Proposal to establish a DFG priority program

Physics of the Interstellar Medium

Figure 1: *This figure shows the star forming region NGC 602 in the Large Magellanic Cloud. Potsdam University leads a large observational program with the* **Chandra** *X-ray satellite to study this star-forming region*

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Total duration of funding: 2 $\times$ 3 years

Program Committee

Prof. Andreas Burkert (Coordinator, University of Munich)
Prof. Ralf Klessen (Vice-Coordinator, University of Heidelberg)
Prof. Thomas Henning (MPIA, Heidelberg)
Dr. Cornelia Jäger (University of Jena)
Prof. Karl Menten (MPIfR, Bonn)
Prof. Sebastian Wolf (University of Kiel)

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1 Summary

Interstellar space is filled with a dilute mixture of charged particles, atoms, molecules and dust grains, called the interstellar medium (**ISM**). The average particle density of the ISM is 1 cm^{-3} which represents a density lower than can be created on Earth. The ISM therefore represents a fascinating laboratory to study the physics of highly attenuated gases, chemical processes and atomic, molecular and solid state physics under extreme conditions and numerous other questions of natural sciences. The physics of the ISM plays a crucial role in many areas of astronomy. Galaxy formation and evolution, the formation of stars, cosmic nucleosynthesis, the origin of large complex, prebiotic molecules and the abundance, structure and growth of dust grains which constitute the fundamental building blocks of planets, all these processes are intimately coupled to the physics of the ISM. However, despite its importance, its structure and evolution is still poorly understood.

The situation is however improving rapidly. New observations with powerful telescopes have revealed that the ISM is a turbulent, multiphase gas, filled with structures on all resolvable spatial scales. This has lead to a paradigm shift in our understanding of the ISM, where the old equilibrium model is being replaced by a highly dynamical picture of strongly coupled, interacting and turbulently mixed gas phases that are far from equilibrium and that are continuously stirred by processes that are not well understood. This insight has attracted enormous interest in the astronomical community as it raises the possibility that we currently witness the era where enough information is available to gain for the first time a **comprehensive physical understanding of the ISM** that will be useful for many fields in astronomy.

This proposal suggests to establish a DFG priority program on the **physics of the interstellar medium**. German astronomers have traditionally played a strong and leading role in this field. However, with ISM physics becoming a major astrophysical focus worldwide, strong centers of ISM research have been created e.g. in the US (Harvard, Berkeley, Princeton, Michigan), the UK (St. Andrews, Exeter, Cambridge, Cardiff), France (Paris), Japan (Mitaka) and China (Bejing and Nanjing). This represents a strong competition for German astrophysics, as science on the ISM in Germany is currently very fragmented with little coordination and interaction between different research groups. Still we are in a very good position to remain key players if we coordinate our activities and efficiently use the enormous resources that are available to us in a concerted effort. Germany has some of the worldwide best laboratories on investigating dust and molecule physics under ISM conditions. Germany's computer centers operate some of the worldwide largest supercomputers where astrophysicists run some of the most sophisticated simulations of the ISM. German astronomers are involved and lead ambitious observational projects on the largest telescopes, like the recently launched infrared space observatory **Herschel**. In order to keep a leading role in this exciting and timely field and to take full advantage of the available resources it is essential to coordinate our research activities and combine Germany's unique expertise in a common priority program.

Two **funding periods** are proposed. Within the **first three years** we will investigate observationally and theoretically how different processes in the ISM that up to now have been studied in isolation interact and shape the ISM. Laboratory work will provide the basic data for chemical reactions and dust physics. During the **second funding period** the first observational results with the largest and most sensitive instrument in the world at millimeter and submillimeter wavelengths, the Atacama Large Millimeter Array **ALMA** will begin to revolutionize high-resolution imaging and will open a new window on the physics of the cold Universe. The expertise gained within the first funding period will then be essential in order to interprete these new observations that will reveal the full multi-scale complexity of the ISM from local galaxies to young protogalaxies at high cosmological redshifts.

2 Scientific Program

2.1 A Window of Opportunity: Towards a Consistent Model of the Dynamical, Multi-Phase Interstellar Medium

The ambitious scientific goal of this priority program is to develop a comprehensive physical understanding of the multi-phase ISM that provides a solid basis for other fields of astrophysics. Early investigations of the ISM were based on a two-phase equilibrium model. Field[29] noted that for typical gas pressures in the Milky Way the atomic gas would spontaneously segregate into a diffuse, warm and a dense, cold phase, with both components in thermal equilibrium between heating and cooling. The final state of this cooling instability would be a system of cold, dense gas clouds (cold neutral medium), embedded and in pressure equilibrium with a warm, diffuse intercloud medium (warm neutral medium)[14]. This "two-phase" model has later on been extended by adding a third, hot phase that is produced by supernova explosions[52].

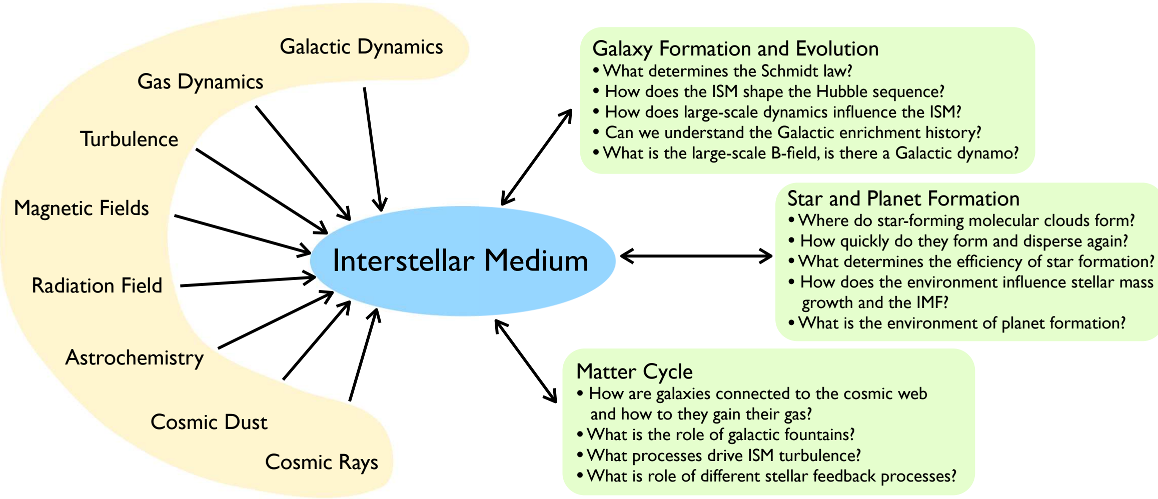
In the last decade, this scenario of several discrete gas phases in thermal and pressure balance has been challenged by new observations[34] that found significant amounts of gas in the forbidden and unstable temperature regime of 300K $<$ T $<$ 5000K. Classical gas phases are characterized by quiescent regions throughout which physical properties like the density or temperature are essentially uniform. Phase transitions are restricted to boundaries that separate gas regions with different thermodynamical properties. Observations, e.g. by the **Spitzer** satellite instead show a highly dynamic ISM with a multi-scale, clumpy, filamentary and even fractal density and velocity structure that is generally believed to result from multi-scale irregular gas motions, termed **interstellar turbulence**. Interstellar turbulence stirs the traditional, optically thin neutral gas phases into a nonlinear mixture of interacting gas components with strong departures from thermal equilibrium. This **paradigm shift** has been a major break-through that attracted enormous interest and that made ISM physics a major astrophysical research topic, not only in Germany but worldwide.

Recently, tremendous progress has been made in identifying the various processes that shape the ISM. It has become clear that its non-linear dynamics and multi-scale structure requires coupling magneto-hydrodynamics with chemical networks that include dust physics, gas phase transitions, and thermodynamical heating and cooling processes, as well as star formation and stellar feedback. All of these processes have to be studied taking into account the appropriate initial and boundary conditions, provided by the specific galactic environment under investigation. In addition, the stellar component and the ISM are strongly linked. Supernova explosions of massive stars generate large-scale shocks in the ISM that collect gas and form dense, optically thick molecular clouds. The clouds become gravitationally unstable, collapse and condense into the next generation of stars that inherit the dynamical and chemical properties of the ISM inside which they formed. At the end of their short life, the massive stars explode again as supernovae that chemically enrich the ISM with heavy elements and that produce new expanding shells that drive large-scale interstellar gas dynamics and that sweep up new molecular clouds. Dust grains, the dominant catalyzers for molecular hydrogen formation and the basic building blocks of planets form in the atmospheres of low- and intermediate-mass stars from gas that had been enriched with heavy elements, ejected by previous generations of supernovae. This continuous nonlinear interaction between stars and the ISM is the key to understand the morphological structure and the star formation history of galaxies, their chemical and dust enrichment and by this ultimately the formation of planetary systems and our own origin.

The **purpose of this priority program** is to combine the expertise of researchers in Germany that work on different aspects of ISM physics, The **goal** is to combine observations with our knowledge about the various fundamental key processes that affect the ISM on different scales and to gain a comprehensive understanding and construct a new model of the dynamical, non-linear, multi-phase ISM that goes beyond the old-fashioned description. This ISM model will provide the basis for many areas of modern astronomy and astrophysics as illustrated in Figure **??**. The timing is perfect for such a joint effort. The most important physical processes that affect the ISM have probably by now been identified and can now be studied in detail. Dust growth- and destruction rates as well as chemical reactions in the ISM can now be analyzed on Earth with specially designed laboratory experiments. The field of computational astrophysics has seen enormous progress with the development of powerful, parallelized numerical algorithms to investigate time-dependent, multi-scale astrophysical processes on large supercomputers. Finally, a new generation of telescopes and instruments provides observational multi-wavelength data with unprecedented resolution and detail.

