Astronomy from Space

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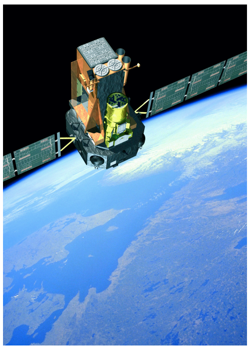
Executive summary

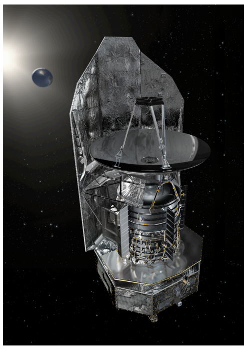
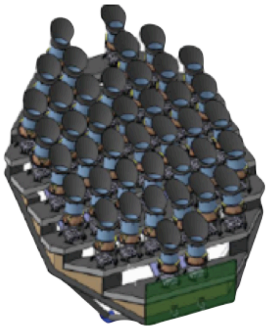
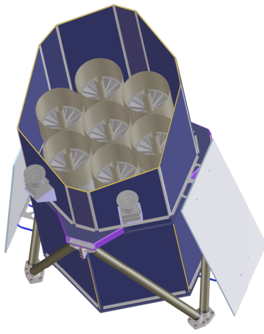
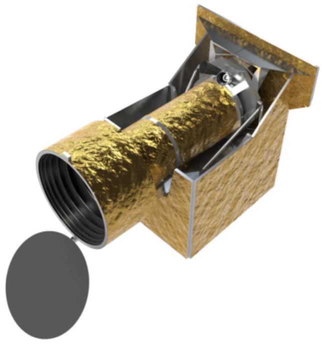
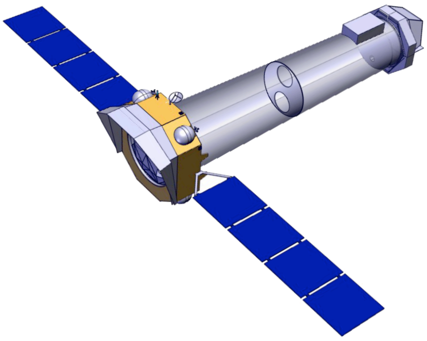
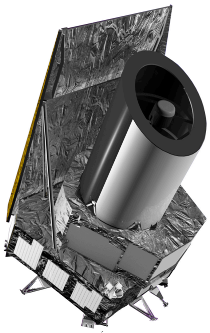
Space astronomy, i.e., the development and scientific exploitation of astronomical facilities in space, is one of the major tools of modern multi-wavelength astrophysics. Facilities with sensitive from the radio through the MeV band are heavily used by the German astronomical community. Germany is one of the leading countries in Europe and contributes hard- and software to most if not all all future European astronomy and astrophysics missions. Amongst others, Germany is responsible for the eROSITA-instrument on Spectrum-X-Gamma, contributes to the focal plane instrumentation of the next cosmology mission, Euclid, hosts the principle investigator of ESA's future facility for exoplanet studies, PLATO, as well as the principle investigator of ESA's next large X-ray astronomy mission, Athena. The dominant science cases in space astronomy in the next 15 years are therefore in the area of the characterization of extrasolar planets as well as in observational cosmology.

Introduction

The subject of space astronomy as defined in this White Paper is the development of hardware and analysis tools for and the use of facilities which perform astronomical observations from space.[1] Due to the high inherent cost of space hardware, it is only used when scientific goals cannot be reached by ground based means. This is the case either when a science case requires observations in a band of the electromagnetic spectrum that is not reachable from ground, such as the (far) infrared, the UV, or the X-rays and gamma-rays, or when atmospheric effects would be detrimental to an observations, i.e., high spatial resolution optical observations or high photometric stability. Due to the high cost and challenging technology, space based astronomy is characterized by a very high level of international collaboration, both on the side of the development of instruments and missions. The level of international collaboration is also very high on the side of data exploitation and scientific analysis. In Germany, this means that the major emphasis in hardware development is to provide (leading) contributions to missions of the mandatory science program of the European Space Agency. In addition, there is a small number of bilateral collaborations. Currently the most important of these is the German-Russian eROSITA experiment, although Germany has also contributed hardware to NASA missions such as Chandra and missions from other space agencies.



