics are directly linked to existing and upcoming observational facilities they are mentioned in brackets.

THz spectroscopy (ALMA, NOEMA, IRAM30m, APEX, SOFIA)

Broad band absorption and emission spectrometers are available in several laboratories in the German community. They are the basis of molecular spectroscopy provided in the data bases and widely used by the astrophysics community. In the coming decade these laboratory instruments will be largely improved by increasing the scanning speed thanks to broad band capabilities based on an equivalent development of fast electronics. The best example in this respect is the development of chirped pulse spectroscopy which allows creating a macroscopic polarization of a molecular probe similar to NMR but now at much higher frequencies addressing molecular rotation. Based on this advancement broad band THz spectra of several GHz width can be recorded “at once”. In fact, this technology currently revolutionizes the field of molecular spectroscopy. The quantity of data will increase dramatically and match much better the needs of astrophysical observations. It can be foreseen that complicated model descriptions for abundant molecules can be ignored since sufficient laboratory data will be available. In the coming years higher and higher frequencies will be accessible. As a consequence the spectral coverage of modern telescopes such as ALMA will become available in corresponding laboratory experiments. In particular many of the unstable or transient species present in space can be studied and discovered on the basis of these developments.

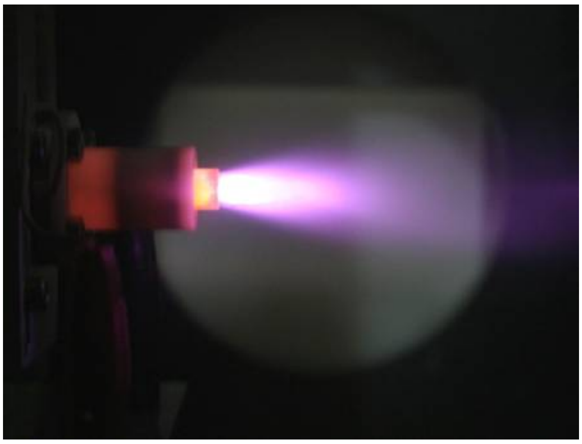

Figure 2: *Production of short lived (transient) molecules by electrical discharge in an adiabatically expanding gas (University Kassel). Light is emitted from electronically excited states of the newly formed molecules in the supersonic jet. Here they are subject to advanced spectroscopy studies in the IR and FIR range, most relevant for the interpretation of observations of the upcoming telescopes. This detailed tool is part of expensive dedicated laboratory instruments.*

Based on the short time excitation of the chirped pulse instrumentation also molecular dynamics information will become available. It has already been demonstrated that the kinetics of inelastic processes can be studied in these instruments. Therefore also new data missing for today's interpretation of astronomical observations will become available. Many more experiments including double resonance excitation or experiments using the benefit of coherent excitation will lead to new prospects of molecular spectroscopy which are not fully explored today.

IR Spectroscopy (JWST, ELT, SOFIA)

New telescope facilities like the James Webb Space Telescope (JWST), the European Extremely Large Telescope (E-ELT) Project, and the Stratospheric Observatory for Infrared Astronomy (SOFIA) will open the sky for high resolution IR-Astronomy relevant for the evaluation of the **gas phase species** in space. Especially the search for Earth-like exo-planets will make use of high resolution instruments in the near- and mid-IR region, e.g. ELT-HIRES (Cero Panal/Chile), EXES (SOFIA), TEXES (Gemini/Hawaii) and CARMENES (Calar Alto /Spain). Only recently the HARPS 1.5µm-laser frequency comb has started operation on the ESO 3.6m-telescope at the La Silla Observatory in Chile in order to find Earth-like exo-planets. For all these new instruments precise laboratory data in the near- and mid-IR are highly on demand. In particular the search for Earth-like planets relies on Doppler-shifted line positions of the order of 1 m/s which corresponds to a frequency accuracy $\Delta\nu/\nu$ of better than 10^{-10}. In order to deliver accurate laboratory data the requested instrumental accuracy needs to be better than 1 kHz, which can be achieved by frequency-comb locked spectrometers which become available in Cologne, Kassel and probably more laboratories over the next decade.