The activities in this priority program are based on three complementary pillars of research.

- **Laboratory studies related to the evolution of the ISM:** Research in this area will provide basic data of molecular and ionic reactions as well as transition frequencies and data on dust physics, required for the physical and chemical description of the ISM.



- **Observations** are the key to constrain theoretical models and give insight into the structure of the ISM and its dependence on galactic environment.
- **Theory and numerical simulations of the ISM:** Various physical ISM processes and especially their coupling are poorly understood and need to be investigated in greater detail. Numerical simulations will determine the spatial density structure and the dynamics of the multi-phase ISM, allowing a detailed comparison with observations.

2.2 Research Status: Key Processes in the ISM

Many processes in the ISM have been studied in isolation and under idealized conditions. It is however their nonlinear coupling that fully characterizes the structure and evolution of the multi-phase, dynamically evolving ISM. This section summarizes our current insight into key questions of ISM physics and discusses important problems that should be investigated within this priority program. The science presented in this section also demonstrates the enormous expertise of German astronomers in this field. Note that the processes discussed here always have to be studied within the context of the galactic environment that provides initial and boundary conditions.

2.2.1 Which are the drivers of turbulence in the ISM and how does turbulence affect the morphology and the energy of the ISM on different scales?

Despite their paramount importance, the physical origin of the irregular gas motions that stir the multi-phase ISM and their detailed statistical characteristics are still poorly understood. Reynolds numbers in the ISM are of order Re $\approx 10^9$ or higher, indicating the presence of highly turbulent flows. This is the so called **interstellar turbulence**. Characteristic HI gas velocities in the diffuse ISM are universal and of order 10 km/s, independent of the star formation rate or galactic environment[63]. We also know that the turbulent kinetic energy is mostly carried by large scale modes with a power distribution that decays as $P(k)dk \propto k^\alpha dk$ as the wave number k increases or the spatial scale $1/k$ decreases, respectively[54]. The observationally deduced exponent $\alpha \approx -1.8$[25] lies between the Kolmogorov[46] value of incompressible turbulence, $\alpha = -5/3$ and the prediction for purely shock-dominated, highly-compressible Burger's turbulence $\alpha = -2$. We however still have little knowledge of whether the interstellar turbulence is dominated by solenoidal or dillatational modes[26].

Similar holds for the physical sources that drive ISM turbulence. A large number of different scenarios have been proposed in the literature[48;25;59]. Large-scale gravitational instabilities in the disk, i.e. spiral density waves, can potentially provide sufficient energy[47]. However, the efficiency of this process and the details of the coupling mechanism are not well understood. The magneto-rotational instability (MRI) has been identified as the major source of turbulence in protostellar accretion disks[4]. Although we have ample evidence of the presence of large-scale magnetic fields[35;8] it is still unclear whether the MRI can provide enough energy to explain the observed levels of turbulence in the ISM[9;60;23;55]. For the star-forming parts of spiral galaxies, clearly stellar feedback in form of expanding HII bubbles, winds, or supernova explosions plays an important role. However, this approach clearly fails in the extended outer HI disks, observed around most spiral galaxies or in young, high-redshift protogalactic disks that are characterized by very high irregular gas motions. Here the energy input from cold accretion streams may drive turbulent motions at the measured rate.

Yet another problem is coupling interstellar turbulence with heating- and cooling processes and chemical reaction rates in order to generate the filamentary mixture of different gas phases that is observed in disk galaxies. Numerical simulations are beginning to investigate these processes under idealized conditions or restricted geometries[16;17;18;30]. Clearly, *a well-orchestrated theoretical-numerical and observational effort as proposed within this SPP is needed to explore the drivers of interstellar turbulence and their affect on the multi-phase and chemical structure of the ISM*.

2.2.2 What is the intrinsic structure of molecular clouds?

Clouds of molecular gas, mostly composed of H_2 and dust, represent the densest and coldest phases in the ISM. At optical wavelength they are seen in silhouette against the background Galactic star light. At longer wavelengths, i.e. in the near infrared (**IR**) and mm regime, dark clouds can become optically thin, revealing the highly reddened background stars. The exceptions are so called infrared dark clouds, the sites of massive star formation, which are optically thick even in the thermal IR regime[11]. The recent development of large-format IR arrays has made it possible to generate high-resolution extinction maps of IR optically thin dark clouds providing a new and accurate tool to determine their large-scale surface density distribution with arcminutes resolution. Future observations of the near IR color excess with 8-m class telescopes will generate surface density maps with a resolution of less than 10 arcsec, allowing us to investigate multi-level hierarchical structures that are expected to form as a result of interstellar turbulence. In parallel with technical advances in near IR observations, sensitive continuum and heterodyne detectors at large bolometer arrays like APEX, SCUBA (JCMT) or MAMBO (IRAM) are now mapping the small-scale structure of thermal dust emission in the mm and sub-mm regime. Molecular line observations, using e.g. different CO isotopes that are sensitive to different density regimes also provide detailed information about the large-scale gas and temperature distribution and in particular about its velocity field and its chemical composition.

The currently available observational data has refined our understanding of the structure of molecular clouds while at the same time raising new interesting questions. For example, molecular clouds, on large scales show a filamentary mass distribution. Often, 2 or 3 large, nearly parallel filaments exist that converge in a dense region which is the site of star formation. The cloud boundaries have a fractal dimension with a universal fractal index of 1.36 which is close to atmospheric clouds on Earth[27]. *The origin of these structures and their fractal dimension is not well understood.* A major break-through has recently been achieved when it was realised that molecular cloud cores provide the link between molecular cloud sub-structure and star formation. While the mean particle density of a cloud is of order 100 cm^{-2}, core densities can exceed 10^6 cm^{-2}. The cores have typical radii of order 0.1 pc and masses similar to the stellar initial mass function (**IMF**). They lie at the transition point from supersonic to subsonic turbulence where thermal pressure effects and gravity begin to dominate[48]. Interestingly, the core mass spectrum resembles the IMF with a steep slope of $\alpha \approx 2.0 - 2.5$ for masses above 1 $M_\odot$ and a plateau at smaller masses. This raises the fascinating question whether the stellar IMF is in principle determined by the same processes that lead to the formation of cloud cores at the scale where the self-similar supersonic turbulent regime breaks down. Infrared observations of the presence of young stellar objects in cores are a direct prove for their capabilities to form stars. However, there are problems with the simple interpretation[15] and many observed cores appear to be starless[13]. This represents a challenge for current numerical simulations of gravoturbulent fragmentation[44] where density enhancements either collapse or are dispersed. Here magnetic fields and protostellar feedback might play a key role. Clearly more work is required to *understand the origin and evolution of molecular cloud cores and their ability to form stars.*

2.2.3 How do molecular clouds form and evolve?

The **formation of molecular clouds** *within the large-scale turbulent ISM, their equilibrium state and their condensation into stars are probably among the most interesting unsolved and controversial questions.* All molecular clouds in the Milky Way should be gravitationally unstable. However, if all clouds with a total mass of $2 \times 10^9 M_\odot$ would collapse on a dynamical timescale which is of order 4×10^6 yrs and condense into stars with typical efficiencies of 10%, the galactic star formation rate would be 50 $M_\odot$/yr which is a factor of 10-20 larger than observed. This leads to the quasi-static scenario where molecular clouds have lifetimes of $10^7 - 10^8$ yrs. Several observations indicate an equipartition between their kinetic, magnetic and potential energy, indicating that they are indeed close to virial equilibrium. An ordered, static magnetic field component might then be strong enough to stabilize them on large scales. Molecular cloud cores and eventually stars would then form by slow ambipolar diffusion, a process that describes the drift of neutrals past ions that are frozen to the magnetic field lines and that occurs on timescales of 10^7 yrs.

More recently an alternative scenario has been advocated where molecular cloud formation and evolution is seen as a dynamical process without any equilibrium phase[24;48]. New generations of high-resolution numerical simulations have the power to resolve the multi-scale dynamical evolution of gas clouds. These simulations demonstrate that turbulent, cold gas clouds can form on timescales of 10^7 yrs in the dense interaction zones of large-scale converging HI gas flows due to cooling and hydrodynamical instabilities. As soon as the inflow stops, the turbulence quickly dissipates, leading to collapse and star formation[36;37;6] on a dynamical timescale. This result is in agreement with the observed age spread of young star clusters.

