High-energy astrophysics

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Executive summary

High-energy astrophysics explores the physics of astronomical objects that are characterised by high-energy and non-thermal processes. The study of the most violent processes in the Universe requires observational data on high-energy electromagnetic radiation (hard X-rays, gamma-rays) or particles (neutrinos, cosmic rays) which are complemented by photons at lower frequencies.

During a dramatic development of the field over the last decade, German groups and institutions have played central, often decisive, roles in high-energy astrophysics. Both spatially resolved and temporal studies of gamma-ray sources are conducted with unprecedented sensitivity, deciphering the physical processes in Galactic and extragalactic sources of high-energy emission, and providing new insights into fundamental physics. Radio observations of compact objects, especially black holes and neutron stars, permit exploring physics under extreme conditions and testing for fundamental properties such as the existence of event horizons around black holes. Observations of ultra-high energy cosmic rays provide information on particle acceleration at the highest energy. The first detection in 2013 of cosmic high-energy neutrinos was named the Physics World breakthrough of the year.

Germany plays a leading role in 2 currently operating TeV-band gamma-ray telescopes and is a central actor in the development of the future gamma-ray observatory, CTA. The German contribution to the neutrino detector IceCube has grown far beyond Germany's original investment, and a mature community develops the next generation of instruments, IceCube-Gen2 and KM3NeT. Germany is a central force behind the world's largest cosmic-ray detector, the Pierre Auger Observatory, and operates 6 stations of LOFAR, the second largest share among all partners. We note with concern the funding hiatus for Germany's participation in the coming radio observatory, SKA. For all large research infrastructures, continued German participation requires sustainable solutions for covering operational costs.

Theoretical studies continue to give direction to research in high-energy astrophysics, and they are indispensable for maximising the scientific return of the experimental and observational programs. Extensive computer simulations play a central role in modern theoretical studies, and continued support for high-performance computing centres is mandatory, ideally complemented with resources for joint algorithm development and code optimisation.

Past successes were based on the development of new methods and techniques, and the same strategy will be necessary in the future to maintain Germany's position on the international stage. Continued recruitment of new faculty engaged in high-energy astrophysics exemplifies the attractiveness, success, and future prospects of this area of astrophysics. The research foci and strategy presented in this section are the result of an extensive discussion process within the German scientific community. They represent careful balancing of the scientific potential, the fundamental character of the scientific questions, and the strengths of German research groups and institutions.

1. Introduction

High-energy astrophysics addresses the most energetic processes in the Universe. It explores cosmic objects such as supermassive black holes and exploding stars which produce extreme conditions that cannot be created in experiments on Earth. High-energy astrophysics is tightly connected to a wide range of other research areas of astronomy, such as cosmology, galaxy evolution, the interstellar medium in the Milky Way, star formation, and evolution. The versatility of high-energy astrophysics has led to a total of nine Nobel prizes in physics to date (1936, 1948, 1960, 1970, 1974, 1983, 1993, 2002, and 2015). The societal relevance of research in high-energy astrophysics reaches beyond answering fundamental scientific questions. Experimental studies foster technological developments that find application in many other areas. The topics of high-energy astrophysics inspire many students to start a career in science and research, or to commence university training in the MINT sector.

We see evidence of high-energy processes and their associated objects by observation of high-energy radiation and energetic particles, both of which fill the Universe. Very energetic particles in space are called cosmic rays: electrons and fully-ionized atoms, traveling through space very close to the speed of light. Their origin is one of the fundamental unsolved questions in modern astrophysics. We know that our Galaxy contains astrophysical systems capable of accelerating particles to energies beyond the reach of any accelerator built by humans. Candidates for cosmic particle accelerators are shocks formed in astrophysical plasmas when a star explodes, when a rapidly spinning neutron star expels electromagnetic energy, or when a black-hole system spews out matter at nearly the speed of light. What drives these cosmic accelerators is a major question in astrophysics today.