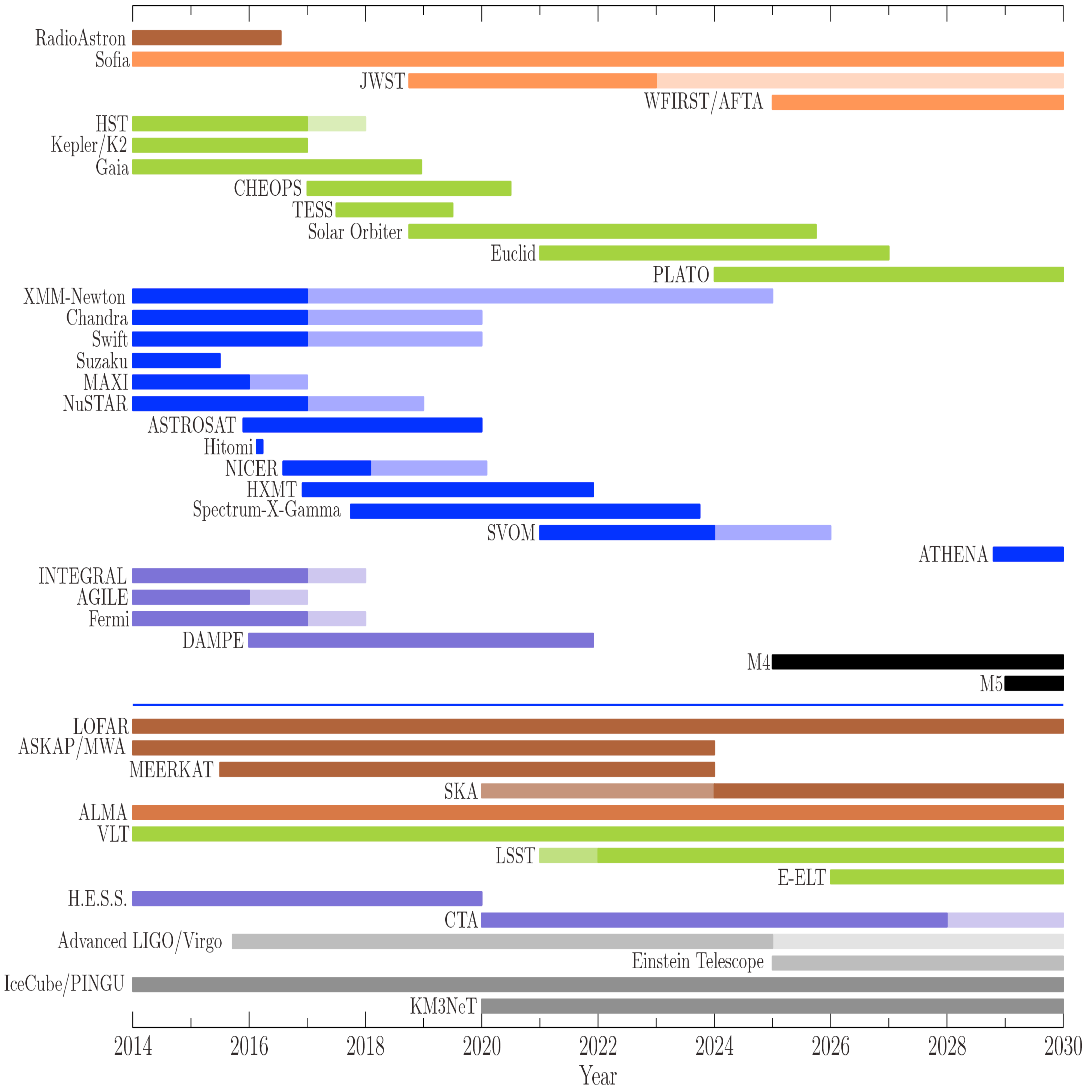
1 Due to the scope of the decadal survey, we exclude planetary missions and solar system science in this White Paper.

Space astronomy is characterized by very long lead times before mission implementation. As an example, technology development for Europe’s next major X-ray mission, Athena, started in the 1990s, with a mission selection in 2014 for a launch in 2028. A typical development cycle for a space mission is therefore comparable to a significant fraction of the scientific lifetime of an astronomer and therefore this paper includes information for missions scheduled up to the year 2030.