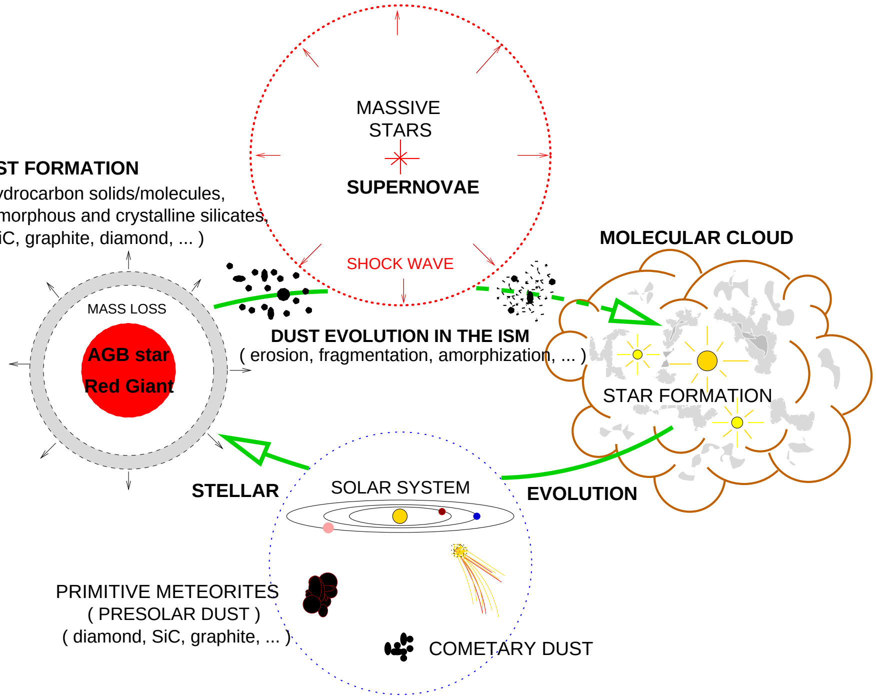
The controversy in molecular cloud lifetimes and evolution is fueled by ambiguous magnetic field measurements and contradicting chemical age determinations. Magneto-hydrodynamical simulations are just now becoming sophisticated enough in order to study magnetised, turbulent gas. In addition, the formation of molecular hydrogen and especially the observed tracer molecule CO has not yet been investigated in details.

2.2.4 How do interstellar dust grains and molecules form and evolve in the ISM and how do they affect physical processes in the ISM?

Interstellar dust consists of particles from a few 100 atoms in PAHs to several microns in size. The dust grains are in general irregularly shaped with a fractal, fluffy structure. They consist of heavy elements, generated in massive stars (star dust), like O, C, N, Mg, Si, Fe and S.

Dust is one of the most important ingredients, determining the physical and chemical conditions in the ISM[20]. It absorbs stellar radiation at short wavelengths and efficiently re-emits energy in the infrared and sub-millimeter wavelength range, thus cooling the ISM and assisting the star formation process. It also influences the chemistry of the ISM via surface reactions, in particular H_2 and molecular cloud formation. Dust grains provide surfaces for chemical catalysis and the freeze-out of molecules in molecular clouds. In their accreted ice layers, more complex molecular species, such as water, methane, methanol, ammonia, and formaldehyde can be formed by UV or cosmic ray irradiation. Interstellar gas dynamics is known to modify and accelerate the effects of coagulation/fragmentation on the dust size distribution although the details are not well understood[53]. *Therefore, the study of the interplay between dust and gas properties is of prime importance to understand the general evolution and phase transitions in the ISM.*

In spite of the almost 80-years history of dust studies, the origin and evolution of dust grains in space remains one of the unsolved puzzles of astrophysical research. The main possibilities under discussion are dust injection by dying stars or condensation in a cold dense phase of the ISM[20]. It is well known from observations, dust condensation models and the isotopic record in presolar grains that dust can condense in stellar winds of evolved stars and supernova ejecta, an indication that they are major dust sources. However, there is a significant mismatch between the timescales of dust injection by asymptotic giant branch stars (several Gyrs) and the dust destruction by sputtering in supernova shocks (~ 0.5 Gyr) in the Milky Way[42].



This apparent disagreement requires an alternative dust source operating faster than destruction, and points to a process acting in the ISM, such as accretion of refractory atoms on pre-existing grains in a cold phase[22]. Models of dust and gas evolution in the ISM indicated that this process can be responsible for most of the dust mass in the Milky Way[65]. *However, the microphysics of this process remains unknown and requires thorough modelling, combining the modern understanding of processes of molecular cloud formation with chemical models of dust condensation and dedicated laboratory experiments.*

New telescopes, used for analytical spectroscopy of stellar and interstellar regions, allowed the identification of **molecules** present in the ISM. More than 140 interstellar molecules have by now been identified and the list of molecules will undoubtedly grow as more powerful telescopes and interferometer arrays are built and applied. In recent years, spectroscopic studies of hot-core star-forming regions such as the heterogeneous region Sagittarius B2 have led to the discovery of many **organic compounds**[40]. Studies of ion-molecule reactions will in the future provide a detailed understanding of the chemistry taking place in these regions, an explanation for the abundance of specific molecules, and yield data that can greatly assist in *developing* **astrochemical models**.

2.2.5 How do stars interact with and shape the multi-phase ISM?

Stars, especially massive stars ($M > 10 M_\odot$) are among the key players in galactic evolution. **Stellar winds** and **supernova explosions** provide a significant input of mechanical and radiative energy into the ISM, driving interstellar turbulence and injecting nuclear-processed material and generating dust. Young, low-mass stars generate giant **jets** that pierce through the molecular surrounding affecting its structure in ways that are not well understood. Associations of massive stars carve and shape the ISM on galactic scales, creating the largest structures known in the ISM – supergiant hot bubbles and dense shells with diameters ~ 600pc. Expanding perpendicular to the galactic disk, supergiant shells create “chimneys” for the hot gas to escape and form hot galactic halos[49]. However, this gas eventually cools and falls back onto the host galaxy. This closes the **matter cycle** on galactic scales. Indeed, clouds of atomic hydrogen, so called HI clouds, falling towards the Galactic plane are observed[56]. Consequently, the outflow of hot metal rich gas into the halo and its delayed return to the disk at places different from the launching site contributes significantly to the chemical mixing and chemical homogenization of the Milky Way.

By the same token, the shells caused by supernovae explosions or by expanding HII bubbles also sweep up interstellar gas which later on cools and condenses into molecular clouds. This can induce a new stellar generation which ionises the surrounding and suppresses star formation again. The details of this scenario of *induced versus suppressed star formation*, the interaction of supernova remnants with the surrounding multi-phase ISM and the evolution of photo-dissociation regions in turbulent, clumpy cloud environments are still poorly known – not even the concept of induced versus suppressed star formation is yet firmly established. In addition, the question of *how the ejected heavy elements in supernova explosions are mixed into the multi-phase ISM* and how the shocks interact with the environment are not clear yet and require GeV to TeV observations (e.g. **HESS**, see section 3.2.4) and new generations of numerical simulations, coupled with detailed state-of-the-art supernova explosion models[58;50].

2.2.6 How are the processes in the ISM affected by magnetic fields?

Magnetic fields are present in almost every place in the Universe, but *the evolution, structure and origin of magnetic fields are still open problems in fundamental physics and astrophysics.* In the ISM, turbulent motions from supernova remnants amplify small-scale fields and, together with large-scale rotation, generate large-scale fields via the dynamo mechanism[32]. The magnetic energy content contributes significantly to the total pressure of the ISM. The average energy density of the magnetic field is comparable to that of the kinetic energy of the turbulent gas motions and is about one order of magnitude larger than the thermal energy.

The interaction of magnetic fields with the cold ISM gives rise to a rich and complex phenomenology. Numerical simulations indicate that in the presence of strong magnetic fields, the cores of molecular clouds may become sub-critical, which may prevent or delay star formation.

In the warm diffuse ISM, observations of polarized radio synchrotron emission and its Faraday rotation can measure the structure of the interstellar magnetic fields from the largest scales to the small scales of interstellar turbulence. Individual objects in the Milky Way (like HII regions, SNRs, PNs and PWNs) act as Faraday screens against the diffuse polarised background, so that the strengths of their fields can be measured. Multi-channel spectro-polarimetry in radio continuum enables "rotation measure synthesis", the Fourier transform of the data cube into a cube in Faraday space, and "Faraday tomography" to separate multiple emitting regions along the line of sight. Such observations will help to understand the structure of the diffuse ISM and the interactions between the various gas components and magnetic fields[33;2]. The implications of such magnetic fields in galactic low metallicity environments (dwarf galaxies) or young galaxies are far from being understood and need to be tested and investigated further. In particular, *the role of dynamos in galactic disks at high cosmological redshift* requires more attention. *EVLA, ALMA* and the *precursor telescopes to the SKA* will allow detailed observational tests.

2.2.7 How do cosmic rays interact with the ISM

Cosmic Rays (CRs) are nowadays considered as an essential component of the ISM, just as gas, dust and magnetic fields. In particular, as charged particles, they are strongly coupled to the latter by Lorentz forces and by strong scattering off field irregularities (MHD waves). Although they consist of relativistic particles with low number densities compared to gas atoms, their energy density of about 1 eV/cm^3 is comparable to the gas and magnetic field in the ISM[28]. CRs are mainly composed of protons and heavier nuclei (99%), electrons and positrons. Gamma rays occur mainly as a by-product of CR interaction with interstellar matter (e.g. π_0 decay as a result of CR spallation with gas), which is also the source of CR secondaries.

