Max Planck Institute for Astronomy

Heidelberg-Königstuhl

Annual Report

2020

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Credit: D. Elsässer

Preface

The year 2020 was for MPIA – as for the rest of the world – a drastic departure from what had come before. The Covid-19 pandemic disrupted daily routines of work and personal life, and severely limited the human contacts that are the defining elements of our community and society. At the same time this disruption provided an impetus to many of us to re-examine priorities in life. But looking back, the MPIA community coped with this year's enormous challenges in an impressive manner. Virtual and hybrid workflows were quickly established, as the institute went into temporary home office mode from one week to the next. And throughout this year, many separate individuals undertook steps to strengthen the sense of togetherness of the MPIA family even though our interactions had become virtual.

There can be no doubt that, for many, this was a difficult year. But we did manage to stay on course towards our fundamental mission as an institute – research, technical development, academic training – without significant losses. Virtual collaboration indeed proved to be a feasible way to continue existing projects and initiatives. We did learn, however, that intensive, personal, direct exchange is still an unrivalled mode of communication when it comes to developing new ideas, resolving conflicts, strengthening trust and sharing enthusiasm.

On the bright side, 2020 was a spectacular milestone for the Institute: half a century after MPIA was founded, the institute opened its third scientific department. We succeeded in persuading Dr Laura Kreidberg, previously of Harvard University, to take up her post as founding director of the new department "Atmospheric Physics of Exoplanets" (APEx). This new development will allow the institute to be at the forefront of national and international research in this young and exciting field.

The year also saw numerous scientific and technological successes, from specific project milestones in instrumentation development for the Extremely Large Telescope to the release of the spectacular "EDR3" dataset from the Gaia mission, in which the MPIA played a key role. In summary: no easy year, but still a year we as an institute can be proud of.

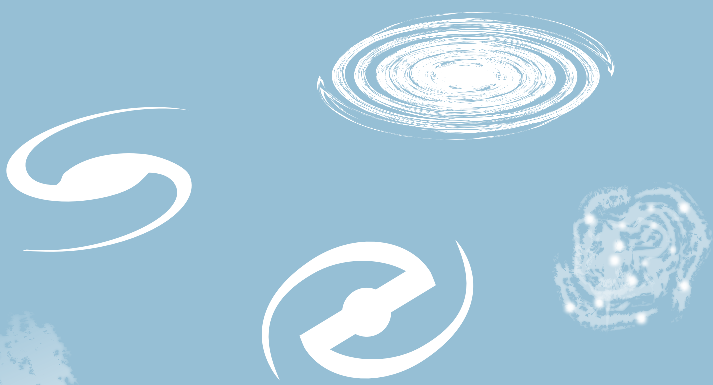
Hans-Walter Rix, Laura Kreidberg, and Thomas Henning

Heidelberg, December 2022

I. MPIA in a Nutshell

Credit: M. Pössel / HdA

Our Fields of Research: Galaxies and Cosmology

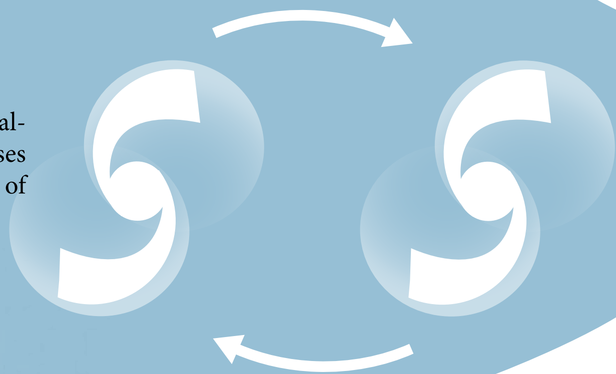


Galaxies come in many shapes and sizes. How do these differences arise? And what factors are responsible for how many stars a galaxy produces?

Our home galaxy, the ***Milky Way***, is a giant spiral galaxy with several hundred billion stars. In the Milky Way, we can study star and structure formation up close – and gather key data that can help us understand galaxy evolution.

Galaxies have ***supermassive black holes*** in their centers. How does the mass of such a black hole correlate with the total mass of a galaxy's stars – despite their totally different sizes? When and how do these black holes trigger some of the most luminous phenomena in the Universe, so-called quasars, when matter falls into them?

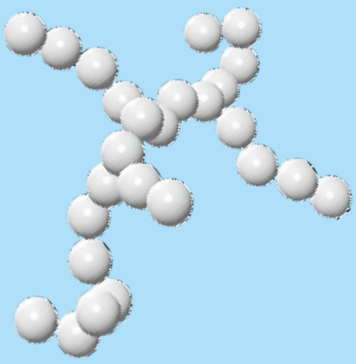
Galaxies grow as they merge with other galaxies or swallow smaller galaxies. How do these growth processes work in detail? How do they influence the properties of different types of galaxies?



How are ***dark matter*** and hydrogen gas distributed on the largest ***cosmic scales***, across hundreds of millions of light-years? How is this distribution linked to the evolution of galaxies over billions of years? How did the complex structure of our Universe arise from an almost perfectly smooth beginning?

Exoplanets and their properties, planet and star formation

Stars form when overdense regions in cold clouds of gas and dust collapse under their own gravity. Around a young star a swirling disk of matter condenses into ***planets***. How does this work in detail and how does this process produce the different kinds of planetary systems?



What are the ***stages of planet formation*** – from the first colliding ***grains of dust*** to objects thousands of kilometers across? What can laboratory experiments tell us about the properties of cosmic dust – and ways to detect these properties?

Since 1995, astronomers have discovered more than 4800 ***exoplanets*** (planets orbiting stars other than the Sun). What can these widely different planetary systems tell us about planet formation?

How can we observe and understand ***exoplanet atmospheres***? What does the data tell us about atmospheric physics and chemistry, including possible traces of life?

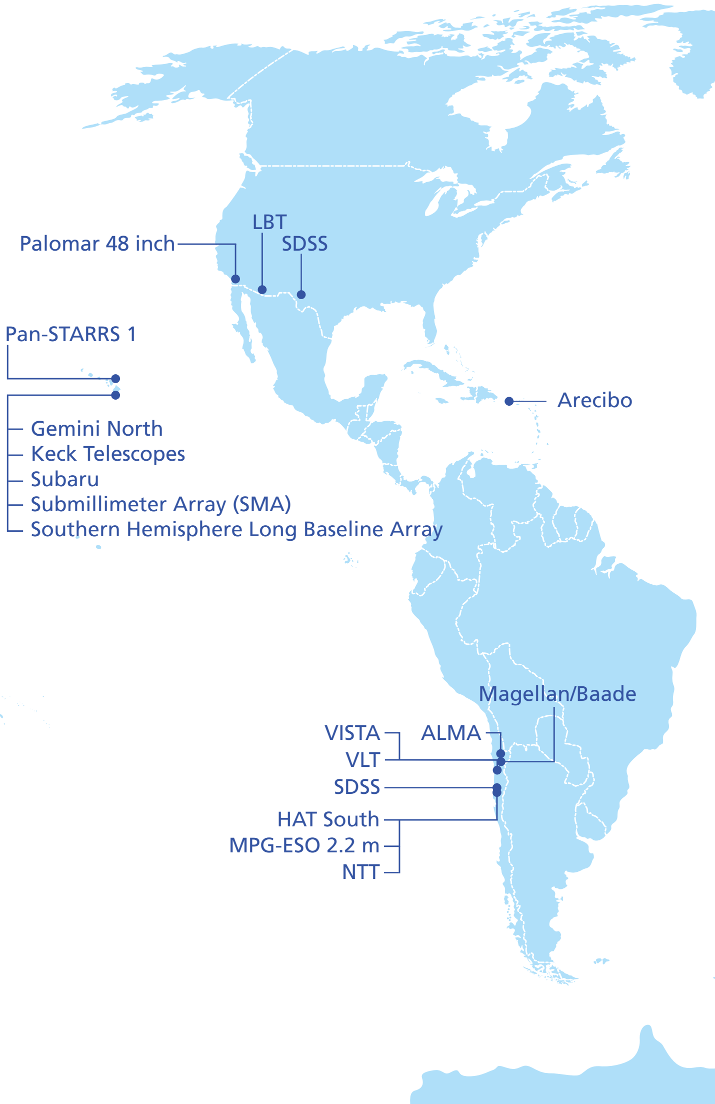
MPIA Telescopes all Over the World

The MPG/ESO 2.2-m telescope at La Silla observatory is owned by the Max Planck Society, and MPIA profits from guaranteed-time observations.

Credit: ESO / J. F. Salgado (josefrancisco.org)

MPIA researchers regularly use the ALMA observatory on the Chajnantor plateau in the Atacama desert to study the coldest and most distant objects in the cosmos. ALMA is an interferometer for observations at millimeter and submillimeter wavelengths, located at an elevation of 5000 m.

Credit: ESO

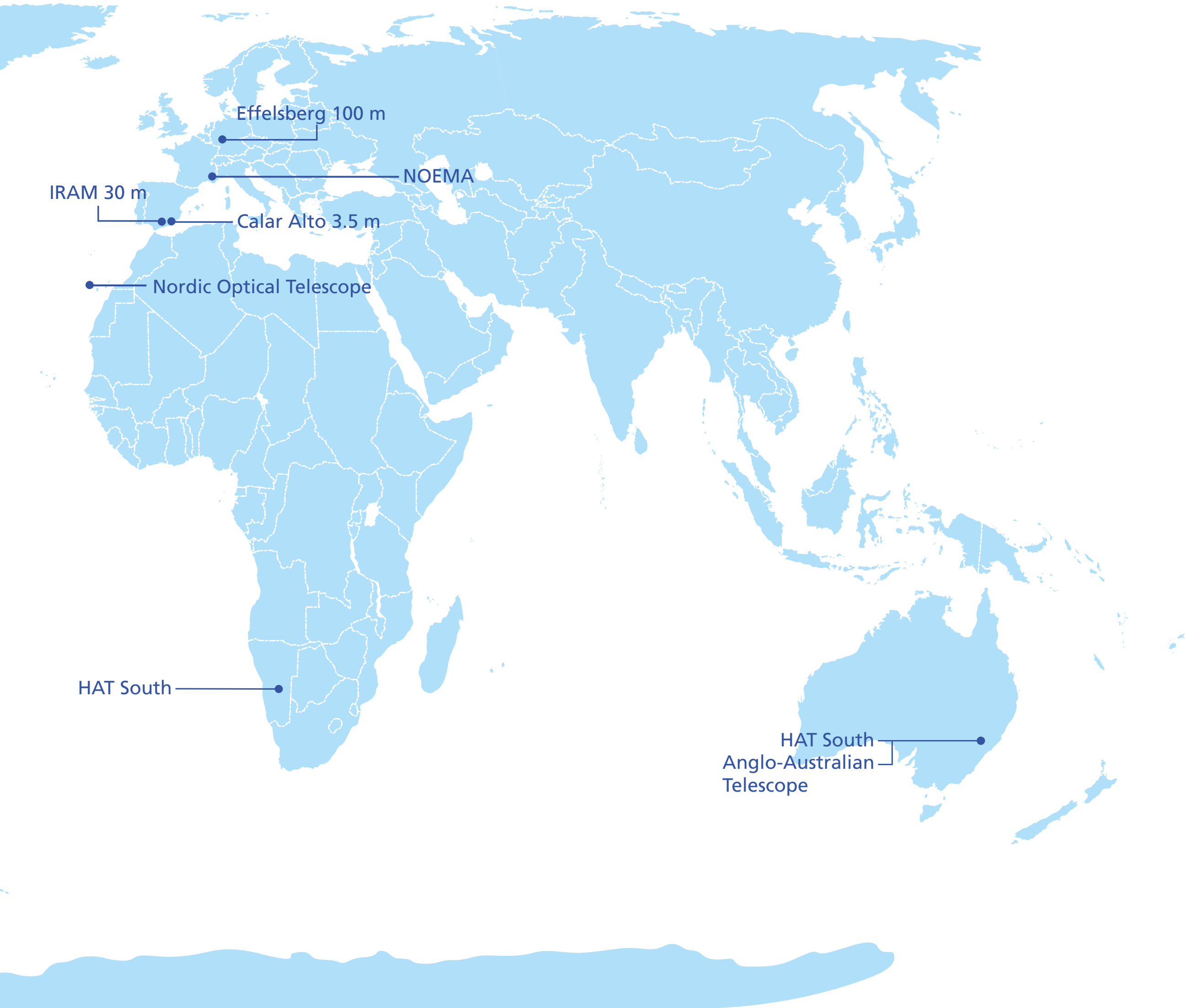


The 100 m radio telescope in Effelsberg is operated by the Max Planck Institute for Radio Astronomy. MPIA astronomers have made use of it e.g. to study star formation in nearby galaxies.

Credit: M. Pössel / HdA

With access to large parts of Earth's airspace, the flying NASA/DLR observatory SOFIA is flexible in its choice of observing location. MPIA astronomers (and others) use SOFIA for observations in the near-, mid- and far-infrared.

Credit: NASA / J. Ross



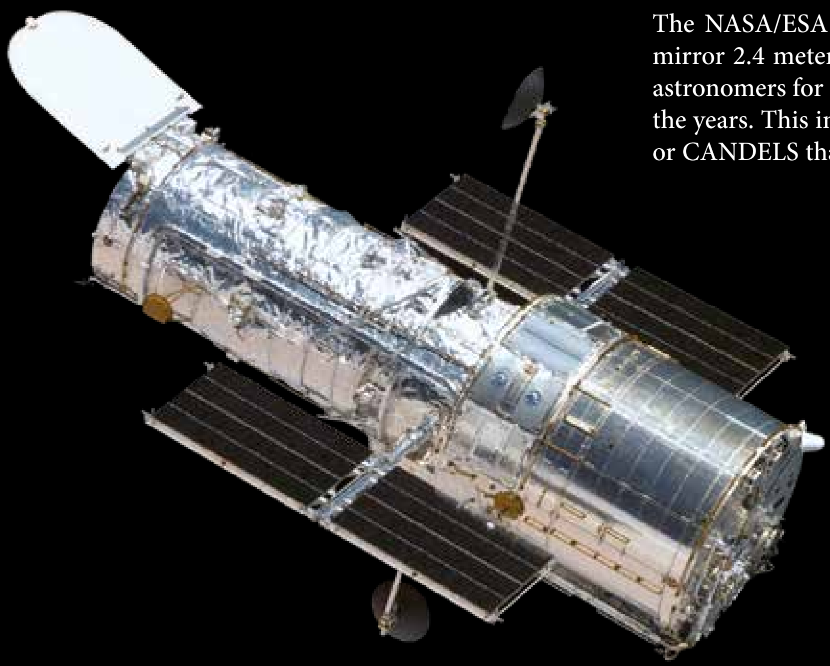
The Nordic Optical Telescope (NOT) on La Palma is a 2.56 m mirror telescope. MPIA is involved in constructing the instrument NTE, the "NOT Transient Explorer".

Credit: B. Tubbs

MPIA is a member of the Sloan Digital Sky Survey (SDSS), a spectroscopic survey using a 2.5-meter telescope in New Mexico. The survey gathers high-quality spectra of a large number of astronomical objects.

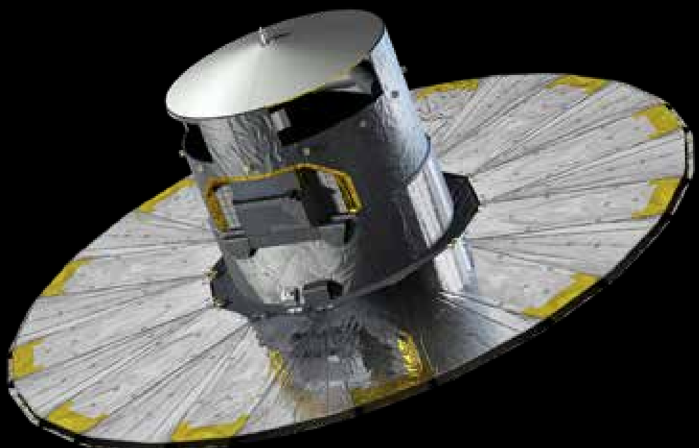
Credit: SDSS

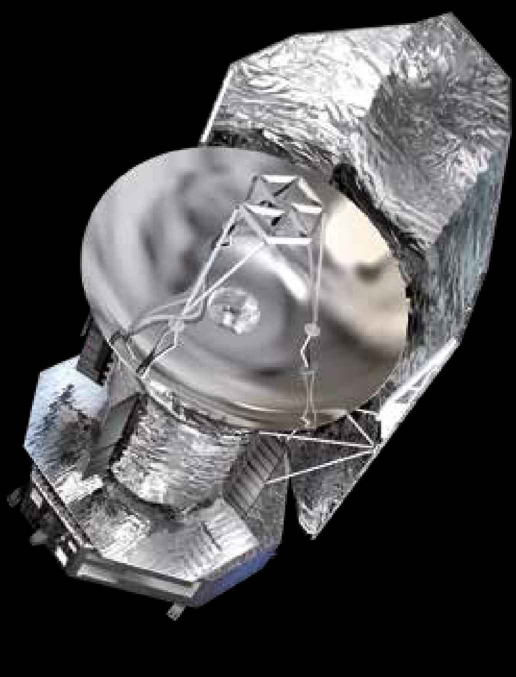
Space Telescopes



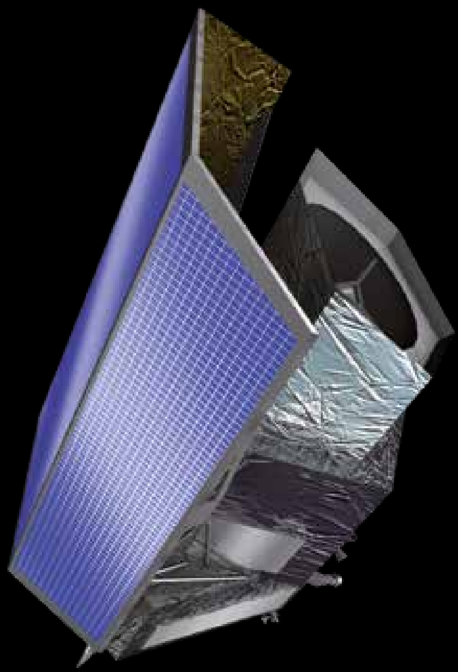
The NASA/ESA Hubble Space Telescope (with a main mirror 2.4 meters in diameter) has been used by MPIA astronomers for a variety of successful observations over the years. This includes larger surveys such as COSMOS or CANDELS that involve MPIA researchers.

ESA's astrometry satellite Gaia is measuring the distance from Earth to more than a billion stars with unprecedented precision. The MPIA Gaia group leads the effort of using this data to reconstruct the astrophysical properties of those stars, played a key role in the data releases DR2 (April 2018), EDR3 (December 2020) and DR3 (June 2022).

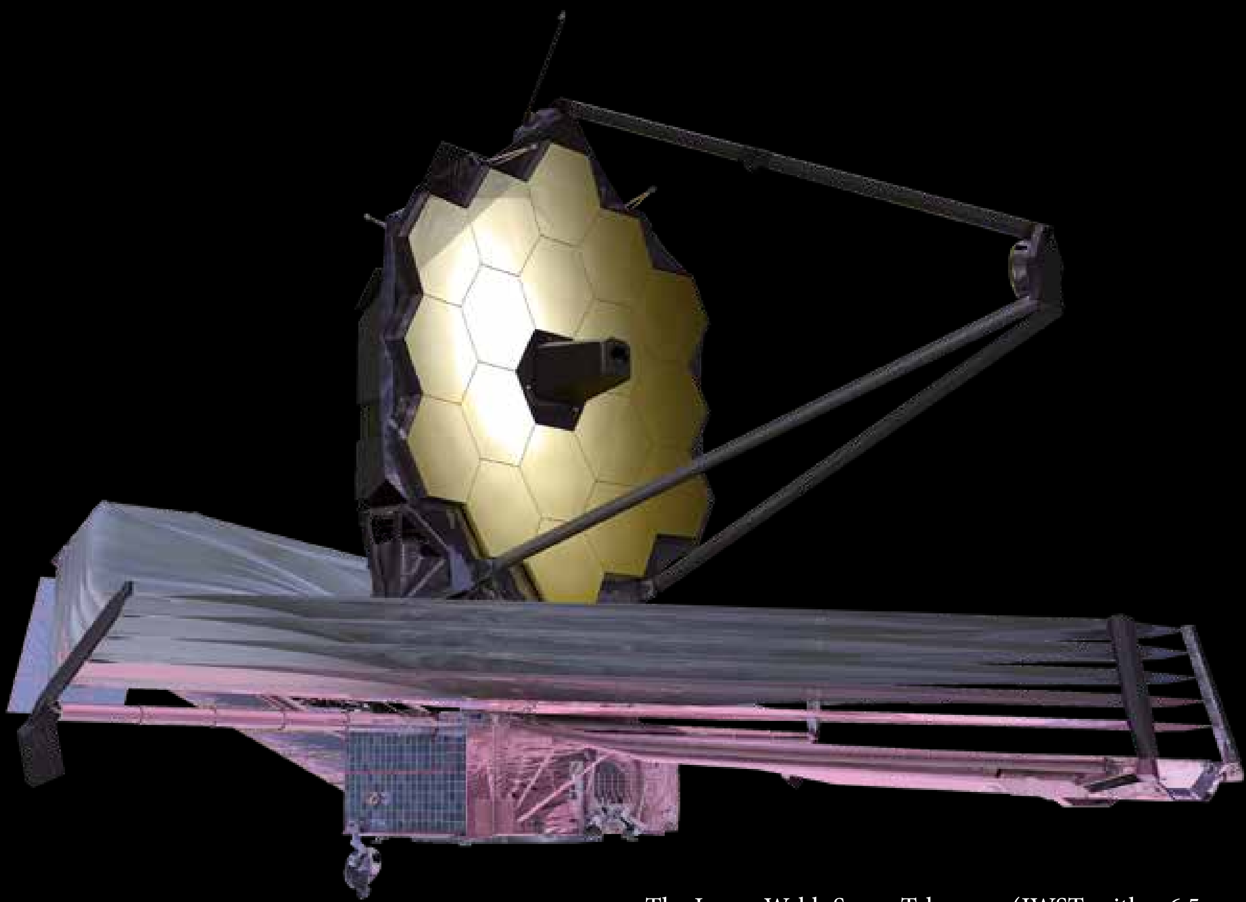




MPIA contributed to the construction of ESA's infrared observatory Herschel: We developed key components for the PACS instrument aboard the Herschel satellite, and were responsible for a number of observational programs undertaken with Herschel.



For ESA's Euclid mission, which is slated for launch in 2023, MPIA scientists have developed calibration strategies and are contributing to the construction of the near-infrared spectrometer and photometer NISP. Euclid is set to answer fundamental questions about the nature of dark matter and dark energy.



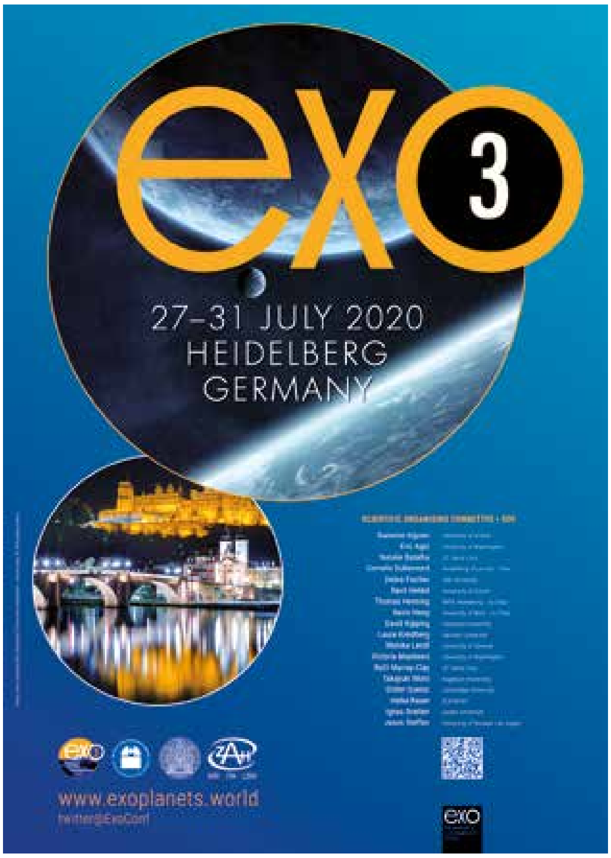
The James Webb Space Telescope (JWST, with a 6.5 meter mirror), the designated successor to the Hubble Space Telescope, to be launched in December 2021. MPIA has contributed to two of the telescope's instruments: the mid-infrared instrument MIRI and the near-infrared spectrograph NIRSpec.

Credits: NASA, ESA

Major conferences

Exoplanets III
21–31 July
Online conference

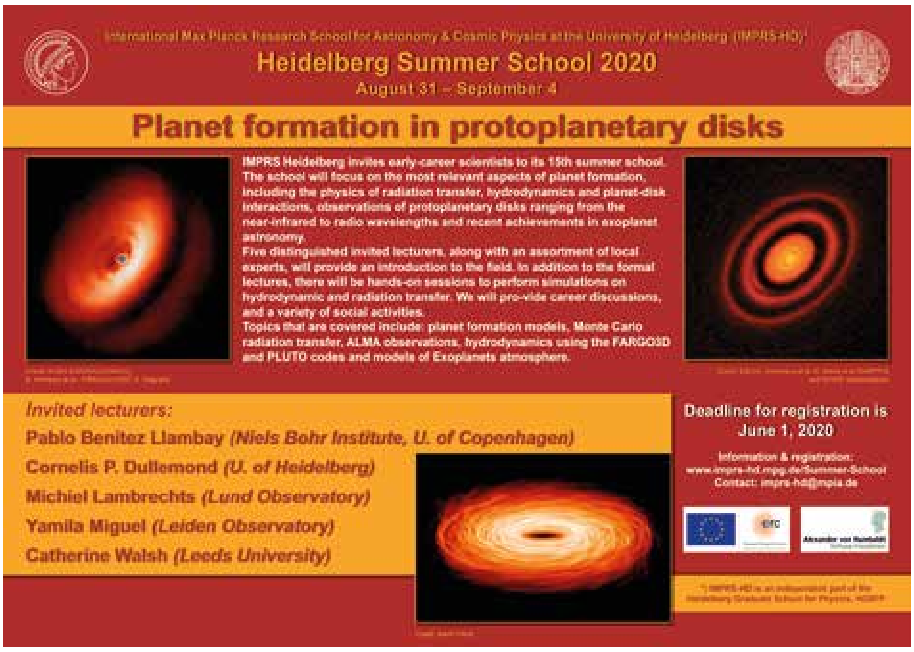
Planet Formation in Protoplanetary Disks: Heidelberg Summer School
31 August – 4 September
Online conference



Design: J. Leibundgut, Bern, Switzerland / Picture credit: Adobe Stock – sdecoret *(top)*, JFL Photography *(bottom)*

Fig. I.1: Poster of this year's IMPRS Summer School on Planet Formation in Protoplanetary Disks

Fig. I.2: Poster of the international "Exoplanets III" conference – the third in a series of large-scale, international conferences on the topic that began in Davos, Switzerland in 2016.