The birth and early evolution of stars from the infall onto dust-enshrouded protostars up to the formation of protoplanetary systems will be studied with JWST and ELT. Therefore these instruments are related to the **condensed phase** component of interstellar material. Other important topics are how stellar winds and ionizing radiation affect the evolution of solids and nearby star formation and how planetoids and planets are formed out of **dust grains** in planetary systems. The mid-IR spectrometer MIRI at the JWST covers a wavelength range of 5 to 28 µm. The IR spectrometer will enable medium-resolution spectroscopy but can achieve a high spatial resolution in astronomical objects. NOEMA (IRAM PdB Interferometer) will be the most advanced facility for millimeter radio astronomy in the Northern Hemisphere. Its spatial resolution and high sensitivity make NOEMA a unique instrument to explore dust and molecules in astrophysical environments. To interpret and relate these observational results to the processing of **cosmic dust**, **interstellar ices**, and astrophysically relevant **molecules** in dense clouds, during the infall and recondensation of dust around young protostars, and in planetary systems, simultaneous experiments in the laboratory are required. A dedicated solid state processing and spectroscopy instrument is currently being built in Jena.

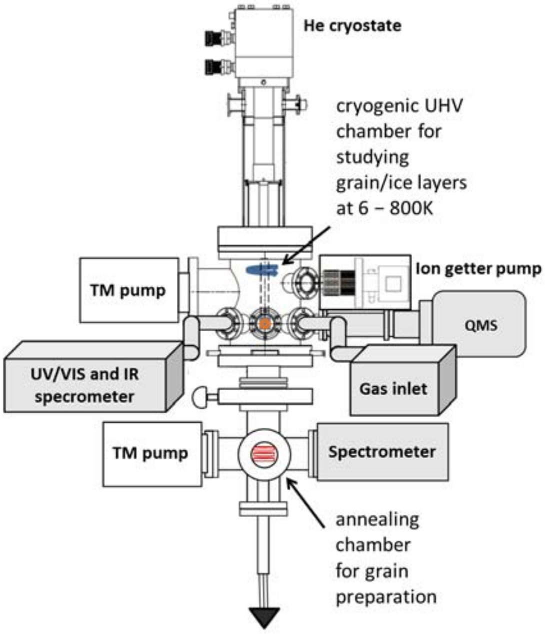

Figure 3: *Ultra-high vacuum dust simulation chamber built in Jena to study the chemical evolution of dust and ice at temperatures ranging from 10 to a few hundred Kelvin. UV/VIS, IR and THz spectroscopy, high-resolution mass spectrometry are dedicated tools (among others) to analyze the reaction products.*

Traps

Ion traps are used to study ion molecule reactions as a function of temperature in great detail. Although the method is well established only a rather limited set of reactions has been studied today, since the number of groups operating these rather sophisticated instruments is small. In particular reactions at higher temperatures are completely missing. Therefore, even with the existing instrumentation there are strong needs from astrophysics. More recently ion traps are also used for spectroscopy of molecular ions. Mass selection, the confinement of the molecules in question and the development of new methods of spectroscopy led to an increase in sensitivity by many orders of magnitude. Therefore the spectroscopy of many highly abundant molecular ions in space can be studied for the first time. An example for the advancement of this field in view of astrophysical interpretation will be discussed in the achievement section below.