In Germany, space astronomy is primarily funded by the Raumfahrt-Agentur of the Deutsches Zentrum für Luft- und Raumfahrt, with MPG and other non-university large research organizations such as the Helmholtz Society also providing significant additional internal funding. On a smaller scale, Universities provides internal funds matching the resources received. The field is under the auspices of the Bundesministerium für Wirtschaft und Energie, rather than the Bundesministerium für Bildung und Forschung, which is responsible for ground based astronomy.

Upcoming Facilities in the Coming Decade



Current and future approved space facilities. Colors indicate the wave band (dark brown: radio, orange: IR, green: optical, blue: X-ray, purple: gamma-ray). Black bars indicate the current estimate for the operations of the ESA M4 and M5 missions. Timelines for a selected list of important ground based facilities are shown below the blue line.

The Figure gives an overview of the major current and (approved) future facilities of space astronomy, comparing them with the time lines of major future facilities of ground based astronomy and astroparticle physics. The strength of Germany in space astronomy is best summarized by the fact that German astronomers are strongly involved in the the majority of all future space missions shown in the figure. In addition, based on the previous track record of, it can be anticipated that the German community will also be active in the exploitation of data from virtually all missions listed in the Figure.

In the following, we describe missions with German contributions and anticipated launch date before 2030 in greater detail:

Cheops is a small mission from ESA that will be launched in 2018. Its aim is to measure the radii of known exoplanets using high precision photometry. Cheops has three German CoIs from the DLR Institut für Planetenforschung, which provides electronics for the mission.

Spectrum-X-Gamma/eROSITA: Built under the PIship of MPE (Peter Predehl) and with contributions from AIP and the Universities of Hamburg, Tübingen, and Erlangen-Nürnberg, the German eROSITA instrument on the Russian Spectrum-X-Gamma satellite will be launched in 2017 in order to survey the X-ray sky in the 0.5keV–10keV band. Following up on the previous German ROSAT mission, eROSITA will find approximately 100000 galaxy clusters and 2Million AGN in a four year long survey phase, in order to obtain an independent measurement of the cosmological constant. eROSITA will perform the by far deepest and most sensitive X-ray survey ever done. The four year survey phase will be followed by a pointed, observing proposal-driven phase. Significant ground based follow up is required to determine the redshifts of the sources detected with the instrument.

The **James Webb Space Telescope** (JWST) is NASA's next space observatory. It is currently scheduled for launch in October 2018. The 6.5m telescope will provide sensitive imaging and spectroscopic data in the long-wavelength optical to mid infrared, with a special emphasis on cosmological observations (first stars, reionization, galaxy formation), but providing capabilities in all areas of optical astronomy. Germany contributed to the development of the Mid-Infrared Instrument on JWST, MIRI (lead institute: UK-ATC, German contributions from MPIA), and to the development of the Near Infrared Spectrograph NIRSpec (prime contractor: Airbus Defence and Space Germany, Ottobrunn; contributions from MPIA [Hans-Walter Rix]).

Solar Orbiter is the first mission of ESA's Cosmic Vision program, with a planned launch date in 2018 and some NASA contributions. The mission will study fundamental plasma physical processes in the heliosphere and the solar corona through in-situ measurements, with the aim of studying the physics driving the solar wind, the origin of the coronal magnetic field, the particle acceleration in the solar corona, and the functioning principle of the solar dynamo. The spacecraft will carry 10 experiments, including optical, EUV, and X-ray imagers and spectrometers, and various particle detectors. Germany contributes the polarimetric and helioseismic imager (PHI; PI Sami Solanki, MPS Göttingen).

Euclid: To be launched in 2020, ESA's Euclid mission will determine the acceleration of the universe through a deep photometric redshift of an area of 20000 square degrees (the extragalactic sky at $b>30^o$) with two instruments behind a 1.2m telescope: the visible imager VIS and a near infrared spectrometer and photometer, NISP, which is built with contributions by MPE and MPIA. The ground segment of the mission will have contributions from MPE, AIfA, and USM. The survey is seen as the low-redshift, 3-dimensional analogue and complement to the map of the high-redshift Universe provided by ESA's Planck mission. Euclid will measure shapes and redshifts of galaxies and galaxy clusters out to $z\sim2$ and probe both, weak gravitational lensing and baryonic acoustic oscillations. The mission will be operated as an experiment, which will release a huge imaging and spectroscopy dataset as its legacy, and strongly relies on ground based follow up observations.