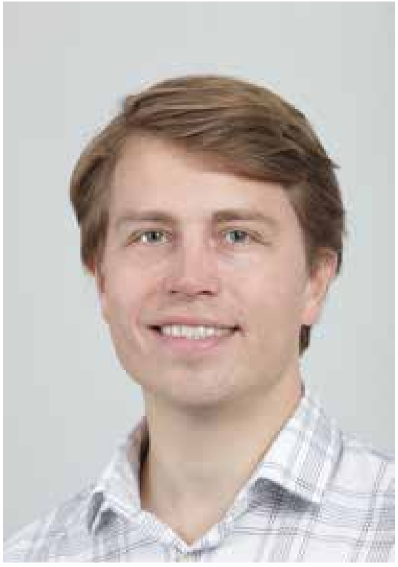


Credit: C. Fendt / MPIA

Major Grants and Awards

Credit: A. Godlinski

Paola Pinilla



Credit: M. Zamani, ESO

Richard Anderson

Credit: Private image

Nadine Neumayer

Concepción Cárdenas Vázquez
was awarded the 2020 MERAC Prize by the European Astronomical Society (EAS) for her PhD thesis

Thomas Henning
received the Gay Lussac Humboldt Prize of the French Academy of Sciences for his extraordinary contributions to astronomy, and was awarded an honorary doctorate by Lund University

Nadine Neumayer
was appointed Lise Meitner Group Leader at MPIA, as part of the Max Planck Society's Lise Meitner Excellence Program

Anna-Christina Eilers
received the Otto Hahn Medal of the Max Planck Society and the Doctoral Prize of the German Astronomical Society for her PhD work at MPIA

Gregory Maurice Green
was awarded a Sofja Kovalevskaja Award of the Humboldt Foundation worth up to 1.65 million Euros, which he will use to establish his research group in MPIA's Galaxies and Cosmology department

Richard Anderson
received an ERC Starting Grant worth 1.84 million Euros, which he will use to start his own research group at MPIA

Maria Bergemann
who leads a Lise Meitner Group at MPIA received an ERC Starting Grant worth 1.37 million Euros

Paola Pinilla
was awarded the German Astronomical Society's Ludwig Biermann Prize. The award is conferred annually on an outstanding young astronomer

Trifon Trifonov
received the "Young Scientists' Prize" of the Mathematics and Natural Sciences Class of the Göttingen Academy of Sciences for his research on exoplanets

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Patzer Prizes 2020

Neige Frankel, MPIA
for her publication "Keeping It Cool: Much Orbit Migration, yet Little Heating, in the Galactic Disk" (2020, ApJ, 896, 15)

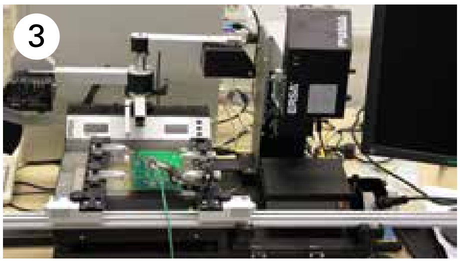
Nico Krieger, MPIA
for his publication "The Turbulent Gas Structure in the Centers of NGC253 and the Milky Way" (2020, ApJ, 899, 158)

Alessandro Savino, ZAH/ARI
for his publication "The age of the Milky Way inner stellar spheroid from RR Lyrae population synthesis" (2020, A&A, 641, A96)

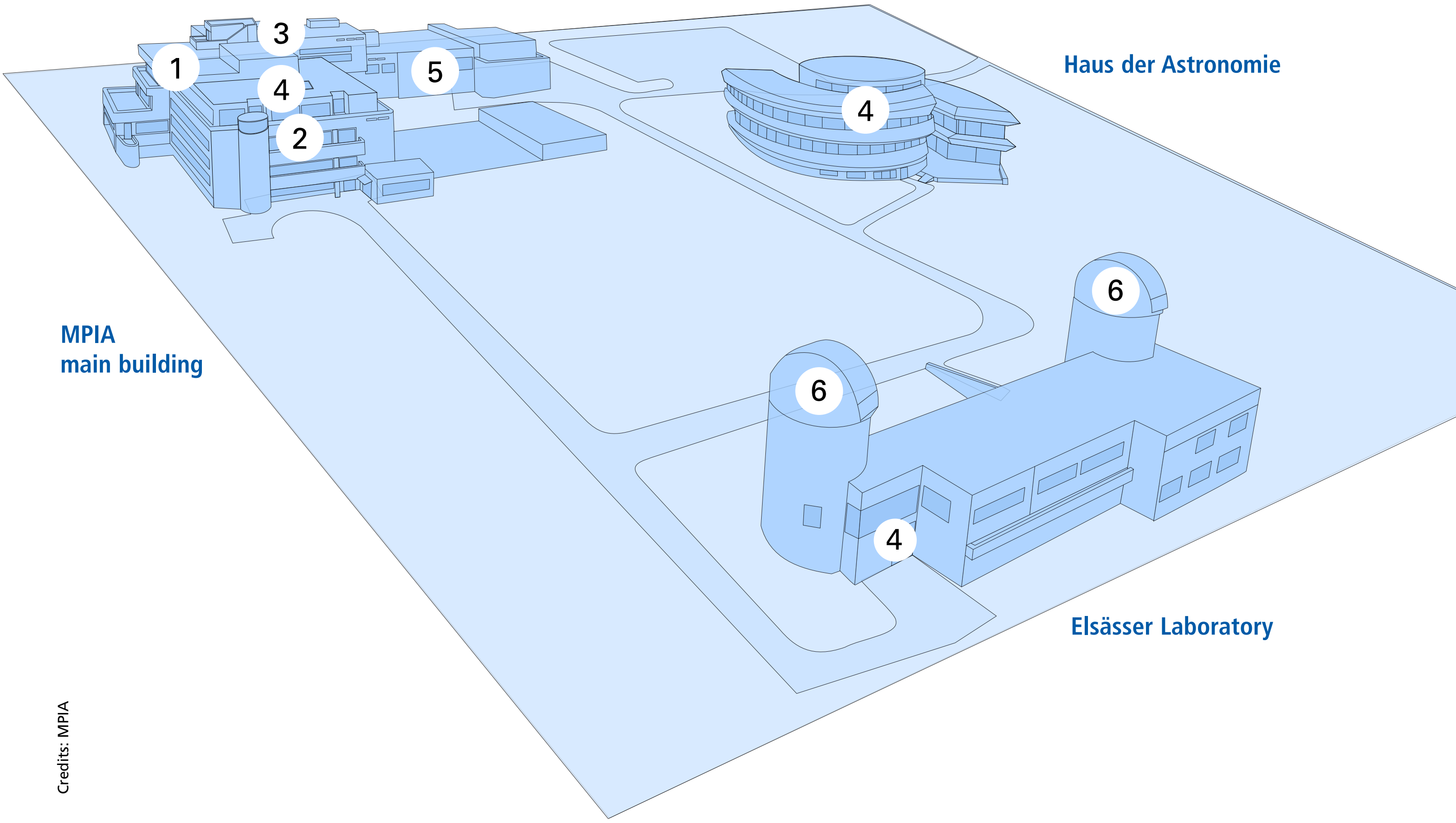
Infrastructure

Specialized library offering nearly 9000 books and access to about 100 astronomical journals.

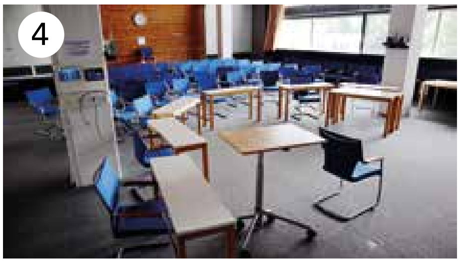
IT infrastructure capable of handling large amounts of data from observations and simulations.



Workshop, construction facilities and lab space, here the electronics workshop.



Credits: MPIA



Two lecture halls and eight seminar/workshop rooms, here the MPIA Lecture Hall.

Experimental and assembly facilities including clean rooms for instrumentation.

50 cm and 70 cm telescopes for testing and training purposes, here the 70 cm KING telescope.

People at MPIA

390

employees
keep the institute running
182 of these are scientists
including 82 junior scientists
or long-term visitors
and 51 PhD students

8

independent research groups
are part of our institute:
four Max Planck Research Groups
two Sofia-Kovalevskaya groups funded by
the Alexander von Humboldt Foundation
two European Research Council groups

Fig. I.3: View of the MPIA main building from the HdA building.

Sustainability

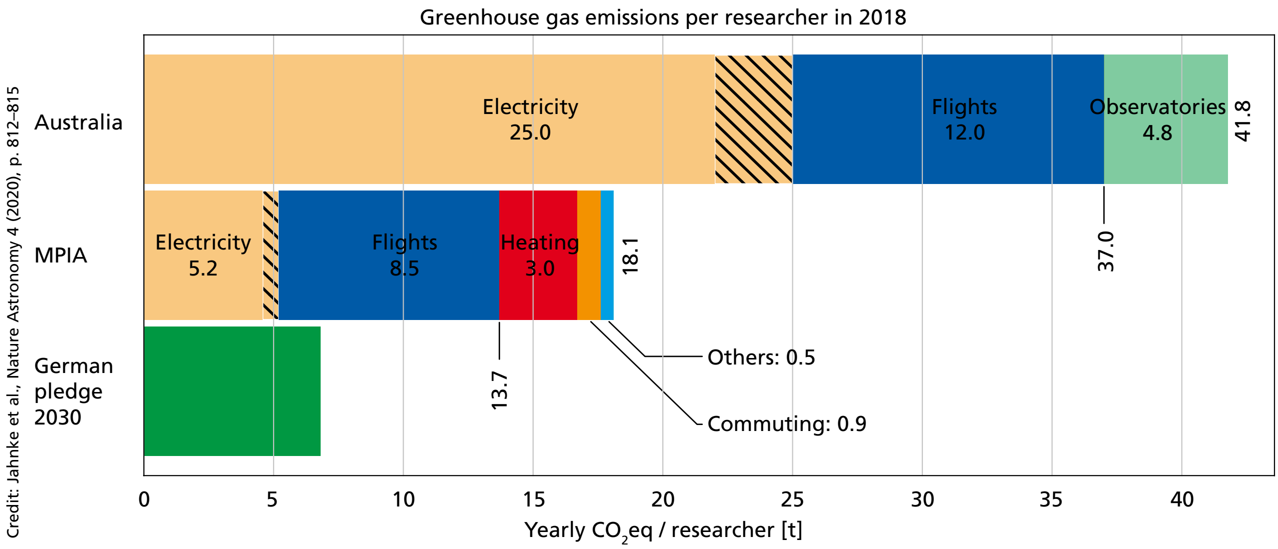
Astronomy research infrastructure and communication require ressources, both in terms of hardware and the need to meet for communication with other scientists. Many of these resources have an impact on the environment and on our climate, from production of hardware, to emissions from fossil fuel-based electricity, to flying. As part of society and the economy, astronomy is not naturally less polluting – but where do our main areas of climate-relevant emissions lie and in which area can we become active and reduce these? To answer the first part of the question, the sustainability group at MPIA assessed the institute's emissions for the year 2018.

MPIA's overall carbon emissions are dominated by travel (mostly intercontinental flights), electricity use (dominated by computing), institute heating, and commuting. Three other areas studied (paper use, computing hardware purchase, meat in the MPIA cafeteria) only added little extra. The total of 2720 tons of CO_2-equivalent corresponds to ~18 tCO_2eq per each of the ~150 researchers, or ~4.5 tCO_2eq per scientific paper. This emission for work only should be put in relation to an average total emission for each German resident of ~10 tCO_2eq/year, the German pledge of CO_2 reduction of about 7 tCO_2/year, or the theoretical remaining "carbon budget" per human until 2030 to retain a mean global temperature increase of less than 1.5°C of 2 tCO_2/year.

Comparison of a 2018 analysis by the Australian astronomy community shows similar emissions, with the exception of a Australian much higher carbon intensity of coal-based electricity. Australian astronomers have since taken steps to reduce the latter to near zero with a roadmap to switch to solar power-based electricity soon.

Overall, astronomy's and MPIA's climate impact per person is substantial – and in line with the global need to drastically reduce carbon emissions very soon, both the astro community in general and MPIA specifically need to start finding solutions for emission reduction beyond the already pandemic-changed travel habits since 2018.

Fig. I.4: Average annual emissions in 2018 for an Australian and MPIA researcher in tCO_2eq/yr, broken down by sources. Electricity is divided into computing and other uses (hatched). Observatory CO_2 is only shown for the Australian researcher.



Knud Jahnke et al.: "An astronomical institute's perspective on meeting the challenges of the climate crisis." Nature Astronomy 4, pp. 812–815 (2020). DOI: 10.1038/s41550-020-1202-4

II. Research Overview

Credit: ESO

II.1 Research Overview

Planet and Star Formation (PSF)

Director: Prof. Dr. Thomas K. Henning

The origin of stars and their planets

Star formation is a fundamental process in the Universe. Stars shape the structure of entire galaxies, enrich their interstellar media with chemical elements and ultimately provide the necessary conditions for the origins of life on planets that are located in their habitable zones.

Stars are born in the densest and coldest parts of molecular clouds, ranging from Giant Molecular Clouds with masses up to a few million solar masses to the tiny Bok globules with masses of a few solar masses. The dominant component of these clouds is molecular hydrogen, enriched with micron-sized dust particles and a large variety of other molecules, including complex organic species. The clouds often occur as filamentary structures, which are prone to fragmentation. With typical temperatures of about 10 K, they are the coldest structures in galaxies. As parts of these clouds collapse under their own gravity, some compact regions become sufficiently hot and dense for nuclear fusion to set in: a star is born. The formation of planetary systems is a natural by-product of low-mass star formation. It takes place in protoplanetary disks of gas and dust surrounding the nascent stars. Our own Solar System came into being in this manner some 4.5 billion years ago.

Scientists in the PSF department investigate a broad range of open questions related to the process of star and planet formation, combining multi-wavelength observations with large-scale numerical simulations and specially designed laboratory experiments.

Observing the formation of stars and planets first-hand

Observational techniques in astronomy have made considerable progress over the past decade. The observing programs of the PSF department cover a wide range of wavelengths, from the optical to the infrared and radio domains, with a special emphasis on high spatial and spectral resolution.

PSF researchers use a comprehensive set of telescopes and facilities for their work, including the Hubble Space Telescope and ground-based facilities such as ESO's Very Large Telescope, the Large Binocular Telescope

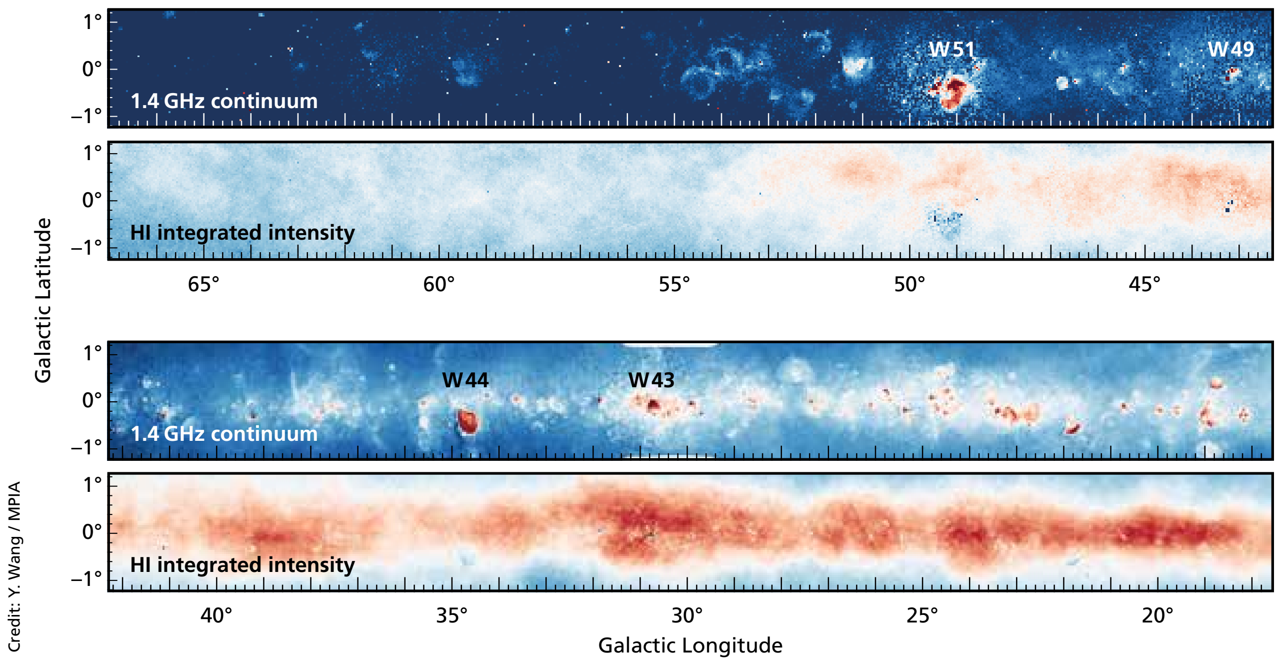


Fig. II.1.1: Mapping the origin of the material in the spiral arms of the Milky Way, from which new stars are ultimately formed: False-colour representation of the radio emission in the Milky Way from the THOR survey at a wavelength of about 21 cm. The upper band (1.4 GHz continuum) shows the emission from different sources, while the lower bands show the distribution of atomic hydrogen.

in Arizona, the NOrthern Extended Millimeter Array (NOEMA), the Atacama Large Millimeter/ Submillimeter Array (ALMA), and the Karl G. Jansky Very Large Array. Scientists in this department are moreover actively involved in laying the foundations for the science projects that will be possible with the James Webb Space Telescope, slated for launch in 2021, and expected to return first science data in summer 2022. PSF scientists together with MPIA engineers are leading the development and production of all mechanisms for the coronograph of the Roman Space Telescope. With a large contribution to the mid-infrared instrument METIS, PSF scientists are contributing to the instrumentation program for ESO's Extremely Large Telescope, which should commence science operations in 2028. Observations with these telescopes provide insights into the physics and chemistry of the interstellar medium and the earliest stages of star and planet formation, and allow MPIA scientists to discover and characterize exoplanets.

High spatial resolution – the ability to discern minute details – is the key to many observations that help advance our understanding of star and planet formation. The spatial scales relevant to molecular cloud fragmentation and planet formation in protoplanetary disks are all comparatively small.

The PSF department is involved in several programs that rise to this considerable challenge. Take, for instance, adaptive optics, a technique to compensate for the distortions of astronomical images by the Earth's atmosphere, allowing large telescopes to reach particularly high resolution. Or interferometry, which enables several telescopes to act together, achieving the same resolution as a single, much larger telescope. Our observations include infrared interferometry with large telescopes and long baselines, as well as the use of (sub) millimeter and radio interferometers.

Fig. II.1.2: Segment of the THOR survey near the Sagittarius arm of the Milky Way, which provides key information about the distribution of atomic hydrogen – the raw material for the formation of new stars. The crosses indicate the position of sources of polarised radio emission. Their sizes correspond to the magnitude of the Faraday rotation effect. The strongest signals were measured in a rather inconspicuous strip to the right of the bright objects in the middle of the image. The strong radio sources indicate the position of the spiral arm.

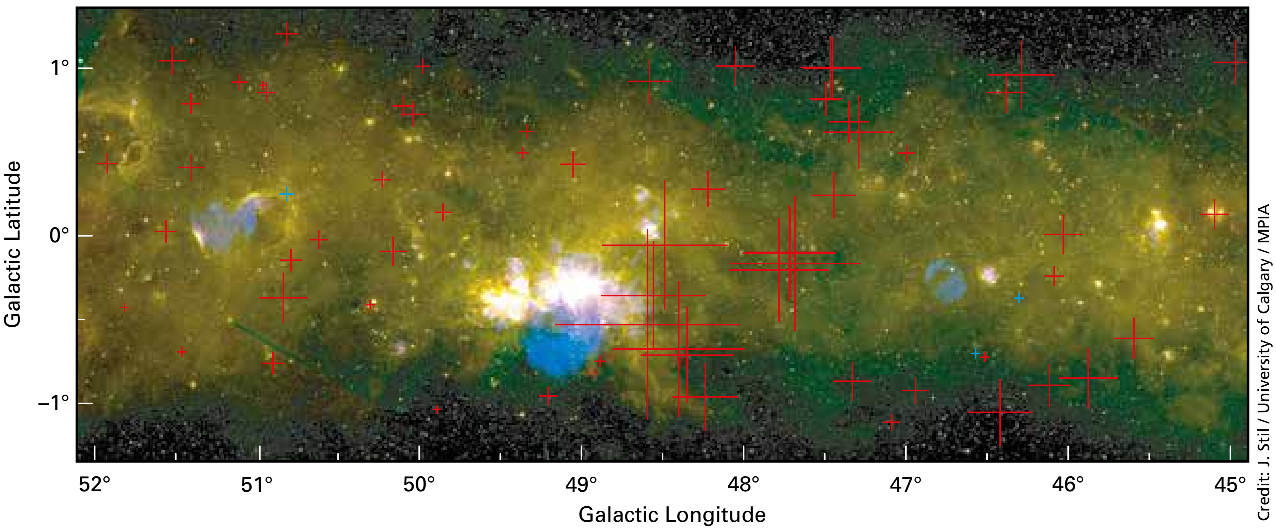
Understanding the origin of stars

One of the central questions of star formation concerns what astronomers call the initial mass function: How probable is it that a molecular cloud will form low-mass stars like the Sun or high-mass stars like some of the objects in the Orion star-forming cloud, or the even more massive star-formation complexes W 49 or NGC 3603?

And more specifically: To what extent does the probability for the formation of a star of a given mass depend on the mass of the star-forming cloud? This leads to the more general question of which properties of the cloud determine the outcome of the star formation process. Key open questions concern the role of magnetic fields and turbulent flows in controlling the onset of star formation – with direct consequences for the initial mass function and the duration of the star formation process.

In general, collapsing individual cloud clumps will fragment to form binary stars or multiple systems. At the high end of the mass scale, the formation of very massive stars takes place in clusters, which makes for exceedingly complex star formation environments and strong feedback processes, also impacting the evolution of protoplanetary disks in such regions through external UV irradiation. The rapid evolution of massive protostars and the associated energetic phenomena provide an enormous challenge in identifying the formation path of massive stars.

How do molecular clouds form from clouds of atomic hydrogen? What regulates the onset of star formation and star formation efficiency? What triggers the fragmentation of molecular clouds? What is the role



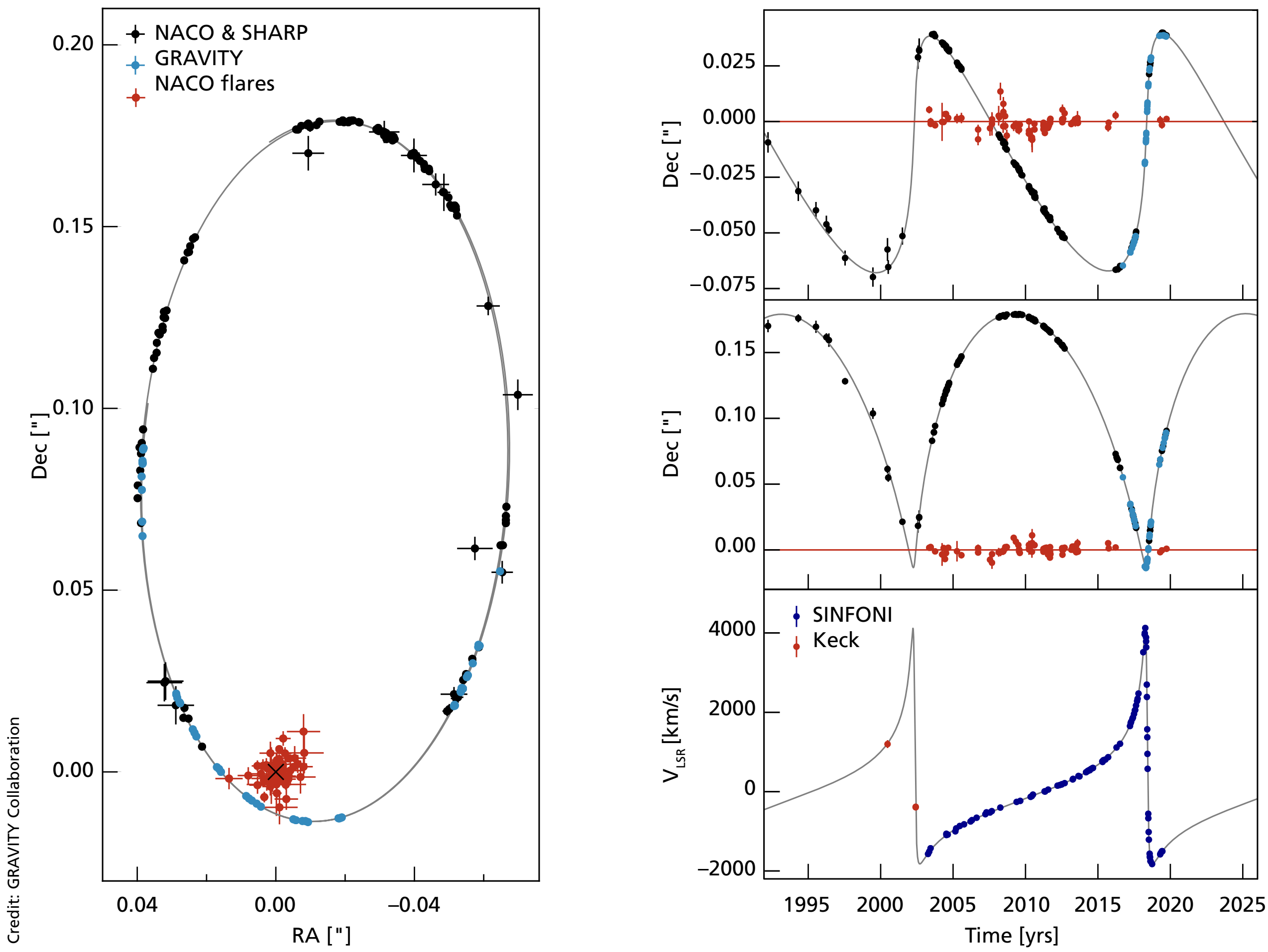
of filamentary structures in the star formation process? What is the mass limit for the highest-mass stars and how long does it take to form a stellar cluster? Are massive stars also using disks to accrete matter? What is the structure of embedded disks around low-mass protostars, and how do they evolve into solar-type stars surrounded by protoplanetary disks? These are just some of the questions under investigation by scientists of the PSF department.

A peek behind the curtain

The earliest phases of star formation are obscured by enormous amounts of dust and gas and can only be detected by sensitive far-infrared and (sub)millimeter observations. At later evolutionary stages, the objects emit what amounts to a thermal glow, becoming visible at near- and mid-infrared wavelengths. Even later, the nascent stars disperse their cocoons of dust and gas and become visible at optical wavelengths.

Due to the basic laws of fluid dynamics – namely the conservation of angular momentum – the accretion of matter onto the central protostar happens predominantly via a circumstellar disk. Disks around the low-mass T Tauri stars and the intermediate-mass Herbig Ae/Be-stars are natural birthplaces for planetary systems. While the pre-main sequence star still accretes matter from the surrounding disk, some of the matter is ejected perpendicular to the disk in the form of molecular outflows, or as collimated, ionized, high-velocity jets. Direct observations of such disks and the associated accretion and outflow phenomena provide insights into both the formation of our own Solar System and the diversity of planetary systems in general. Rings, spirals, and enormously large inner holes in planet-forming

Fig. II.1.3: The first time that the so-called Schwarzschild precession, a subtle change in an orbit around a compact object, has been determined for a star orbiting our home galaxy's central black hole. The connection with planet and star formation? The MPIA PSF department made crucial contributions to the GRAVITY instrument at ESO's Very Large Telescope. While the department's main motivation is to use GRAVITY to detect exoplanet motions, and structures within the disks of emerging new solar systems, the work of Wolfgang Brandner, Thomas Henning, Stefan Hippler, Silvia Scheithauer and others on this instrument has the collateral benefit of enabling precision observations like the ones behind these new measurements, as well.



disks all point to a vigorous planet formation process. As a matter of fact, scientists of the PSF Department were the first to discover a young giant planet embedded in such a disk. In addition, we could demonstrate the impact of the exoplanet on its birth environment and discovered a circumplanetary disk with ALMA observations.

Observing from the ground and from space

One of the goals of the PSF department is to understand the earliest phases of stars both in the low-mass regime relevant to the formation of planetary systems and the high-mass regime, which is important for galaxy evolution. Using space observatories such as the Hubble Space Telescope as well as ground-based infrared, (sub) millimeter and radio telescopes, scientists of the PSF department are able to detect and characterize star formation and study the subsequent evolution of young stars – from the substellar mass regime to the most massive known stars. To this end, scientists in this department have established large observing programs at internationally competitive astronomical facilities.

Presently, a strong focus of the department's work is on preparing projects in the field of star formation, protoplanetary disks, and exoplanets for the James Webb Space Telescope (JWST), the designated successor of the Hubble Space Telescope. As a member of the consortium for the JWST mid-infrared instrument MIRI, we will have access to guaranteed time for this instrument.

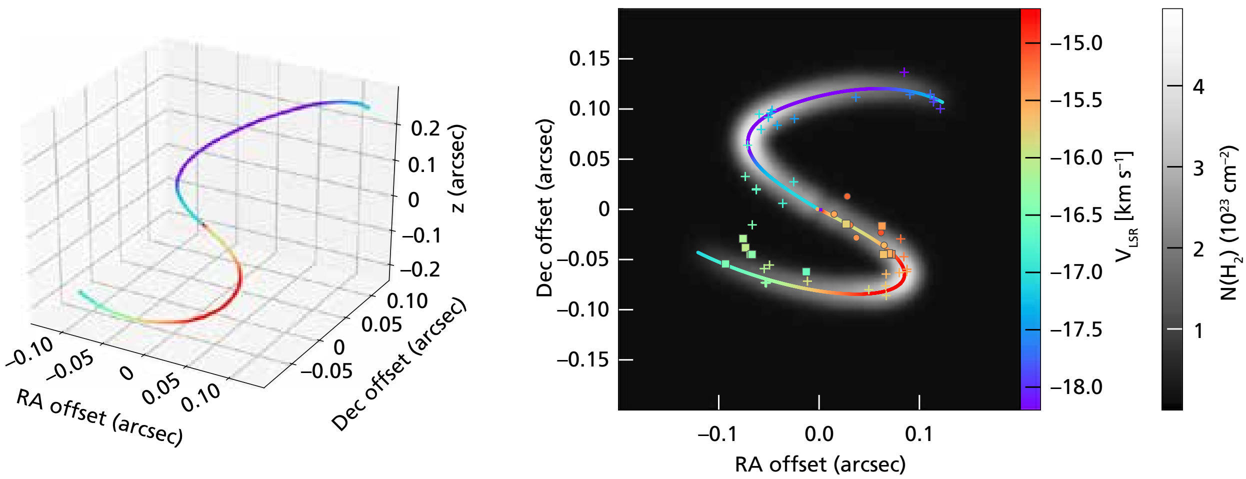
With another large instrumentation project, we are looking towards the largest ground-based telescope yet: The PSF department will provide the camera and adaptive optics system for METIS, the mid-infrared instrument for the Extremely Large Telescope, a 39-meter telescope currently under construction in Chile.