The distribution of cosmic rays in energy and space is governed by cosmic electric and magnetic fields. A fundamental self-organization arises that, through interactions between particles and electromagnetic fields, arranges the atoms and available energy in three components: a cool or warm gas that carries the bulk of the mass, energetic particles with a wide range of energies, and the turbulent electromagnetic fields that link the two. High-energy particles have a significant effect on the medium they traverse. The presence of cosmic-ray particles affects the ionization and excitation states of the interstellar gas. By deeply penetrating dense molecular clouds, the energetic particles also activate chemical reactions inside of them. Heavy nuclei hit by energetic particles break apart, thereby enriching the interstellar medium with light fragments. All of these processes are crucial for the understanding of the interstellar medium, the cycle of matter, and, eventually, the development of life.

How does nature produce such high-energy particles? How is gravitational energy converted into relativistic particle beams near compact objects, so-called jets? How are the sources of cosmic rays related to the sources of high-energy radiation or the sites of nucleosynthesis in the Galaxy? Do interactions of high-energy particles generate the magnetic field that permeates large structures in the Universe such as clusters of galaxies? How does magnetic turbulence generated by cosmic rays evolve?

To address these questions, we need to measure the properties of energetic particles, high-energy radiation and their sources. The latter are studied with multi-wavelengths astronomy, using observations across the electromagnetic spectrum from radio wavelengths up to gamma rays of the highest energy. Whereas the direction of photons and neutrinos directly tells us about the location of their sources, cosmic-ray particles are usually charged and have lost their directional information by deflection in cosmic magnetic fields, except for cosmic rays of the highest energy. The spectrum and nuclear composition of cosmic rays can be directly observed near Earth and convey information about their distant astronomical sources. The recently discovered extra-terrestrial neutrinos are of particular interest because neutrinos are electrically neutral and can escape from otherwise opaque sources. The combination of high-energy astronomical observations with direct studies of cosmic rays provides invaluable insight into the most extreme physical environments and the most violent processes in the Universe that cannot be obtained in any other way. The observational investigations are complemented by theoretical studies, in particular state-of-the-art simulations of plasma processes operating on very small scales and global simulations describing the evolution of magnetized plasma on very large spatial scales, as well as laboratory astrophysics (with very powerful laser facilities), to finally arrive at a deep understanding of high-energy astrophysical processes in the Universe.

2. Key Questions for the Upcoming Decade

Astrophysics of high-energy processes aims at finding answers to fundamental questions concerning

- the origin of cosmic rays, magnetic fields and turbulence from small to large scales,
- the sources of high-energy cosmic neutrinos,
- the physics of accretion and jet ejection from compact objects such as black holes, neutron stars, and white dwarfs,
- the diagnosis of violent processes such as mergers of compact objects in a multi-messenger approach including gravitational waves, cosmic rays, and neutrinos,
- the understanding of the interplay between energetic particles and the interstellar and intergalactic plasma, and
- the identification of signatures of the most elusive components of our Universe, such as dark matter, the quantum-gravitational structure of space-time, rare interactions, and elementary particles beyond the standard model. A detailed description of the science case for studying fundamental physics with astrophysical observations will be given elsewhere.

The ***origin of cosmic rays*** is one of the oldest fundamental questions in modern astrophysics. Remnants of exploded stars have long been thought to be the Galactic accelerators of cosmic rays but other Galactic sources found in star-forming regions may contribute as well. Interesting questions include how a tiny fraction of particles can be accelerated to enormous energies so that their population collects the majority of the internal energy of the macroscopic system, and how these particles interact with their magnetised environment. How do these cosmic rays propagate and what is their role in shaping galaxies and giant clusters over cosmic time? What does the isotopic composition of cosmic ray tell us about nucleosynthesis in the Galaxy? At ultra-high energies we observe cosmic rays that cannot be confined by our Galaxy, suggesting an extragalactic origin. It is an outstanding challenge to identify how and where those particles are accelerated to those extreme energies: suggestions include very energetic outflows of supermassive black holes, jets of exploding supernovae, or pulsar winds. Galaxies are already magnetised very early in the evolution of the Universe, close to the cosmic dawn, and we observe magnetic fields embedded in giant galaxy clusters, extending in size over several million light years. Which processes are responsible for the magneto-genesis in these objects, and what is the role turbulence, plasma instabilities, and high-energy particles play in shaping those fields?