The most remarkable property of CRs is their differential energy spectrum, which is a power-law between 10^9 and 10^{20} eV, with two breaks, one at 10^{15} eV (the so-called knee) and at 10^{18} eV ("ankle"), strongly constraining possible acceleration mechanism. In addition, the small measured anisotropy (about 0.1%), argues for a strong coupling between CRs and MHD waves, leading to a drift velocity of a few hundred km/s, rather than propagating by the speed of light. As a result, spatial information about their origin is completely erased. The transport of CRs from their sources must be diffusive due to strong resonant scattering, and the particles perform a random walk both in momentum and ordinary space, which can be described by an energy dependent diffusion coefficient. Most likely the origin of CR is related to supernova remnants (SNR), where suprathermal interstellar particles are injected into the outer shock propagating into the ISM. The theory of diffusive shock acceleration (DSA), also known as 1st order Fermi mechanism, has been worked out more than three decades ago[3;10]. It is a stochastic process, in which the CR residence time in the shock region is inversely proportional to the particle energy, and hence naturally leads to a powerlaw.

Since MHD waves are frozen into the ISM plasma, CR scattering can also induce momentum transfer to the gas. This happens, because CRs escape from the Galaxy, and hence introduce a small anisotropy in the CR distribution function as seen in the wave frame. This leads to a resonant streaming instability and hence to the self-generation of waves. As a consequence more CRs are scattered in the forward than in the backward direction, thus transferring a net momentum to the gas. If the coupling between CRs and the gas via the waves as a mediator becomes strong enough, a CR driven galactic outflow can be generated[12].

Altogether, *realistic investigations of ISM dynamics* with a high degree of predictive power *must include the effects of CRs on the gas and the interstellar turbulence*. To improve upon the existing models is a key goal of this SPP.

3 Approach within the SPP

Studying the non-linear dynamical evolution of the multi-phase ISM requires detailed insight into the various relevant processes, their interaction and coupling. This can best be achieved if the expertise of various research groups is combined in a concerted effort for which a DFG priority programme would ideally be suited.

Our research will be based on three research pillars that will be presented in this section: laboratory studies, observations as well as theory and computations.

3.1 Laboratory studies

Recent progress in the **experimental tools** gives access to the reactions under precise control of the initial molecular state of ionic reactants. New powerful techniques have become available for event-by-event reaction studies in ion traps[41]. and in fast beams colliding with electrons, photons, and heavy reaction partners. For studies of dissociative recombination with colliding merged ion and electron beams, large progress was made on reaching minimal translational and internal motion for in-beam collisions at well-controlled interaction energies [magnetic ion storage rings, in particular CRYRING, Stockholm University, and TSR, MPI for nuclear physics (MPI-K), Heidelberg]. At MPI-K a cold photocathode electron beam for collision studies, also used for preparing cold stored ion beams by phase-space cooling, has become available and made it possible to reach the lowest collision energies, corresponding to about 10 K. Further experimental developments are underway towards storing fast beams of molecular ions under cryogenic conditions in cold ion traps and in the electrostatic Cryogenic Storage Ring (CSR); this facility presently under construction will offer cold electron interaction in merged beams for much higher molecular ion masses. Through the new storage ring concept, in addition also merged beams experiments with atomic, isotope-selected beams (H or D, O, C, etc.) in interaction with stored molecular ion beams will become possible. Based on these developments, expertise is available for measurements of absolute cross sections, final state branching ratios and internal molecular structures in fast beams and radiofrequency ion traps on molecular cations, highly charged ions, and anions important in the ISM.

Strong German expertise also exists in the field of spectroscopy of molecules and ions, relevant to the astrophysics of the ISM. High-resolution spectrometers provide accurate laboratory data for observations with ALMA, Herschel, SOFIA and other telescopes which allows to address key questions discussed in this proposal. New technological developments enable the study of ISM molecules. German leading competence is also available to understand dust processing as well as the destruction and reformation of abundant materials such as silicates and carbonaceous materials using state-of-the art spectroscopic (UV and IR) and advanced microscopic tools.

3.2 Observational Approach

Major new facilities for observing the ISM have recently become available or will see first light over the next few years.

3.2.1 Herschel and APEX

The next 5 years will provide measurements of key properties of the different phases of the ISM with the Herschel Space Observatory (**HSO**) and with **ALMA** (see below). These observations will cover galaxies of all types, from normal and starbursting galaxies in the local Universe out to quasar host galaxies at the highest redshifts.

The three instruments aboard the Herschel Space Observatory (**HSO**) will allow observations of the submillimeter and far-infrared wavelength ranges with unprecedented sensitivity and (shortward of 300μm) unprecedented angular resolution. **PACS** was built under the direction of the Max-Planck-Institut for Astronomy, Heidelberg. It allows imaging specto/photometry between 60 and 210μm and, apart from covering the peak of the spectral energy distribution (SED) from warm dust, will deliver the emission distributions of the major ISM cooling lines (CII, NII, OI). **SPIRE** photometry covers the 250, 360, and 520 μm wavelength ranges and thus samples cooler dust, while **HIFI** (built with strong contribution from Bonn/Köln) will allow high(est) resolution spectroscopy between 157 and 625μm. Observing time on Herschel can be proposed to a review committee of the European Space Agency. Various German astronomer belong to teams that have already been granted observing time in Guaranteed and Open Time Key Programs.

The Atacama Pathfinder Experiment (**APEX**) operates a 12 meter diameter telescope located at the 5100 meter high site in the Chilean Atacama desert where ALMA is currently being built. APEX heterodyne instrumentation (for high resolution spectroscopy) covers all of the atmospheric windows between 1.5 mm and 200 μm wavelength. In addition, bolometer array receivers are available for continuum observations. The 300 element Large APEX Bolometer Camera (**LABOCA**) covers the 850μm window. In addition, the 37 elements Submillimeter APEX Bolometer Camera (**SABOCA**) covers the 350 μm window. In November 2009, an incarnation of the Polarization Kamera (**PolKa**) has been successfully commissioned at APEX. PolKa observations will allow determinations of the magnetic field morphology in dust clouds. Since PolKa can be operated with, both, LABOCA and SABOCA, dual frequency observations will allow detailed studies of the magnetic field, including of depolarization of dust grains in the densest regions. German scientists can propose APEX observing time to programm committees at ESO and the Max-Planck-Society; the latter holds 45% of the total observing time. APEX heterodyne receivers for wavelengths below 600μm as well as the bolometer arrays are facility instruments. Some of the high frequency instrumentation, including the powerful 14 element CHAMP+ array[1], are principal investigator instruments (PI) for which observing time can be obtained for collaborative projects with the PIs. Here is great complementarity between the 12 m APEX and the 3.5 m HSO telescopes: APEX has the same angular resolution as Herschel at three times longer wavelength.

3.2.2 The Atacama Large Millimeter Array (ALMA)

ALMA will revolutionize few and (sub) arcsecond resolution imaging, of the ISM in the wavelength range from 7 mm to 300μm. ALMA is a North-American/European/Japanese project operating an interferometer of fifty antennas with 12 m diameter each plus the Atacama Compact Array (**ACA**) consisting of twelve 7 meter antennas and four 12 m dishes. ACA will provide information on spatial scales where ALMA is not sensitive and, thus, is important for studies of the general ISM. German scientist will send observing proposals to ESO; the first call for proposals for ALMA is expected to have a deadline in November 2010, for observations starting in July 2011.

3.2.3 The Stratospheric Observatory For Infrared Astronomy (SOFIA)

SOFIA consists of a German-built 2.7m telescope, mounted in a modified Boeing 747 aircraft. SOFIA will fly at altitudes up to 45,000 feet, above more than 99% of the atmospheric water vapor, opening win-

[1]CHAMP+ has 7 elements each covering the whole 350 and 450μm atmospheric windows.

dows to the Universe that are not accessable from the ground. It will be the only far-infrared observatory after Herschel will run out of cryogenic cooling (in 3 years) for a long time to come. Early science observations will start in 2010 with a projected lifetime of 20 years. Operation costs and observing time will be shared by the US (80%) and Germany (20%). Nine first-generation science instruments are under development that will allow a detailed investigation of physical processes in the ISM, the origin of dust and the role of dust and ISM chemistry.

3.2.4 Other Facilities and Initiatives

A major revolution in infrared observations has recently occured with the first instruments for high-resolution IR spectroscopy (e.g. **CIRES** and **SINFONI**) at the ESO **VLT**, exploring the ISM in distant, high-redshift galaxies or the galactic center.

The high energy stereoscopic system (**HESS**) investigates cosmic gamma rays in the 100 GeV to 100 TeV energy range, exploring the non-thermal Universe as e.g. cosmic rays (see section 2.2.7). With a strong participation from Germany, the spectacular recent results of this instruments have revolutionised our understanding of the ISM.

For the last more than 20 years the most powerful instruments for millimeter astronomy have been operated by the Institute for Radio Astronomy at Millimeter Wavelenghts (**IRAM**). While operated by the Max-Planck-Society, the French CNRS and the Spanish IGN, the IRAM 30 meter telescope on Pico Veleta, Spain, and the Plateau der Bure Interferometer in the French Alpes have been open to the German community via an open proposal process. Both IRAM facilities are currently undergoing major up-grades and technical enhancements.

The most powerful radio interferometer, the Very Large Array (**VLA**) operated by the US National Radio Astronomy Observatory (NRAO), is currently undergoing an extensive upgrade – the VLA expansion project. The resulting **EVLA**, will (in 2011) be a vastly more powerful instrument with continuous freguency coverage from 1 to 50 GHz and up to 10 times the continuum sensitivity of the VLA. NRAO has an “open sky policy”: Observing time is based on scientific merit via a proposal process to which German scientist can submit observing requests.