Collisional Cells and Molecular Jets

While ions can be stored in electrical and magnetic fields, it is much harder to store neutral species. The slowing and trapping of neutral molecules is an exciting new field of molecular physics. Groups in the German community are active in this field. New experiments similar to the ion trap experiments will become available. It remains to be seen how valuable collisions at ultra-low temperatures are for the interpretation of astrophysical observations. However, on the way to store molecules they are cooled by collisions. In a thermal environment this can be a perfect simulator of interstellar conditions and therefore experiments conducted in collisional cells have the potential to provide similar data for neutral species as do traps for ionic species, including molecular spectroscopy. More common place are spectroscopic studies in molecular free jets which prepare a sample of cold molecules. The suit of different technologies focusing on the production of cold and often transient molecules will lead to the discovery of many new molecules which tell us about the very different and sometimes extreme conditions prevailing in space.

Cryogenic Storage Ring (CSR)

Modern databases on interstellar chemistry contain thousands of reactions, linking hundreds of atoms and molecules. The majority of the processes that are listed concern collisions between charged species – atomic and molecular ions – and neutral collision partners. These reactions are of outstanding importance for interstellar gas phase chemistry due to their high rate coefficients and the absence of activation barriers, which renders them particularly efficient even at low temperatures and low densities. The destructive counterpart of ion-neutral reactions is the dissociative electron recombination (DR), which limits the build-

up of larger and larger ionic species by disrupting the reaction chains and producing neutral fragments. DR rate coefficients and branching ratios of key molecular species are needed for reliable models of interstellar clouds.
Most of the reactions in the databases have not been studied in the laboratory, and if experimental data exist, they often have to be extrapolated to low temperatures and densities as the experiments were carried out in room temperature environments. To provide energy-resolved rate coefficients for the formation and destruction of interstellar molecules is one of the main goals of the Cryogenic Storage Ring (CSR) project at the Max-Planck-Institut für Kernphysik in Heidelberg.

Figure 4: *The Heidelberg CSR is the largest electrostatic storage ring project in the world. It has a circumference of 35.1m and a nested cryogenic vacuum structure. The electrostatic deflection makes it a very versatile instrument for molecular physics, as it does not impose any mass limit on singly charged ions (in stark contrast to magnetic storage rings). In the first commissioning phase in 2015, the inner experimental vacuum chambers reached a pressure better than 10^{-14} mbar and temperatures of 5 K.*

The CSR will be equipped with an electron cooler that will make it possible for the first time to study the important DR process in a cryogenic storage device. Branching ratios resulting from the DR process will be recorded using state of the art detectors, including micro-calorimeters and multi-channel plates. Furthermore, a novel setup to couple neutral atomic beams into the CSR is under development. With this setup it will be possible to study reactions between cold, stored molecular ions in specific quantum states with ground state atoms. This class of processes is of paramount importance for molecular astrophysics, but it is notoriously difficult to study under controlled conditions in the laboratory, because both reactants are difficult to prepare. In summary, the CSR will provide a unique, ideal testbed for experimental studies of gas phase reactions under true interstellar conditions.

3. Main Achievements in the Past Decade

Biomolecules in Space: Complex Organic Molecules

Complex organic molecules (COMs) are important tracers of the chemical development in various astrophysical environments. Key questions for the coming years are *how are they formed in space* or *how large can they grow* under the extreme conditions (density, temperature, radiation field etc.). One interesting simple question would be whether COMs can be as large as **biomolecules**.

Amino acids are building blocks of proteins and therefore key ingredients for the origin of life. The simplest amino acid, glycine (NH_2CH_2COOH), has long been searched for in the interstellar medium but has not been unambiguously detected so far. At the same time, more and more complex molecules have been newly found toward the prolific Galactic center source Sagittarius B2 and many other sources. Since the search for glycine has turned out to be extremely difficult, detecting a chemically related species, possibly a direct precursor, amino acetonitrile (NH_2CH_2CN) was aimed for in an IRAM 30 m telescope line survey. The emission arises from a known hot core, the Large Molecule Heimat. The high abundance and temperature of this molecule could only be derived on the basis of extensive laboratory data on this particular molecule and the myriad of other molecules which also appear in the survey. Based on the amino acetonitrile detection the column density of glycine could be reliably predicted and probably is below the confusion limit in the 1-3 mm range.