A new path towards finding the origin of cosmic rays is opened up by the recent discovery of ***high-energy cosmic neutrinos*** with the IceCube experiment. High-energy neutrinos are produced in hadronic processes, which also create cosmic rays but, unlike charged particles, the trajectories of cosmic neutrinos point back to their sources. The sources of these cosmic neutrinos have not been identified to date, which reflects the small number of detected neutrinos and the large population of potential sources. A major task for the coming decade is to find the sources of the high-energy cosmic neutrinos via statistical analyses, the search for correlated variability, and by deeply exploring physical processes in candidate sources. Neutrino astronomy also offers a huge potential for unexpected discoveries, and high-energy astrophysics will play a major role in exploiting this potential.

Supermassive black holes reside at the centres of most galaxies. The space time near the event horizon of such supermassive black holes is a target of research in its own right, described in section XX[1]. A black hole that is well-fed with infalling gas can produce collimated relativistic outflows, or jets, of gigantic proportions. The SKA will yield highly-sensitive imaging results of such jets in radio galaxies and blazars, providing an unprecedented new tool for probing the relativistic plasma which carries the bulk of the jets kinetic power. Low-surface brightness emission regions and faint radio cores in `radio-quiet' AGN will become visible, arguably providing the best census of AGN and their jets across a wide range of different cosmological redshifts. The study of the formation and collimation of jets or the cosmic history of supermassive black holes and their influence on the cosmological evolution of galaxies and clusters is the subject of section YY[2]. The measurement of both gravitational waves and high-energy emission from merging compact objects promises to provide key insights into the physical processes govering the formation of black holes.

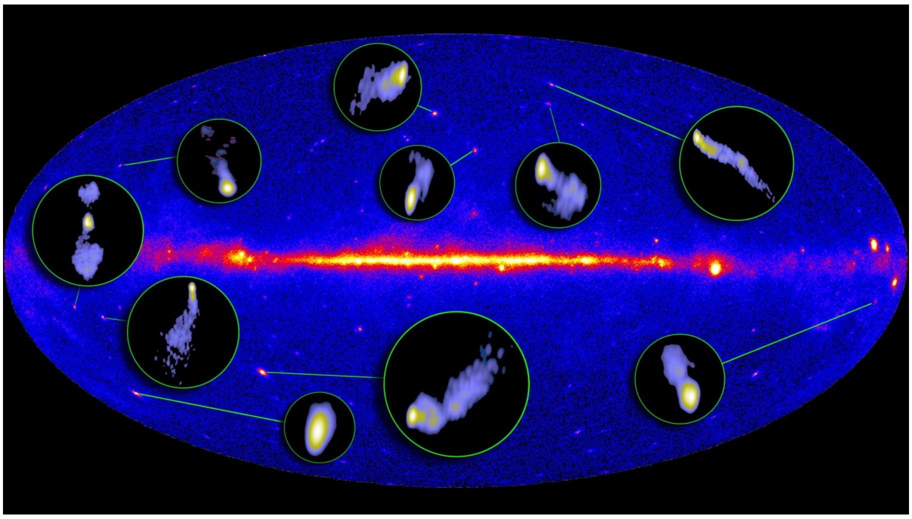

Figure 1: Radio jets emanating from supermassive black holes can be resolved with high-resolution radio-interferometric techniques. In the gamma-ray band they appear as bright point-like sources in the all-sky distribution of gamma-ray intensity measured with the Fermi Gamma-ray Space Telescope. Credit: NASA/DOE/Fermi LAT Collaboration and NRAO/AUI/MOJAVE Team/M. Kadler.

Relativistic outflows occur also in other systems such as ***pulsar wind nebulae or gamma-ray bursts***. Such outflows provide unique environments to study plasma processes of particle acceleration that give rise to puzzling flares of gamma radiation emitted by extremely energetic electrons or positrons. The strong beams of gamma-rays from supermassive black holes can be used to probe the extragalactic infrared background radiation produced by all the stars and quasars in the universe, and thus to constrain the star-formation history of the Universe. Moreover, understanding the physical processes governing the propagation of gamma rays through intergalactic space may help us to elucidate the possibility of primordial magneto-genesis and their impact on the thermal history of the intergalactic medium. Rapid brightness variations of the beamed gamma-ray emission probe the

[1] Kramer, Rezzola, Wex
[2] Merloni, Brüggen, Gillessen, Neumayer

nature of space-time at the smallest scales itself and thus may give directions in the quest to unify our four fundamental forces of nature.