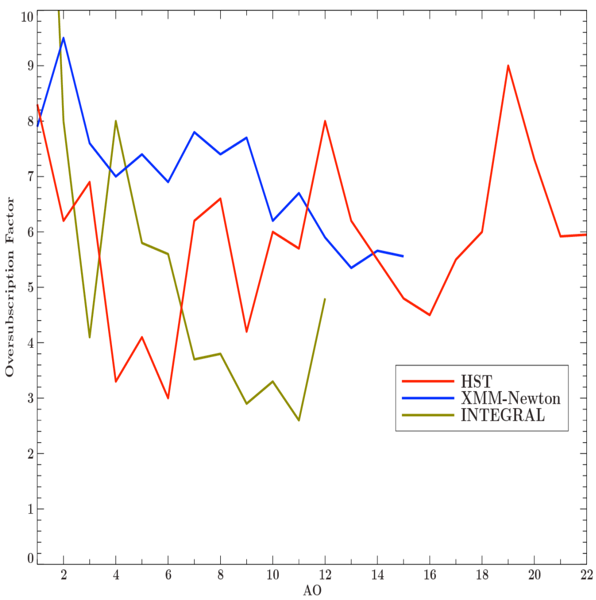
SVOM, the Space-based multiband astronomical Variable Objects Monitor, is a joint Chinese-French mission dedicated to the prompt detection and study of Gamma-ray bursts, with a planned launch in 2021 and a three year mission duration. The prime instrument is the French Eclairs telescope, a coded mask instrument with a field of view of 2sr in the 4–150keV band and a GRB location accuracy of ~16'. Through MPE, Germany contributes X-ray detectors to the Multi-channel X-ray telescope, which is sensitive in the 0.2–10keV band and will be used to follow up GRBs detected with Eclairs.

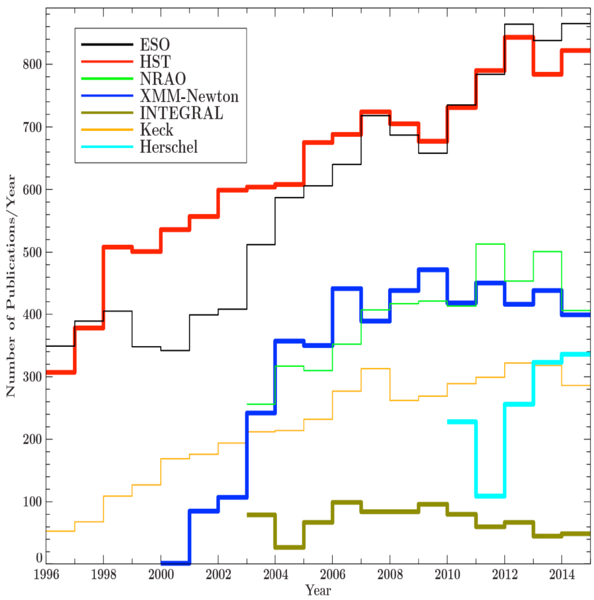
PLATO: With a launch in 2024, PLATO is a M-class mission led by DLR's Institut für Planetenforschung in Berlin (PI: Heike Rauer). Its aim is to detect and characterize exoplanets, specifically to measure their mass, radius, and age, including terrestrial planets in the habitable zone. These goals will be reached using high precision photometry, which will yield planetary radii and stellar lightcurves. Asteroseismological studies will give stellar masses, radii, and ages. Combined with ground based radial velocity measurements PLATO will also allow to measure planetary masses. PLATO will survey fields in the sky from a few months up to 3years each. Field and target selection will involve the community to select the best science cases. In addition, a guest observer program will allow for non core-science cases. Together with the large number of observed stellar lightcurves, these data will provide a huge legacy for planetary, stellar, and Galactic science. The data set on stellar patameters will complement the Gaia catalogue.

Athena, a large X-ray observatory, is the second L-class mission, with a planned launch date in 2028. Athena is the successor to ESA's successful XMM-Newton satellite, with a significantly improved collecting area (2m^2) and spectral sensitivity in the 0.5–10keV band. Athena's main science goals are the search for the missing baryons through absorption spectroscopy, studies of the large-scale structure of the universe through deep observations of X-ray fields, and studies of general relativity in the strong field limit. Athena will be operated as an observatory, with most of the available time dedicated to guest observers. The satellite will carry two instruments, the Wide Field Imager (WFI) and the X-ray Integral Field Unit (X-IFU). The WFI is developed under the leadership of MPE (PI: Kirpal Nandra), further German contributions come from the Universities of Tübingen and Erlangen-Nürnberg. It has good spectral resolution comparable to todays solid state detectors, 5" spatial resolution and a 40' field of view. The X-IFU is a transition edge sensor array with a field of view of 5' and a very high spectral resolution of 1.5eV. Germany provides a small contribution through the University of Erlangen-Nürnberg.