Planet formation and the search for exoplanets

The detection of the first extrasolar planet around a Sun-like star in 1995 initiated a new era in the study of planet formation and the search and characterization of extrasolar planets. Suddenly, instead of a single example of a planetary system – our own Solar System – astronomers were able to examine, compare and contrast thousands of such systems.

PSF astronomers are heavily involved in observing programs to search for extrasolar planets through direct imaging, the transit technique and radial velocity observations of objects discovered with the Transiting Exoplanet Survey Satellite (TESS). The HATSouth transit network, with its three stations in Australia, Chile and Namibia, is currently returning a wealth of new discoveries and is one of the most successful ground-based transit networks. With the Chilean-MPIA collaboration WINE, we are at the forefront of detecting and characterizing long-period giant planets from TESS, and we hunt for super-Earths. The project EDEN with MPIA, Steward Observatory, the Vatican Observatory and the NCU Institute for Astrophysics in Taiwan, has the goal to discover and explore habitable planets around very low-mass stars and to determine their occurrence rate. It is using a battery of mid-sized telescopes for transit observations. At MPIA, the observations are led by a dedicated group of PhD students and postdocs.

Fig. II.1.4: MPIA researchers discovered a spiral structure in a disk surrounding a young star of about 12 solar masses, which had just experienced a dramatic increase in brightness. The presence of the structure confirms the hypothesis that such disks become temporarily unstable and therefore partially disintegrate into compact packets. The diagrams show the shape of the spiral as reconstructed from so-called maser measurements – regions that act as natural microwave versions of lasers. The left side shows the spatial position of this structure. The right graphic offers the view in projection along the viewing direction as well as the positions of the masers to the determined shape of the spiral. The colour scale indicates the velocities of the gas in the spiral along the viewing direction.



Credit: Chen et al. / MPIA

The CARMENES spectrograph at the Calar Alto Observatory is one of the most versatile instruments to search for exoplanets around M-type stars. A multi-year survey to unravel the statistics of low-mass planets around these red stars is near completion and has already returned a flood of exciting planet discoveries. The consortium of the SPHERE planet finder instrument, in which MPIA is the Co-PI institute, is conducting the largest direct imaging survey for exoplanets at a 10-meter class telescope. In addition, this instrument is revealing unprecedented details of planet-forming disks, from gaps and rings to spiral arms, which point to complex dynamics and planet-disk interactions. The department has just completed a large survey for young planets with the adaptive-optics instrument NACO, and has started a parallel radial velocity survey to search for young planets in debris disks.

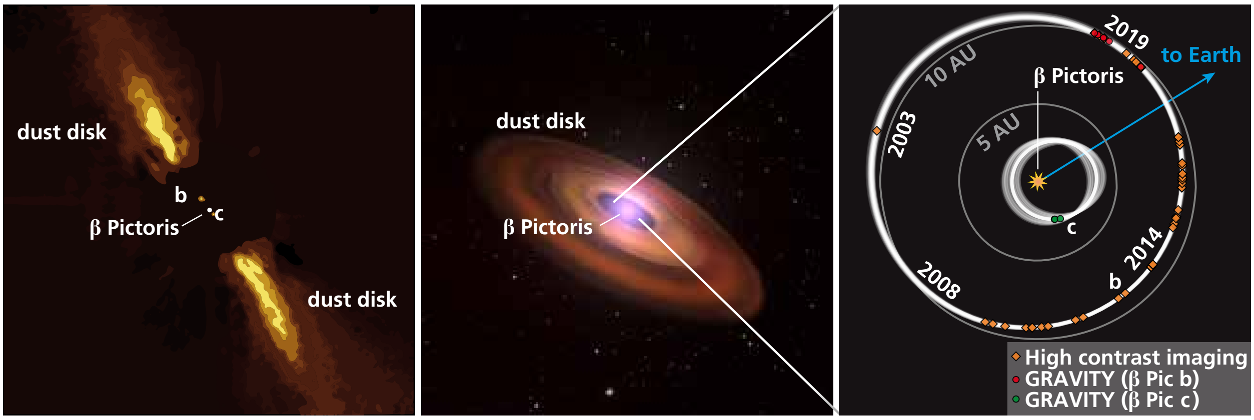
Furthermore, two instruments for ESO's Very Large Telescope Interferometer, GRAVITY and MATISSE, to both of which have the PSF department has greatly contributed – have seen first light and are now delivering exciting results. GRAVITY has produced amazing scientific results in various fields, ranging from the black hole in the Galactic Center to the spectroscopic characterization of exoplanets. MATISSE has detected a vortex-like structure in the inner regions of a disks and has revealed the structure of nearby AGNs. Both instruments are allowing us to study the cradles of planets – protoplanetary disks – and the accretion process with unprecedented spatial resolution, complementing our observations with the IRAM and ALMA (sub)millimeter interferometers for the region where terrestrial planets form.

Star and planet formation in a computer

A comprehensive understanding of planet and star formation can only be reached when astronomical observations make a connection with fundamental physical processes. The theory program of the PSF department focuses on large-scale numerical simulations of protoplanetary disks, including the interplay between radiation, dynamics, chemistry and the evolution of dust grains, in order to link observations with an in-depth understanding of the physical and chemical processes during star and planet formation. The theory group of the PSF department is developing multi-dimensional radiative transfer codes which simulate the way radiation travels through molecular clouds and their cores, protoplanetary disks and the atmospheres of planets. These codes can be used for interpreting cloud and disk images and spectra, and they also allow researchers to employ magneto-hydrodynamic simulations and reconstruct how the object in question would look to observers. Simulations now allow us to connect the conditions in planet-forming disks with the observed properties of planet populations. Another important application is models of planetary atmospheres, where these codes allow for calculating transmission and emission spectra as they would be measured by telescopes on the ground or in space. High-resolution spectroscopy with CARMENES and measurements with the LBT have been used to characterize planetary atmospheres.

A versatile program has been launched to link planet formation with the properties of planets and their atmospheres in preparation for the analysis of the planetary spectra that will be obtained with JWST. This includes the development of radiative transfer codes, non-equilibrium chemistry models, cloud description and retrieval techniques to reconstruct planet formation processes.

Fig. II.1.5: A team of astronomers using the ESO instrument GRAVITY has taken the first image of an exoplanet that had previously only been detected indirectly via the spectrum of its star. The result is the first set of measurements that allows astronomers to both determine an exoplanet's intrinsic brightness and estimate its mass. The images show the geometry of the β Pictoris system. Left: Artist's impression of star and two planets embedded in the dusty disk, based in part on actual observations. Center: Artist's impression of the disk-planet system. Right: Dimensions of the system viewed from above. Previous observations of β Pictoris b (orange diamonds and red circles) and the new observations of β Pictoris c (green circles) are shown as well. The planetary orbits are shown in white. Remaining uncertainties in the reconstruction of the orbit of β Pictoris c are shown as grey areas.



Credit: GRAVITY Collaboration, A. M. Quetz / MPIA Graphics Department

Linking the cosmos and the laboratory

Understanding the physics of the interstellar medium and protoplanetary disks requires in-depth knowledge of microphysical processes in the respective dust and gas populations, and the same holds for interpreting observational signatures in the spectra of these objects. This, in turn, can only be achieved by dedicated laboratory studies.

Such an astrophysics laboratory facility is part of the PSF department, and is located at the Institute for Solid-State Physics at the University of Jena. The Laboratory Astrophysics and Cluster Physics Group investigates the spectroscopic properties of nano- and micron-sized solid particles, as well as of complex molecules, especially polycyclic aromatic hydrocarbons (PAHs), an important class of organic molecules found in astronomical settings in the gas phase. The scientists of the astrophysics laboratory group also study the formation pathways of small particles and their interaction with molecular ice layers up to the formation of simple amino acids.

To link the production of organic molecules with the orgins of life is the aim of another initiative: the Heidelberg Initiative for the Origins of Life (HIFOL) established by the PSF department in collaboration with other scientific institutes in Heidelberg. The goal of this initiative is to understand the basic physical, chemical and biological processes involved in the origins of life, and to connect them with the astrophysical conditions important for the emergence of life. As part of this initiative, MPIA has established new Origins of Life laboratories, with the goal of investigating the formation of pre-biotic molecules under conditions typically found on comets and the parent bodies of meteorites.

II.2 Research Overview

Galaxies and Cosmology (GC)

Director: Prof. Dr. Hans-Walter Rix

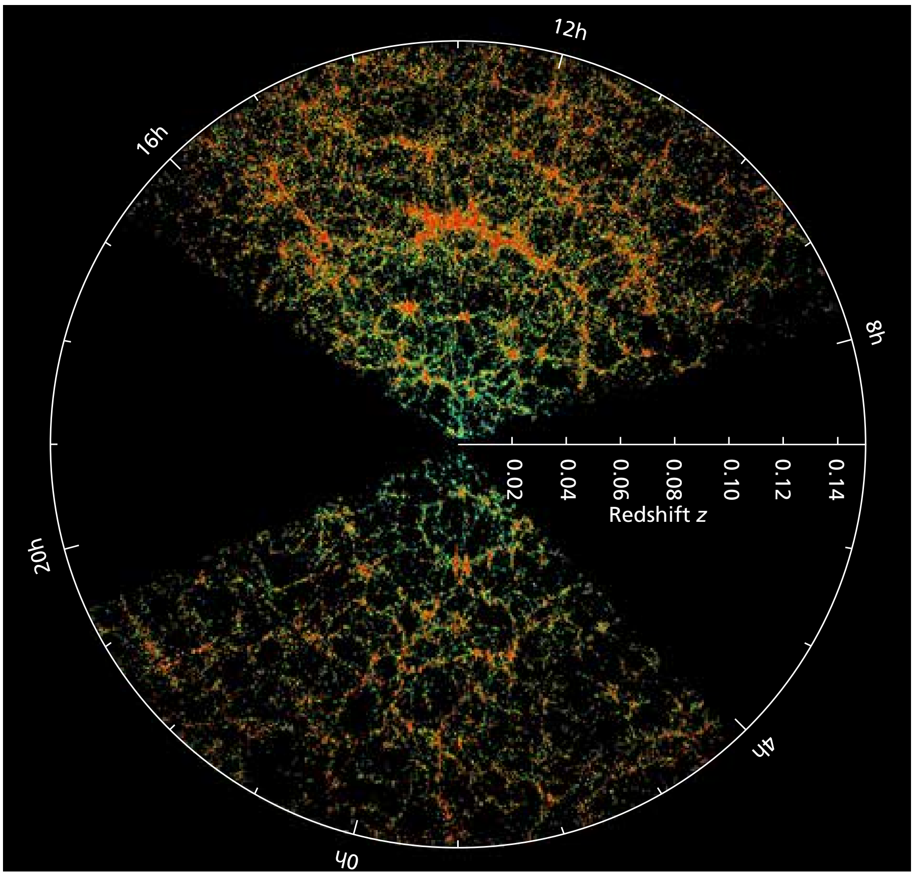
How the Universe became interesting

Shortly after the Big Bang, the Universe was almost perfectly homogeneous and simple, arguably both elegant and boring. In stark contrast, the present cosmos exhibits a rich hierarchy of structures. These structures span a wide range of physical scales from the filamentary distribution of galaxies known as the "cosmic web" down to single galaxies, clusters of stars and individual stars with their planets. It is this structure that makes our Universe interesting, yet also complex. The formation of cosmic large-scale structure appears to be driven by the ubiquitous self-clumping influence of gravity, mitigated mostly by the cosmic expansion.

Fig. II.2.1: Comprehensive surveys like the Sloan Digital Sky Survey (SDSS), where the GC department is currently involved in the fourth and fifth phase (SDSS IV and SDSS V) yield data about hundreds of thousands of galaxies, allowing for statistical analysis of various galaxy properties. Shown here is the SDSS map of the universe, where each dot is a galaxy studied by the survey.

In shaping individual galaxies, a plethora of other physical effects come into play, making these galaxy ecosystems so diverse and interesting.

To understand quantitatively how such structure arose in an expanding Universe, however, current models need an unusual extra ingredient: dark matter, which possesses mass, and hence gravitational attraction, but does not interact at all with electromagnetic radiation. The specific nature of this dark matter has yet to be understood. To make things worse, the expansion of the Universe is observed to be accelerating, which forces astronomers to postulate an even more exotic ingredient: dark energy, which acts as a form of repulsive force. There are places throughout the Universe where dense dark matter concentration arises from gravitational instability and where consequently normal matter is distilled, so that stars form from dense gas clouds: we call these places galaxies, and they arguably form the centerpiece of the overall hierarchical structure of the cosmos.



Credit: M. Blanton and SDSS

The “formation” of galaxies is difficult to understand, mostly because it encompasses such a vast range of scales, from individual stars – perhaps the defining constituents of galaxies – to the Universe as a whole. Therefore, our own Milky Way, the only large galaxy that we can dissect in detail star-by-star, has become a central testbed for understanding the physics of galaxy formation. Galaxy formation theory should statistically predict the structure of our galaxy, and all the intricate connection between the age, chemical composition and orbits of stars. Understanding the physics and element composition of stars, that reflect the successive enrichment or pollution of the star-forming gas by stellar nucleosynthesis, is hard but indispensable.

Emerging order in the realm of galaxies

Galaxies exist over a vast range of physical scales: they vary by many orders of magnitude in their stellar masses, in their rate of producing new stars, the mass of the black holes at their very centers, and their sheer physical size. Yet, as Edwin Hubble realized 80 years ago, these “island universes” are not as varied in their appearance and structure as the laws of physics would allow. Observations, particularly those made over the last 15 years, have confirmed this in ever greater detail: only a small fraction of the possible combinations of galaxies’ characteristic quantities (stellar masses and ages, size, shape and central black hole mass) are actually realized in the Universe. Virtually all these physical properties are strongly correlated. In other words, the “realm of galaxies”, to use Hubble’s expression, exhibits a high degree of order. How did this order develop from the initial random mass fluctuations? That is the fundamental question of galaxy formation and a central issue in cosmology.

There are three broad lines of explanation for why the population of galaxies shows such immense regularity: observed galaxies represent the only configurations that are dynamically stable over long times; or, it is possible that the initial conditions of our Universe only permitted the formation of the galaxies we see. Or, it is conceivable that galaxy formation is a highly self-regulating process that leads to a very limited set of outcomes – namely those combinations of properties that we actually observe. Current research suggests that all three aspects may play a role.

Fig. II.2.2: For nearby galaxies in particular, high-resolution observations like these with the Hubble Space Telescope yield copious amounts of information about structural details. The images are part of the PHANGS ("Physics at High Angular Resolution in Nearby GalaxieS") project which is led by MPIA's Eva Schinnerer. The project studies how star formation in a galaxy depends on that galaxy's size, age, and internal dynamics.

Gas: the fuel for making the stars in galaxies

Stars, the most obvious, ubiquitous and defining constituents of galaxies, are made from interstellar gas, in particular from molecular gas – gas whose atoms are sufficiently cool to have bonded into molecules, notably hydrogen molecules H_2. But most of the gas in the Universe is not part of any galaxy. Throughout the history of the Universe, the lion's share of gas has always resided in between galaxies, forming the intergalactic medium.

In order to understand galaxy formation, it is crucial to understand the ways in which gas cools and condenses at the centers of gravitational potential wells which are due to the presence of dark matter, gets transformed into molecular gas, and finally forms stars. Understanding the processes that suppress or at least hinder star formation is just as important: how does gas get reheated and possibly ejected from galaxies, either by the intense radiation of luminous young stars, by supernova explosions, or by the presence of an active central black hole?

The galactic and circum-galactic gas cycle is far from understood. In order to improve our understanding, we need to find ways of studying all the different varieties of gas: dense molecular gas, neutral (atomic), and ionized gas. This requires a wide range of techniques, from submillimeter observations of molecular lines to studies of UV absorption lines caused by hot gas. Facilities such as the IRAM NOEMA Interferometer, ALMA, and large optical telescopes to study quasar absorption lines are crucial tools for this research.

Fig. II.2.3: Solar spectrum in the green channel between 516 and 573 nm, taken with the 4MOST High-Resolution Spectrograph during test in Landessternwarte in 2020. 4MOST is set to survey a large fraction of the Southern Sky, using ESO's VISTA survey telescope, beginning in 2024. The spectrograph will be used, among other tasks, as part of the 4MOST High-resolution Milky Way Disc and Bulge Survey, for which Maria Bergemann is a Co-PI.

The Milky Way and its stars, a model organism for understanding galaxies

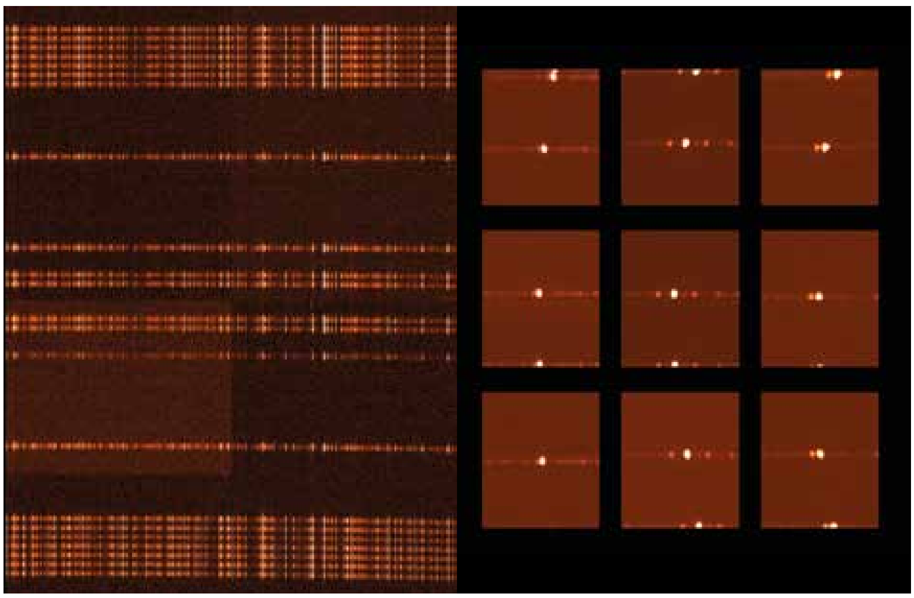
Our own Milky Way is a very average galaxy, making it eminently suitable as a test case for understanding the more general physical mechanisms at work in shaping galaxies. Our Galaxy is, of course, absolutely exceptional with respect to the detail in which we can study it: we can now observe it in 3D, determining the orbits, ages and element compositions star by star.

This puts us in a position to ask empirically: when and where were stars born? Did their orbits show substantial subsequent evolution? How did the chemical elements build up in the Milky Way? These pieces of information provide an unprecedented way of testing cosmological galaxy formation scenarios and simulations. The advent of powerful new photometric, astrometric and spectroscopic surveys makes this Galactic Archaeology a rapidly evolving and exciting field.

Much of Galactic Archeology is based on the spectroscopy of millions of stars, as spectra are the prime tools to diagnose the physical properties of stars. The delightful deluge of survey-data has shown that we don't understand the physics of stars well enough: we are not limited in learning about the Galaxy by the quality and quantity of data, but by our ability to model them. This has led to a renaissance of stellar spectroscopy as a cutting-edge research direction, also at MPIA.

Asking the right questions

The fundamental questions raised here inform numerous projects currently undertaken by researchers in the GC department. As always, the key to success lies in transforming fundamental questions into specific ones that can be addressed using current tools and methods.



Credit: 4MOST

A number of these questions concern the broader aspects of galaxy formation: what is the state of the intergalactic medium – the extremely rarefied gas in the space between galaxies, where most of the atoms in the Universe reside? How did gas get from the cosmic web into galaxies, to be processed there into new stars? In turn, how does it get expelled from galaxies? And when and where does gas get converted from atomic to molecular, in order to be ready to form stars? Or, to bring up a more general question about the relationship between galaxies and dark matter's cosmic web: which kinds of galaxies reside in dark matter halos of different size?

The process of star formation on the scale of galaxies must be the key to understanding why galaxies look the way they do. When, how and how efficiently did gas in galaxies get converted into stars? The when can be addressed by looking at distant galaxies, which we see at an earlier epoch – because the speed of light is not infinite. The how can be addressed by mapping the gas (the fuel for star formation) and the star formation itself in great detail in closer galaxies.

Another area of particular interest to MPIA concerns the central black holes of galaxies: Why is it possible to predict the properties of the central black hole from a galaxy's overall properties? And how did the central black holes in galaxies form and grow in the first place?

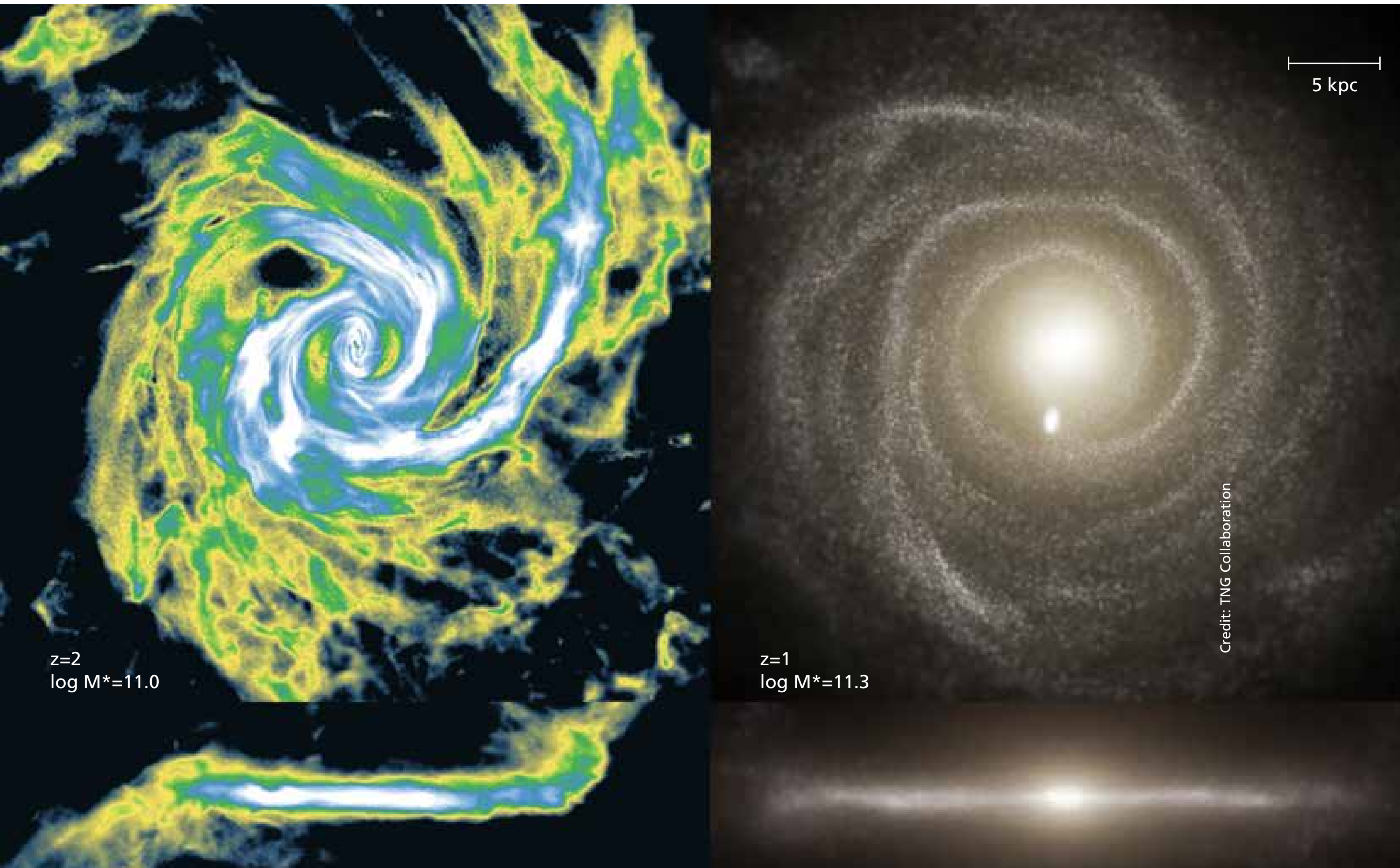
Most galaxies are so far away that we cannot study their stars – their central and defining ingredients – individually. Yet, the chemical composition and the orbits of individual stars hold clues to when and where they were formed. Looking at stars individually, mostly in our own galaxy, can therefore test our understanding of galaxy formation processes in absolutely unique ways. But it remains a challenge ahead to make the Milky Way a Rosetta Stone of galaxy formation. In particular, it requires learning all we can about the individual and population properties of stars, from spectra and from the ongoing Gaia space mission.

From observations to simulations

In order to tackle these questions, the GC department follows a three-pronged approach.

- We study galaxies in the present-day Universe, including our own Milky Way, making the most of the level of detail afforded by observations in our direct cosmic neighborhood.
- We study galaxies at earlier cosmic epochs directly by observing very distant objects (corresponding to high cosmological redshifts z); after all, astronomy always means observing the past: when light from a distant galaxy takes, say, 10 billion years to reach us, our present observations show us that galaxy as it was 10 billion years ago, affording us a glimpse into the distant past.

Fig. II.2.4: In simulations like TNG50, it is possible to follow the evolution of a model universe from the Big Bang to the present. This is a key part of the GC department's research. The image shows the details with which TNG50 simulates separate galaxies in a model universe. The left-hand image shows the gaseous content of one of the simulated spiral galaxies, and the right-hand image another galaxy's appearance in stellar-light observations with the James Webb Space Telescope (F200W, F115W, F070W rest-frame bands).



- We develop physical models and progressively improve both them and our understanding of galaxy formation by testing their outcome against observations. The models developed and analyzed at MPIA follow the co-evolution of dark matter, stars, cosmic gas and supermassive black holes starting from the initial conditions shortly after the Big Bang and require computing investments of tens of hundreds of million computing hours using thousands of computers.

This strategy requires diverse observational capabilities: survey telescopes to obtain large samples of cosmic objects, the largest available telescopes for the sheer photon collecting power necessary to examine faint sources, and techniques such as adaptive optics and interferometry in order to achieve high spatial resolutions.

Collaborations and initiatives

MPIA is leading, or co-leading, a number of major, global observing programs and surveys to tackle these questions, in particular

- Spectroscopic sky surveys, in particular the SDSS-V spectroscopic sky survey, which is pioneering panoptic spectroscopy, by obtaining multi-epoch spectra across the entire sky starting in late 2020. We also lead the high-resolution stellar spectroscopy survey with the 4MOST facility that is being built for Paranal Observatory.
- Determining the astrophysical parameters of sources observed with the Gaia space mission, which is constructing a 3D map of our galaxy.
- The infrared photometry from the Euclid space mission, which set out to elucidate the nature of dark energy.
- Large observing programs at NOEMA and ALMA at mm and sub-mm wavelengths, such as ASPECS or PHANGS, that study the gas in galaxies near and far.
- Ultra-high resolution cosmological simulations of galaxy formation, TNG 50, to link the detailed structure of galaxies to their formation history.

II.3 Research Overview

Atmospheric Physics of Exoplanets (APEx)

Director: Dr. Laura Kreidberg

Planets are ubiquitous in the Galaxy – most stars host at least one. Since the discovery of the first extrasolar planet 25 years ago, extensive survey efforts have revealed that planets are both common and that they show a much greater diversity of properties than is seen in the Solar System. A few examples of this diversity are planets on short period orbits (some orbit their host stars in less than a day!), planets with density as low as cotton candy (so-called super-puffs), and an abundant population of planets with radii intermediate between the Earth and Neptune, which have no analogue in our own Solar System.

Characterizing diverse atmospheres

Now that this diverse population has been uncovered, the next step is to characterize the planetary atmospheres in detail. The atmospheric physics and chemistry hold the keys to the planets' formation and evolutionary histories, present-day climate, and even habitability. For gas giant planets, the atmospheric chemical composition provides a record of the formation conditions in the disk, including the distance from the host star. For intermediate size planets, knowledge of the atmospheric composition reveals whether the planets are more like super-Earths, with large rocky cores, or mini-Neptunes, with a large fraction of water ice. Finally, for terrestrial worlds with rocky bulk compositions like the Earth, the detection of an atmosphere can teach us how the planet evolved over billions of years, and how the initial chemical inventory was influenced by volcanic activity, atmospheric escape, and the possible presence of life.

Over the past few years, MPIA has been keen on expanding in this interesting direction, in the form of a new, third scientific department. That plan was realized in spring of 2020, with the foundation of the Atmospheric Physics of Exoplanets (APEx) department, headed by new director Laura Kreidberg. APEx now provides a unique opportunity to assemble a critical mass of exoplanet characterisation experts in a single place. The department will grow over the coming years to include in-house experts on exoplanet observations, theory, and instrumentation development.

Fig. II.3.1: Laura Kreidberg, director of the newly founded APEx department at the MPIA.

Credit: L. Kreidberg

A diversity of challenges

Exoplanet atmosphere characterisation provides major challenges on multiple fronts: from pushing detectors beyond their design limits to search for the tiny signal of atmospheric absorption, to modeling atmospheric physics and chemistry over orders of magnitude in time and distance. Tackling these challenges requires close collaboration between experts, and progress in the field will be greatly accelerated with an entire department devoted to these topics. Hiring was a major focus for the first year of the department, and APExers were glad to welcome two graduate students and two postdoctoral fellows, as well as two current MPIA staff members who transferred to the new department to give it a running start.