A combination of high-energy astrophysical observations, accelerator studies, and direct detection experiments may lead to one of the most spectacular discoveries of the 21st century: The unambiguous identification of the ***enigmatic dark matter*** that holds together the cosmic entities in which we live - galaxies and galaxy clusters - and thus solving one of the greatest problems of modern physics. Moreover, phenomena at extreme energies have the potential to find new elementary particles beyond the standard model of particle physics, such as axions or sterile neutrinos

3. Key results of the previous decade

The previous decade has seen a breakthrough in our understanding of the high-energy universe. This progress is most prominently demonstrated by the increased number of detected sources in the GeV band (from 200 to more than 3000 sources) and in TeV gamma-ray astronomy (from a handful to more than 170 sources), in the detection of significant nuclear contributions in ultra-high-energy cosmic rays, and in the first detection of astrophysical neutrinos. At the same time, our theoretical understanding of the processes governing cosmic energetic particles and their radiation has advanced significantly. With these discoveries and with future installations that will substantially enhance the sensitivity of high-energy astrophysical observatories (CTA, SKA, IceCube Gen-2, KM3NeT), we are deepening our understanding of the physics of the high-energy universe. More details on currently operating and planned observatories are found in section WW[3].

Gamma-ray spectroscopy has matured to become an excellent tool for measuring the yield of nucleosynthesis in stars and stellar explosions, an example of which is the recent detection of gamma-ray lines of ^{56}Ni from the supernova SN2014J. High-energy astrophysics can thus in a unique way constrain stellar parameters and the processes operating inside stars, that are the subject of section ZZ[4]. Among the products of stellar nucleosynthesis are positrons, the antiparticle siblings of electrons, whose presence was revealed through measurements with INTEGRAL of their 511-keV gamma-ray line. The observed high concentration of positrons in the innermost regions of the Galaxy is at odds with standard models of the Galactic distribution of supernovae and other sites of nucleosynthesis. The high-energy positrons detected with, e.g., Pamela, Fermi-LAT and AMS point at previously unknown sources of antimatter. Too energetic to be produced through nucleosynthesis, and too numerous to be collision products of ordinary cosmic rays, the positrons may in fact result from annihilation or decay of dark matter. Along with positrons, other particles and photons would be generated if the signal were due to dark-matter annihilations or its decay. Measurements of gamma-ray by-products of the annihilation already place severe constraints on the dark-matter interpretation of the excess in high-energy positrons. Pulsars, rapidly spinning magnetised neutron stars, are an alternative explanation, as they are known to produce copious amounts of high-energy positrons.

Recent measurements have revolutionised our understanding of pulsars. The detection of very-high-energy gamma-ray emission up to 1 TeV in energy implies that the radiation cannot be produced close to the neutron star, because it would be absorbed in that case. Instead, particles must be accelerated further out, where the magnetic field is detached from the neutron star and blown off in a so-called pulsar wind. Further localized particle acceleration ensues at large distance in the pulsar wind, leading to short flares of gamma-ray emission caused by extremely energetic electrons or positrons. The discovery of *fast radio bursts* was a completely unexpected finding, and their origin and nature are

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[3] Mannheim, Hinton, Kowalski
[4] Barnes, Bergemann, Röpke, Weiss

still open questions. Radio observations of compact objects, especially black holes and neutron stars, represent a sensitive laboratory to study the strong-field gravity regime and the equation of state of neutron stars.