Molecules as Chemical Clocks

Hydrogen, H_2, is the most abundant molecule in space but it cannot be observed by radio telescopes since the molecule does not have a dipole moment. Hydrogen is formed on grains when two H atoms scan the surface and meet. The resulting hydrogen molecule comes in two nuclear spin configurations (ortho and para) in a statistical ratio 3:1. This value for the ortho to para ratio (o/p ratio) is far from the thermal equilibrium value for most interstellar conditions, in particular in the pre-stellar and proto-stellar phase when the gas and dust can be as cold as 10 K. Due to chemical reactions of the hydrogen when it is released from the grain the o/p ratio drops gradually from 3/1 to very small values. Based on laboratory experiments the o/p ratio of hydrogen has been related to the observable H_2D^+ molecule. Once the lowest rotational transitions of this molecule had been determined in the laboratory, observations with APEX and SOFIA have been used to determine the o/p ratio of H_2D^+ and H_2 for the first time. Based on these observations it became clear that the formation of the protostellar environment in the dense cloud core IRAS 16293-2422 A/B took at least 1 million years. This time scale turns out to be much longer than the respective free fall time. This example shows that based on extensive laboratory data (spectroscopy and collisions) molecular abundances from observations can be used as a **chemical clock**.

Data Bases: CDMS and VADMC

Worldwide, the results of THz spectroscopic research are archived mainly in two databases one of which is maintained at NASA's Jet Propulsion Laboratory (http:// http://spec.jpl.nasa.gov) and the other one being the Cologne Database for Molecular Spectroscopy (CDMS) hosted by the Köln group. The CDMS is the largest repository of this information publically available. Much of the experimental data stored in CDMS has been conducted in the Cologne laboratories but many entries are also based on data obtained elsewhere. About ten groups in the world are actively working in the development of laboratory high-resolution spectroscopy at THz frequencies. The THz window became routinely available only after technical challenges had been mastered over the last 10-20 years. Still, viewed from the outside the scientific advancement in this field often appears rather slow which is associated mainly with one fundamental challenge: The richness of THz spectra. While this circumstance ultimately leads to very detailed information about each molecule, the analysis of the spectral richness often may take much longer than the actual experiment. Only because of the long lasting engagement in analyzing the laboratory data and the continuous feeding of the data bases with high-quality data from a tedious evaluation process after almost 20 years the essential data is publically available to analyze the rich spectra from broad band observations obtained from the latest (and very expensive) generation of telescopes like the Herschel satellite (http://www.esa.int/Our_Activities/Space_Science/Herschel), the Atacama Large Millimeter Array (ALMA, http://www.eso.org/sci/facilities/alma.html) and the stratospheric observatory for far-infrared astronomy (SOFIA, http://www.sofia.usra.edu), just to name a few.

In fact many sophisticated computer programs use automated access to the wealth of the catalogues. The further development of the data input and the infrastructure are community services essential for the analysis of radio observations. Based on an international effort the rich data in the CDMS and JPL catalogues are combined with other atomic and molecular information within the framework of the virtual atomic and molecular data center (VAMDC). Over many years a common scheme to store the data has been defined and the participating databases have been transformed into the new common platform. Not only the richness of data is increased, also interoperability among the different data bases is guaranteed. This will allow the combined analysis of more complex observational situations. This infrastructure is made available via new software tools which are the subject of another community paper.

Dust as a tracer for physical conditions and Data bases for optical constants

Spectral properties of major dust components in a broad wavelength range and temperature dependent optical data coupled with an expanding understanding of **condensation and processing of dust** and of astrophysically relevant molecules are the main achievements for the Laboratory Groups working on dust and condensed matter. This is clearly documented in the successful assembly and extension of the Heidelberg - Jena - St.Petersburg - Database of Optical Constants for Cosmic Dust (HJPDOC) that is frequently used for the identification of cosmic dust components in different astrophysical environments.