Already, APEx astronomers are leading observing and modeling initiatives with state-of-the-art facilities and tools. These include Hubble and Spitzer observations of lava worlds and ultra-hot Jupiters, interpretation of some of the first exoplanet spectra directly measured by K-band interferometry, and 3D modeling of atmospheric dynamics. A recent highlight is a measurement of the atmospheric water content for the hot Saturn KELT-11b with the Hubble Space Telescope (shown in Fig. II.3.2).

Thanks to Hubble's stability and position above the contamination from Earth's own atmosphere, it is an ideal instrument to detect water on exoplanets. The amount of water detected in the planet's atmosphere was over a hundred times smaller than predictions from typical models of planet formation, posing a new challenge to theorists. This surprise was par for the course for exoplanets, which never cease to surprise compared to the much more limited sample of Solar System planets.

APEx scientists are looking forward with great anticipation to new and better data from the James Webb Space Telescope, expected to launch in late 2021. The larger mirror and broader wavelength cover will open the door to studying a wider variety of planets in greater detail than ever before. Laura Kreidberg will lead a team to analyse some of the first Webb data, through her collaboration with the Transiting Exoplanet Community Early Release Science Team.

Instrumentation

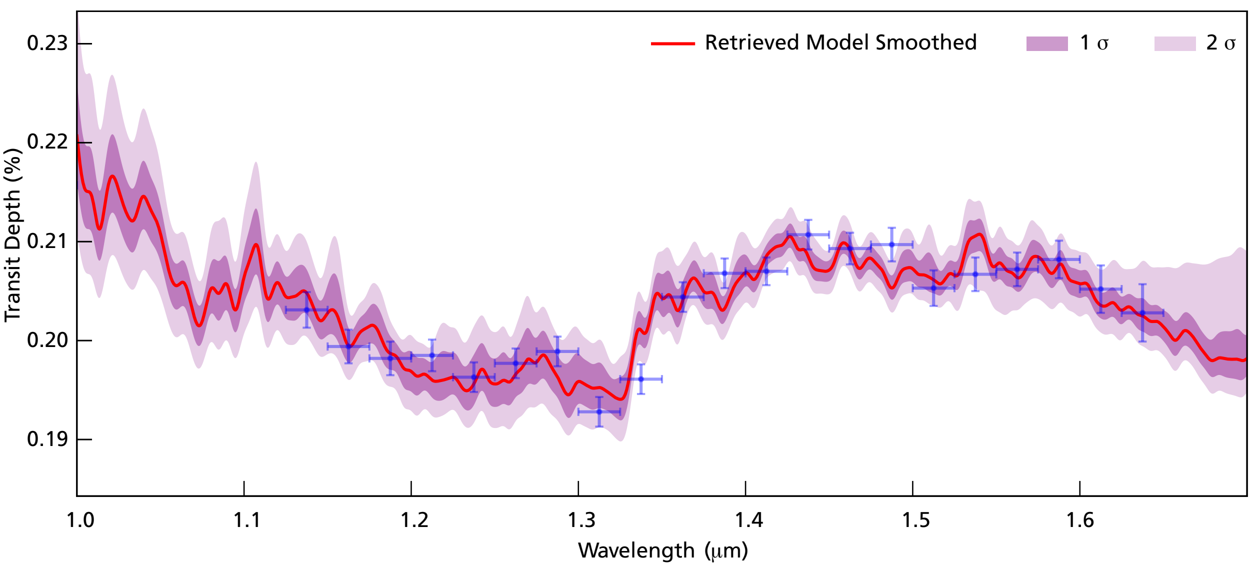
Another focus for the APEx department is instrumentation. Exoplanet detection alone is a challenging proposition, and characterisation is more difficult still. Planets are at least 10 000 times fainter than their host stars, and are best studied with purpose-built instrumentation. Many of the advances in exoplanet characterisation are the direct result of new instruments and observing capabilities. APEx is therefore investing in two ground-based instrumentation projects that will provide unprecedented capability to study exoplanet atmospheres.

One of these is the METIS instrument, a first-light instrument for the ELT. METIS will be capable of both direct imaging and high-resolution spectroscopy, and can detect thermal emission from Earth analogs around the nearest stars. It will also be able to measure the wind speeds in exoplanet atmospheres and detect rare molecules, providing a complete chemical inventory for gas giants. APEx is providing the new GeoSnap detector for METIS and designing the readout electronics.

The second instrumentation project is the upgrade to the Very Large Telescope GRAVITY instrument. GRAVITY is the first K-band interferometer ever built, and can spatially resolve planets from their host stars without the need for a coronagraph. The resulting exquisite spectra provide the most precise constraints to date on fundamental atmospheric properties like the carbon-to-oxygen ratio. The upgraded instrument, GRAVITY+, will have higher sensitivity and contrast thanks to improved adaptive optics, and it will be capable of searching for new planets including Jupiter analogs. Known planets will also be studied in even greater detail, including second-order effects like weather.

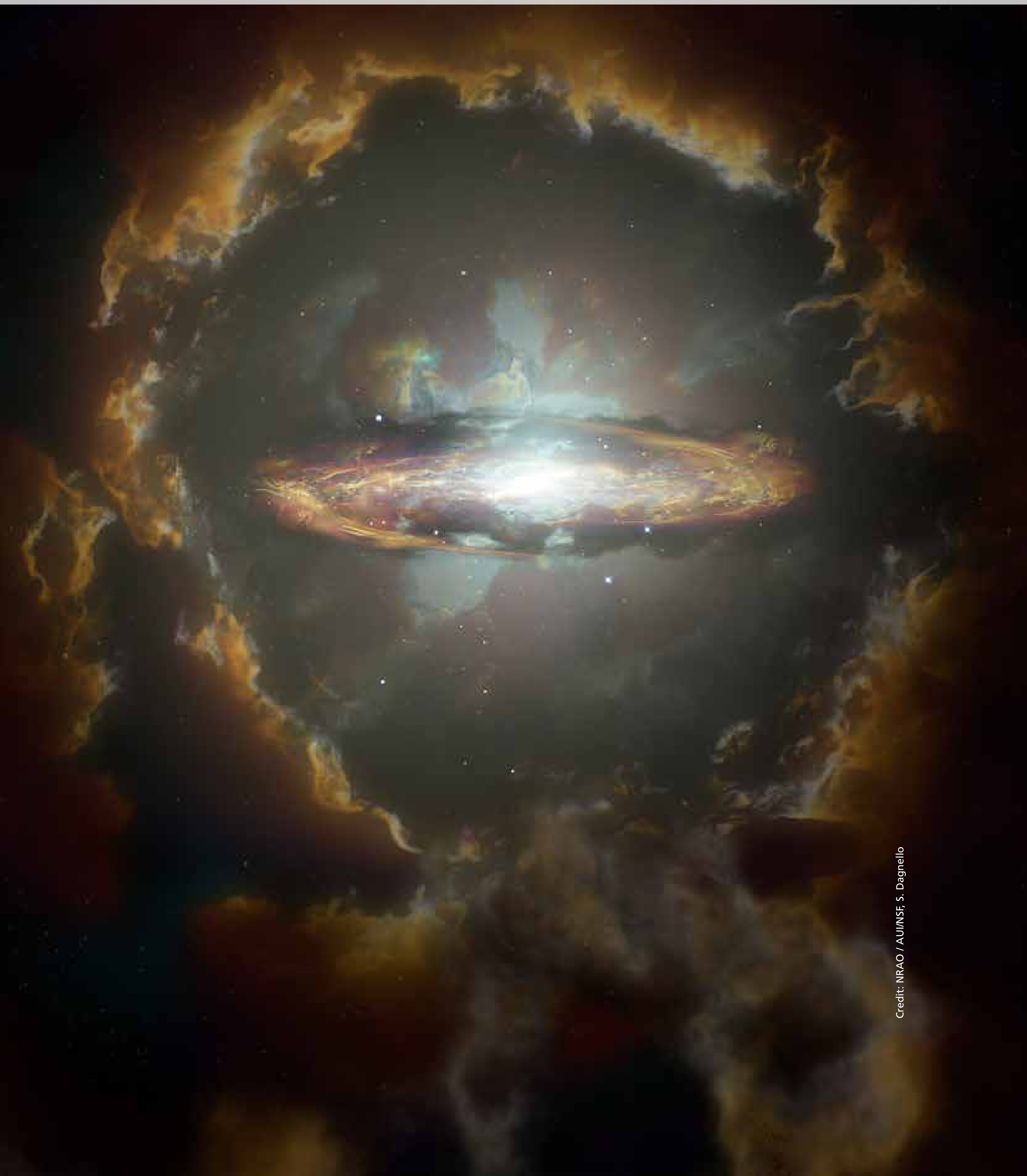
The APEx department is already off to a running start, and with many new hires and new observing capability on the horizon, it is certain to be an exciting decade to come for exoplanet atmosphere characterisation at MPIA.

Fig. II.3.2: The near-infrared transmission spectrum of the hot Saturn KELT-11b measured with the Hubble Space Telescope. Water vapor has a peak in opacity near 1.4 microns, leading to the characteristic increase in transit depth near that wavelength. The water abundance measured for KELT-11b was over one hundred times smaller than predictions from typical planet formation models – a typical example of the surprises that come with the study of exoplanets.



Credit: Colón et al. 2020, Astronomical Journal, 160, 280.

III. Science Highlights



Credit: NRAO / AUI/NSF, S. Dagnello

III.1 Science Highlights

A puzzle piece from stellar chemistry could change our measurements of cosmic expansion

Astronomers led by Maria Bergemann (MPIA) have performed chemical measurements on stars that could markedly change the way cosmologists measure the Hubble constant and determine the amount of Dark Energy in the Universe. Using improved models of how the presence of chemical elements affects a star's spectrum, the researchers found that supernovae of type Ia have different properties than previously thought. Based on assumptions about their brightness, cosmologists have used those supernovae to measure the expansion history of the Universe. In light of the new results, it is now likely those assumptions will need to be revised.

Over the past decade or so, Maria Bergemann, one of MPIA's Lise Meitner Research Group Leaders, at the Max Planck Institute for Astronomy (MPIA), developed improved ways of measuring the chemical properties of stars. Now, it seems that her efforts may affect the way how astronomers measure cosmic expansion, the Hubble constant, and the amount of Dark Energy in the Universe.

Using the analytic tools Bergemann developed on the spectroscopic observations of 42 stars, she and her collaborators traced the abundance of the chemical elements manganese and iron over the past 13 billion years of galactic history. Their unexpected result of a surprisingly constant abundance ratio of those two elements puts constraints on the properties of the stellar explosions, the so-called supernovae (SN) of type Ia, needed to produce the element.

Previously, scientists believed that most SN Ia were caused by a White Dwarf star orbiting an ordinary star, sucking off the hydrogen from the star's outer layers. In contrast, the manganese abundances of stars within our Milky Way show that three in four such explosions result from other kinds of type Ia SN mechanisms. One of them could be a scenario in which two White Dwarf stars orbit each other. Another mechanism involves a White Dwarf that accretes helium from a companion and undergoes sequential "outside-in" detonations.

The difference between the standard scenario and alternative explosion mechanisms for SN Ia may have significant consequences for the relation between the brightness maximum, how the brightness changes over time, and the overall time scale of these SN explosions. That, in turn, is important for some of the most basic observations of cosmology. Those observations use SN Ia as "standard candles," that is, as light sources whose intrinsic brightness astronomers derive from observations. Comparing a source's intrinsic brightness and its observed brightness allows astronomers to calculate its distance to us.

Detections of the so-called Dark Energy, thought to be responsible for around 70 % of the Universe's total energy density, go back to observations of this kind. Likewise,

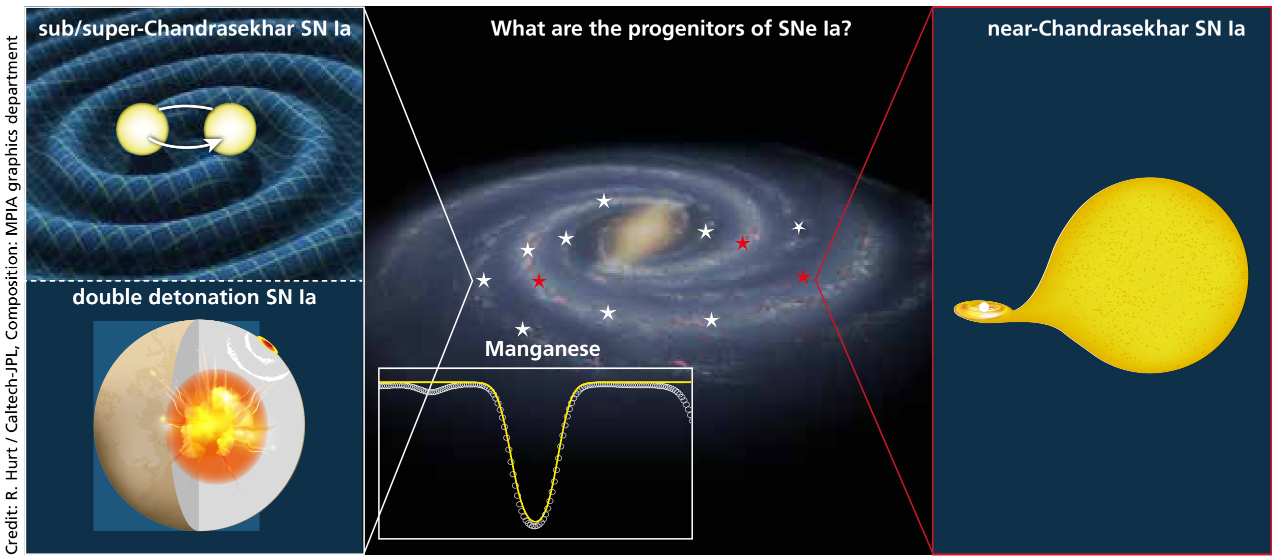


Fig. III.1.1: By examining the abundance of the element manganese, a group of astronomers has revised our best estimates for the processes behind supernovae of type Ia.

they affect measurements of the Hubble constant, which specifies the current expansion rate of the Universe. Suppose the SN used for those measurements are not standard candles of one of the same type but instead are of at least two different kinds whose intrinsic properties differ systematically. In that case, astrophysicists will need to revisit the cosmological deductions.

Bergemann's analytic tools are the latest in a series of developments that derive the physical properties of stars from their spectra. By the early 20th century, astronomers were using simplified models for those spectral lines to examine the atmospheres of stars. This progress paved the way to measuring the stars' temperatures, surface pressures, and chemical compositions. However, these models assumed stars were perfect spheres – in contrast to the complex three-dimensional structure of real stars. Another simplification comprised the equilibrium of their pressure and gravitational force, known as hydrostatic equilibrium. The models also required, at least locally, "thermodynamic equilibrium" between gas and radiation. That is, in each sufficiently small region, the available energy had had time to spread evenly between the different parts of the system, allowing us to assign one single temperature to it.

Models of stellar atmospheres and radiation emitted by stars in the absence of a local thermodynamic equilibrium are a relatively recent development. Such novel models are known as non-LTE models (since they assume no Local Thermal Equilibrium). These models go hand in hand with three-dimensional simulations of the convection beneath the star's surface, similar to the motion of boiling water in a pot, with matter moving upwards in some regions, downwards in others. They also include the interaction of a highly dynamic plasma with the star's radiation. The theory behind non-LTE and hydrodynamics had already been formulated in the late 1970s. However, applying these models to analyzing the chemical composition of many stars in the Galaxy only became possible about 20 years ago. This breakthrough happened when powerful modern supercomputers became available for scientific research, coinciding with recent advances in the description of atomic structure and light-matter interactions that resulted in robust data for atomic physics needed in non-LTE models. Bergemann worked on different aspects of such models since 2005, making her one of the pioneers of the field.

The new, refined methods yield virtually the same result as their simplified precursors for some elements, such as iron. But for others, there are notable differences. Bergemann and her team, including Andrew Gallagher, Camilla Juul Hansen, and Philipp Eitner, found an example of this when tracing the chemical evolution of the element manganese, a metal next to iron in the periodic table of elements. Gallagher succeeded in greatly improving the performance of the 3D non-LTE code. Hansen delivered high-quality near-UV observational data covering the spectral regions essential for the analysis. Eitner, a bachelor student at Heidelberg University, developed a robust framework to apply non-LTE to modeling stellar spectra. He also extended the analysis to cases where we can observe a spectrum not for separate stars but only for the combined light from numerous stars in a stellar cluster. This improvement is essential for the analysis of extragalactic star clusters.

Tracing the history of manganese in our Galaxy and beyond

Using high-resolution stellar spectra from 8–10-meter telescopes – both ESO's Very Large Telescope and the Keck Observatory – Bergemann and her colleagues measured the abundances for both iron and manganese for 42 stars, some as old as 13 billion years.

Chemistry-wise, the Universe started very simple, with almost nothing else but hydrogen and helium shortly after the Big Bang, 13.8 billion years ago. A large fraction of heavier elements synthesized between now and then in the interior of stars. Other species – like manganese and iron – are produced in the violent SN explosions marking the end of certain stars' lives. SN disperse the exploding star's matter, seeding the surrounding space with heavier elements. When stars of later generations form, they incorporate them. Spectral traces of these elements are observable in the stars' atmospheres.

Because of this kind of cumulative chemical history, the abundance of elements such as iron in a star's atmosphere directly indicates how long ago that star was born. Using the iron abundance as an indicator of each star's age relative to the others, the astronomers reconstructed our Galaxy's history of manganese production. To their considerable surprise, the new and improved analysis showed that the manganese to iron ratio was fairly constant over that long period. Earlier, less advanced studies had found a trend in manganese production steadily increasing over the past 13 billion years of Galactic history. Even more surprisingly, the astronomers found the same constant ratio between manganese and iron in all the different regions of our Galaxy and nearby galaxies of the Local Group. At least in our cosmic neighborhood, the manganese-to-iron ratio appears to be a universal chemical constant.

Supernovae with a fundamental limit

At this point, the supernovae come into play. Manganese needs the impressively high energy liberated in SN explosions to form. Different types of SN produce iron and manganese in different ratios. One contributor is a so-called core-collapse SN when a massive star implodes at the end of its life after having exhausted its nuclear fuel in the core. The others are more interesting in this context: If a White Dwarf star, a remnant of a star similar to the

Sun, is orbiting a giant star closely enough, its gravity will pull hydrogen from its companion onto its surface. Once the mass reaches a limiting value, the White Dwarf becomes unstable, resulting in a thermonuclear explosion, a so-called SN of type Ia. The limiting mass follows from the fundamental principles of physics, first discovered by Subrahmanian Chandrasekhar in 1930. In this scenario, the fundamental "Chandrasekhar limit" always tunes the total mass of the exploding star, and thus the total brightness of the explosion to the same values.

This universal law is good news for astronomers tracing the expansion of our cosmos: when they observe such an explosion, they know how bright it is at the source; by comparing this brightness with the observed brightness, they can deduce the SN's distance. Measuring the galaxy's redshift where the explosion occurred (i.e., how fast it is moving away from us), cosmologists can write down a redshift-distance relation. From this, they calculate the Universe's expansion rate (encoded in the Hubble constant) and whether that expansion is accelerating or becoming slower over time. The late 1990s discovery of an accelerating Universe resulted in the 2011 Nobel Prize in Physics. Cosmologists explain the acceleration by assuming that our cosmos is filled with an unusual ingredient that astronomers call "Dark Energy".

A different take on supernovae Ia

That, at least, is the story so far. With the previous, less accurate manganese measurements, astronomers had concluded that a significant fraction of SN Ia happens in the way described above, with a White Dwarf gobbling up hydrogen from a giant companion star. But to explain why the manganese-to-iron ratio has been constant throughout Galactic history, things must have been different. There are several other ways of producing an SN Ia. To observers measuring the explosion's light curve, that is, the way that its brightness changes over time, these scenarios are indistinguishable from the White-Dwarf-plus-giant scheme.

In one special case, a star accretes matter from a companion leading to nuclear instability in the outer helium shell, triggering an off-center explosion and a detonation front. This burning wave propagates into the star's carbon-oxygen core at supersonic speed, triggering another detonation. This scenario is known as double-detonation SN Ia.

In the other case, the protagonists are two White Dwarfs in narrow orbit around each other. By the time the stars have become so close that, in effect, their outer gas swirls around them as a common envelope, gravitational waves emitted by the orbiting binary force the White Dwarfs ever closer together. As the two White Dwarfs merge, the result is a thermonuclear explosion.

Last but not least, even double White Dwarf binaries can experience a double-detonation, resulting in a "dynamically driven double-degenerate double-detonation" SN Ia.

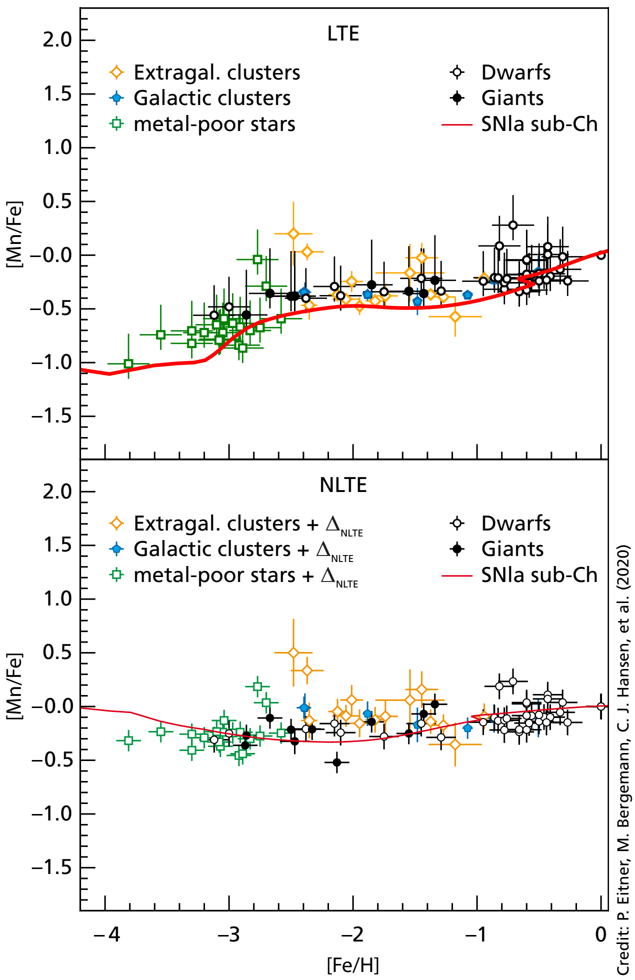


Fig. III.1.2: Manganese abundance ratios [Mn/Fe] as a function of metallicity [Fe/H]. *Top panel:* LTE data presented with different symbols; the line shows the model's results used to calculate the mixture of different SNe. *Bottom panel:* NLTE data.

In all these alternative scenarios, the brightness of the explosion is not fixed by a physical constant. The double-detonation explosions do not require the star to attain a Chandrasekhar mass limit: in fact, they explode at lower masses and are, therefore, called sub-Chandrasekhar explosions. In a violent merger, the combined exploding object may be less or more massive than the Chandrasekhar limit. Sub-Chandrasekhar mass explosions are bound to be a bit fainter, while physicists expect super-Chandrasekhar explosions to be brighter than their Chandrasekhar-mass kin. These mechanisms are bad news for cosmologists who rely on SN Ia standard candles, where such explosions should have a uniform, well-defined intrinsic brightness. Even worse: to explain the observed constant ratio of manganese to iron, Bergemann and her colleagues had to assume that compact binary White Dwarf explosions or double detonation explosions cause three-quarters of all SN Ia in the Milky Way. Non-standard SNe Ia are the rule, not the exception.

Next steps

The next data release (DR3) of ESA's Gaia satellite, due in 2021, could yield additional data about the prevalence of double White Dwarf binaries, potentially bolstering the case for the new type of SN Ia. Much later, the spaceborne gravitational wave detector LISA, currently scheduled for launch in 2034, promises to detect the gravitational wave mergers of White Dwarf binaries to great distances, permitting a direct check of the predictions by Bergemann and her colleagues.

In the meantime, cosmologists will be busy checking up on what consequences the new SN types might have for their deductions about the Universe as a whole. In one regard, the expected corrections might even be welcome. Currently, there is a discrepancy in the Hubble constant depending on whether it is measured with type Ia SN or with the residual radiation from the earliest phases of our cosmos, the "Cosmic Microwave Background". The new results on SN Ia might help us make the current cosmological models and observations more consistent. All in all, the depicted results are an impressive demonstration of the interconnectedness of astronomical research. Develop a new method of analyzing the chemistry of the stars, and you might just end up effecting a change in our view of the Universe as a whole.

Maria Bergemann, Philipp Eitner (also Heidelberg University) and Andy Gallagher, and Camilla Juul Hansen

in collaboration with

Soeren Larsen (Radboud University in Nijmegen)

P. Eitner, M. Bergemann, C. J. Hansen et al. 2020, "Observational constraints on the origin of the elements. III. Evidence for the dominant role of sub-Chandrasekhar SN Ia in the chemical evolution of Mn and Fe in the Galaxy" in Astronomy & Astrophysics, Vol. 635, A38. DOI: 10.1051/0004-6361/201936603

Maria Bergemann, Andrew J. Gallagher, Philipp Eitner et al. 2019, "Observational constraints on the origin of the elements. I. 3D NLTE formation of Mn lines in late-type stars" in Astronomy & Astrophysics, Vol. 631, A80. DOI: 10.1051/0004-6361/201935811

A. J. Gallagher, M. Bergemann, R. Collet et al. 2020, "Observational constraints on the origin of the elements. II. 3D non-LTE formation of Ba II lines in the solar atmosphere" in Astronomy & Astrophysics, Vol. 634, A55. DOI: 10.1051/0004-6361/20193610

III.2 Science Highlights

They grow up so fast – New observations show that massive disk galaxies formed surprisingly early in cosmic history

In our 13.8 billion-year-old Universe, most disk galaxies like our Milky Way were thought to form gradually, reaching their large mass relatively late. However, astronomers led by Marcel Neeleman (MPIA) using the ALMA observatory, have found a massive rotating disk galaxy, seen when the Universe was only ten percent of its current age. The observation shows that some disk galaxies must have formed much more quickly. This finding supports earlier computer simulations that had indicated the role of a quick, "cold" mode of galaxy formation.

Fig. III.2.1: Artist impression of the Wolfe Disk, a massive rotating disk galaxy in the early, dusty universe. The galaxy was initially discovered when ALMA examined the light from a more distant quasar *(top left)*.

At the time of the Big Bang, the Universe was featureless and uniform – a bland plasma of charged particles. How a rich array of structures formed in our cosmos, including a diverse variety of galaxies with countless stars over the following 13.8 billion years, is one of the fundamental questions of modern cosmology. During an effort to contribute to an answer, a group of astronomers led by Marcel Neeleman discovered a critical piece of the puzzle. The astronomers detected a disk galaxy – similar to the Milky Way – that had reached a considerable mass of 70 billion solar masses as early as 1.5 billion years after the Big Bang when the Universe was 10 % its current age.

The result provides valuable input for a present-day discussion about how galaxies form, featuring two fundamentally different mechanisms. In the "hot mode" scenario, hot gas needs to cool down for a long time to develop a disk. The more recent "cold mode accretion" picture involves cool gas converging onto a newly formed galaxy in a way that creates a disk on shorter time scales.

Finding a fully-fledged, massive disk a mere 1.5 billion years after the Big Bang indicates that cold mode accretion must play a significant role in galaxy formation – which is indeed what computer simulations like the Auriga and TNG50 simulations had indicated.

From cosmic uniformity to diversity

According to modern cosmology, the Universe as we know it began in a hot dense phase 13.8 billion years ago, as an almost perfectly homogeneous plasma made of electrons and protons. Even after that plasma had cooled down sufficiently for atoms to form, it had nearly the same density everywhere. One of the central tasks of astrophysics is to explain how the Universe evolved from this almost featureless state to the cosmos we see around us today, with its galaxies, stars, and planets.

Going by the best available simulations, the "backbone" of cosmic structure is a network of so-called dark matter, which does not interact with light at all, and thus remains invisible. With gravity at work, minute inhomogeneities in the density of dark matter grow over billions of years. Gravitational attraction is slightly stronger at locations with a marginal overabundance of dark matter, so additional dark matter is pulled in. The result is an enormous cosmic network of filaments and nodes (with greater density) surrounding cosmic voids (with lower density).