Substantial advances in high-performance computing now permit studying particle-acceleration processes with unprecedented resolution and veracity. It appears that efficient acceleration of cosmic rays proceeds in systems with outflow phenomena, in which material slams into ambient gas, forming a shock front. More than fifty years ago the eminent Italian physicist Enrico Fermi suggested that the energy of moving magnetic structures can be stochastically transferred to cosmic rays, and cosmic shock fronts are an environment in which this process operates in a systematic way. Now we can simulate the process in detail with large computer experiments. Various plasma instabilities provide shock fronts with a complex structure in which particles are pre-accelerated before they undergo the energisation process envisioned by Fermi. Magnetic turbulence is generated that influences both the propagation of the accelerated particles and the efficiency with which they radiate. Satellites probe these processes in the heliosphere. An exciting new area of research is studying shock fronts and plasma instabilities in the laboratory (cf. section VV[5]), where high-power optical and X-ray lasers permit complementing the view offered by computer simulations and in-situ measurements with satellites.

The radiation products of cosmic rays allow measuring the spectrum of energetic particles in individual sources and in entire galaxies. As example of the data mining described in section YY[6], advances in count-based imaging have been achieved through a novel method to denoise, deconvolve, and decompose photon observations (D^3PO). Applying this method to Fermi data permitted the separation of the Galactic gamma ray emission in two components that result from the denser ISM and from the hot, dilute ISM, which also includes the Fermi bubbles. From observations of supernova remnants we now know that electrons are accelerated to very high energies beyond 100 TeV, and the ions that make up 99% of Galactic cosmic rays are accelerated as well. The energy that is funnelled into energetic particles scales with the star-formation rate in a Galaxy. Part of that energy is returned as the pressure carried by cosmic rays. This pressure pushes and heats interstellar gas, in cases driving it off as galactic wind.

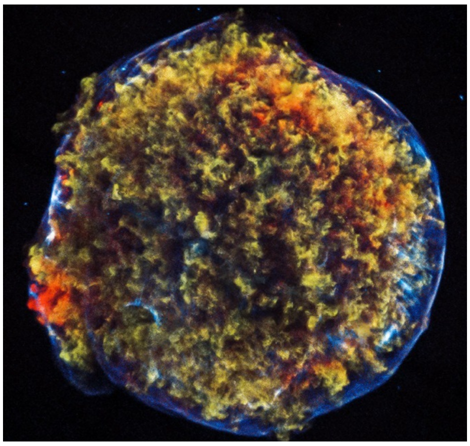

Figure 2: The remnant of a supernova observed by Tycho Brahe 4 centuries ago is now a bright source of X-rays. This X-ray image taken with the Chandra observatory reveals the dynamics of the explosion in exquisite detail. The outer shock has produced a rapidly moving shell of extremely high-energy electrons (blue), and the reverse (inner) shock has heated the expanding debris to millions of degrees (red and green). Image credit: NASA/CXC/SAO.

[5] Schlemmer, Jäger, Giesen, Caselli, and Kreckel
[6] Polsterer, Enke, and Ensslin

Similar processes are observed on larger scale around active galactic nuclei, in which a supermassive black hole drives powerful jets of matter into the ambient gas. At typical resolutions of light-years, Very Long Baseline Interferometry (VLBI) yields a detailed picture of the structure and dynamics of relativistic jets in supermassive black-hole systems, and apparent superluminal motion of jet components indicates a plasma speed approaching that of light.

The jets from supermassive black holes are laboratories to study turbulence and particle acceleration in the most extreme setting. A tight connection between the compact radio emission of extragalactic jets and their high-energy emission has recently been established (see Figures 1 and 3). Pinpointing the origin of the high-energy emission provides clues on the physics of jet formation. Invaluable insight has been gained on the impact jets have on the ambient medium as well as the star formation in the environment.

The observation of rapid flux variability on time scales of minutes together with high luminosity implies that efficient particle acceleration occurs in a very compact region in the jet. What causes the sudden localized transfer of energy is a matter of active research. VLBI polarimetry reveals the structure of magnetic field in the jet region where particle acceleration and emission arise, which is a major step forward toward identifying the underlying physical. New long-wavelength interferometers, such as LOFAR, enable further insights into jet physics but also provide other key data for high-energy astrophysics, such as deep surveys of the radio sky and studies of cosmic magnetism.