Herschel PACS spectra revealed the existence of a FIR emission band at 69 µm of crystalline forsterite in disks associated with Herbig Ae/Be stars. The feature analysed in terms of position and shape to derive the temperature and composition of the dust by comparison to laboratory spectra demonstrated that most of the forsterite grains are found to be warm (~100–200 K) and iron-poor (less than ~2% iron). Important constraints were placed on the spatial distribution of the mineral in the disk and the formation history of the crystalline grains, which supports an equilibrium condensation process at high temperatures.

The Mid-Infrared Interferometric Instrument (MIDI) at the VLTI was used for spatially resolved detections and compositional analyses of the building blocks in the innermost two astronomical units of three protoplanetary disks. The observations were fitted using laboratory measurements of dominant species. From the observations, strong evidence for a crystallization process during the active-disk phase before planet formation was found.

4. Particular Role/Strengths of Research Groups in Germany

Laboratory astrophysics has been an active part of German astrophysics for many decades. A number of concerted DFG funding activities - in particular priority programs over the past 20 years led – to a high degree of self-organisation among the participating groups. Below is a list of laboratories which participate in the German laboratory astrophysics community. The groups listed below, each specializing in complementary fields of research are all world re-knowned experts, providing particular data necessary for the interpretation of astronomical observations. This community is taking a leading role on the European (EU Marie-Curie training programs) and international level. This becomes most obvious for the data base activities where German contributions are taking a world lead as well in quality as quantity of the data provided for astrophysics.

Köln

The Köln laboratories specialize in molecular spectroscopy and astrochemistry. High resolution spectroscopy is carried out at Terahertz (THz) frequencies and Infrared (IR) wavelengths. Experimental data is accompanied by sophisticated molecular modelling which allows to predict molecular spectra (transition frequencies, intensities) over the entire frequency range available in present and future telescopes, observed under the vastly different conditions (temperature, density) prevailing in space. Ion molecule reactions are studied in detail in ion trap experiments as a function of temperature. The development of the light induced reaction (LIR) technique leads to unprecedented spectroscopy of molecular ions with respect to sensitivity and spectral resolution. The Köln group is home of the Cologne Data Base for Molecular Spectroscopy (CDMS), the largest data base for molecular spectroscopy world-wide.

Kassel

The spectrometers available at Kassel cover to a large extend the THz- and IR-frequency range relevant to current world wide telescopes. Molecule specific spectra of high temperature tracers (e.g. metal oxides and refractory elements containing species) can be recorded with high precision and sub-Doppler resolution. A wide range of reactive short lived astrophysical molecules and their isotopologs can be produced using laser ablation and electrical discharge techniques combined with adiabatically cooled supersonic jets. All spectral data are recorded at highest frequency accuracy and spectral resolution revealing fine- and hyperfine splitting. State of the art molecular modelling is used to derive accurate line lists for the detection of new interstellar molecules which are made available via the CDMS data base. Most relevant recent instrumental developments include frequency-comb stabilized IR-spectrometers, chirped pulse THz-radiation sources and cavity-ring down enhanced detection schemes.

Garching

A new laboratory has been set up by the Center for Astrochemical Studies (CAS) at the MPE in Garching specialized on molecular spectroscopy and astrochemistry. The primary objectives are to study high resolution spectra of astrophysically important molecules from small molecules, in particular ions and isotopologues, to small organics, and to improve our understanding of the physico-chemical processes in which they participate within icy grain mantles. Precise spectroscopic information based on the laboratory data is provided in particular for the frequency range of current and future radio telescope facilities. Several spectrometers are currently set up covering the wavelength regime from centimetre to infrared wavelengths, for studying molecules both in the gas and in solid phase, to investigate molecular de-excitation processes and to study the spectroscopic properties of ice samples at cryogenic temperatures.