Scientists in Germany have long-standing expertise in radio wavelength polarisation observations, which trace magnetic fields in the diffuse ISM. The **Effelsberg** dish is still the best radio telescope to measure such diffuse polarised synchrotron emission. Installation of a multi-channel polarimeter in 2010 will allow Faraday-tomographic measurements in the Milky Way. **LOFAR**, the low frequency array, will give access to the emission of low-energy electrons and small Faraday rotation measures, and hence allow the detection of much weaker magnetic fields than today.

3.3 Theoretical and Numerical Approach

The **dynamics** of the interstellar medium is extremely complex. It involves many physical processes and many different spatial and temporal scales. The different phases of the ISM and stars are interconnected via a network of feedback loops. On global scales we need to consider the connection of the galaxy to the cosmic web by hot and cold accretion and galactic winds and fountains. On intermediate scales, we need to describe the formation of molecular clouds via large-scale flows of mostly atomic gas in a galactic disk. On the smallest scales, internal turbulent compression in the star-forming cloud then sets the initial stage for the protostellar collapse of individual objects. The thermodynamics of the gas, and thus its ability to respond to external compression and consequently to go into collapse, depends on the balance between heating and cooling processes. Magnetic fields and radiative processes also play an important role. *Modelling the ISM realistically therefore requires the accurate and simultaneous treatment of many different physical processes over many different scales.* As a consequence **analytical models** are usually restricted to highly idealized cases. These can yield insight, but the complexity of the problem means that they must be used in concert with **large and sophisticated numerical simulations**.

Computational astrophysics has made considerable progress in recent years. For example, large numerical simulations have been performed to model both the large scales of the interstellar medium and the formation of molecular clouds[45], the internal dynamics of the molecular clouds[5] and the collapse of individual objects[38]. At the same time, there has been considerable progress in modelling the microphysical processes which are central to understanding the heating and cooling of the gas and to obtaining reliable diagnostics of its chemical and thermodynamical state as well as its dynamical evolution[39;57]. It has proved crucial to adequately treat radiative transfer in the continuum as well as in atomic and molecular emission lines. The advent of novel algorithms and highly efficient software packages to solve the multi-dimensional radiative transfer equations has provided additional stimulus to this field[7;43;64;61]. However, these advances have only been achievable by dividing the problem into smaller bits and pieces and by focusing on few physical processes or single scales only. *Today, algorithmic advances and increasing computational power has reached a maturity that allows for a more integrated approach to modelling the ISM*. For the first time we are able to combine, for example, magnetohydrodynamics with chemical and radiative processes, in a consistent manner while at the same time reach sufficient spatial and temporal resolution (e.g. using adaptive mesh refinement techniques in grid-based codes, or multi-mass particles in smoothed particle hydrodynamics) so that we can apply these numerical schemes in a realistic manner to astrophysical problems. It is this integrated view of the ISM that is at the very heart of this SPP.

For the first time, there is sufficient computational power available to reach these ambitious goals. The German supercomputing centers now provide resources that had been unthinkable five to ten years ago. The latest generation of massive-parallel supercomputers reach a performance in the petaflop/s regime. This progress will continue with rapid pace. For example, PRACE, the Partnership for Advanced Computing in Europe funded in the 7th Framework Program of the European Union will create a persistent pan-European high-performance computing service and infrastructure. European scientists and technologists will have access to world-class supercomputing capabilities equal to or better than those available in the USA and Japan. Germany is part of this partnership via the Gauss Center for Supercomputing, which is an alliance of the three computing centers in Jülich, Stuttgart and Garching. Researchers within the SPP will be in the pool position to take advantage of these rapid developments. However, we want to mention that it is not just high-performance computing, which is subject to enormous growth. This also holds for normal desk-top computers where we see the advent of using graphics processing units (**GPUs**) as hardware accelerators for scientific computing.

We foresee the **first funding period** of the SPP to be dedicated to the investigation of the interplay between different processes in the ISM. This requires the development of integrated and versatile software tools. Specific focus in the first three years of the SPP will also lie on designing analysis tools that connect directly to the ALMA and Herschel wavebands and instruments. Our aim is to provide a direct link between the simulations and the observations. Our focus will shift in the **second phase of the SPP** to the execution of high-resolution multi-scale and multi-physics numerical simulations and their interpretation in the light of these new ground-based and space-borne observatories. We will also apply the numerical simulations to different galactic environments, focussing especially on galactic centers, the interaction between halo and disk and to high-redshift galaxies where the structure of the ISM appears to be very different compared to local galaxies.

3.4 Selected Examples of Synergies / Collaborations within the SPP

To provide evidence for the diversity of topics covered within this SPP and illustrate the range of complementary expertise in the German astrophysical community, we give a few examples of potential research projects proposed in the framework of the SPP. We group them loosely in terms of the three pillars of ISM research identified above.

3.4.1 Selected Projects for Laboratory studies

1. **Recondensation of dust grains**
   In order to study the processing and recondensation of dust grains in the ISM, the formation of solids at low temperature and pressure (70 K, p (10-6 mbar) has to be simulated in the laboratory. Molecular species that could be erosional and sputtering products of abundant dust material in the ISM will be produced by laser ablation of suitable targets and forced to accrete on cold siliceous or carbonaceous substrates resembling the surfaces of large grains that have survived the destruction processes in the

ISM. Reactions between accreted species will be triggered by UV irradiation or interaction with ions from an accelerator. The formation of solid films on the substrate can be monitored by absorption spectroscopy in the UV, visible, and IR spectral ranges and by electron microscopy and EDX analysis. Recondensation processes and the resulting change of the spectral properties of the parent circumstellar dust components in the ISM can be well monitored by these techniques.

2. **Formation of polycyclic aromatic compounds (PAHs)**
   Among siliceous and carbonaceous grains (**PAHs**)belong to the most abundant species in the ISM. Small PAHs can be easily destroyed and medium-sized PAHs will be dehydrogenated by UV irradiation due to photodissociation reactions. However, for larger species, chemical processing such as the formation of large PAH molecules from smaller fragments has to be invoked. Simultaneous UV photolysis and hydrogenation reactions of PAHs by exposure to atomic hydrogen can lead to the formation of saturated sp3-hybridized carbon atoms within aromatic units. In addition to UV photolysis, PAHs can be processed by ion irradiation. Restructuring of PAHs by irradiation with H+ and He+ ions in different energy ranges (4 and 10 keV, 1 MeV) has not been investigated so far. Destructive processes as well as the formation of large PAHs are expected to result in completely different spectroscopic properties. Both scenarios can be simulated in the laboratory, in order to understand the destruction and reformation of PAHs in the ISM.

3. **Infrared spectroscopy of polyatomic anion and cation beams**
   Resonantly enhanced multiphoton dissociation, as already performed for molecular ions in traps, can be applied for rovibrational spectroscopy on a broad range of ionic species. Fast beams yield full event-by-event detection efficiency in the photodissociation step, while the cryogenic beam storage in the CSR facility ensures the high population of a single initial ro-vibrational level for the resonant excitation in the first step of the spectroscopic scheme. Carbon chain molecular ions and aromatic hydrocarbon ions are considered for these studies. Extension to very heavy ionized aggregates can be considered exploiting the fact that the purely electric fields of the CSR can store ions of any mass for a given beam energy and that phase space cooling (limited to masses below about 150 amu) will not be mandatory for this spectroscopy scheme. This project opens many ramifications of interest for ISM studies, such as the use of sub-millimeter radiation sources.

3.4.2 Selected Observational Projects

1. **An investigation of the ISM in the solar neighborhood**
   Many large and small gas and dust clouds have been found within 0.5 kpc. They together form the so-called "Gould Belt", a ring-like structure around the Sun with 150 to 500 pc distance. The Gould Belt environment allow us to study all processes and ISM aspects nearby: Giant molecular clouds (e.g. Orion), OB and T associations, intermediate and small clouds down to globules, recent and ongoing low-, intermediate- to high-mass star formation, evolution of highest-mass stars across the H-R diagramm, possibly dust formation in the wind of massive stars, ejection of material into the interstellar medium, and formation of new clouds and new generations of stars from that material, i.e. all parts of the cycle of matter. We can also investigate how supernova explosions (e.g. in Orion and Upper Sco) affect the surrounding ISM. Those SN explosions may have created Al26 gamma sources. Excess of 60Fe was indeed found in the deep Earth crust, which can be explained only as supernova debris from a nearby recent supernova, which would also have been in the Gould Belt. Hence, we can - for the first time - even study interstellar medium on Earth. A detailed investigation of the nearby ISM will requird a concerted multi-wavelength observational effort of several groups (Jena, MPE, MPIA, Munich, Bonn), combined with a suit of numerical simulations (Berlin, Bonn, Munich).