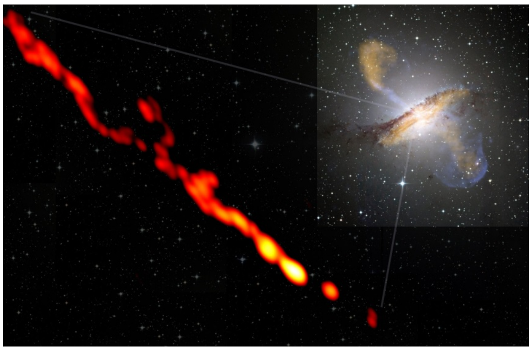

Figure 3: Blow up of the centre of the active galaxy Centaurus A. Radiointerferometric measurements reveal the fine structure of the relativistic jets that emanate from the central black hole and reach out into intergalactic space. Credit: M. Kadler, Inset: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray).

The brief spikes in radiation sent from active galactic nuclei and gamma-ray bursts are a probe of space-time itself. The nature of space-time on very small scales is shaped by gravity, relativity, and quantum physics, and we do not yet know how they combine. The structure of space-time may impose tiny imperfections of Einstein's theory of relativity that we would observe as energy-dependent delays of photons or neutrinos, none of which has been detected to date.

On their way to us, very-high-energy gamma rays can be absorbed through collisions with optical and infrared light emitted by stars that turn them into electron-positron pairs. Measuring this modification of the gamma-ray spectra of sources, we can constrain the early history of star and galaxy formation in the Universe. Current data indicate the Universe to be more transparent to gamma rays than previously thought. In this process the gamma rays are not fully lost, and their energy should reappear in the form of gamma-rays of lower energy. Combining observations in the GeV band and in the TeV band, the reprocessed gamma rays were found absent in some sources. Magnetic field in intergalactic space may have caused deflection of the electrons and positrons, and the reprocessed low-energy gamma rays are no longer propagating toward us. Some of the lost energy may also have been transferred to plasma turbulence, thereby providing a means to heat the intergalactic plasma.

The recent observation with IceCube of cosmic high-energy neutrinos was named the Physics World breakthrough of the year 2013. Neutrinos pass through matter largely without interaction, and so they are unique messengers of physical processes in the Universe. Whereas gamma rays and other photons can be absorbed, and their site of origin thus be shielded from our view, neutrinos propagate unhindered from their sources to us. High-energy photons can be emitted by both hadrons and leptons, making the interpretation of broadband spectral measurements difficult. In contrast, neutrinos are products of cosmic-ray hadrons only. The spectrum of neutrinos can thus be related to that of ultra-high-energy cosmic rays, essentially all of which are hadrons, and can serve as a probe of cosmic rays at very large distances, from where very-high-energy gamma rays cannot reach us.

The energy spectrum and composition of ultra-high-energy cosmic rays was recently determined with unprecedented precision. The spectrum exhibits a cut-off at the highest energies which in principle was expected on account of interactions between cosmic protons and the cosmological background. Given the substantial nuclear contributions at ultra-high energies, this cut-off could also reflect the maximum energies that can be obtained from the dominant acceleration process. The notion of maximum possible acceleration energy for cosmic nuclei would give new insight into ultra-high astrophysics and reveal important new aspects of the accelerator sites.

4. Particular Role/Strengths of research groups in Germany

Together with the United States of America, Italy, and France, Germany plays a leading role in high-energy astrophysics. A number of Max-Planck institutes and two Helmholtz Centres have established themselves as international pillars of this research area. In addition, 58 professors at 20 universities in Germany are engaged in high-energy astrophysics and significantly contribute to this vibrant field. The connection between the Max-Planck institutes, the Helmholtz Centres, and the universities is fertile and strongly adds to the strength of the field. The Helmholtz-Alliance for Astroparticle Physics, HAP, has been a successful instrument in forming a coherent and strong research community within Germany. This strength manifests itself in leading role in the key experiments of the fields, such as in the gamma-ray telescopes H.E.S.S. in Namibia and MAGIC on the Canary Island of La Palma, the operation of 6 German LOFAR stations in tandem with Effelsberg, one of the world's largest steerable radio telescope, neutrino telescopes like IceCube and ANTARES/KM3NeT, and the Pierre Auger Observatory, the largest detector for ultra-high energy cosmic rays. With leading involvements in future installations, such as the Cherenkov Telescope Array (CTA), a new ground-based gamma-ray observatory, and IceCube-Gen2 and KM3NeT, the next-generation neutrino observatories, and the upgrade of the Pierre Auger Observatory, AugerPrime, the community is poised to continue its strong impact in this area of research. Germany has been directly involved in the *Fermi* mission via its Gamma-Ray Burst Monitor (GBM) instrument, and German scientists actively contribute to the science activities of the *Fermi* Large Area Telescope (LAT). The recent scientific success stories in astroparticle physics in the discovery of astrophysical neutrinos and in gravitational waves (both of which had significant participation by German groups) exemplify the value of multi-messenger astronomy, as German groups have long advocated. We are on the verge of seeing this strategy pay off in a very large way. A vibrant theory community that is well integrated into the experimental efforts further strengthens the field and gives direction to the observational program.