We note that in the post INTEGRAL and Fermi era there will be an evident lack of instruments with sensitivity above 50keV. With the demise of HST there will also be no coverage available in the UV, and there will also be a gap in the far infra-red. Another challenge for the next decade is that many of the missions will require significant ground follow up.

Main Achievements in the Past Decade





Germany has been a strong player in space astronomy for the past decades, with early highlights such as the German contributions to EXOSAT, the successful ROSAT mission, or the ORFEUS instrument, amongst many others. The current operational facilities of space astronomy with German contributions enjoy continued high oversubscription rates, and have a very high productivity that is comparable to large ground based observatories). German papers continue to be among the very highly cited ones from these facilities. For example, seven of the twenty most cited papers from XMM-Newton have first authors from German institutions.

The **Hubble Space Telescope** (HST) is the current work horse of space-based optical astronomy. HST is a 2.5m telescope which was launched in 1990. It is the most productive observatory facility world wide. While HST as the major optical/UV facility is used by all groups in optical astronomy, the German strength in the area of modeling stellar atmospheres has been evident. As the only UV facility in the forseeable future, HST observations under German leadership have driven extensive modeling efforts in this area. However, German proposers to HST have been successful in virtually all fields of astronomy, from planetary formation to the study of the epoch of reionization.

A second OIR project with strong German contributions is **SOFIA**, a joint NASA-DLR project. It consists of a Boeing 747 aircraft that was converted into an infrared observatory. While formally not space based, it is included here since the German contributions to SOFIA, including 20% of the operating costs, are coordinated by DLR. SOFIA carries a German-built 2.5m telescope and instrumentation for imaging, spectroscopy, polarimetry and variability in the infrared (1–210μm), including the German-built Far Infrared Field-Imaging Line Spectrometer (FIFI-LS; DSI) and the German REceiver for Astronomy at Terahertz Frequencies (GREAT; PI institution: MPIfR).

XMM-Newton is an ESA cornerstone mission. It was launched in 1999, is sensitive from 0.2–12keV. Through MPE Germany contributed the PI institution for the EPIC-pn camera, one of the three cameras onboard this X-ray satellite. Further German contributions came from IAAT. XMM-Newton is operated as an observatory. German astronomers have been successful in areas as various as studies of nearby galaxies (e.g., Pietsch et al., 2007, A&A 465, 364, Stiele et al., 2011, A&A 534, 55), relativistic iron lines (e.g., Duro et al., 2011 A&A 533, L3, Boller et al., 2002 MNRAS 329, L1), galaxy formation (e.g., Tüllmann et al., 2006, A&A 448, 43), galaxy clusters (Chen et al., 2007, A&A 466, 805), or deep cosmological fields (e.g., Hasinger et al., 2007, ApJS 172, 29).

In the gamma-rays, ESA's **INTEGRAL** is an imaging instrument sensitive in the X-rays to soft gamma-rays (3keV–10MeV). German institutions (MPE, IAAT) contributed to the two major instruments, SPI and IBIS, and to the ground segment. INTEGRAL is operated as an observatory, its major strengths are high spectral resolution measurements in the MeV for nuclear astrophysics (Diehl et al., 2006, Nature 439, 45), polarization capabilities (Laurent et al., 2011, Science 332, 438), and X-ray/gamma-ray monitoring capabilities, all areas with strong German contributions.

Germany was also strongly involved in the development and data analysis effort of ESA's **Gaia** satellite, with first results expected to be published in September 2016. Gaia will provide astrometric and photometric information for more than 10^9 objects, mainly in our Galaxy. It is complete to 20mag. Contrary to other missions, all instrumentation from Gaia was provided by industry. The complex data analysis, however, necessitates a far larger ground segment investment than in other missions. In Germany, the by far largest involvement in these actvities is at Heidelberg (ZAH/ARI), with smaller contributions from MPIA, AIP, TU Dresden, ZARM, and DLR.