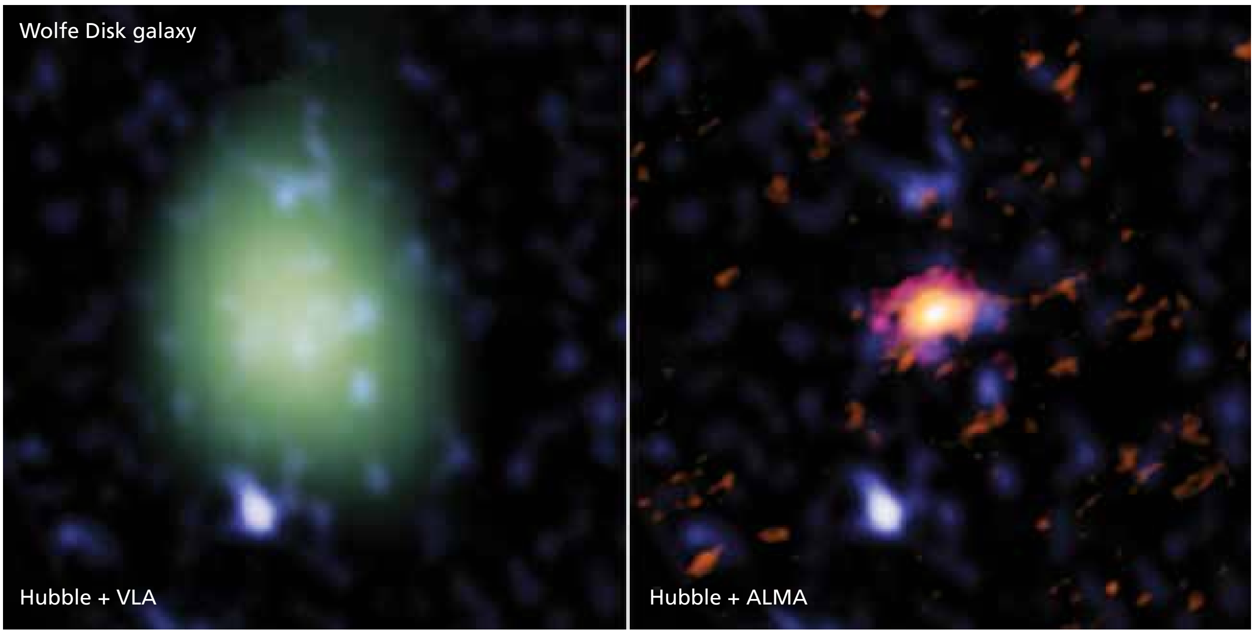
By mass, dark matter accounts for roughly 85 % of all matter in the Universe. Instead, atoms like those of which all stars, planets, and our bodies are made account for only 15 %. In terms of mass, the dark matter network is the most prominent large-scale structure in the Universe by far. But as human beings, we are particularly interested in the material we, and our environment, are made of – and for astronomers, they can observe only ordinary matter using telescopes and astronomical instruments.

Forming galaxies and stars

Galaxies form within clumps of the cosmic dark matter network, so-called halos, which have a markedly higher density than the surrounding material. It is natural that these dark matter concentrations gravitationally attract ordinary matter. Still, for that ordinary matter to form luminous stars and thus to become visible over large distances, it needs to meet certain conditions. Stars are born when smaller regions within a cloud of molecular gas collapse and heat up. But for that to happen, and for gas to form molecules in the first place, the gas needs to be sufficiently cool – directly before star formation, a mere 10 degrees Celsius above absolute zero, or 10 Kelvin.

Under those conditions, it is quite challenging to build large galaxies like our Milky Way that comprise a massive disk of cool gas in which new stars are forming. A major mode of galaxy growth are collisions and mergers of smaller galaxies. However, most galaxies that we find early in the Universe look heavily distorted because they underwent persistent and frequent "violent" merging.

Fig. III.2.2: The Wolfe Disk as seen with ALMA *(right - in red)*, VLA *(left - in green)*, and the Hubble Space Telescope *(both images - blue)*. ALMA looked at the galaxy's movements and mass of atomic gas and dust in radio light, and the VLA measured the amount of molecular mass. In UV-light, Hubble observed massive stars. The VLA image is made in a lower spatial resolution than the ALMA image and therefore appears more extended and pixelated.



Credit: ALMA (ESO / NAOJ / NRAO), M. Neeleman; NRAO / AUI/NSF, S. Dagnello; NASA / ESA Hubble

These hot mergers make it difficult to form well-ordered, cold rotating disks like the ones we observe in the present Universe. Wherever gas falling onto such galaxies heats up, which happens inevitably when gas clouds collide and form so-called shock fronts, it takes a few billion years of cooling before an orderly gas disk can form.

A cool alternative way of forming large disk galaxies

Modern simulations of structure formation employ supercomputers to follow dark matter and gas over billions of years after the Big Bang. In effect, they create a virtual universe based on the known physical laws, allowing scientists to analyze all phases of cosmic evolution.

Two recent simulations, the smaller-scale Auriga simulation of Milky-Way-like galaxies and the large-scale detailed TNG50-Simulation, opened up the possibility of an alternative mode of formation. Already cold gas flowing into the galaxies, following the filaments of the dark matter network and avoiding the collisions that would heat the gas, permits the formation of massive disk galaxies at a much earlier time than in the collision and cooling scenario.

How to find those early, cool galaxies?

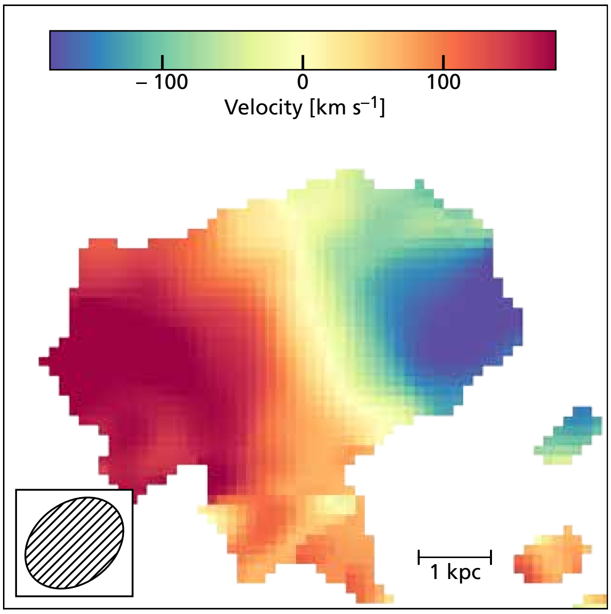
At this point, it was clear that the most direct way of testing the prediction from the simulations would be to find massive galactic disks in the early universe. After all, that is what the hot-then-cooling-down scenario could not explain, while the cold flow scenario could. Fortunately, astronomers are in a position to observe the distant past. Light from remote regions takes some time to reach us. If they are so far away, light may travel 12 billion years before it enters our telescopes today and carries with it information about how that region looked 12 billion years ago. This prospect motivated Marcel Neeleman and his colleagues to search for early disk galaxies.

The problem is that distant galaxies are hard to observe. Not only do you need a powerful telescope. You also need to know where to look. Neeleman's collaborator and former PhD co-advisor J. Xavier Prochaska is an expert on employing extremely bright and distant quasars for probing far-off galaxies. The quasars' luminosity results from matter falling onto a galaxy's central black hole. By carefully inspecting the quasar light, they can infer the presence, distance, and properties of absorbing foreground gas, particularly inside a galaxy.

ALMA finds the Wolfe disk

Neeleman and his colleagues used observations with the ALMA observatory, an array of dozens of radio telescopes in Chile, to identify six early galaxy candidates associated with gas seen in absorption towards quasars. They were so distant that their light had traveled on the order of 10 billion years to reach us. When they used ALMA's unrivaled sensitivity and resolution to observe the brightest of those candidate objects, DLA0817g, in more detail, they found tell-tale wavelength shifts, known as Doppler shifts. These signals told them they were indeed dealing with a large, stable, rotating disk. They also obtained additional observations with the VLA radio telescopes. Combining the apparent size with the data quantifying disk rotation, the researchers concluded they were looking at a disk with a mass of 70 billion suns. The observations reveal the disk's appearance when the Universe was a mere 1.5 billion years old, about 10% of its current age.

The researchers named DLA0817g the "Wolfe Disk", after the late Arthur M. Wolfe, former PhD advisor to three of the paper's four authors, including Prochaska and Neeleman. Wolfe's long-term research program on the absorption of quasar light is what made this and many other discoveries possible. The Wolfe Disk's mass and age are a strong indication that the cold mode accretion scenario has indeed played a significant role in cosmic evolution – vindicating simulations like Auriga and TNG50. The details will still need additional input from both simulations and observation. The astronomers think the Wolfe Disk has grown primarily through the steady accretion of cold gas. Still, one of the remaining questions is how to assemble such a large gas mass while maintaining a relatively stable, rotating disk.



Credit: M. Neeleman / MPIA

Fig. III.2.3: Map of radial velocities of the Wolfe disk measured by the Doppler shift of the ionized carbon spectral line. Astronomers associate this species with dense material as expected in the disk component of spiral galaxies. The pattern of receding and approaching gas indicates rotation of the galactic disk. The astronomers derived a rotation curve from which they deduced the mass by analyzing the spatial distribution of radial velocities in detail.

Wolfe Disks are probably quite common out there

A galaxy will only be detectable by its absorption of quasar light if there is a chance alignment between us as the observers, the galaxy, and the quasar. Such alignments are rare in and of themselves; if the Wolfe Disk were itself an unusual, uncommon object, that would increase the improbability of this chance discovery considerably. Much more probable is the assumption that galaxies like the Wolfe Disk are comparatively common in the early universe.

Finding the Wolfe Disk using this method indicates that it belongs to the average population of galaxies present at early times. When the newest observations with ALMA surprisingly showed that it is rotating, it became evident that early rotating disk galaxies are not as rare as previously thought. There should be a lot more of them out there. That, too, is a claim that the astronomers hope to test by continuing their search and detecting other massive disk galaxies in the early universe.

Marcel Neeleman

in collaboration with

J. Xavier Prochaska (UCSC and University of Tokyo), Nissim Kanekar (National Centre for Radio Astrophysics, Pune) and Marc Rafelski (Space Telescope Science Institute and Johns Hopkins University)

Marcel Neeleman, J. Xavier Prochaska, Nissim Kanekar, Marc Rafelski 2020, "A Cold, Massive, Rotating Disk 1.5 Billion Years after the Big Bang" in Nature, Vol. 581, 269. DOI: 10.1038/s41586-020-2276-y

III.3 Science Highlights

From dust to, possibly, life – New experiments show complex astrochemistry on thin ice covering dust grains

Astronomers of the Max Planck Institute for Astronomy (MPIA) and Jena University have obtained a clearer view of nature's miniature deep-space laboratories: tiny dust grains covered with ice. Instead of regular shapes covered thickly in ice, such grains appear to be fluffy networks of dust, with thin ice layers. In particular, this means the dust grains have considerably larger surfaces, where most of the chemical reactions occur. Hence, the newly revealed structure has fundamental consequences for astronomers' view of organic chemistry in space – and thus for the genesis of prebiotic molecules that may have been essential for the origin of life on Earth.

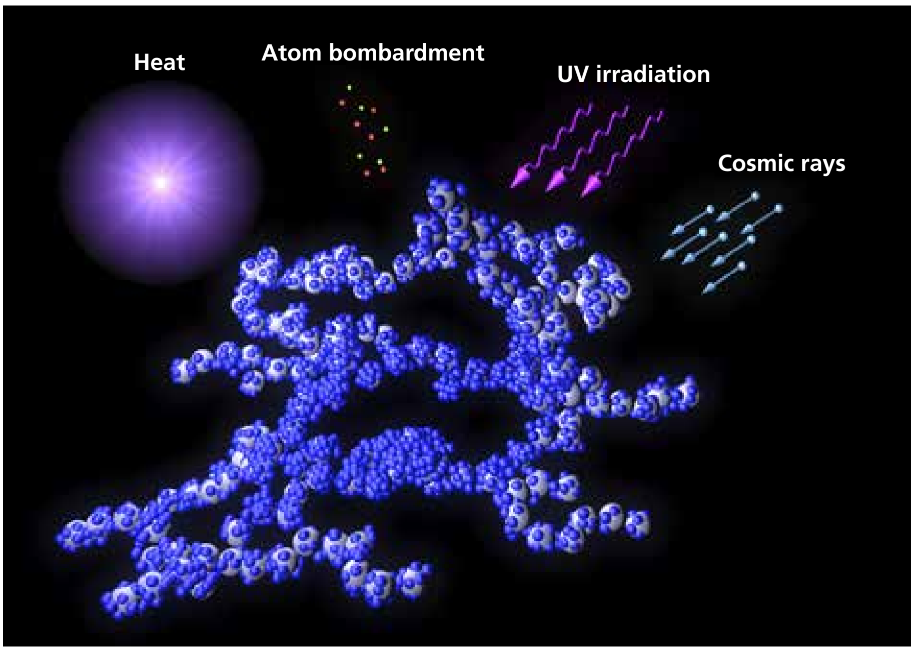
Creating complex molecules in deep space is anything but easy. To the best of our current knowledge, interstellar dust grains with icy surfaces are the natural laboratories in which the necessary reactions occur. Alexey Potapov of the MPIA Laboratory Astrophysics Group at Jena University and his colleagues have conducted experiments that demonstrate that, under realistic conditions, the ice layers may well be extremely thin. As a result, the dust grains' structure, composition, and properties can play an important role in the chemical processes on their surfaces.

These results open up a new field of study: Scientists working on the cosmic origins of life's organic precursor molecules need to take a closer look at the properties of the cosmic dust grain surfaces. In particular, they must consider interactions with atomic and molecular species adsorbed from the gas phase. Depending on pressure and temperature, these chemicals bound to the grains can form larger compounds and ices. Therefore, astrochemists must consider the complex environments and how they support the synthesis of complex organic and prebiotic molecules.

Cosmic precursors of life

When we think about how life, and eventually how we ourselves, have come to be in this Universe, several vital steps had to be taken, encompassing physics, chemistry, and biology. As far as we know, the earliest biology in

Fig. III.3.1: Schematic figure showing dust grains (in grey) mixed with ice molecules (in blue), as well as the primary external influences that facilitate chemical processing in deep space: heat, bombardment by atoms, ultraviolet radiation, and cosmic particle streams (cosmic rays).



Credit: A. M. Quetz / MPIA, Alexey Potapov / hab. Astrophysics Group, MPIA the story of our own origins took place here on Earth. However, the same is not valid for either physics or chemistry: most chemical elements, including carbon and nitrogen, assemble by nuclear fusion inside stars. “We are made of star-stuff,” as Carl Sagan famously said.

Molecules, including the organic compounds necessary to build amino acids, or our very DNA, can form in the interstellar medium (ISM). From there, they are inherited into new planetary systems like our Solar System that subsequently originate from condensed clouds of ISM. On the few occasions when probes like Stardust, Rosetta, and Hayabusa 2 have managed to investigate cosmic dust directly inside the borders of the Solar System, the analysis found complex molecules, such as the simple amino acid glycine. Likewise, throughout the evolution of a planetary system, organic molecules can be transported to planetary surfaces by meteorites and early comets.

How those molecules can take shape in the first place, particularly in the nearly empty expanses between stars, is not a simple question at all. In outer space, most atoms and molecules are part of an ultrathin gas, with hardly any interaction – let alone the interactions needed to build up more complex organic molecules.

Icy dust grain laboratories

In the 1960s, astronomers interested in interstellar chemistry began to develop the idea that interstellar dust grains could serve as “cosmic laboratories” to facilitate more complex chemical reactions. Whether carbon-based or silicate-based, such grains typically form in the outer layers of cool stars or in the aftermath of supernova explosions. In a cloud of gas and dust, different kinds of molecules would stick to the (cold) grain. As a result, these molecules would accumulate, eventually promoting interesting chemical reactions.

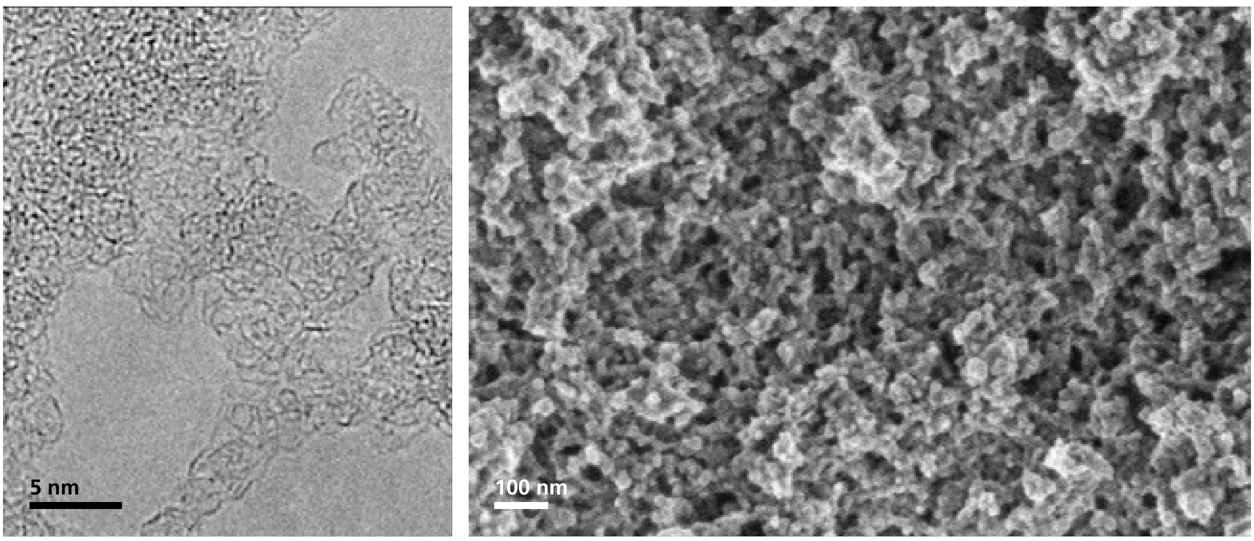
Specifically, it would take on the order of 100 000 years for a dust grain to accumulate a mantle of ice (mainly water ice, but also some other molecules like carbon monoxide). This icy layer would then serve as a tiny cosmic chemistry lab.

Astronomers interested in this topic soon realized that they needed experiments to interpret their observations of interstellar gas clouds. They would need to study ice-covered dust grains and their interactions with molecules in laboratories here on Earth. To this end, they would use vacuum chambers simulating the emptiness of space and appropriate temperatures. Since scientists used to assume that what counted was chemistry on the icy surface, it became common practice to use ice layers for such experiments, applied to an ordinary surface such as a potassium bromide (KBr) crystal plate or a metal surface. Unfortunately, the new results show that this can only be part of the picture, at best.

Artificial dust grains and their ice

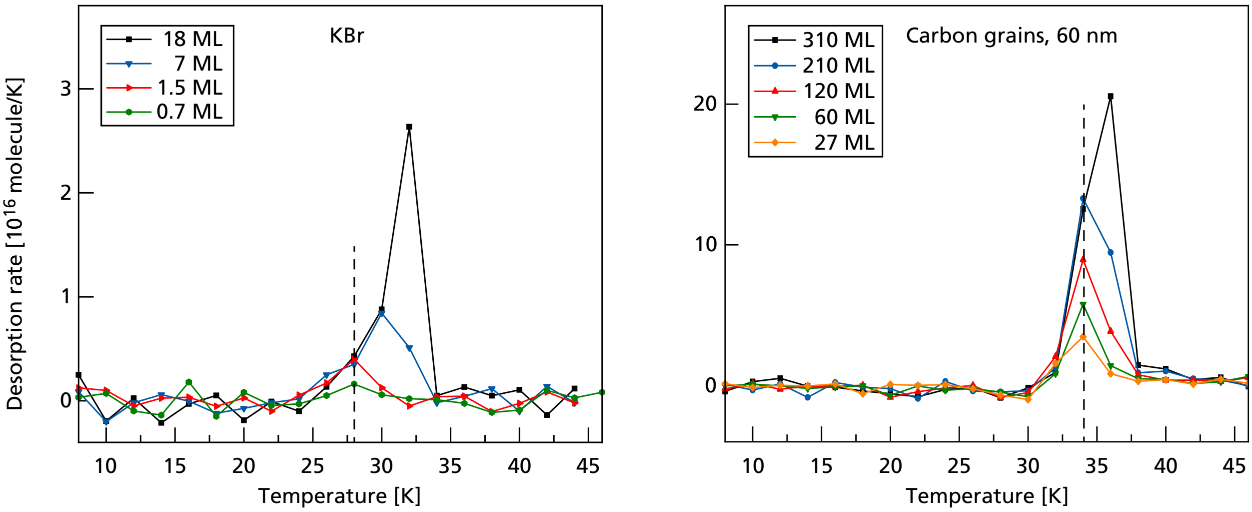
Planet formation and the search for the origins of life are key research goals for MPIA, and icy dust grains play a crucial role in both. For this reason, since 2003, MPIA has maintained a Laboratory Astrophysics and Cluster Physics Group at the Institute of Solid State Physics of Friedrich Schiller University, Jena.

Part of the group’s equipment is lasers employed to create artificial cosmic dust grains. For this purpose, a laser is pointed at a graphite specimen, eroding (ablating)



Credit: C. Jäger / MPIA, FSU Jena

Fig. III.3.2: Electron microscopy images of the artificial cosmic dust grains at different resolutions (transmission electron microscopy on the left, scanning electron microscopy on the right). Both show the complex, intricate surface structures of grains, resulting in high porosity and corresponding large surfaces.



Credit: A. Potapov et al. / MPIA, FSU Jena

Fig. III.3.3: The diagrams visualize the results of CO ice desorption experiments on two substrates (KBr and carbon grains). It shows the desorption rates of ice layers whose thickness is indicated as a number of monolayers (ML) of nominal thickness, i.e., the number of single layers the ice had if the substrate was non-porous. Curves with peak rates at identical temperatures indicate the monolayer regime. While for KBr, the peak position shifts to higher temperatures at around 1 ML, the peak location for carbon grains remains at the same temperature up to 210 ML. The result points to a single ice layer even though the amount of ice present would form a multilayer of 210 sheets on smooth surfaces.

minute particles from the surface, mere nanometers across (where one nanometer is one billionth of a meter). Using this technique, Alexey Potapov of the Jena Laboratory Astrophysics Group, the lead author of the underlying paper, and his colleagues studied such artificial dust grains. They induced different kinds of ice to form on their surfaces. During the process, they began to doubt the standard picture of chemistry on thick icy surfaces.

Cosmic laboratories are fluffy and dusty

Their results did not point to grains fully covered with many layers of solid ice (water or carbon monoxide ice) accumulated to an onion-like structure. Instead, the dust grains they produced in the laboratory, staying as close as possible to realistic deep-space conditions, were extended, many-tendrilled shapes – fluffy networks of dust and ice.

With this shape, their total surface area is much larger (a factor of a few hundred) than for simpler configurations, and this is a game-changer for calculations of how the detected amount of water in molecular clouds would cover some grains: from grains with low surface areas, thus entirely covered by the available water, we arrive instead at a more extended surface that will have thicker layers in some places, while in other sites there is no more than a single layer of ice crystals – simply because there is not enough water to cover all of the hugely extended surface area with several layers of ice.

Changing the pathway to life in the Universe

This different kind of structure has profound consequences for the role of icy dust grains as microscopic cosmic laboratories. For example, chemical reactions depend on molecules that have “gotten stuck” on the surface, and on how those molecules can move around (diffuse), meet other molecules, react, become stuck, or unstuck again. Those environmental conditions are completely different in the new, fluffy, dusty version of the cosmic laboratories.

Now that Potapov and his colleagues established dust grains matter, a new player has entered the astrochemical game. Being aware of it gives scientists a better chance to understand the fundamental chemical reactions that, at a later stage, might have led to the emergence of life in the Universe.

Also, if the grains are not hidden under thick ice layers but can interact with the molecules adhering to the surface, they can act as catalysts, altering the rate of chemical reactions by their mere presence. Suddenly, reactions specific to forming organic molecules like formaldehyde, or certain ammonia compounds, should become much more common. Both are essential precursors of prebiotic molecules, so this change in focus would directly affect our explanations for the chemical prehistory of life on Earth.

These are exciting new directions in the search for the formation of complex molecules in space. To follow up, MPIA has installed its new “Origins of Life” laboratory, which is tailored to this new type of research.

More generally, the new results, together with a number of similar discoveries obtained in previous experiments, constitute a wake-up call for the astrochemistry community. If you want to understand astrochemistry in the interstellar medium and its consequences for the origins of life, move away from icy onions. Instead, embrace the role of dust surfaces. Embrace the possible fluffiness of nature's tiny cosmic laboratories.

Alexey Potapov, Cornelia Jäger
(also Laboratory Astrophysics Group of the Max Planck Institute for Astronomy at the Friedrich Schiller University Jena, Institute of Solid State Physics)
and Thomas Henning

Alexey Potapov, Cornelia Jäger, Thomas Henning 2020, "Ice Coverage of Dust Grains in Cold Astrophysical Environments" in Phys. Rev. Lett., Vol. 124, 221103. DOI: 10.1103/PhysRevLett.124.221103

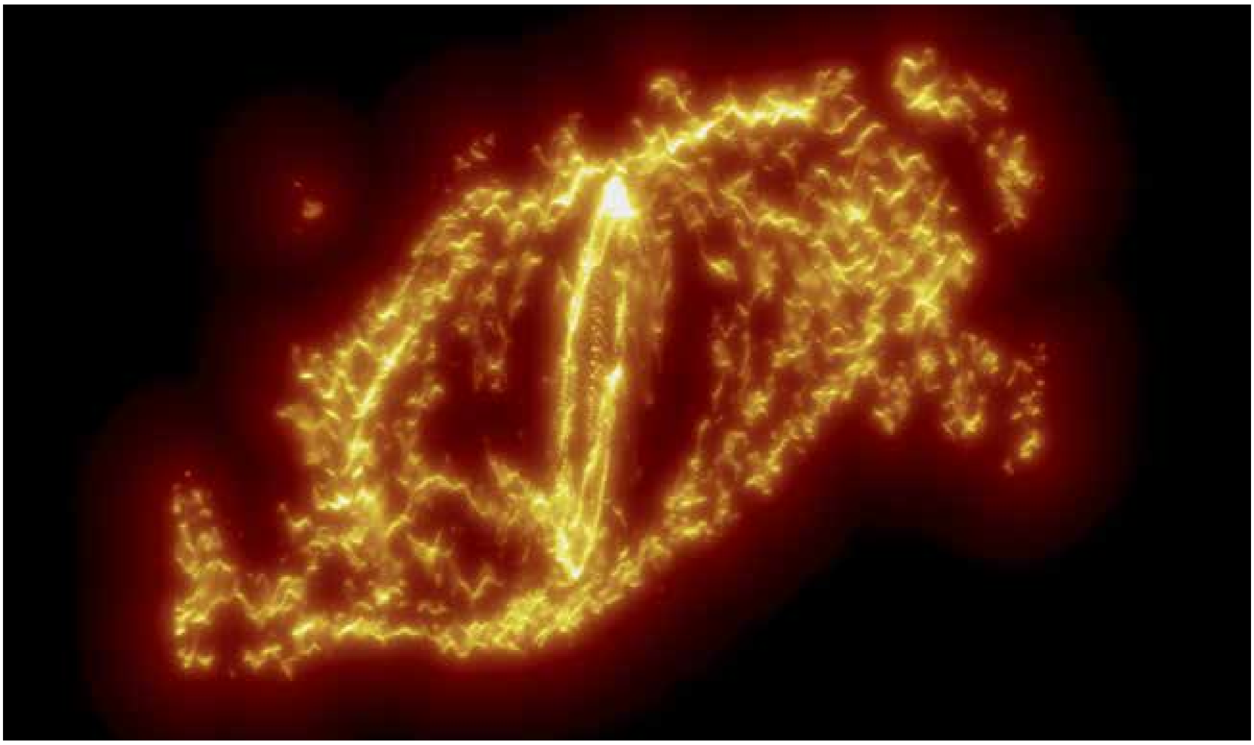
III.4 Science Highlights

The cosmic commute towards star and planet formation

The molecular gas in galaxies builds a hierarchy of structures. In vast molecular gas clouds travels along intricate networks of filamentary gas lanes towards the congested centers of gas and dust, where it condenses into stars and planets. To better understand this process, a team of astronomers led by Jonathan Henshaw (MPIA) have measured the motion of gas flowing from galaxy scales down to the scales of the gas clumps within which individual stars form. Their results show that the gas flowing through each scale is dynamically interconnected. While star and planet formation occurs on the smallest scales, this process is controlled by a cascade of matter flows that begin on galactic scales.

Inside galaxies, the molecular gas is set into motion by a combination of physical processes. The motions associated with galactic rotation, supernova explosions, magnetic fields, turbulence, and gravity all shape the gas structure in galaxies. Understanding how these motions directly impact star and planet formation is tricky because it requires quantifying gas motion over a vast range in spatial scale and then linking it to the physical structures we observe. Modern astrophysical facilities now routinely map enormous stretches of the sky, with some maps containing millions of pixels, each with hundreds to thousands of independent velocity measurements. As a result, measuring these motions is both scientifically and technologically challenging.

To address these challenges, an international team of researchers led by Jonathan Henshaw set out to measure gas motions throughout various environments using observations of gas in the Milky Way and a nearby galaxy. They detected these motions by measuring the apparent change in the frequency of light emitted by molecules caused by the relative motion between the light source and the observer. This phenomenon is known as the Doppler effect. By applying novel software designed by



Credit: T. Müller, J. Henshaw / MPIA

Fig. III.4.1: Visualisation of the observed velocity flows in the spiral galaxy NGC 4321, measured using the radio emission of the molecular gas (carbon monoxide): along the vertical axis, this image shows the velocities of the gas, while the horizontal axis represents the spatial extent of the galaxy. The wave-like oscillations in gas velocity are visible throughout the galaxy.

Henshaw and MPIA PhD student Manuel Riener, the team analyzed millions of measurements.