The connection between high-energy astrophysics and laboratory astrophysics has been growing in recent years with the advent of powerful lasers. With the commissioning of the European XFEL and the HIBEF laser, this connection of astroparticle physics to a different community is expected to further develop. Areas of common interest are readily available, for example in measuring the physics of particle-accelerating shocks in the laboratory, or in understanding complex astrophysical processes, such as fluid instabilities, magnetic reconnection, or the behaviour of pair plasmas.

5. Key Infrastructures needed/relevant for Researchers in Germany

Stronger than any other field in astronomy, high-energy astrophysics is concerned with multi-messenger and multi-wavelengths observations of the cosmos. Key results in high-energy astrophysics are obtained from the interplay of radio-interferometric imaging, X-ray and gamma-ray spectroscopy, time-domain measurements and analysis at all frequencies, observations of cosmic-ray particles including neutrinos, and many other means. A strong theory wing is indispensable for developing promising experiments and fully harvesting their scientific return. Given the increasing trend towards large international research infrastructures, the key requirement for a strong German role in high-energy astrophysics is a balanced access to the leading observational facilities in all different wavebands. The connection between high-energy astrophysics and gravitational-wave physics with existing and planned ground-based or space-borne observatories should be strengthened to exploit the potential of the multi-messenger approach to the understanding of merging compact objects. Likewise, significant arise between high-energy astrophysics and nuclear astrophysics.

In the coming decades, the dominant global infrastructure in the radio regime will be the Square-Kilometer Array (SKA), which will be constructed on two continents (Australia and South Africa). Many science goals of the SKA project fall under the umbrella of high-energy astrophysics, such as tests of gravity with pulsars and black holes, studies of cosmic magnetic fields, cosmology, and transient radio sources. Scientifically, Germany is in a premium position to participate in the SKA, given its strong tradition in radio astronomy, the broad and healthy German radio astronomical community, and its strong involvement in the SKA precursor LOFAR. We note with concern that federal investments in SKA are not foreseen at this point, which, if sustained, will have detrimental consequences for the German astrophysics community and also the involvement of German industry.

Germany is leading the upcoming X-ray mission eROSITA, which is planned to be launched in 2017. It is going to perform the first imaging all-sky survey in the medium-energy X-ray range up to 10 keV with an unprecedented spectral and angular resolution. Germany also plays a major role in Athena, an X-ray observatory projected as large mission in the ESA science program. In the next decade, eROSITA will be one of the most important high-energy astronomical missions and will bring Germany into an excellent situation for the following era, which will be dominated by Athena. A continued strong support for eROSITA is highly desirable.

Since the beginning of ground-based TeV gamma-ray astronomy, Germany has played a strong role in this field. The BMBF *Verbundforschung* has supported the German involvement in H.E.S.S. and MAGIC and the preparation for CTA. In the upcoming CTA era, a continued support model is needed, allowing German universities and other institutes to define the final design of CTA and to get into a position to exploit the full potential of this new facility. In particular, the question of common funds to be contributed to the international CTA consortium has to be solved.

The availability of funding for operational costs is a generic problem (in particular for university groups) that applies not only to CTA. The instrument *Verbundforschung* primarily covers building an experiment or an observatory and not running it, which leaves a gap to the mission of DFG that the in-house budget of university groups is too small to bridge.