In addition to these operative missions, many of the most prominent missions from the past decade had significant German contributions to both, their instrumentation and also to their scientific exploitation:

The Infrared Space Observatory **ISO** was the first versatile infrared observatory, with sensitivity in the 2.5μm–240μm band. It can be seen as the successor to NASA's IRAS survey. ISO was launched in November 1995 and operational until April 1998. The mission included two spectrometers for short and long wavelengths (the ISO-SWS was developed by SRON in the Netherlands jointly with MPE), the camera ISOCAM, and the photo-polarimeter ISOPHOT (developed at MPIA).

With a diameter of 3.5m, ESA's **Herschel** mission, launched in 2009, is the successor to ISO. It contained the largest telescope ever flown in space. One of its three instruments, the Photodetector Array Camera and Spectrometer for Herschel (PACS), was developed under the leadership of MPE. Herschel was operated as an observatory, so far Herschel observations have resulted in more than 1500 publications. Results from German researchers cover all areas of astronomy, from the detection of massive outflows from ultra luminous infrared galaxies (Sturm et al., 2011, ApJ 773, L16) and deep infrared observations of multiwavelength fields for galaxy evolution studies (Lutz et al., 2011, A&A 532, A90) to studies of the water torus of Saturn's moon Enceladus (Hartogh et al., 2011, A&A 532, L2).

ESA's **Planck** mission was launched together with Herschel. The satellite provided a 30months long survey of the 3K Cosmic Microwave Background. German scientists provided significantly to the development of the simulation and data analysis pipelines for this experiment, which led to the up to now best determination of the cosmological parameters (Ade et al., 2014, A&A 571, 16).

The **CoRoT** mission was operational between 2007 and 2012. It was led by CNES with smaller contributions from other countries, including Germany. It consisted of a 27cm diameter telescope with a field of view of 2.7º x 3.05º, dedicated to long-term photometric monitoring of stars to search for exoplanet transits in bright stars and to perform asteroseismological studies.

Finally, German astronomers are strong users of international facilities, such as Chandra, Fermi, NuSTAR, RadioASTRON, Spitzer, Kepler/K2, Suzaku, or Swift. As an example, German PIs contributed 18% of all non-US proposals submitted to Chandra's AO16.

Particular Role/Strengths of Research Groups in Germany

Selected German institutions participating in developments for space astronomy.

Germany is a very strong participant in space astronomy, both as a user and developer of space instrumentation. In total 16 research institutions are currently contributing hard- or software to future astrophysics missions.[2] Hardware efforts are clearly led by Max Planck institutes and DLR institutes, with the strongest institutions being MPE (X-ray, infrared), MIPA (optical), MPS (solar system instrumentation), and DLR Berlin (solar system, exoplanet searching). As discussed above, these

2 Hamburg: eROSITA; AIP: eROSITA, Gaia, Solar Orbiter; DLR Institut für Planetenforschung, Berlin: PLATO, Gaia; Göttingen: PLATO; MPS: Solar Orbiter; TU Dresden: Gaia; Köln: Herschel, Sofia; Bonn: eROSITA, ATHENA; ECAP Bamberg: eROSITA, ATHENA; MPIA+ZAH: Euclid, Gaia; MPA: Planck, Euclid; MPE: Herschel, Planck, eROSITA, ATHENA, XMM-Newton, Chandra, Euclid, INTEGRAL, SVOM (amongst others); USM: Euclid; IAAT: eROSITA, XMM-Newton, ATHENA, INTEGRAL; KIS: Solar Orbiter; ZARM: Gaia.

institutions also provide principle investigators for major instrumentation on the next DLR and ESA missions and regularly contribute to missions from other space agencies such as NASA. Significant contributions at subsystem level (e.g., electronics, on-board software, mission planning, simulations and low- and high-level analysis software) come from institutes in the Leibniz society as well as from universities.

The major speciality of Germany for space astronomy is in the development of new detectors for soft X-rays and their associated electronics (XMM-Newton, eROSITA, Athena), the development of instrumentation in the infrared (Herschel, JWST), and in optical cameras (Gaia, PLATO).

On the side of data exploitation of currently active space astronomy missions, as already discussed above groups from virtually all German institutions involved in astrophysics are active users of space facilities. The analysis of data from ESA missions with direct German contributions – Herschel, HST, XMM-Newton, and INTEGRAL – is considered of special German national interest and funded through the DLR Verbundforschung. This approach to funding space-based research has had a very large impact on the development of expertise in the exploitation of data from space missions.