Heidelberg

The atomic and molecular physics groups at the Max-Planck-Institut für Kernphysik have been operating at the forefront of the heavy ion storage ring community for years. Using the magnetic Test Storage Ring (1989-2012) and the new Cryogenic Storage Ring (first cryogenic operation in 2015), the groups at MPIK have pioneered many of the now established techniques for electron recombination measurements and provided numerous rate coefficients and branching ratios for astrochemical databases and models. Once the CSR is fully operational - including the electron cooler and neutral beamline - it will be a unique instrument for state-selected studies of astrophysical processes. Besides the storage ring activities, the group is actively pursuing spectroscopy in ion traps, in particular developing a novel approach to observe mid-IR emission of large molecules for comparison to astronomical observations.

Jena

The Laboratory Astrophysics Group in Jena is focused on measuring the spectral data and performing experimental studies and laboratory simulations of condensation and processing of dust and dust-related molecules in various astrophysical environments comprising hot circumstellar environments, cold and dense interstellar clouds, protostellar cores, and young protoplanetary systems. To study the processing of dust and ice and the corresponding spectral properties of the materials, dedicated devices were developed. UV/VIS, IR, and THz spectroscopy were used to measure spectral properties and monitor the chemical evolution. Dust condensation at very low temperature, erosion of dust at the interface between grains and ice, and chemistry in ice layers are the most recent topics studied in this group. The Jena groups have essentially contributed to the Heidelberg - Jena - St.Petersburg - Database of Optical Constants for Cosmic Dust (HJPDOC), one of the most widely used data base for cosmic dust.

Braunschweig / Duisburg

The laboratories at the TU Braunschweig and University of Duisburg/Essen investigates processes that lead to the formation of the first macroscopic solid bodies in protoplanetary disks. Working with dust and ice particles, collision and agglomeration processes are studied in the laboratory's own mini drop towers or using any of the available microgravity facilities (drop tower, parabolic flights, suborbital rockets). Moreover, the physical properties of macroscopic aggregates consisting of (sub-)µm sized dust or ice particles, such as their strengths, are being investigated. The laboratories also deal with measurements of heat conductivity and gas permeability of porous bodies, with applications to planetesimals, asteroidal surfaces and comets. Thermophysical models of primitive Solar System bodies have been developed at TU Braunschweig. In the framework of debris disks, the TU Braunschweig laboratory is operating a powder gun for impact studies with velocities up to 2 km/s.

5. Dominant Science Cases

Based on the present expertise the groups organized in the German laboratory astrophysics community are already prepared to provide data urgently needed for the following astrophysical topics

Star and Planetformation:

- Molecular Astrophysics (High-resolution THz spectroscopy)
- Astrochemistry (Gas Phase, solid state chemistry)
- Early Universe (Formation of the first stars)
- Grain Grain interaction (From grains to rocks to planetesimals)

Exoplanets:

- Infrared Spectroscopy (spectral signatures of exoplanet atmospheres)

6. Summary and Conclusion

Laboratory research is an essential part of today's astrophysics. In addition to the fundamental science where interstellar matter is studied under the extreme conditions prevailing in space, extensive measurement series are conducted to supply the astronomers with the relevant data to analyze and interpret their observations. Specialized instruments are built by the laboratory astrophysics community. In order to meet the astrophysical needs of the coming decade particular funding is needed for setting up **state-of-the-art laboratory techniques**, conducting the **community service measurements** and building the mandatory **infrastructures** such as data bases and computer tools. Laboratory spectra and reaction rate coefficients allow us to decipher the wealth of observational data that modern telescopes provide and transform them into true understanding of astronomical environments. To make the best use of the latest generation of telescopes and to facilitate accurate predictions for future missions and instruments laboratory research is an indispensable part of astrophysics, and it needs to be fostered and supported as such.