The researchers found that cold molecular gas motions appear to fluctuate in velocity, reminiscent of the appearance of waves on the ocean's surface. These fluctuations represent gas motion. While the fluctuations themselves did not surprise the astronomers, they were intrigued by how similar the velocity structure of these different regions appeared. They looked more or less the same, regardless of the scales of the motions they studied.

The team selected several regions for close examination to better understand the nature of the gas flows, using advanced statistical techniques to look for differences between the fluctuations.

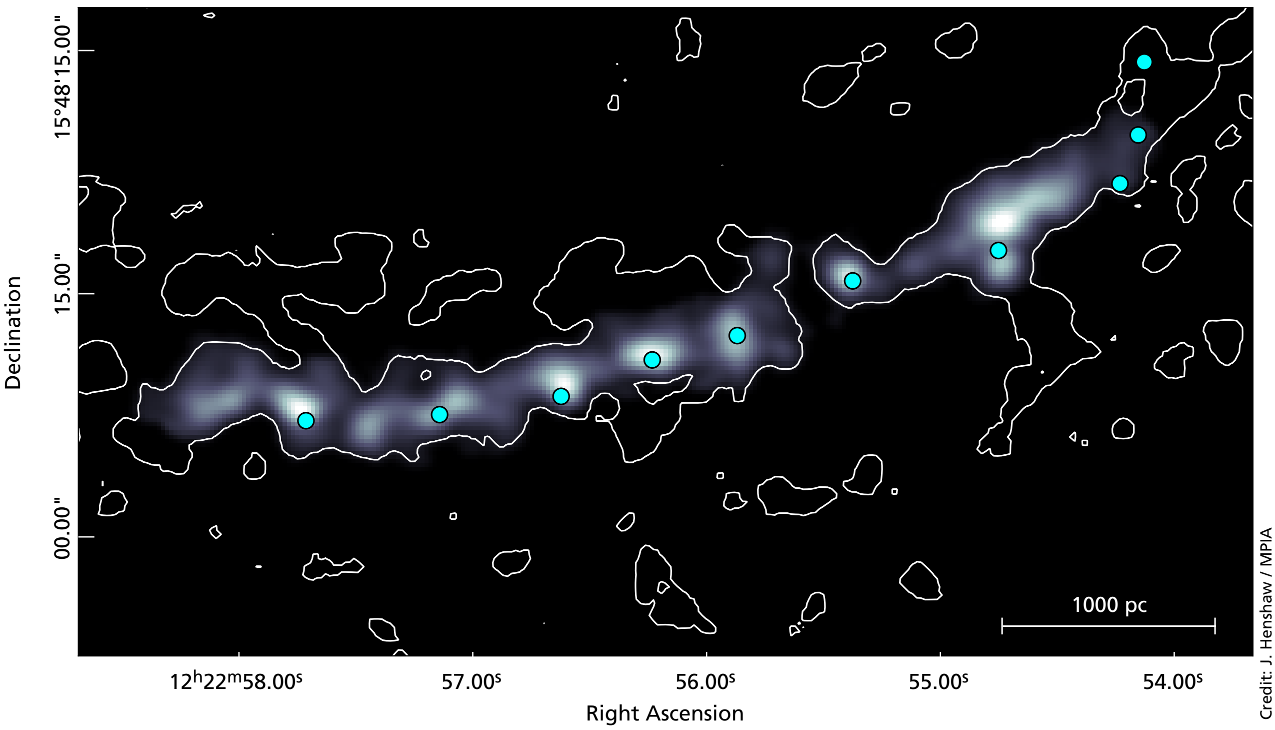
The primary tool they employed is the second-order structure function $S_2(\ell)$. It measures the difference in a given quantity, such as density or velocity, between pairs of points separated by a given distance. The value of the structure function then attains a local minimum for spacings, or lags ℓ, with similar densities or velocities indicating periodic structures. By combining a variety of different measurements, the researchers determined how the velocity fluctuations depend on the spatial scale.

Fig. III.4.2: Image of the molecular gas (carbon monoxide) distribution in the southern spiral arm of the galaxy NGC 4321 spanning roughly 15,000 light-years across. The bright spots indicate giant molecular clouds semi-regularly spaced inside the ridge of more dilute gas inside the spiral arm. The cyan circles depict the locations of star-forming complexes.

One useful feature of the analysis techniques is their sensitivity to periodicity. If there are repeating patterns in the data, such as equally spaced giant molecular clouds along a spiral arm, one can directly identify the scale on which the pattern repeats. The team identified three filamentary gas lanes. Despite tracing vastly different scales, all seemed to show structure roughly equidistantly spaced along their crests, like beads on a string. It made no difference whether they looked at giant molecular clouds along a spiral arm or tiny "cores" forming stars along a filament.

The team discovered that the velocity fluctuations associated with equidistantly spaced structures all showed a distinctive pattern. They look like waves oscillating along the crests of the filaments exhibiting a well-defined amplitude and a wavelength. Henshaw interprets the periodic spacing of the giant molecular clouds on large scales or individual star-forming cores on small scales to result from their parent filaments becoming gravitationally unstable. He believes that these oscillatory flows signify gas streaming along spiral arms or converging towards the density peaks, supplying new fuel for star formation.

In contrast, the team found that the velocity fluctuations measured throughout giant molecular clouds, on scales intermediate between entire clouds and the tiny cores within them, show no obvious characteristic scale. The density and velocity structures astronomers observe in giant molecular clouds are "scale-free". While generating these structures, the turbulent gas flows form a chaotic cascade, revealing ever-smaller fluctuations as you zoom in – much like a Romanesco broccoli or a snowflake.



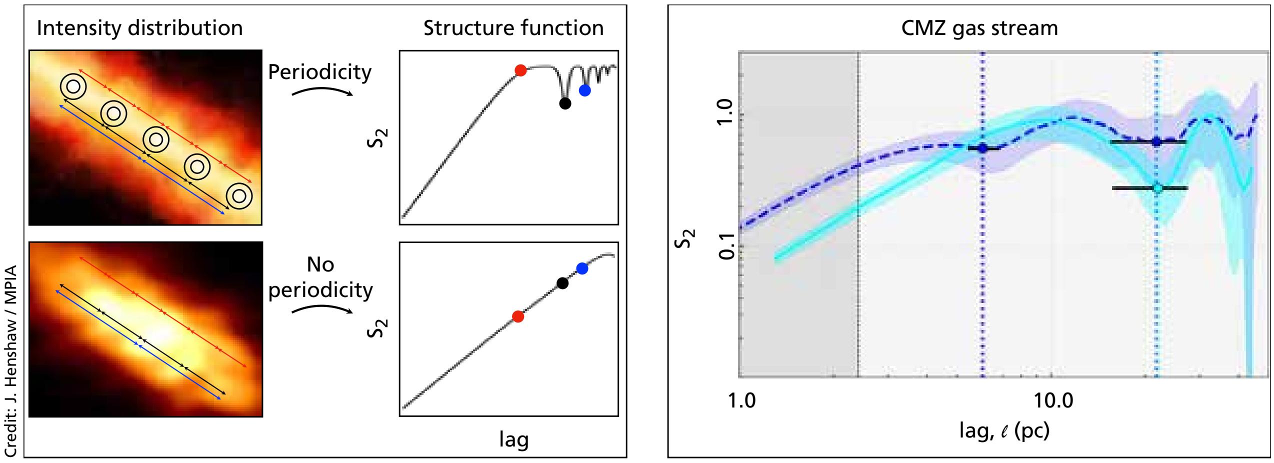


Fig. III.4.3: This figure illustrates the shape of the second-order structure function $S_2(\ell)$ both schematically (left) and for a gas stream in the central molecular zone (CMZ) of the Milky Way as measured in the underlying study (right). Repeating periodic structures are represented as minima of the structure function at characteristic spacings or lags. In the CMZ gas stream, the density distribution (dashed line) presents two periodicities at roughly 6 and 22 pc. The velocity distribution (solid line) exhibits a periodic feature that coincides with the wider spacing of the structure in the density distribution.

This scale-free behavior occurs between two well-defined extremes: the large scale of the entire cloud and the small scale of the cores forming individual stars. The team found these extremes to possess well-defined characteristic sizes, but chaos rules in between.

Altogether, one can picture the giant molecular clouds as equally-spaced mega-cities connected by highways. From a birds-eye view, the structure of these cities, and the cars and people moving through them, appears chaotic and disordered. However, when you zoom in on individual roads, you see people who have traveled from far and wide, each entering their individual office buildings in an orderly fashion. The office buildings represent the dense and cold gas cores from which stars and planets are born.

Jonathan D. Henshaw, Manuel Riener, Eva Schinnerer, Henrik Beuther and Thomas Henning

in collaboration with

J. M. Diederik Kruijssen (ARI, ZAH, Heidelberg University), Steven N. Longmore (Astrophysics Research Institute, Liverpool John Moores University, Liverpool, UK) and Adam K. Leroy (Department of Astronomy, The Ohio State University, Columbus, OH, USA)

Jonathan D. Henshaw, J. M. Diederik Kruijssen, Steven N. Longmore et al. 2020, "Ubiquitous velocity fluctuations throughout the molecular interstellar medium" in Nature Astronomy, Vol. 4, 1064. DOI: 10.1038/s41550-020-1126-z

III.5 Science Highlights

How galaxies have produced their stars: ASPECS survey provides key chapter of cosmic history

Astronomers have used the ALMA observatory to trace the fuel for star formation – molecular hydrogen gas – in the iconic Hubble Ultra-Deep Field, one of the best-studied regions in the sky. The observations allowed a group led by Fabian Walter (MPIA) to track how the Universe's inventories of gas and dust have changed over time from just two billion years after the Big Bang to the present. Comparing their own observations with additional observational data and modern simulations, the astronomers characterised and quantified the gas flows preceding the formation of stars within galaxies. The result is a broad-brush history of cosmic star formation that includes all the essential pieces: the history of star production itself and information about the supply chain that enables stars formation in the first place.

The supply chain for star production

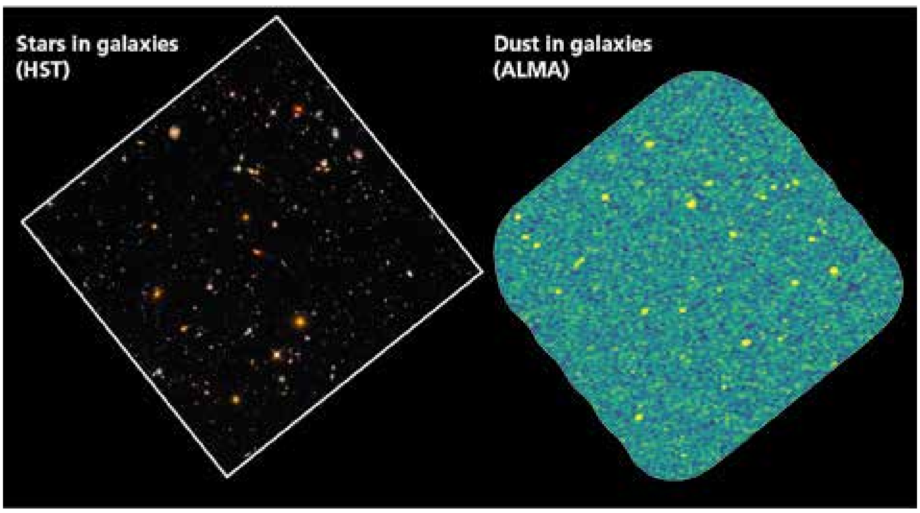
Tracing the origin of a common household item, like an appliance, amounts to reconstructing a supply chain: the raw materials transformed into more elaborate components, and those components assembled into a finished product. If supplies are missing, production will slow down, or might even grind to a halt. Documenting the factory's inventory of the necessary components or raw materials is valuable to learn about production history.

When galaxies form stars, there is, of course, no planning behind it, economic or otherwise. Stars form whenever the conditions are right, whenever the suitable material is available. To produce stars, we need cool gas made of hydrogen molecules. Such cool gas emerges when a sufficiently dense cloud of warmer gas made of hydrogen atoms cools down.

Atomic hydrogen originates from a massive reservoir of ionized hydrogen in the vast spaces between galaxies, warm intergalactic plasma that contains more than 90% of all hydrogen in the Universe. Keep track of how those inventories change over time, reconstruct the supply chain, and you can learn about the production history of stars. Keeping track of change is possible because astronomers always look into the past.

Our current knowledge strongly suggests that, on average, the Universe is the same everywhere. That allows astronomers to reconstruct a cross-section of cosmic history. If you want to know what the average properties of the Universe were, say, a billion years ago, look at objects so distant that their light takes a billion years to reach us! Repeat the process for different distances, corresponding

Fig. III.5.1: The Hubble Ultra-Deep Field *(UDF, left)* is one of the best-studied regions of the sky. Using the Hubble Space Telescope, astronomers have identified hundreds of galaxies in the UDF. The light of the most distant of those galaxies has traveled more than 13 billion years to reach us. The right-hand image shows the same region on the sky, observed as part of the ASPECS ALMA Large Program. That image shows millimeter waves emitted by the dust of the UDF galaxies. It provides the deepest view of the distant dusty universe to date.



Credit: Space Telescope Science Institute and ASPECS team to different cosmic epochs, and you will obtain at least an average history of the cosmos. The details will vary, but the big picture of cosmic evolution obtained in this way should be valid universally, providing clues about our own cosmic history over billions of years.

The history of stellar production rates

Over the past two decades, deep sky surveys using visible light and infrared radiation have given us a fairly complete picture of the number of stars in galaxies in each cosmic epoch, from the first billion years after the Big Bang to the present. Particularly important was the Hubble Ultra-Deep Field (UDF): a small region in the sky, about one-tenth the apparent diameter of the full moon, where the Hubble Space Telescope captured hundreds of images between 2003 and 2004, with a total of nearly 16 days exposure time combined into a single image.

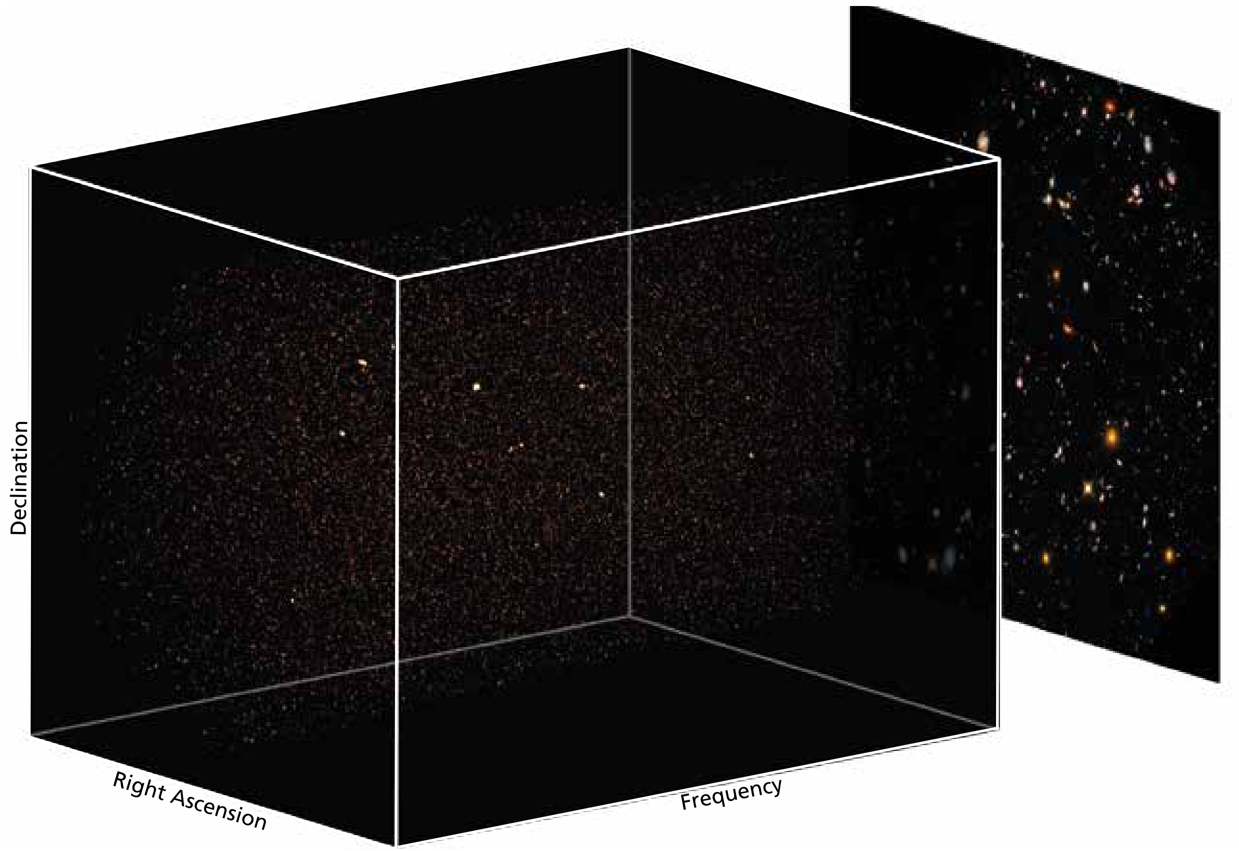
The UDF and other surveys lead to a consistent picture of star formation history, with star production ramping up to a veritable boom some 10 billion years ago, followed by a continuous decline in production rates. Half the stars in the Universe already existed by the time it was 4.5 billion years old, a third of its current age. But why the increase and decline? To answer that, it makes sense to see how much raw material, molecular hydrogen, was available at different times.

Molecular gas: the missing piece of the puzzle

This is where ASPECS comes in, the ALMA Spectroscopic Survey in the Hubble Ultra-Deep Field, organized by Fabian Walter and his colleagues. The astronomers used the ALMA observatory in Chile, which can combine up to 50 large (sub)millimeter telescopes in what is called interferometry. This technique permits imaging of fine details that would only be accessible to a much larger single telescope.

For studying molecular gas in distant galaxies, facilities like ALMA are ideal. Detecting cosmic molecules requires measuring light at specific wavelengths. Because our universe is expanding, the cosmological redshift correlates with the distance of the observed objects. Thus, for distant galaxies, the wavelengths needed to deduce the presence of hydrogen molecules fall into the millimeter region of the electromagnetic spectrum, corresponding to short radio waves – precisely for what ALMA was designed to observe.

Fig. III.5.2: The ASPECS observations revealed a three-dimensional view of distant galaxies in the Hubble Ultra-Deep Field (UDF). ALMA observes molecular gas using spectral lines of carbon monoxide and dust continuum emission. For more distant galaxies, those lines shift towards lower frequencies due to the expansion of the Universe. Hence, that third dimension of the observations, frequency, is equivalent to line-of-sight distance, resulting in an overall three-dimensional image. The figure shows a rendering of the ALMA data in which the "islands" in the volume correspond to molecular gas emission lines of distant galaxies.



Credit: Space Telescope Science Institute and ASPECS team

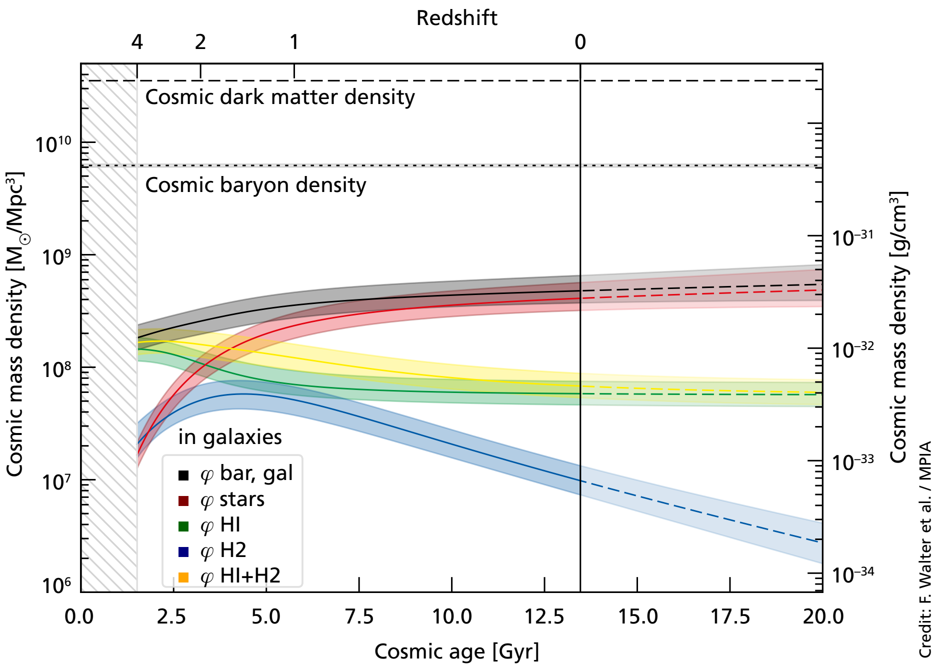


Fig. III.5.3: This plot shows the evolution of normal matter densities throughout cosmic history. The curves distinguish between atomic (HI) and molecular (H2) hydrogen, their combined properties, and the matter bound in stars. The top black curve represents the sum of all baryonic matter. The molecular hydrogen density reached a maximum at about 4 billion years after the Big Bang, until which the number of stars rose steeply. When extrapolating the trend into the future, we see a constant decline in molecular hydrogen density resulting in a low increase of new stars.

ALMA's overall collecting area is much larger than any previous millimeter/submillimeter telescopes, making the observatory very sensitive. That is necessary, as the light reaching us from galaxies billions of light-years away is exceedingly faint. Before ALMA, a survey with the sensitivity of ASPECS would not have been possible. Even with ALMA, ASPECS needed a total of almost 200 hours of observation time, making it one of ALMA's so-called large programs – the first such program specifically searching for molecular gas in the distant universe.

An unbiased view of Hubble Ultra-Deep Field

To yield information that can be generalized to the Universe as a whole, a survey such as ASPECS needs to be unbiased, i.e., it should contain a representative sample of objects and regions. To that end, ASPECS chose the best-studied region of the sky, at least for distant galaxies: the UDF. The combined image contains around 10,000 identifiable galaxies. Light from the most distant galaxy took 13 billion years to reach us. ASPECS scanned the UDF at wavelengths around 1.3 mm and 3 mm. At those specific wavelengths, the Earth's atmosphere is virtually transparent, particularly at high-elevation locations such as the Chajnantor plateau in Chile, where ALMA is located, at an altitude of 5000 meters.

More specifically, at each location within the UDF, the astronomers took two spectra, carefully mapping the intensity of radiation received at different wavelengths between 1.1 and 1.4 mm and between 2.6 and 3.6 mm. In such spectra, molecules reveal themselves via emission lines. While molecular hydrogen has no detectable emission lines, a molecule typically found in its company does: carbon monoxide (CO).

From the nearby cosmos, we know that in a typical interstellar gas cloud, for each CO molecule, you will find on the order of 10,000 hydrogen molecules. Measure the intensity of those CO lines, and you can deduce the amount of molecular hydrogen in that specific region. By considering the redshift observed for a particular set of lines, it is possible to reconstruct the distance of the gas in question. In this way, ASPECS was able to probe the cosmological volume of the UDF, mapping gas-cloud positions in three dimensions.

Keeping track of galaxies – and their molecular gas

The estimate can be made more precise by combining it with observations of cosmic dust. It acts as a catalyst in the formation of molecular hydrogen. ALMA can measure the thermal radiation from that dust parallel to the CO, allowing for a cross-check.

In the end, the ASPECS data provided the deepest view of the dusty universe to date. They helped pinpoint which of the many galaxies visible in the Hubble Space Telescope observations are rich in molecular gas and dust. These galaxies showed a wide range of physical properties. For example, many of them are "normal galaxies" (with average stellar masses and star formation rates). Still, others are classified as starbursts (with unusually high star formation activity) or quiescent galaxies (markedly low activity).

Reconstructing the star-production supply chain

Subsequently, Fabian Walter and his colleagues reconstructed the molecular hydrogen supplies throughout cosmic history – more specifically: from about 2 billion years after the Big Bang (nearly 12 billion years ago) to the present. They complemented their observations with data from previous studies and compared their findings with large-scale simulations of cosmic history from the Big Bang to the present.

The final result captures a profound insight into how our cosmos has changed over time. In that history, the amount of molecular hydrogen steadily increased until about 10 billion years ago, about 4 billion years after the Big Bang, equivalent to a cosmic redshift z=1.5, with the inventory almost doubling within 3 billion years. Previous studies had already suggested this evolution. But it is only now that the observations were sufficiently accurate to firmly conclude that cosmic gas density rises and falls over cosmic time. That rise corresponds to the Golden Age of star formation: With plenty of raw material just waiting to evolve into blazing suns and with half of the stars that ever existed coming into being in that first third of cosmic history. At the high point, there was about as much molecular hydrogen as atomic hydrogen.

What is behind the history of star formation?

In comparing their data with simulations, the astronomers found that behind those boom times was a combination of factors. Galaxies are only the visible tip of the iceberg along a backbone of accumulations of dark matter. This substance does not interact with electromagnetic radiation and thus remains invisible to direct observations. Dark matter accounts for about 80% of all mass in the Universe. Like all other matter, dark matter started out distributed almost perfectly homogeneously through the cosmos shortly after the Big Bang but has clumped by gravitational attraction and thus become increasingly inhomogeneous. In the present-day universe, on a scale of hundreds of millions of light-years, dark matter forms a sponge-like network of filaments sprinkled with particularly dense regions known as halos.

Galaxies formed when ordinary matter, mostly hydrogen gas, was drawn into those halos, following their gravitational attraction. First, plasma falls onto halos from the vast reservoir in intergalactic space, cooling down to form atoms and replenishing the supply of atomic hydrogen within galaxies. Then, the atomic hydrogen is drawn towards the centers of galaxies, cooling down further until it forms molecular hydrogen and eventually stars. Through the ASPECS observations, Walter and his colleagues managed to quantify these gas flows as a function of cosmic time.

As halo growth slowed down and galaxies captured less hydrogen plasma, star production became less and less effective. At present, galaxies form stars at a mere tenth of the production rate of the Golden Age. Production rates have been in sharp decline for the past 9 billion years. Based on their observations, Walter and his colleagues predict a continuing trend: Over the next 5 billion years, the molecular gas reservoirs will shrink by an additional factor of two, while the total mass of stars in the universe increases by a mere 10%. In this picture, star production would eventually cease altogether.

Next steps

The ASPECS observations were designed to be very sensitive by summing up the light from a larger region in each image pixel. But that automatically meant they could not distinguish smaller details – such as mapping the molecular hydrogen within each galaxy. But now that the combination and ASPECS and Ultra-Deep Field images have enabled astronomers to identify its gas-rich and dust-rich galaxies, the next step will be to take a closer look at those galaxies individually. ALMA has a high-resolution mode that is ideal for that kind of detailed scrutiny, allowing Walter and his colleagues to compare the molecular gas and dust structure in those galaxies to the distribution of stars. Are the two directly related?

With that new ALMA data, plus complementary results from observing campaigns of the Ultra-Deep Field planned for the upcoming James Webb Space Telescope (JWST), the astronomers hope to reconstruct the cosmic history of star formation in even more detail.

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in collaboration with

Manuel Aravena (Universidad Diego Portales, Chile), Chris Carilli (NRAO, Socorro, USA) and Roberto Decarli (INAF, Bologna, Italy)

Fabian Walter et al., 2020 "The Evolution of the Baryons Associated with Galaxies Averaged over Cosmic Time and Space", in: The Astrophysical Journal, Vol. 902, 2. DOI: 10.3847/1538-4357/abb82e

III.6 Science Highlights

Encounter of generations in the heart of the Galaxy

The center of our home galaxy is one of the regions richest in stars in the known Universe. Within this region, scientists have identified a previously unknown, ancient stellar population with surprising properties. With significant participation from the Max Planck Institute for Astronomy, an international team of astronomers has identified the origin of these stars as globular clusters within our galaxy, which moved to the center of the Milky Way long ago.

It is still visible on clear and dark nights – the milky white, diffuse band of the Milky Way across the night sky. Since the invention of the telescope, scientists have known that this faint strip consists of countless stars. Today, we understand that our home galaxy is mainly a large flat disk of hundreds of billions of stars, surrounded by dust and gas, rotating around its center.