In the area of infrared astronomy with Herschel, as well as in optical/UV astronomy with HST German astronomers are active in virtually all areas of astronomy, from the formation of stars, the physics of stellar atmospheres to black hole formation in galaxy collisions and studies of the epoch of reionization. In addition to the German ESO contributions, HST can be considered to be the second most important tool used by German IR/optical/UV astronomers.

In X-ray astronomy, German institutions are strong users of XMM-Newton and Chandra. In recent years, particular strengths have been in the area of the X-ray stellar activity, accreting neutron stars and Galactic black holes, mapping the X-ray populations of nearby galaxies, observations of active galaxies, surveys of galaxy clusters, and deep X-ray fields for cosmology. The strength of German X-ray astronomy is also seen by the success in obtaining observing time on non-european facilities. For example, 18% of the all non-US proposals to NASA's Chandra satellite were from German institutions, and German astronomers were also active users of Swift, NuSTAR, RadioAstron, and Suzaku.

In Gamma-ray astronomy, the community concentrates on X-ray binaries and nucleosynthesis observations with INTEGRAL, with additional observations mainly in X-ray binaries and AGN being performed with Fermi.

Dominant Science Cases

The dominant science cases in space astronomy for the next 15 years are clearly in two areas:

1. The characterization of extrasolar planets. Apart from the development of PLATO itself, ground based observations will be needed in order to exploit fully the data from this mission.
2. Cosmological measurements, which will be performed with Euclid, the eROSITA survey, and later with Athena. Again, ground based observations will be instrumental in order to allow the full exploitation of data from these missions.

We emphasize that in addition to these primary science goals, all of these missions will provide a large amount of that will impact many fields of astronomical research. This is true for both, missions that will be operated as observatories or will have an observatory phase (e.g., Athena, eROSITA), or PI-led facilities. As an example, while the primary science goal of eROSITA is the measurement of the cosmological constant through detecting galaxy clusters, the mission is expected to provide X-ray data on 300000–500000 stars, allowing to measure X-ray properties of stellar populations through a volume limited sample in the solar neighborhood, studying young stellar objects in star forming regions, including their flaring behavior, and studying stellar variability on months to years timescales (Merloni et al., The eROSITA Science Book, arXiv:1209.3114). For PLATO, the mission will result in a leap forward in measured basic stellar parameters with consequences throughout Galactic stellar astronomy, while Euclid's huge database of properties of Galaxies properties is expected to revolutionize extragalactic astronomy research.

Space based missions are also required in all areas of astronomy where multi-wavelength or even multi-messenger data are needed. Space observations therefore also contribute significantly to the science cases in other areas of astronomy and astroparticle physics. For example, studies of blazar jets require broad-band observations from the radio radio over the IR, optical, X-rays, gamma-rays out to ground based Cherenkov-telescopes in order to constrain their physics, while observations of a large variety of TeV emitters need to be supplemented with imaging information in the X-rays, and gravitational wave detections will need follow up observations throughout the electromagnetic spectrum in order to allow the astrophysical interpretation of the data.

Summary and Conclusion

In the past decades, space astronomy has evolved from being a specialized nishe science to be part of the main stream of observational astronomy. Virtually all astronomical institutes in Germany make use of space facilities, either as their main source of observational data – as is the case for X-ray, gamma-ray, UV- or far IR astronomers – or as indispensable data for multiwavelength studies. The large databases of observations that will become available for scientists with the next generation of missions will continue this trend.

At the same time, however, the number of available space observatories will decrease with respect to the current decade. This change will change the way how astronomers work, with a general trend from individual, proposal driven research, to large-scale collaboration driven endeavours. Despite this trend, continued funding through the Verbundforschung for proposal-driven research is recommended to continue.

On the side of space instrumentation, Germany is particularly strong in optical/IR instrumentation and in soft X-ray instrumentation. As a result, German astronomers have been very successful in achieving principle investigator status for some of the most important missions or main instruments of these missions, including eROSITA/Spectrum-X-Gamma, Plato, Euclid, and Athena. Although the leading role of MPI and DLR institutes is recognised, University involvement in the development of hardware and software related to space-mission should continue to be encouraged and supported.

An important and new aspect for future space missions is their need for ground-based support, e.g., for eROSITA, Euclid, or PLATO. The funding situation for this area is currently unclear, as DLR will in general not provide funding for ground-based observations while BMBF does not fund space mission related work.