2. **Gas dynamics, star formation and chemistry in different galactic environments**
   While in the past decades observations of the neutral (molecular) ISM in nearby galaxies have been restricted to line emission from CO the recently up-graded IRAM Plateau de Bure interferometer has

now opened up the possibility to observe fainter lines that can be used as tracers of the physical conditions present in the ISM. Combining observations of molecules like CH3OH, SiO (tracing kinematic shocks) with 12CO, CS, HCO+,HCN,HNC,HC3N, N2H+ (probing the temperature and density of clouds harboring embedded star formation) and, e.g., CCH (produced in regions dominated by photo-dissociation) will allow one to obtain a full picture of the interplay between large scale dynamics such as densities, the sites prone for or of ongoing star formation and the impact of already more evolved star forming regions. All these new observations will probe spatial scales ranging from a few parsec up to a few 100pc and thus connect the chemistry observed in Galactic star forming region to larger scales where the global (dynamical) drivers for star formation are expected to play a role. The advent of ALMA with its wide instantaneous bandwith and much higher sensitivity will clearly revolutionize this field of chemical diagnostics in nearby galaxies and several exciting projects will become possible. This will require a joint effort of researchers working on laboratory astrophysics, theorists and observers.

3. **The Effect of Massive Star Feedback on the ISM**

   Feedback from the ionizing radiation, the stellar winds, protostellar jets/outflows and eventually supernova explosions of massive stars has a strong impact on the thermal, dynamical and chemical state of the surrounding ISM. The details of how much kinetic and thermal energy is generated in these events, how the ejected heavy elements and dust particles mix with the surrounding ISM and whether this feedback is negative (i.e. suppresses molecular cloud and star formation) or positive (i.e. triggers cloud and star formation) are not well understood and require detailed multi-wavelength observations of star-forming regions that are now becoming available e.g. with **APEX** that has opened unmatched opportunities for studies in the sub-mm and far-infrared wavelength regimes as well as X-ray data from satellites such as **Chandra** or **XMM-Newton**. These observations have to be compared with detailed numerical simulations that include e.g. the prescriptions of modelling the explosion mechanisms of thermonuclear supernovae, radiative ionisation and turbulent mixing (Tautenburg, Heidelberg, Garching, Munich, Berlin, Potsdam).

3.4.3 Selected Theoretical/Computational Projects

1. **ISM Physics of Different Galactic Environments: The Disk-Halo Interface and the X-Ray Dominated Regions in Active Galactic Nuclei**
   Over the last few years it has become clear that the Milky Way - like other galaxies - is surrounded by large amounts of neutral and ionized gas, which appears to be confined into cloud-like structures (e.g., the HI intermediate- and high-velocity clouds). This gas is direct signpost of the circulation of matter between disk and halo, such as galactic fountains driven by supernova explosions or gas accretion from satellite galaxies and the intergalactic medium. To better understand this intricate interplay, several projects are proposed. One is observational, where researchers from Potsdam aim at analysing the physical conditions in high-velocity clouds using quasar absorption spectroscopy in the ultraviolet with the Hubble Space Telescope and in the optical with the UVES spectrograph at the ESO Very Large Telescope in Chile. The others are theoretical in nature, where researchers in Bremen and Berlin perform detailed high-precision numerical simulations of starburst-driven outflows from the disk, while researchers in Heidelberg and Munich study the thermal condensation of dense clumps in the tenuous hot halo gas that surrounds virtually all spiral galaxies, using detailed chemo-hydrodynamical calculations.

   The upcoming mm/sub-mm telescope ALMA will probe the centers of active galaxies in unprecedented detail. The conditions it may find are currently unknown and may depend on the intricate interplay of X-rays emitted by the central black hole, soft UV-photons produced in a nuclear starburst ring, and mechanical energy injection from shocks or decaying turbulence. To account for these complex conditions, a consortium of researchers from Groningen, Leiden, and Heidelberg plans to work on a unified model for molecular cloud chemistry that takes into account all of these energy injection mechanisms. With such a model, it is possible to derive approximate equations of state that provide temperature and chemical abundances in terms of density, X-ray flux, soft UV-flux and mechanical energy input. These can be combined with state-of-the-art radiation-hydrodynamical codes to model the chemical conditions in the centers of active galaxies and the feedback of the chemistry on the formation of molecular clouds. Such modelling will be of central importance to understand upcoming observations on the conditions in active galaxies.

2. **Design of New Radiative Transfer Schemes**
   Radiation physics is of crucial importance to models of the ISM. A realistic treatment of radiative transfer in 3 dimensions and their combination with (magneto)hydrodynamic models is extremely expensive in terms of computational cost. Most models therefore employ drastic approximations, such as local cooling functions. However, it is clear that a true description of ISM physics and chemistry requires full radiative transport. Despite some recent progress, the development of efficient algorithms for radiation-hydrodynamics is still in its infancy. There are a number of world-class experts in radiative transfer in the German astrophysical community (e.g. at MPIA and the Universities of Hamburg, Kiel, München, and Tübingen). These groups will join forces within the SPP to work on efficient continuum and line radiative transfer schemes geared towards describing the ISM that can be coupled with state-of-the-art AMR (magneto)hydrodynamic codes.

3. **Development of Subgrid-Scale Models for Simulating ISM Turbulence**
   Current attempts to model interstellar turbulence are limited by the fact that the Reynolds numbers reached by even the best numerical simulations are many orders of magnitude below the true values in the ISM. These so called large-eddy simulations at best cover the upper scales of the turbulent cascade. This approach assumes that energy on the on unresolved small scales is simply dissipated. This is questionable. It becomes even more problematic when time-dependent chemistry is included, because some rates may be dominated by strong intermittent density and velocity fluctuations on unresolved scales. It clearly becomes wrong, when energy actually is inserted on these smallest scales, for example, through processes like magnetic reconnection of ambipolar diffusion heating. Groups in Göttingen and Garching, have been working on developing turbulent subgrid-scale models in the past years and plan on extending these studies to magnetized ISM turbulence. In addition, researchers within the SPP will build-up a 'turbulence' task force to engage in an active exchange on the current developments in turbulence theory. This task force will establish contact to other research areas such as applied mathematics, engineering, and laboratory experiments.

4 Specific Reasons for Funding this SPP and Added Value of the Collaboration within the SPP

The ISM is a **fundamental component** of the Universe. Its structure and physics if fascinating and of great importance for many different fields in astrophysics. We are currently witnessing the **emergence of a new understanding of the ISM** with the old idea of an equilibrium gas being replaced by a non-linear, highly turbulent, multiphase medium that is far from equilibrium. German astronomers have played a leading role in this field. They have access to powerful new instruments and observatories that will revolutionize observational studies of the ISM. Laboratory astronomy has recently made enormous advances allowing us to study complex chemical reactions under realistic ISM conditions. Finally, new numerical methods have been developed that can investigate the complex interplay between hydrodynamical flows, magnetic fields as well as chemical and radiative processes consistently, using Germany's supercomputing centers that belong to the top in the world. Given this enormous potential, the timing seems perfect to combine all resources and expertise in a multidisciplinary effort to construct a new dynamical ISM model, that will provide a solid basis for many other fields of astronomy. This **unique window of opportunity** has of course also been recognised by other countries where strong centers of ISM research have been established in response to this challenge, leading to a disadvantage for German scientists where ISM research, especially at universities, is strongy fragmented. We have many excellent research groups that are however small and distributed all over the country (see section 8). An SPP on the ISM would be perfectly suited and probably is the only possibility that we have in Germany in order to combine our expertise and coordinate our work into a focussed German effort for a new, deep understanding of the ISM, guaranteeing that we remain a key player worldwide in this exciting and timely research field. We have taken measures to enhance and guarantee interdisciplinary research and interaction between different groups within this SPP by requiring that in general projects that request personal funding equivalent to 1 postdoctoral position or more should be supported by at least **2 PIs** from complementary research fields. The exception are dedicated laboratory experiments.

Another reason for funding this SPP is **Germany's large investment** in powerful new instruments and observatories. In fact our financial contributions in funding ESO and ESA are the largest while the number of German astronomers using these facilities is smaller compared to countries, like France or the UK. A joint effort like this SPP would help in using these expensive facilities more efficiently and in increasing the number of successful proposals, by this justifying this investment.

The funding proposed within the SPP will make it easy for the participants to collaborate through regular visits, small topical workshops or large conferences and through inviting external scientists and experts. Especially small University groups will greatly profit from this **enhanced mobility**.

The SPP will maintain a **web site** that will contain important information related to the SPP, a **data space**, where useful scientific data, programs and other information will be made available and a **public outreach area** where important results will be published. We expect that this PR area could also be very useful in order to attract students which is crucial in order to raise the next generation of researchers. We will generate a website where **all PhD projects** funded within the SPP will be listed, including a short abstract of the planned research. We expect that this will be very useful in order to coordinate PhD projects within the SPP and make other groups aware of the science that is currently being persued elsewhere. In addition, it will increase the visibility of our PhD students, providing a basis for new collaborations and contacts which is crucial for a successful scientific carreer.

Our students will get a **broad interdisciplinary, scientific training** through yearly summer schools. We however also believe that training in e.g. working and interacting in large groups, preparing and giving a presentation, or in writing an application or a scientific paper is essential for a successful career. The SPP will therefore regularly offer **special soft skills training seminars** that will be open to its young researchers.

5 Proposed Budget

- **Personal costs:** A survey of tentative proposals and an evaluation of the relevant questions that would need to be investigated indicate of order 20 different projects that would have to be supported continuously. As discussed in section 4 we expect that the majority of project proposals will be joint research, supported by at least 2 PIs who will apply either for a PhD student or a postdoc each, depending on the expertise, that is required for the project. We therefore propose a budget for **personal costs, equivalent of 30 positions TVL 13**. We intend to employ PhD students on the same bases (TVL 13/2) throughout the SPP.