A high-energy astrophysical key facility of the past decade has been the Fermi Gamma-Ray Space Telescope with its two main instruments the LAT and the GBM. After more than seven years in orbit, both instruments are fully functional, and the mission is planned to be continued for several years to come. LAT science benefits dramatically from the long multi-year time baseline of data available now and from the development of the new Pass-8 event processing, which has increased the LAT sensitivity and expanded its scientific reach to lower and higher energies. At this time, no direct follow-up mission in the GeV gamma-ray regime is foreseen, but several initiatives are underway to investigate the underexplored MeV band, in which cosmic nucleosynthesis can be studied, and nuclear tracers permit key insights into the enrichment of the universe with the chemical elements heavier than helium. Designs for a MeV gamma-ray telescope are currently being discussed as a possible ESA M5 mission (eASTROGAM). A German involvement is highly desirable, in particular in anticipation of synergies with Athena in the X-ray regime and CTA at TeV energies.

Given the excellent German track record in operating and harvesting the neutrino-telescopes ANTARES and IceCube, and given the recent breakthrough in the detection of extraterrestrial high-energy neutrinos, it is highly desirable to maintain Germany's position for the next generation of facilities: IceCube-Gen2 and KM3NeT. The goal for the new generation of neutrino telescope is to deliver statistically significant samples of astrophysical neutrinos at high energies with sufficient angular resolution to enable detailed spectral studies and the detection of neutrino point sources.

Measurements of ultra-high energy cosmic rays have an outstanding record in Germany. The energy spectrum and the nuclear composition measured with the Pierre Auger Observatory have boosted ultra-high energy astrophysics. The upgrade to *AugerPrime*, geared toward better nuclear identification, is expected to provide significantly refined information on acceleration sites and processes.

A continued investment in theoretical high-energy astrophysics is indispensable for maximising the scientific return on the substantial German investments in experimental hardware and observational programs. A vibrant theory community will also give direction to the research program of the coming decades. Efforts should be made to appropriately anchor kinetic theory describing particle transport and acceleration, as well as non-thermal radiative processes, in the research landscape. A large part of theoretical investigations is conducted in the form of extensive computer simulations and involves other numerical techniques, for which continued access to high-performance computing centres is a must. Codes are so advanced that their maintenance and development represents a heavy burden for individual professorial groups at German universities. Structures should be found that provide resources for joint algorithm development and code optimisation.

6. Conclusions

Researchers engaged in high-energy astrophysics explore the fundamental processes of energetic particles and their interactions from sub-atomic scales to the largest structures in the Universe. High-energy astrophysics has successfully established itself at the interface of astrophysics, plasma physics, particle physics, and cosmology, where central questions of these areas of research meet that cannot be individually addressed by each of these science disciplines.

A characteristic trait of high-energy astrophysics is its diversity. Long is the list of sources that are studied, and many are the messengers, including photons across the entire electromagnetic spectrum, cosmic rays, and neutrinos. The fundamental processes governing the acceleration, the transport, and the interactions of energetic particles are similar in different cosmic environments, but the parameters vary, and so does the nonlinear interplay between these processes. Recognising those relations permits researchers to extrapolate insights gained in the study of, e.g., supernova remnants to further our understanding of black-hole systems. The scientific challenges in high-energy astrophysics inspire young men and women to very intensively engage in technology, research, and development, and they can be a decisive factor for their enrolling in MINT programs.

Over the last decade, high-energy astrophysics has experienced a series of breakthroughs, including the detailing exploration of the sky in high-energy gamma rays and opening of a new window to the

Universe through the first detection of cosmic high-energy neutrinos. The properties of dark matter are now constrained more than a factor 10 better than they were 10 years ago. Spatially resolved gamma-ray studies of Galactic particle accelerators are conducted with unprecedented sensitivity. A substantially gain in knowledge was achieved through the development of new methods and scientific instruments. Similar advances are to be expected in the future, and both technical progress and recent scientific insight pave the way. The scientific community in Germany has a well-defined plan for high-energy astrophysics in the next decade and beyond, that is based on careful consideration of scientific potential, the fundamental character of the scientific questions, the strengths of German research groups and institutions, and financial aspects.

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