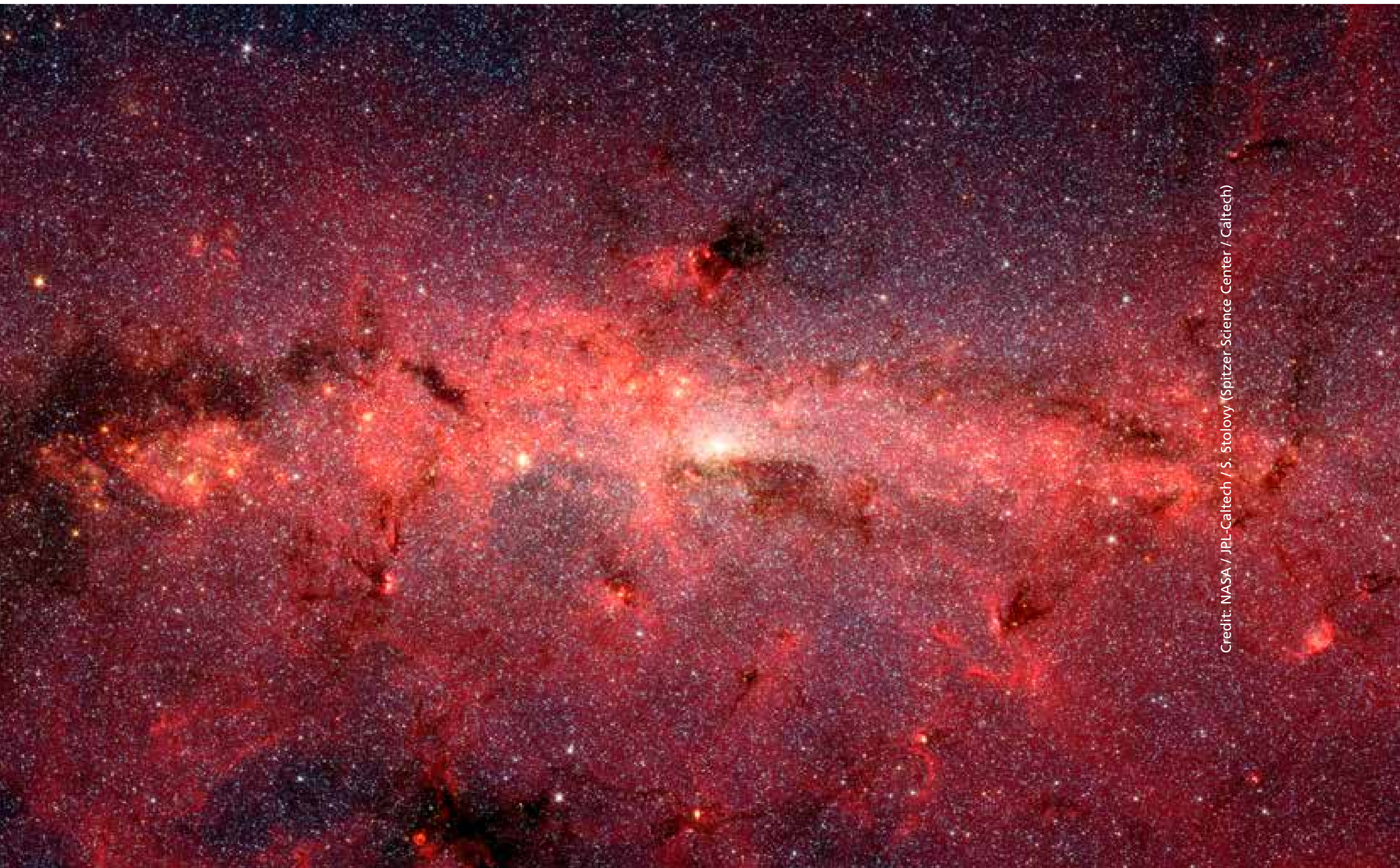
The nuclear star cluster is one of the regions richest in stars in the known Universe

About 25 000 light-years away from Earth, located in the constellation of Sagittarius, lies the center of the Milky Way. This so-called Galactic Center was only discovered in the last century and has been the subject of astronomical research ever since.

In the core of the Milky Way rests a very massive black hole. It is surrounded by one of the densest agglomerations of stars in the known Universe – a so-called "Nuclear Star Cluster" (NSC). Astronomers today assume that there are around 20 million stars in the innermost 26 light-years of the Galaxy.

However, it is not visible without special equipment because numerous dust clouds between the Galactic Center and us obscure the visible light. It, therefore,

Fig. III.6.1: Central region of the Milky Way in infrared light. With this image, NASA's Spitzer Space Telescope has photographed the inner 890 × 640 light-years of the Milky Way. The nuclear star cluster is located in a small area near the central massive black hole. The extended structures in the image are primarily clouds of gas and dust from the spiral arms of the Milky Way, which obscure the line of sight between Earth and the Galactic Center.



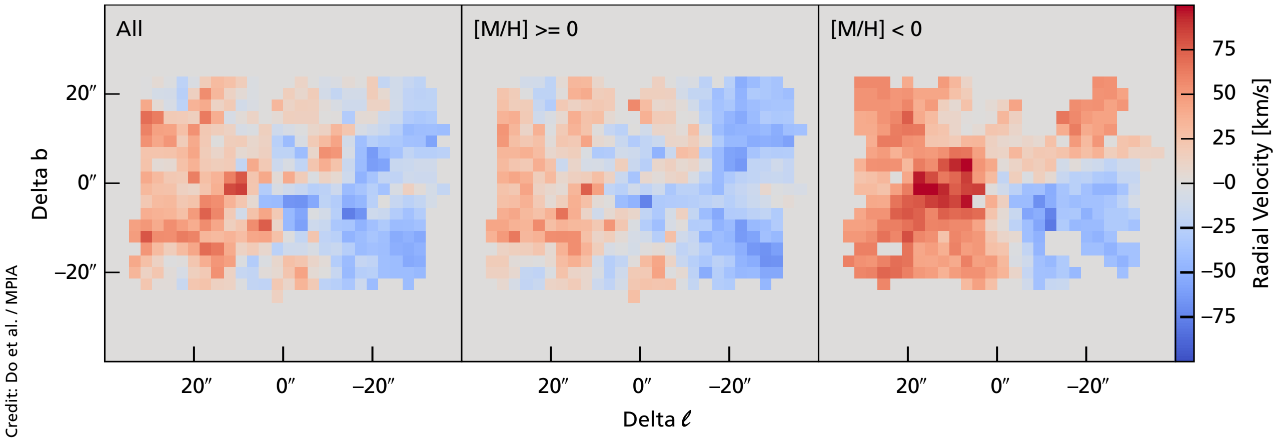


Fig. III.6.2: Spatial distribution of stellar radial velocities of the central 1.5 pc radius around the supermassive black hole at the Galactic center. Left: the complete stellar sample. Center: stars with higher than solar metallicity. Right: stars with lower than solar metallicity. The stars above and below solar metallicity appear to show distinctively different kinematic features. This behavior indicates a common history and origin of the metal-poor stars, different from the other stars in the nuclear star cluster.

appears darker than other parts of the Milky Way. Only observations at much shorter or longer wavelengths, such as infrared light, reveal the structure of this region of the sky, which is much more massive than any other region of the Galaxy.

The Milky Way is by no means unique, and astronomers now believe that most spiral galaxies could contain both a central black hole and a nuclear star cluster. However, the one within the Milky Way is the only place where astronomers can resolve individual stars because of its relatively close distance, making it an ideal laboratory for studying the properties of these massive groups of stars.

A study of the nuclear star cluster as a basis for further insights

To overcome the mentioned visibility restrictions, astronomers led by Anja Feldmeier-Krause, the main author of one of three publications summarized in this report, and Nadine Neumayer used special instruments at ESO's Very Large Telescope (VLT) in Chile to observe this unique region. In a different study, they analyzed about 700 stars and not only examined their brightnesses and colors but also inferred their motions and speeds as well as their chemical compositions. These observations form the basis for several important discoveries about this so far unexplored part of the Galaxy.

The chemical composition of a star is an important indicator in astronomy, as it tells us something about its age. Metallicity – the abundance of elements heavier than hydrogen and helium – is a relevant quantity. All other elements can only form in those very stars. Therefore, if a star contains a large number of heavy elements such as oxygen, carbon, or iron, it must have formed from the remains of a precursor star. Hence, it is relatively young. Conversely, a low metallicity indicates a very old star, which dates back to the early days of the Universe, when there were hardly any heavy elements present in the Cosmos. Therefore, metallicity almost directly indicates the age of the respective star, which makes it a valuable tool for astronomers.

A hitherto unknown population of stars hides in the very heart of the Galaxy

Members of the same group of astronomers, this time led by Tuan Do from the University of California, Los Angeles, reanalyzed the observations. Supported by Nadine Neumayer and Manuel Arca Sedda, both working in the Collaborative Research Center SFB 881 at the Center for Astronomy at the University of Heidelberg, they discovered a previously unknown population of stars inside the nuclear star cluster. While most stars in the central region of the Milky Way have higher metallicities than the Sun, the scientists identified a group of stars that contained significantly fewer heavy elements. In addition, these stars exhibit a mutual, higher velocity than that of the surrounding stars, and their direction of motion may be slightly tilted in relation to the Galactic plane. The properties of these stars, which account for about 7% of all stars in the nuclear star cluster, are surprisingly similar. Therefore, it is evident they share a common origin. But how did they reach the innermost part of the Galaxy?

An answer to this question may lie in the formation mechanism of nuclear star clusters: according to a commonly accepted theory, they could at least partly have formed by collisions of several individual clusters, i.e., spatially denser collections of stars of similar ages, within a galaxy. Held together by the mutual gravitational pull, they move jointly through a bath of surrounding

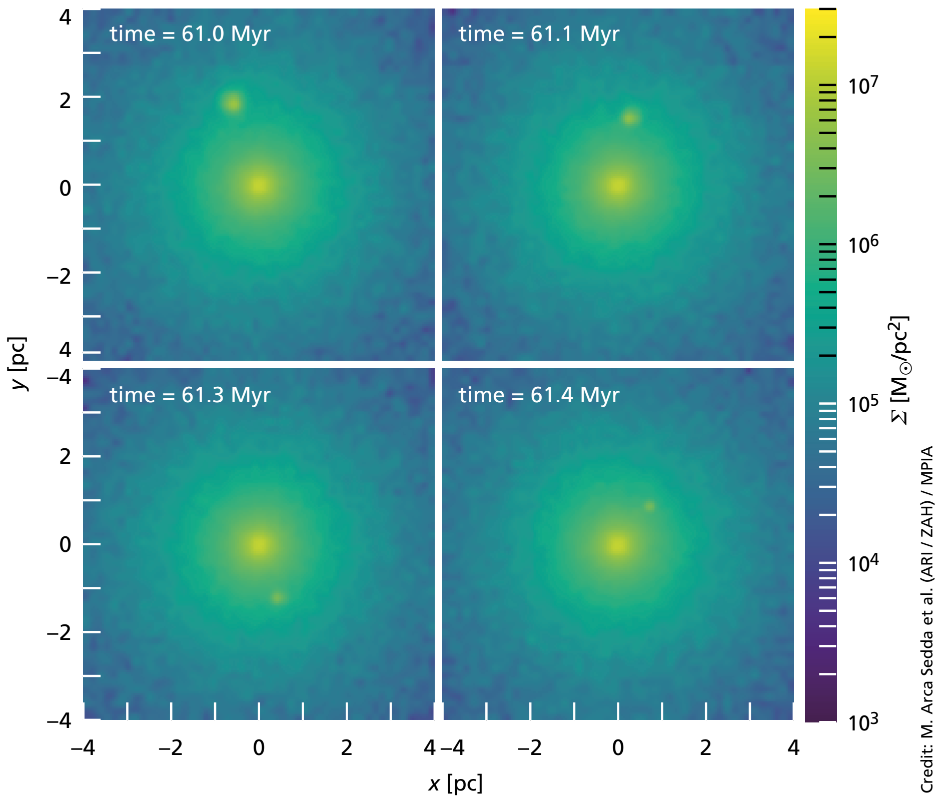


Fig. III.6.3: Visualization of a simulation showing the infall of a globular star cluster into the nuclear star cluster of the Milky Way. The color scale shows the distribution of star densities along the lines of sight within the Galactic Center. The globular cluster is recognizable as an isolated point that gradually merges with the nuclear star cluster over 400 million years and dissolves in the process. Despite the resulting mixing of the two stellar populations, specific properties of the globular cluster stars remain

field stars. Stellar clusters exist in all known galaxies. Due to dynamical friction, a gravitational effect of the surrounding matter, they lose speed on their orbits and thus drift towards the Galactic Center. At this point, they merge with other clusters and form the much larger nuclear star clusters. The newly discovered population may be a remnant of such an older group of stars.

Sophisticated simulations help to clarify the history of the nuclear star cluster

To test this theory, the scientists used powerful computer simulations. They calculated a virtual system consisting of many individual objects, mapping the innermost 300 light-years of the Milky Way. In addition to the nuclear star cluster and the central black hole, it includes a massive star cluster with about one million solar masses. At the beginning of the simulation, it was about 160 light-years from the Galactic Center. Among other things, their goal was to find out how long ago such a stellar cluster could have entered the region around the Galactic Center and from where it originally came.

When a stellar cluster falls towards the Galactic Center, the gravitational interactions with its environment cause stars to be ejected. Once it reaches the innermost part of the Galaxy, it dissolves within a relatively short timescale. Its stars become largely indistinguishable from all the other stars in its new environment.

Since the newly discovered stellar population members still have some very characteristic similarities despite their dispersal, astronomers suspect a common origin of these stars outside the nuclear star cluster. The simulations now suggest they could have entered the central area within the last three billion, but certainly less than five billion years.

The origin of the newly discovered stars

But from where does the stellar cluster originate? There are several possibilities. The scientists have investigated the two most probable ones in their publication. Firstly, the stars may have come from regions farther out in the Milky Way itself, from where they jointly migrated inward. Another possibility is the entry of a dwarf galaxy from the Milky Way's neighborhood. The remaining galactic core or a stellar cluster of this dwarf galaxy could have made it to the Galactic Center. The scientists investigated both scenarios in their simulations.

The results indicate that an infall of a relatively nearby stellar cluster from the Milky Way itself is more likely. It probably assembled about 10 000 to 16 000 light-years away.

To support this hypothesis, the astronomers also compared the observed properties of the newly discovered stellar population with old globular clusters in the Milky Way and those that entered our Milky Way together with dwarf galaxies. They found a better match with Milky Way globular clusters. The calculated distances of the preceding stellar groups also correspond well with those of existing globular clusters. Although they cannot entirely rule out an extragalactic origin, it seems unlikely.

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in collaboration with

Manuel Arca Sedda (ARI/ZAH Universität Heidelberg) and Tuan Do (UCLA Galactic Center Group)

Manuel Arca Sedda et al. 2020 “On the Origin of a Rotating Metal-poor Stellar Population in the Milky Way Nuclear Cluster” in The Astrophysical Journal Letters, Vol. 901, L29. DOI: 10.3847/2041-8213/abb245

Tuan Do et al. 2020 “Revealing the Formation of the Milky Way Nuclear Star Cluster via Chemo-dynamical Modeling” in The Astrophysical Journal Letters, Vol. 901, L28. DOI: 10.3847/2041-8213/abb246

Anja Feldmeier-Krause et al. 2020 “Asymmetric spatial distribution of subsolar metallicity stars in the Milky Way nuclear star cluster” in Monthly Notices of the Royal Astronomical Society, Vol. 494, 396. DOI: 10.1093/mnras/staa703

III.7 Science Highlights

Dry super-Earths with thin atmospheres often come with a bodyguard

An international group of astronomers, led by Martin Schlecker (MPIA), found that the arrangement of rocky, gaseous, and icy planets in planetary systems is apparently not random and depends on only a few initial conditions. The study is based on a new simulation that tracks their evolution over several billion years. Planetary systems around Sun-like stars, which produce in their inner regions super-Earths with little water and gas, often form a planet comparable to our Jupiter on an outer orbit. Such planets help to keep potentially dangerous objects away from the inner regions.

Scientists suspect that the planet Jupiter played an essential role in the development of life on Earth because its gravity often deflects potentially dangerous asteroids and comets on their orbits into the zone of rocky planets in a way that reduces the number of catastrophic collisions. This circumstance repeatedly raises the question of whether such a combination of planets is rather random or whether it is a typical result of the formation of planetary systems.

Dry super-Earths and cold Jupiters

Scientists from the Max Planck Institute for Astronomy (MPIA), the University of Bern, and the University of Arizona have found evidence that rocky planets similar to Earth occur conspicuously often together with a Jupiter-like planet in a wide orbit. At this distance from their central stars, such giant planets receive only little radiation and water exists in the form of ice. Hence, they are called cold Jupiters.

The dry super-Earths investigated in their research are rocky planets larger and more massive than Earth with a thin atmosphere at most and hardly any water or ice. They populate the inner, i.e., temperate zone of the planetary systems and are very similar to Earth except

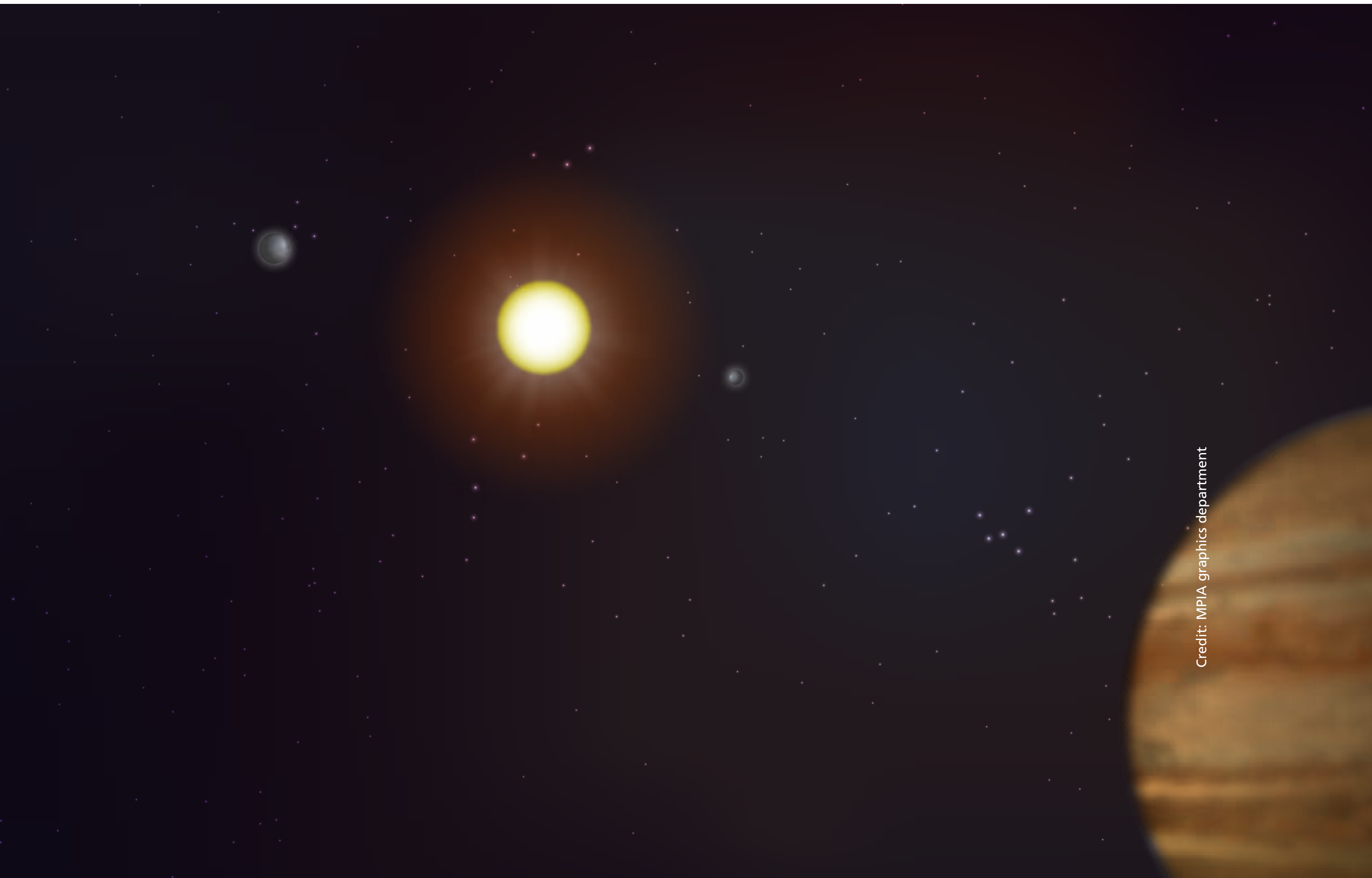


Fig. III.7.1: Artistic impression of a planetary system with two super-Earths and one Jupiter-like planet in orbits around a Sun-like star. Simulations show that massive protoplanetary disks hosting rocky Super-Earths with small amounts of ice and gas often form a cold Jupiter in the outer regions of the planetary systems.

for their size. Also, Earth is, despite its enormous oceans and icy polar regions, with a volume fraction for water of only 0.12% altogether a dry planet.

Finding a cold Jupiter together with an ice-rich super-Earth in the inner region is therefore very unlikely. Furthermore, dense, extended gas envelopes are mainly found in more massive super-Earths.

Simulations provide insights into processes challenging to measure

These conclusions are based on a statistical evaluation of new simulations of 1000 planetary systems evolving in a protoplanetary disk around a Sun-like star. These simulations are the latest achievement in a long-standing collaboration between the University of Bern and MPIA to study the origins of planets from a theoretical perspective. Starting from random initial conditions, e.g., for the masses of gas and solid matter, the disk size, and the positions of the seeds of new planets, the scientists tracked the life cycles of these systems over several billion years. The simulations follow the core accretion model, in which kilometre-sized planetesimals accumulate on the main bodies. During the simulations, the planetary embryos collected material, grew into planets, changed their orbits, collided or were ejected from the system. The simulated planetary systems eventually consisted of planets of different sizes, masses, and compositions on varying orbits around the central star.

Such simulations support the investigation of exoplanetary systems since planets like cold Jupiters require a lot of time to orbit their parent star on wide orbits. This fact makes it difficult to find them through observation, which implies the exoplanets astronomers discover with their telescopes do not realistically reflect the actual composition of planetary systems. Astronomers are more likely to find high-mass planets in close orbits around low-mass stars. Simulations, on the other hand, are in principle independent of such limitations.

Observations and simulations do not match

Therefore, the group of astronomers wanted to verify with simulations a surprising finding other scientists had made by observations: planetary systems with a cold Jupiter almost always contain a super-Earth. Conversely, observations seemed to show that about 30% of all planetary systems with super-Earths also appear to possess a cold Jupiter. It would be plausible to expect that massive planets are more likely to disrupt planetary systems during their formation and hinder their assembly. However, these cold Jupiters seem to be sufficiently far away from the interiors so that their influence on the development of inner planets appears to be relatively small.

However, the evaluation of the simulated planetary systems could not confirm this trend. Only one-third of all cold Jupiters were accompanied by at least one super-Earth. Furthermore, astronomers found a cold Jupiter in only 10% of all synthetic planetary systems with super-Earths. Thus, the simulations show that both

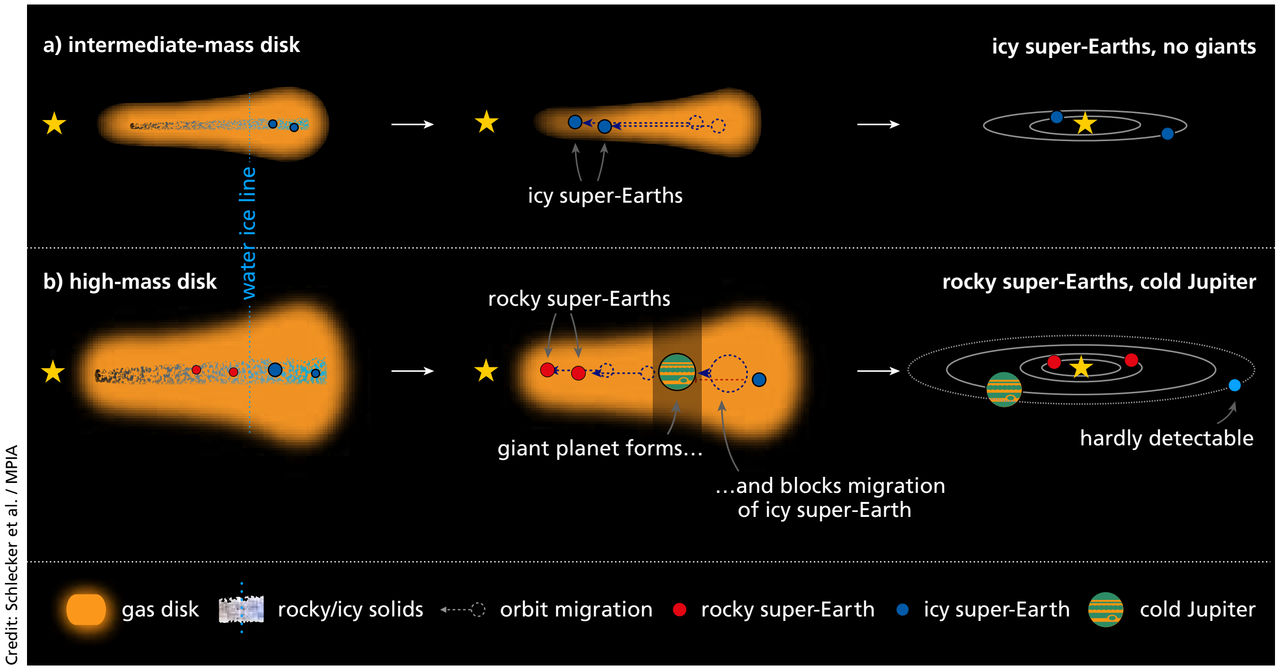


Fig. III.7.2: Schematic diagram of the two proposed formation channels. Either icy, isolated super-Earths (a) or rocky (ice-poor) super-Earths with a cold Jupiter companion (b) form. The mass of the protoplanetary disk determines the result.

super-Earths and cold Jupiters are only slightly more likely to occur together in a planetary system than if they appeared alone. The scientists attribute this result to several reasons.

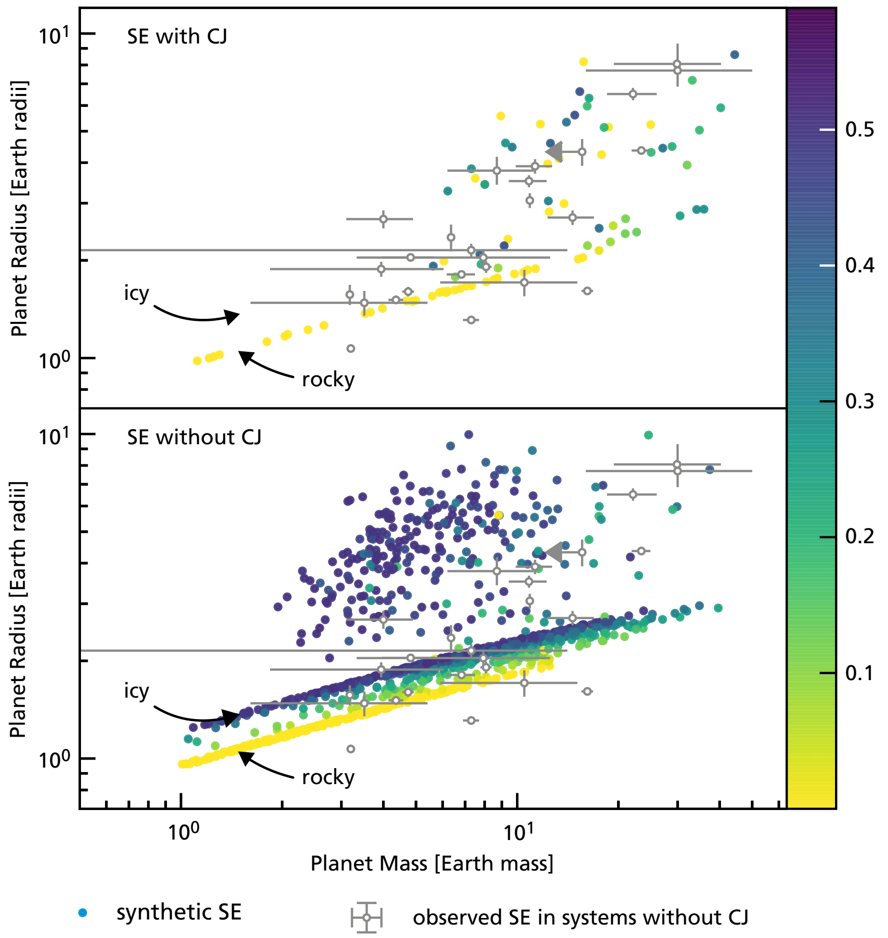
One explanation has to do with the rate at which gas planets gradually migrate inward. Planet formation theory seems to predict higher rates than observed, leading to an increased accumulation of gas giants on orbits of intermediate distance. In the simulations, these “warm Jupiters” interfere with the inner orbits and cause more super-Earths to be ejected or even break up in giant collisions. With a slightly lower tendency of the simulated gas planets to migrate, more super-Earths would remain, which would be more compatible with the observations.

Simulations predict future discoveries

Observations only roughly distinguish between different kinds of super-Earths, e.g. whether they possess large amounts or only little water. The precise mass and radius measurements required for their detailed characterization are rarely obtainable with today’s instruments. In contrast, the simulations of the Bern-Heidelberg group achieve this by tracing the planetary trajectories and their encounters with other planets within the protoplanetary disk. By doing this, they found a significant excess of planetary systems containing both a cold Jupiter and at least one super-Earth that is dry, i.e., with little water or ice, and a thin atmosphere at best. On the other hand, there are hardly any planetary systems in which an icy super-Earth and a cold Jupiter exist simultaneously. A comparison with observational data is difficult, because of the approximately 3500 planetary systems known to date only 24 have been proven to be comparable with such a constellation. Nevertheless, the available results are in good agreement.

Based on these findings, the astronomers of this study have developed a scenario that could explain the formation of these quite different types of planetary systems. As the simulations show, the final constellation is mainly determined by the mass of the protoplanetary disk, i.e., the number and density of planetesimals available for the accretion of planets.