  We expect that several research projects within the SPP will require **special hardware items** like special purpose hardware boards or filters for cameras. For example, an investment of 30,000 Euros for a filter for the visible and infrared survey telescope **VISTA** at the Paranal Observatory in Chile would allow us to become a member of the consortium with enormous scientific profits. We suggest, that of order **50,000 Euros per year** should be reserved for this. In addition, the planned lab experiments require a one-time investment of **100,000 Euros** for instrumentation and **75,000 Euros per year** for consumables. It would be important for two teams to replace their old, outdated equipment with new moderately-sized PC-Cluster. The total costs are of order **100,000 Euros**. In addition **100,000 Euro** are needed for a dedicated special purpose GPU cluster for simulations and data visualisation, using this new and very promising technology.

- **Travel money** is required in order to guarantee intensive interaction and frequent visits between

German researchers as well as for international collaborations. Especially young researchers and one or two team members should attend conferences at least once a year. Adopting of order 15,000 Euros per year per project, we estimate that a total amount of **300,000 Euros will be required per year for travel**, including observing trips.

- As part of the **interdisciplinary training of young researchers** we will organise a summer school and at least one soft-skill school every year. The expected costs are expected to be **10,000 Euros** per year. Given a funding period of 3 years, the DFG will organise a meeting every 3rd year. As we plan a large SPP meeting every year we therefore request funds to support the 4 remaining workshops where we plan to cover the local costs from coordination funds. Assuming of order 70 participants for a 3-day meeting, this corresponds to $\sim$**15,000 Euros** per meeting, i.e. 30,000 Euros per funding period. We hope that research groups will meet frequently in topical 1-2 days mini-workshops which should be supported by central funds. With 3 workshops per year, we expect costs of **15000 Euros per year**.
- We will organise a centrally coordinated international **visitor program** where outstanding scientist will be invited that should visit different groups. We expect both, longer-term visitors that stay for up to 3 months and short term visitors (1-2 weeks). We suggest to commit **50,000 Euros per year** for our SPP guests.
- **Publication charges:** Although we expect most of the publications to be submitted to major Astronomy journals which are free of charge it can be reasonable to submit a paper sometimes to another journal. We expect that **20,000 Euros per year** are required for these exceptional cases.
- We request funds for **one postdoc TVL 13** to help with the **organization and daily work of the SPP**. The tasks will include administrative work, maintaining a web site, inviting SPP visitors, organising schools, soft skills seminars or the yearly SPP meetings and assisting the coordinator.

  Adding up all of these contributions, adopting 58,800 Euros per TVL 13 leads to a **total budget of 14,386,800 Euros** for 6 years or **2,400,000 Euros per year**.

6 Relation to other Funded Research Projects

In this section we discuss the relation of the proposed SPP to other strategic research projects in Germany.

Collaborative Research Centers – Sonderforschungsbereiche (SFB)

SFB 846 – Conditions and Impact of Star Formation: Astrophysics, Instrumentation and Laboratory Research will be established in Bonn and Cologne in 2010. Its focus is on understanding stellar birth in different environments from high-redshift galaxies to the solar neighborhood. Important aspects are instrument development at far-infrared wavelengths, as well as laboratory work on astrochemical rates and observations and theoretical modelling of the relation between gas and stars. As such, there is overlap with the SPP proposed here. However, the SPP aims at understanding the ISM itself. It thus includes all physical aspects relevant to the ISM and is not focused on the process of star formation only. In addition, the SPP will be a condensation point to ISM research throughout *all of Germany* and is not restricted to the Bonn / Cologne area.

Further potential overlap existed with the *SFB 439 – Galaxies in the Young Universe* in Heidelberg. However, this SFB ended in 2008. Researchers in Heidelberg are currently working on building up a *new SFB* on *The Milky Way System*. One aspect will be to gain better insight into the Galactic matter cycle. There is thus some overlap with the proposed SPP, however, the focus is clearly on the Milky Way and thus is more narrow in scope. The decision on this SFB will be made towards the middle of next year.

Transregional Collaborative Research Centers – Transregios (TR)

TR 33 – The Dark Universe is a collaborative project between the Universities of Heidelberg, Bonn, the LMU Munich, Max-Planck Institutes in Garching, and the European Southern Observatory. The goal is to unveil the nature of dark energy and its interrelation with dark matter. There is little to no overlap with this SPP.

Priority Programs – Schwerpunktprogramme (SPP)

SPP 1177 – Witnesses of Cosmic History: Formation and evolution of black holes, galaxies and their environment ends next year. Its aim is to improve our understanding of the temporal evolution of galaxies in the context of today's standard cosmological model. As gas physics is an important ingredient of galaxy evolution, there is some overlap with the SPP proposed here. However, our goal here is to gain a deeper understanding of the underlying physical processes that shape the ISM, while in SPP 1177 gas physics was a tool to understand galaxies as a whole.

There is a *competing SPP proposal* on *observational surveys*. It was submitted at the same time as this proposal. There is little to no scientific overlap between the two.

Research Units – Forschergruppen (FOR)

FOR 759 – The Formation of Planets: The Critical First Growth Phase was established in 2006 and includes scientists at the University of Tübingen (lead), Heidelberg, Braunschweig, and MPIA. The research unit focuses on the first stage in the planet formation scenario, i.e. on the growth process from dust to planetesimals. This SPP can provide a better understanding of the initial and environmental conditions for planet formation as studied in FOR 759.

FOR 1048 – Instabilities, Turbulence and Transport in Cosmic Magnetic Fields was established in 2008 at the University of Bochum and covers magnetohydrodynamic phenomena, turbulence and transport, and kinetic instabilities in magnetized plasmas. This detailed investigation of the microphysical aspects of the coupling between magnetic fields and (partially) ionized gases will provide valuable insight for those SPP projects with study the influence of magnetic fields on ISM dynamics.

FOR 1254 – Magnetization of Interstellar and Intergalactic Media: The Prospects of Low-Frequency Radio Observations with researchers from Bochum, Bonn, Bremen, Munich, and Potsdam will start in 2010. Its focus is to exploit the superb capabilities of LOFAR – the new LOw Frequency ARray that is currently being built at different sites in Europe – of detecting cosmic magnetic fields in distant galaxies as well as in the Milky Way. The research proposed within this SPP is highly complementary to the predominantly observational projects in the FOR. The observational data as well as the theoretical predictions on galactic dynamos and cosmic ray transport from the FOR will be a valuable input to our SPP.

Graduate Schools (GS) in the Framework of the Excellence Initiative

There are currently two GS which are related to astronomy and astrophysics, *GS 129* in Heidelberg and *GS 260* in Bonn and Cologne. We will strongly encourage PhD students funded by the SPP in Heidelberg, Bonn, and Cologne to become members of the GSs.

Clusters of Excellence in the Framework of the Excellence Initiative

Excellence Cluster 153 – Origin and Structure of the Universe was established in 2006 at the Technical University and the Ludwig Maximilian University in Munich. It covers a broad range of physical and astrophysical topics related to formation and evolution of cosmic structure. In research area G, it treats certain aspects of the cosmic matter cycle, but by no means with the breadth and width covered in this SPP.

7 International Collaborations

Scientists in Germany studying the ISM are connected to the international research community on various levels and organisational degrees. First of all, there is a large number of *personal collaborations* between researchers in Germany and abroad in virtually all fields of modern ISM research, ranging from laboratory experiments, the design and construction of new astronomical instruments, or the development of numerical methods, to applications in high-precision observations and in state-of-the-art theoretical calculations. The bibliography of this SPP proposal provides excellent testimony of this highly successful international integration of German ISM research.

There are also several *coordinated research projects* which should be mentioned here. German scientists lead and are strongly involved in several *Herschel key projects*. There are three ASTRONET projects which aim at preparing the theoretical grounds for the interpretation of the expected wealth of data from Herschel and ALMA: *STAR FORMAT (Star Formation Models and Tools: A Theoretical Database)* is a joint project between teams in Paris, Heidelberg and Hamburg. *CATS (Coherent Set of Astrophysical Tools for Spectroscopy)* involves teams from Bonn, Cologne, Paris, Grenoble, Bordeaux, and Gothenburg and is led by Peter Schilke (MPIfR). *ARTIST (Adaptable Radiative Transfer Innovations for Submillimeter Telescopes)* coordinated by Jes Jørgensen (University of Bonn) involves researchers from Bonn, Leiden, and Barcelona. The database of theoretical molecular cloud models currently build up in *STAR FORMAT*, for example, will act as a seed for the more extended simulation database as planned within the SPP.

Essential aspects of large-scale collaborative projects such as the proposed SPP on ISM dynamics are the free flow of information amongst the contributing scientists, the archiving of research data, and the dissemination and communication of results to colleagues within the community and to the general public. We plan to establish the necessary information infrastructure and provide the computational as well has human resources needed to achieve these goals in the best possible way. Our approach will be based on the framework developed by the *Virtual Observatory* (VO). This is the attempt to make astronomical observations and simulations available to the community at large.

8 Prospective Participants

The initiators and prospective participants of this proposed SPP come from most universities and Max-Planck-Institutes with groups working in ISM research. Most of them attended the preparatory workshop that was held in Garching on March, 17th, 2009.

Technical University, Berlin: D. Breitschwerdt, B. Patzer. **Ruhr University, Bochum:** R-J Dettmar. **University of Bonn:** F. Bertoldi, P. Kalberla, J. Kerp, U. Klein. **Max Planck Institute for Radio Astronomy, Bonn:** R. Beck, K. Menten. **University Erlangen:** U. Heber. **Max Planck Institute for Extraterrestrial Physics, Garching:** R. Diehl, M. Krause, M. Schartmann. **Max Planck Institute for Astrophysics, Garching:** W. Hillebrandt, F. Röpke. **University of Göttingen:** J. Niemeyer, W. Schmidt. **Max Planck Institute for Astronomy, Heidelberg:** H. Beuther, C. Dullemond, Thomas Henning, Oliver Krause, Eva Schinnerer, D. Semenov, F. Walter. **Max Planck Institute for Nuclear Physics, Heidelberg:** O. Novotny, R. Tuffs, A. Wolf. **Center of Astronomy Heidelberg, Institute for Theoretical Astrophysics:** R. Banerjee, I. Berentzen, P. Clark, S. Glover, R. Klessen. **Center of Astronomy Heidelberg, Landessternwarte Königstuhl:** S. Wagner, A. Quirrenbach. **Friedrich Schiller University, Jena:** F. Huisken (also MPIA), C. Jäger (also MPIA), R. Neuhäuser, K. Schreyer, H. Mutschke. **Max Planck Institute for Solar System Research, Katlenburg-Lindau:** H. Krüger. **Christian-Albrechts-University, Kiel:** W. Duschl, S. Wolf. **University of Cologne:** T. Giesen, P. Schilke. **University of Munich:** A. Burkert, C. Dobbs, T. Naab, T. Preibisch, T. Ratzka. **University of Postdam:** L. Oskinova, P. Richter. **Astronomical Institute, Potsdam:** D. Elstner, G. Rüdiger, H. Zinnecker. **Thüringer Landessternwarte, Tautenburg:** M. Hoeft, B. Stecklum. **University of Stuttgart:** A. Krabbe. **University of Tübingen:** G. Pühlhofer, T. Rauch. **University Wien:** J. Alves, G. Hensler.

References

[1] Aharonian, F. A., Akhperjanian, A. G., Aye, K.-M., et al. 2004, Nature, 432, 75
[2] Arshakian, T. G., Beck, R., Krause, M., & Sokoloff, D. 2009, A&A, 494, 21
[3] Axford, W. I., Leer, E., & Skadron, G. 1977, 15th International Cosmic Ray Conference, 11, 132
[4] Balbus, S. A. & Hawley, J. F. 1998, Reviews of Modern Physics, 70, 1
[5] Ballesteros-Paredes, J., Klessen, R. S., Low, M.-M., & Vazquez-Semadeni, E. 2007, Protostars & Planets V, 63
[6] Banerjee, R., Vázquez-Semadeni, E., Hennebelle, P., & Klessen, R. S. 2009, MNRAS, 398, 1082
[7] Baron, E., Hauschildt, P. H., & Mezzacappa, A. 1996, MNRAS, 278, 763
[8] Beck, R. 2007, A&A, 470, 539

[9] Beck, R., Brandenburg, A., Moss, D., Shukurov, A., & Sokoloff, D. 1996, Annu. Rev. Astro. Astrophys., 34, 155
[10] Bell, A. R. 1978, MNRAS, 182, 147
[11] Beuther, H. & Steinacker, J. 2007, ApJ, 656, L85
[12] Breitschwerdt, D., McKenzie, J. F., & Vök, H. J. 1993, A&A, 269, 54
[13] Burkert, A. & Alves, J. 2009, ApJ, 695, 1308
[14] Burkert, A. & Lin, D. N. C. 2000, ApJ, 537, 270
[15] Clark, P. C., Klessen, R. S., & Bonnell, I. A. 2007, MNRAS, 379, 57
[16] de Avillez, M. A. & Breitschwerdt, D. 2005, ApJ, 634, L65
[17] Dib, S., Bell, E., & Burkert, A. 2006, ApJ, 638, 797
[18] Dobbs, C. L., Glover, S. C. O., Clark, P. C., & Klessen, R. S. 2008, MNRAS, 389, 1097
[19] Dorschner, J. & Henning, T. 1995, The Astronomy and Astrophysics Review, 6, 271
[20] Draine, B. T. 2003, Annual Review of Astronomy & Astrophysics, 41, 241
[21] Dwek, E., Galliano, F., & Jones, A. P. 2007, ApJ, 662, 927
[22] Dwek, E. & Scalo, J. M. 1980, ApJ, 239, 193
[23] Dziourkevitch, N., Elstner, D., & Rüdiger, G. 2004, A&A, 423, L29
[24] Elmegreen, B. G. 2000, ApJ, 530, 277
[25] Elmegreen, B. G. & Scalo, J. 2004, Annual Review of Astronomy & Astrophysics, 42, 211
[26] Federrath, C., Duval, J., Klessen, R., Schmidt, W., & Low, M. M. M. 2009, ApJ submitted (arXiv:0905.1060)
[27] Federrath, C., Klessen, R. S., & Schmidt, W. 2009, ApJ, 692, 364
[28] Ferrière, K. M. 2001, Reviews of Modern Physics, 73, 1031
[29] Field, G. B., Goldsmith, D. W., & Habing, H. J. 1969, ApJ, 155, L149
[30] Glover, S. C. O., Federrath, C., Low, M. M. M., & Klessen, R. S. 2009, MNRAS in press (arXiv:0907.4081)
[31] Glover, S. C. O. & Low, M.-M. M. 2007, ApJSS, 169, 239
[32] Gressel, O., Elstner, D., Ziegler, U., & Rüdiger, G. 2008, A&A, 486, L35
[33] Hanasz, M., Otmianowska-Mazur, K., Kowal, G., & Lesch, H. 2009, A&A, 498, 335
[34] Heiles, C. 2001, ApJ, 551, L105
[35] Heiles, C. & Troland, T. H. 2005, ApJ, 624, 773
[36] Heitsch, F., Slyz, A. D., Devriendt, J. E. G., & Burkert, A. 2006, MNRAS, 373, 1379
[37] Hennebelle, P., Banerjee, R., Vázquez-Semadeni, E., Klessen, R. S., & Audit, E. 2008, A&A, 486, L43
[38] Hennebelle, P. & Ciardi, A. 2009, A&A in press (arXiv:0909.3190) publication in A&A
[39] Hollenbach, D. J. & Tielens, A. G. G. M. 1999, Reviews of Modern Physics, 71, 173
[40] Hollis, J. M., Jewell, P. R., Lovas, F. J., Remijan, A., & Møllendal, H. 2004, ApJ, 610, L21
[41] Hugo, E., Asvany, O., & Schlemmer, S. 2009, J. Chem. Phys., 130, 164302
[42] Jones, A. P., Tielens, A. G. G. M., Hollenbach, D. J., & McKee, C. F. 1994, ApJ, 433, 797
[43] Juvela, M. 1997, A&A, 322, 943
[44] Klessen, R. S., Heitsch, F., & Low, M.-M. M. 2000, ApJ, 535, 887
[45] Klessen, R. S., Krumholz, M. R., & Heitsch, F. 2009, Advanced Science Letters in press (arXiv:0906.4452)
[46] Kolmogorov, A. 1941, Dokl. Akad. Nauk SSSR, 30, 301
[47] Li, Y., Low, M.-M. M., & Klessen, R. S. 2005, ApJ, 620, L19
[48] Low, M.-M. M. & Klessen, R. S. 2004, Reviews of Modern Physics, 76, 125
[49] Low, M.-M. M. & McCray, R. 1988, ApJ , 324, 776
[50] Marek, A. & Janka, H.-T. 2009, ApJ, 694, 664
[51] Matsuura, M., Barlow, M. J., Zijlstra, A. A., et al. 2009, MNRAS, 396, 918
[52] McKee, C. F. & Ostriker, J. P. 1977, ApJ, 218, 148
[53] Ossenkopf, V. & Henning, T. 1994, A&A, 291, 943
[54] Ossenkopf, V. & Low, M.-M. M. 2002, A&A, 390, 307
[55] Piontek, R. A. & Ostriker, E. C. 2007, ApJ, 663, 183
[56] Richter, P. 2006, Reviews in Modern Astronomy, 19, 31
[57] Röllig, M., Abel, N. P., Bell, T., et al. 2007, A&A, 467, 187
[58] Röpke, F. K. & Hillebrandt, W. 2005, A&A, 431, 635
[59] Scalo, J. & Elmegreen, B. G. 2004, Annual Review of Astronomy & Astrophysics, 42, 275
[60] Sellwood, J. A. & Balbus, S. A. 1999, ApJ, 511, 660
[61] Steinacker, J., Henning, T., Bacmann, A., & Semenov, D. 2003, A&A, 401, 405
[62] Tamburro, D., Rix, H.-W., Walter, F., et al. 2008, ApJ, 136, 2872
[63] Walter, F., Brinks, E., de Blok, W. J. G., et al. 2008, AJ, 136, 2563
[64] Wolf, S., Henning, T., & Stecklum, B. 1999, A&A, 349, 839
[65] Zhukovska, S., Gail, H.-P., & Trieloff, M. 2008, A&A, 479, 453