Fig. III.7.3: Mass-radius diagram of inner super-Earths (SE) with *(top)* and without *(bottom)* cold Jupiters (CJ). Included are all planets with masses of 1 – 47 Earth masses and semi-major axes of less than 0.3 astronomical units. Their core ice mass fractions are color-coded. On average, super-Earths in cold Jupiter-hosting systems exhibit higher bulk densities. Observed super-Earths in systems with cold Jupiters are added as gray symbols. These planets match their synthetic counterparts well.



Credit: Schlecker et al. / MPIA

There is not enough material in the inner, warm regions to produce super-Earths in disks with medium mass. At the same time, the amount is also too small to form massive planets like Jupiter in the outer parts beyond the snowline, where water is present in frozen form, and the proportion of ice chunks is quite significant. Instead, the material condenses into super-Earths with a high proportion of ice with a possibly extended gas envelope. These super-Earths gradually migrate inwards.

In comparison, there is enough material in massive disks to form both Earth-like rocky planets at moderate separations from the central star and cold giant planets beyond the snowline. These rocky planets have little ice or gas. Outside the orbit of the cold Jupiter, ice-rich super-Earths can form, but the gas giant's influence limits their migration in the radial direction. Therefore, they cannot enter the inner, warm zone where they would be detectable.

Verifying the prediction is only possible in a few years time

However, it will only be possible to verify this concept with powerful and sophisticated telescopes. Besides specially designed space telescopes like TESS and Cheops that are already operational, astronomers are awaiting ESO's Extremely Large Telescope (ELT) or the James Webb Space Telescope (JWST). The ELT and the JWST are expected to see first light within this decade. With these next-generation instruments about to be deployed, astronomers will be able to test whether the new model will hold up or whether they have to go back to the drawing boards.

In principle, this result could also apply to such dry and rocky planets that have roughly the Earth's size and mass. It might thus not be a coincidence that the Solar System contains planets like Jupiter and Earth. However, the measuring devices available today are not sensitive enough to reliably detect such Earth twins in large numbers through observations. For this reason, astronomers must currently still largely confine themselves to studying Earth's more massive siblings. Only with the next generation of astronomical instruments can we expect progress in this direction.

Martin Schlecker (now Steward Observatory, University of Arizona)
Hubert Klahr and Thomas Henning

in collaboration with

Christoph Mordasini, Alexandre Emsenhuber (also Lunar and Planetary Laboratory, University of Arizona, Tucson, USA), Remo Burn, Yann Alibert and Willy Benz (Institute of Physics, University of Bern, Switzerland)

M. Schlecker, C. Mordasini, A. Emsenhuber, H. Klahr, Th. Henning, R. Burn, Y. Alibert, W. Benz 2020, "The New Generation Planetary Population Synthesis (NGPPS). III. Warm super-Earths and cold Jupiters: A weak occurrence correlation, but with a strong architecture-composition link" in Astronomy & Astrophysics, DOI: 10.1051/0004-6361/202038554

III.8 Science Highlights

The archaeological record of the Milky Way written by atomic hydrogen

An international group of astronomers, led by Juan Diego Soler, have found a complex network of filamentary structures of atomic hydrogen gas that pervades the Milky Way. They made this intricate web of gas visible by applying techniques from machine vision to THOR survey data that provides the most detailed view on the distribution of atomic hydrogen in the inner Milky Way to date. The scientists inferred that the structure conserved an imprint of historic dynamical processes induced by the rotation of the galactic disk and feedback from ancient supernova explosions.

Hydrogen is the key ingredient to forming new stars. Although it is the most abundant chemical element in the Universe, the question of how this gas assembles into clouds from which stars ultimately evolve is still an open one. A collaboration of astronomers headed by Juan Diego Soler (MPIA) has taken a significant step to answering it.

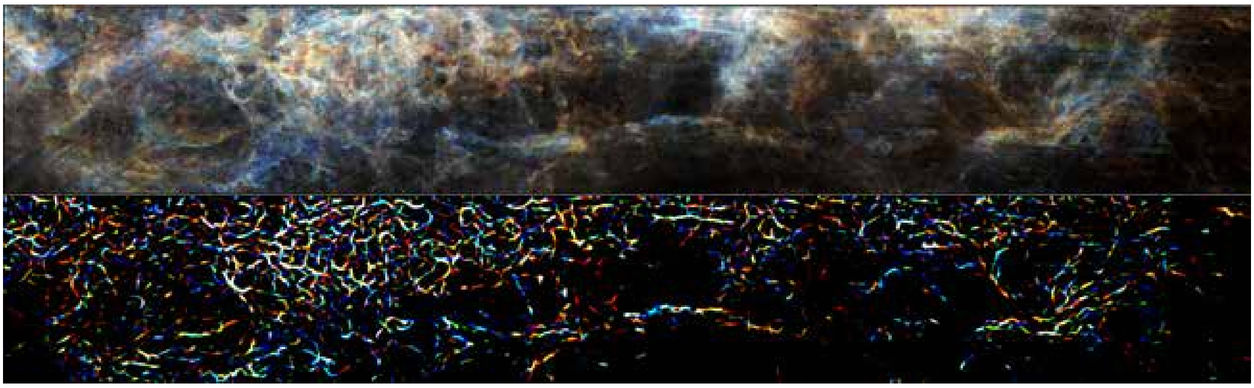
Soler processed the MPIA-led THOR (The HI/OH/recombination line) survey data, which contains observations obtained with the Karl G. Jansky Very Large Array (VLA) radio interferometer based in New Mexico, USA. The survey provides maps of gas distributed across the inner region of the Milky Way that have the highest spatial resolution to date. The latest addition to the THOR data set is data release 2, which includes a census of the neutral atomic hydrogen at an angular resolution of 40 arcseconds.

The group investigated the famous spectral line of hydrogen located at a wavelength of 21 cm. These data also provide the gas velocity along the direction of observation. Combined with a model of how the gas in the Milky Way disk rotates around its center, they inferred distances, which is one of the crucial methods that astronomers use to determine the Milky Way's general structure. However, the unprecedented resolution of the THOR observations enabled completely new studies.

Soler applied a mathematical algorithm to the data commonly used in character recognition and satellite image analysis to better resolve the atomic hydrogen gas distribution. This algorithm resulted in revealing an extensive and intricate network of hydrogen filaments. The astronomers found most of them to be parallel to the disk of the Milky Way, including a 3000 light-years-long hydrogen lane, which Soler named Magdalena or "Maggie" to honor the longest river in Colombia, his country of birth. Maggie could be the largest known coherent object in the Milky Way. Astronomers have studied many molecular filaments in recent years, but Maggie seems to be purely atomic. However, it was a population of vertical filaments that particularly attracted the attention of the researchers.

Soler and his collaborators expected that most filaments would be parallel to the plane and stretched by rotation like spinning pizza dough. While the data essentially confirmed their anticipation, the astronomers also found many intriguing vertical filaments around regions known for their high star formation activity.

Fig. III.8.1: Atomic hydrogen emission from an excerpt from the THOR survey *(top)* and associated filamentary structures around the Magdalena filament *(bottom)*. Colors represent the emission at three radial velocities.



Credit: J. Soler et al. 2020

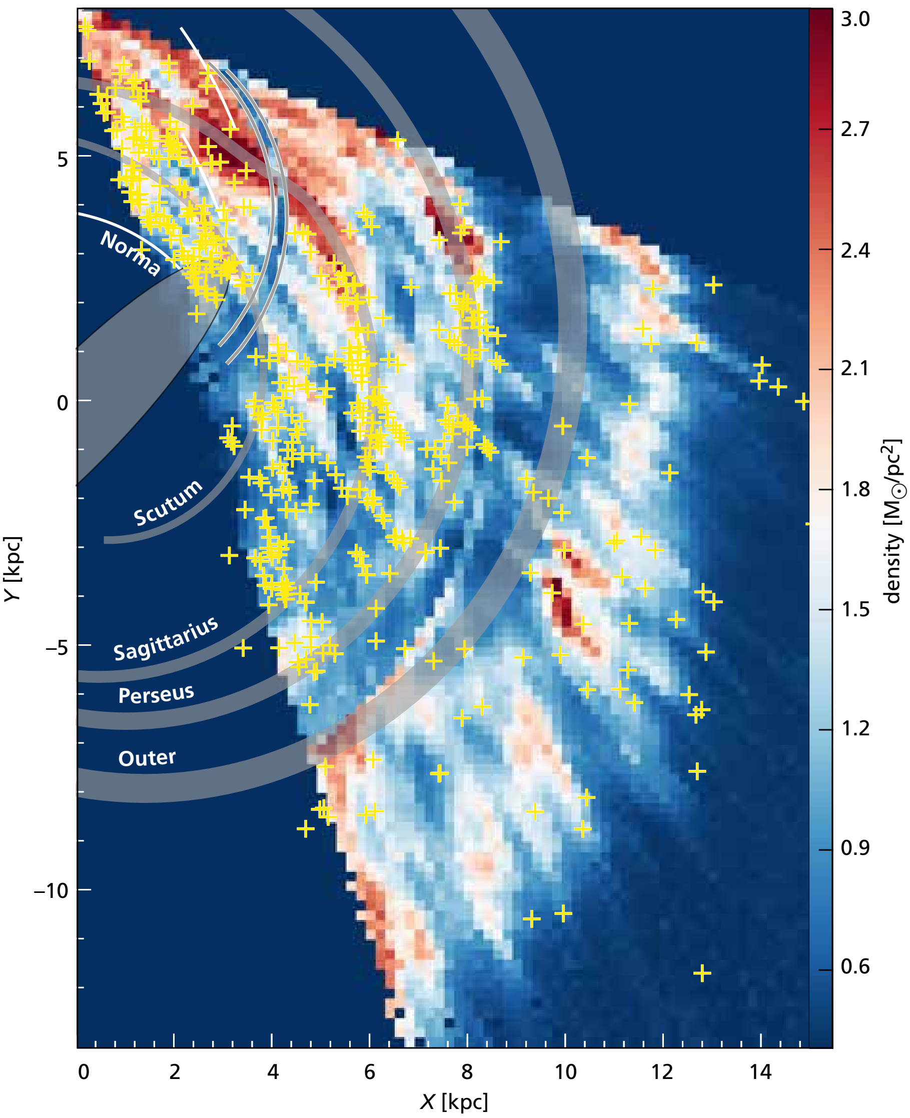
Some process must have been blowing material off the Galactic plane. High mass stars (more than eight times the Sun's mass) inject large quantities of energy into their environment through winds, ionizing radiation, and at the end of their lives through supernova explosions.

In the past, astronomers have used atomic hydrogen observations to identify the shells around supernova explosions that are up to a few million years old. The shock waves from these explosions cause diffuse and ubiquitous hydrogen gas to pile up in denser clouds, which scientists suspect to be the first steps in the process of star formation. But this is different. Since most of the vertical filaments of atomic hydrogen appear concentrated in regions with a long history of star formation, where several generations of stars and supernova explosions have shaped the environment, the researchers linked them to events that preceded the known shells.

Most likely, they represent the remnants of many older shells that popped when they reached the edge of the Galactic disk, accumulated over millions of years, and remained coherent thanks to the magnetic fields. The team inferred this conclusion from using advanced numerical simulations of the dynamics of supernova explosions, magnetic fields, and galactic motions provided by a research group led by Rowan Smith at the Jodrell Bank Centre for Astrophysics in the UK and Patrick Hennebelle at the CEA/Saclay in France.

This study's results and analysis tools offer a new link between the observations and the physical processes that lead to the accumulation of gas that precedes the formation of new stars in the Milky Way and other

Fig. III.8.2: Illustration of the reconstructed hydrogen gas distribution in a portion of the Milky Way based on the THOR survey observations. The image approximates what an observer would see from the top of the Galaxy with the gray bands depicting the Milky Way's spiral arms locations. The colors correspond to the density of atomic hydrogen. Crosses locate clouds of ionized gas that mark the high-mass star-forming regions.



Credit: Wang et al. 2020 / MPIA

galaxies. Galaxies are complex dynamical systems, and new clues are hard to obtain. Archaeologists reconstitute civilizations from the ruins of cities. Paleontologists piece together ancient ecosystems from dinosaur bones. Now, astronomers like Soler are reconstructing the Milky Way's history using its clouds of atomic hydrogen gas.

Juan Diego Soler, Henrik Beuther, Jonas Syed, Yuan Wang, Thomas Henning and Hendrik Linz

in collaboration with

Loren D. Anderson (West Virginia University, Morgantown, USA), Patrick Hennebelle (CEA, Saclay, France), Michael R. Rugel (Max Planck Institute for Radioastronomy, Bonn, Germany) and Rowan Smith (Jodrell Bank Centre for Astrophysics, Manchester, UK)

J. D. Soler, H. Beuther, J. Syed, Y. Wang et al. 2020, "The history of dynamics and stellar feedback revealed by the Hifilamentary structure in the disk of the Milky Way" in Astronomy & Astrophysics, Vol. 642, A163. DOI: 10.1051/0004-6361/202038882

Y. Wang, H. Beuther, M. R. Rugel, J. D. Soler et al. 2020, "The HI/OH/Recombination line survey of the inner Milky Way (THOR): data release 2 and H I overview" in Astronomy & Astrophysics, Vol. 634, A83. DOI: 10.1051/0004-6361/201937095

IV. Instrumentation and Technology

IV.1 Overview

Instrumentation for Ground-based Astronomy

In 2020, MPIA activities in the area of ground-based instrumentation were slowed down by the pandemic and the resulting temporary lack of access to the MPIA workshops, labs, and integration facilities. Design work could partially be continued by the engineers at home, but workshop activities had to be suspended or reduced for several months. After a final run in February 2020, commissioning work for a high-resolution imager for the Large Binocular Telescope (LBT) had to be suspended as well.

The MPIA technical departments continued to concentrate on spectroscopy and high fidelity imaging for the future Extremely Large Telescope (ELT) of the European Southern Observatory (ESO), on multi-object spectroscopy for ESO's VISTA telescope, as well as on survey instrumentation for Calar Alto, a contribution to a new imaging and spectroscopy instrument for the 2.5-meter Nordic Optical Telescope on La Palma, and the development of four telescope systems to be located at Las Campanas Observatory in Chile.

To keep up with the latest developments in infrared detectors MPIA also embarked on a project to adapt our in-house read-out electronics to a novel type of detector. MPIA's principal instrumentation projects consist of building two of the three first-light instruments for the ELT, a next-generation telescope with a main mirror 39 meters in diameter.

Instrumentation for the Large Binocular Telescope (LBT)

The largest ongoing MPIA instrumentation project up to now has been the near-infrared high-resolution imager LINC-NIRVANA (L–N). This instrument was finally installed at the LBT on Mt. Graham, Arizona, in late September 2016. It saw nine separate commissioning runs

Fig. IV.1.1: The 4.1-meter VISTA telescope in its dome near ESO's observatory next to Cerro Paranal. VISTA is a wide-field infrared survey telescope dedicated to mapping the sky. It will feed the 4MOST multi-object spectrograph, which is to be installed in summer 2023.

up to 2019, and one in February 2020, with three or four more to come, but suspended because of the pandemic situation both in Europe and the USA. MPIA is the lead institute in the L-N consortium, which also includes the Italian Observatories (INAF), the Max Planck Institute for Radio Astronomy in Bonn, and the University of Cologne.

The initial aim of the instrument is to deliver multi-conjugated adaptive optics imagery over a 10.5″ × 10.5″ field-of-view in the near-infrared regime: at wavelengths between 1 and 2.4 micrometers. An optional future implementation step could provide diffraction-limited imaging with the spatial resolution of a 23-meter telescope. This would be achieved by a coherent combination of light from the two LBT primary mirrors via Fizeau interferometry.

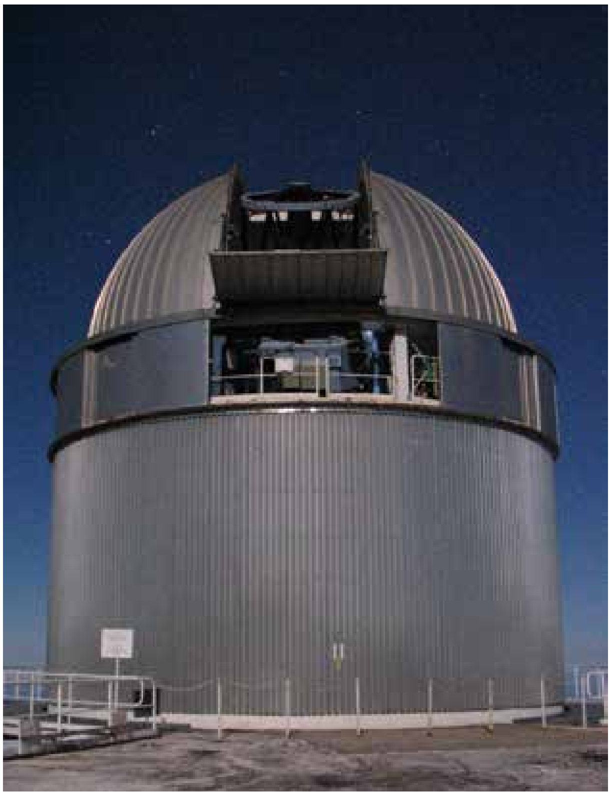
Scientific targets of LINC-NIRVANA range from supernova cosmology, galaxy formation and extragalactic stellar populations and star formation to extrasolar planets, stellar multiplicity, the structure of circumstellar disks and the imaging of Solar System planets and their atmospheres.

Instrumentation for ESO's VISTA telescope

Project 4MOST, which MPIA joined in 2014, is a multi-object spectrograph for the 4.1-meter VISTA telescope at ESO's Paranal observatory. After completion of the Final Design Review in February 2019, MPIA delivered its contributions to the partner institutes in the course of the same year and continued to assist manufacture, assembly, integration, and testing at the leading institute, the Astrophysical Institute Potsdam (AIP). MPIA is responsible for the instrument control electronics. It also provided the carbon-fiber housing of the metrology camera of the instrument. 4MOST is set to study the origin of the Milky Way and its chemical and kinematic substructure, as well as the evolution of galaxies. To this end it will employ 2400 fibers over a field of view of 4 square degrees, enabling simultaneous spectrography of up to 2400 different objects within its field of view.

Instrumentation for Calar Alto (CAHA) and for the NOT on La Palma

While MPIA's formal involvement in the Calar Alto Observatory came to an end in December 2018, the institute has continued to cooperate with Calar Alto in the framework of an upgrade of the PANIC instrument as well as in the scientific exploitation of the guaranteed-time observations from an exoplanet survey carried out with the instrument CARMENES. MPIA will continue to be involved in these two endeavors until 2022 for PANIC, and until 2023 for the CARMENES survey, as in the meantime an extension of this planet search program has been approved.



Credit: Brian Krog and the Nordic Optical Telescope

Fig. IV.1.2: The 2.5-meter Nordic Optical telescope (NOT) on the Roque de los Muchachos Observatory on La Palma, Canary Islands. NOT will be the operating telescope for the NTE instrument.

The Panoramic Near-Infrared Camera (PANIC), which had previously been operational between April 2015 and mid-2018, is a wide-field general-purpose instrument for the CAHA 2.2-meter-telescope. PANIC was a joint development of the MPIA and the Instituto de Astrofísica de Andalucía. Originally, namely with four HAWAII-2-RG detectors, it provided a field of view of 30′ × 30′ (corresponding to the apparent size of the full moon in the sky), allowing for surveys of extragalactic, galactic and Solar System objects. The instrument returned to MPIA in August 2018 for refurbishment, specifically for the replacement of its detector mosaic by a better-quality single HAWAII-4-RG detector, which will cover the same field of view. Reinstallation on Calar Alto suffered from a delay due both to the pandemic and to necessary repairs of the new detector carried out by the manufacturer. It is now planned for 2022, to be followed by the required commissioning phase.

CARMENES is a pair of high-resolution Échelle Spectrographs at the CAHA 3.5-meter telescope, operating, respectively, at visual and infrared wavelengths. The instrument was built by a consortium of five German and six Spanish institutions. With originally 750 guaranteed observing nights available, CARMENES began a radial velocity survey for extrasolar planets in January 2016. The survey targets 300 M-type main-sequence stars in order to find low-mass exoplanets in their habitable zones. The guaranteed time was used up by mid-2020, but the survey received a substantial extension which will keep it running until 2023.

In November 2018, a Memorandum of Understanding was signed between MPIA and the Niels Bohr Institute of the University of Copenhagen. Thus began a collaboration for a new project for the 2.5-meter Nordic Optical Telescope (NOT), which is located at the Roque de los Muchachos Observatory on La Palma. The instrument, which is called the NOT Transient Explorer (NTE), will be a medium-resolution imager and spectrograph covering wavelengths from the near-UV to the near-infrared. Its goal is to enable rapid follow-up of transient phenomena such as gamma-ray bursts and supernovae. MPIA contributes to this project three systems of the read-out electronics, as well as software that had previously been developed at the institute. MPIA is also responsible for characterizing the infrared detectors. Two of the three read-out units were manufactured by December 2019, and the third by the end of 2020. Characterization work for the infrared detectors commenced in 2020 and is slated for completion in April 2021. The NTE instrument is slated for installation at the NOT in mid-2023.

Instrumentation for the SDSS V – Local Volume Mapper

In January 2020, the kick-off took place for MPIA's involvement in project Local Volume Mapper Telescopes (LVM telescopes). LVM is a project carried out in the framework of the Sloan Digital Sky Survey V (SDSS V), in which MPIA is a partner, with MPIA director Hans-Walter Rix as SDSS V project scientist. The goal of SDSS V is a complete survey of the southern Milky Way and its dwarf galaxy companions, in order to resolve the scale on which the feedback between the stellar content and the interstellar medium occurs. MPIA's contribution consists of four 16 centimeter telescopes to be delivered to Las Campanas Observatory, Chile, in the course of 2022. The survey is planned to start by the end of the same year.

The future Extremely Large Telescope – (ELT)

Construction work for the 39-meter Extremely Large Telescope (ELT) began in 2018 on the Cerro Armazones mountain in Chile's Atacama Desert, in close proximity to ESO's existing Paranal observatory.

MPIA participates in the construction of two of the ELT's three first-light instrumentation projects: METIS and MICADO. In May 2019, METIS passed its preliminary design review and entered the final design phase. MICADO had already passed its preliminary design review in November 2018. The final design reviews are planned for March 2022 for MICADO, and for November 2022 for METIS.

METIS is a thermal/mid-infrared imager and spectrograph covering a wavelength range between 3 and 19 micrometers. Adaptive optics will permit the instrument to perform diffraction-limited observations, making full use of the telescope's impressive size. The instrument's science case includes exoplanet detection and characterization, the formation and evolution of protoplanetary disks and extrasolar planets, conditions in the early Solar System, studies of the Galactic Center and of the luminous centers of nearby galaxies, high-redshift active galactic nuclei and high-redshift gamma-ray bursts.

MICADO is a near-infrared imaging camera with multi-conjugated adaptive optics that will provide spatial resolution exceeding that of the James Webb Space Telescope (JWST, the successor to the Hubble Space Telescope) by a factor between six and seven. MICADO will be sufficiently sensitive to observe stars down to a brightness of 29 magnitudes – in visible light, this would include stars more than a billion times fainter than are visible with the naked eye – in the near-infrared bandpasses from I to K.

Fig. IV.1.3: Overview of Las Campanas Observatory. The picture was taken from the future site of the Giant Magellan Telescope. Installation of the LVM in this observatory is planned for summer 2022.

Credit: Las Campanas Observatory

Fig. IV.1.4: Artistic rendering of ESO's Extremely Large Telescope in operation. The beams of light, which are clearly visible in this picture, shooting toward the sky, are produced by the telescope's laser guide star system.

Scientific goals for MICADO include fully resolving stellar chemical and kinematical properties in the centers of galaxies, star clusters, and stellar populations in the Local Group (the group of galaxies to which our own galaxy, the Milky Way, belongs), detailed morphological galaxy studies at high redshift, constraining the history of light in the Universe via stars in galaxies, and searching for intermediate-mass black holes. Further studies will involve the dynamical properties of globular clusters, coronagraphic imaging for high-contrast imaging of extrasolar planets, the ages, metallicities, and masses of the first elliptical galaxies, and the physics of pulsars, magnetars and accreting white dwarfs.

Technology development at MPIA

The latest developments in infrared detectors have led to Geosnap, a device with paticularly low read-out noise and very rapid read-out. The MPIA electronics department has begun to adapt its read-out electronics – an in-house development – to this novel detector type. A first complete system will be prepared for use together with the METIS instrument.

Martin Kürster
for the MPIA Technical Departments

IV.2 Overview

Instrumentation Highlight: The SDSS-V Local Volume Mapper

MPIA has a long tradition of contributions to the Sloan Digital Sky Survey (SDSS): The institute was a participating institution in the first international extension of the survey, SDSS-II, as well as part of the German Participation Group for its successor SDSS-III, and a full member institution in SDSS-IV. For the ongoing fifth generation of the Sloan Digital Sky Survey, known as SDSS-V, which started observations in October 2020, MPIA is not only a participating institution, but also MPIA director Hans-Walter Rix is the survey's project scientist.

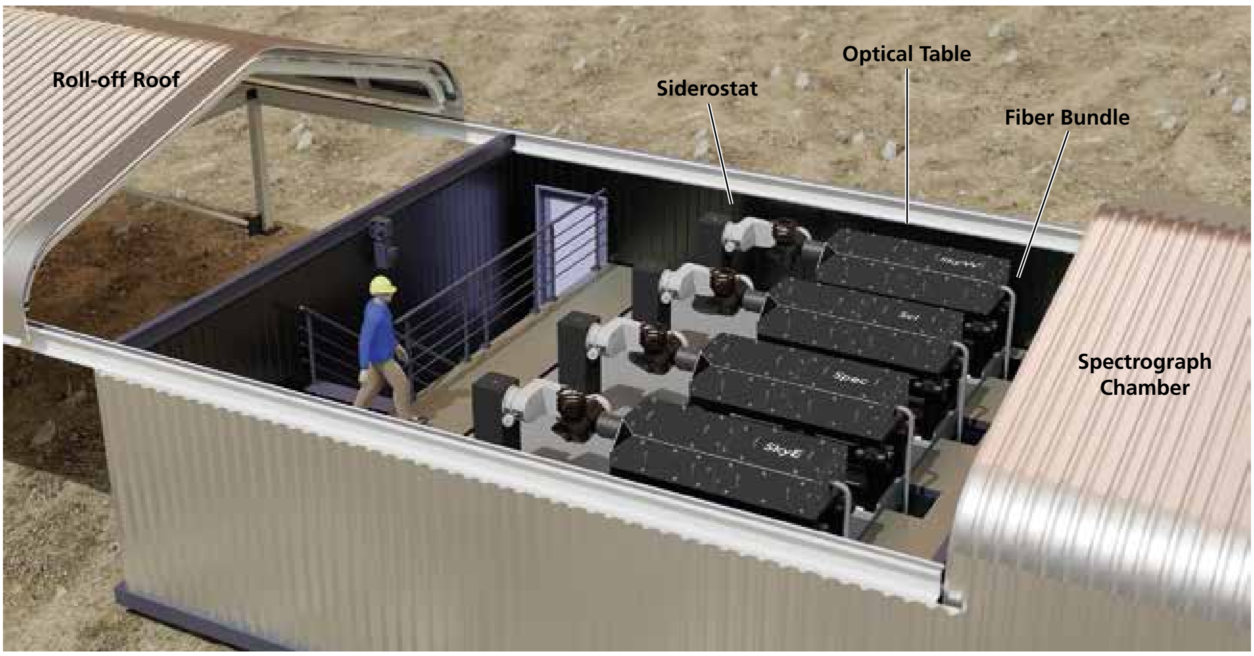
MPIA has significant scientific engagement in all three SDSS-V surveys. The Milky Way Mapper (MWM) is a multi-object spectroscopic survey to obtain near-infrared and visible-wavelength spectra of more than 4 million stars in the Milky Way and Local Group Galaxies, with the goal of solving a number of long-standing mysteries of galaxy formation physics. The second survey, known as the Black Hole Mapper (BHM), will take visible-wavelength spectra of more than 300 000 quasars to understand the masses, accretion physics, growth and evolution of supermassive black holes. For the third survey, the Local Volume mapper (LVM), the institute is not only involved in the science, but also makes important contributions on the instrumentation side.

The Local Volume Mapper and its telescopes

The Local Volume Mapper (LVM), will spectrally map approximately 2500 square degrees of the Galactic plane, corresponding to about 6% of the total sky, over wavelengths ranging from the near ultraviolet to the near infrared. LVM will also target the Magellanic Clouds and other Local Group galaxies. This amounts to some 25 million individual spectra, which will reveal how distinct gaseous environments interact with the stellar population, producing the large-scale interstellar medium that we observe.

LVM exploits the challenging technique of integral field spectroscopy, in which the instrument records a complete spectrum for each location on the sky. The result is a three-dimensional picture – a "data cube" – of the galaxy, which will have profound diagnostic power for understanding the underlying astrophysics driving the phenomena we observe.

Fig. IV.2.1: Each of the four LVM telescopes consists of a siderostat in horizontal, alt-alt configuration feeding fixed components on an optical table. Fiber bundles convey the light to an environmentally controlled spectrograph chamber, and a roll-off roof protects the instrument during daytime and inclement weather.



Credit: MPIA LVM team

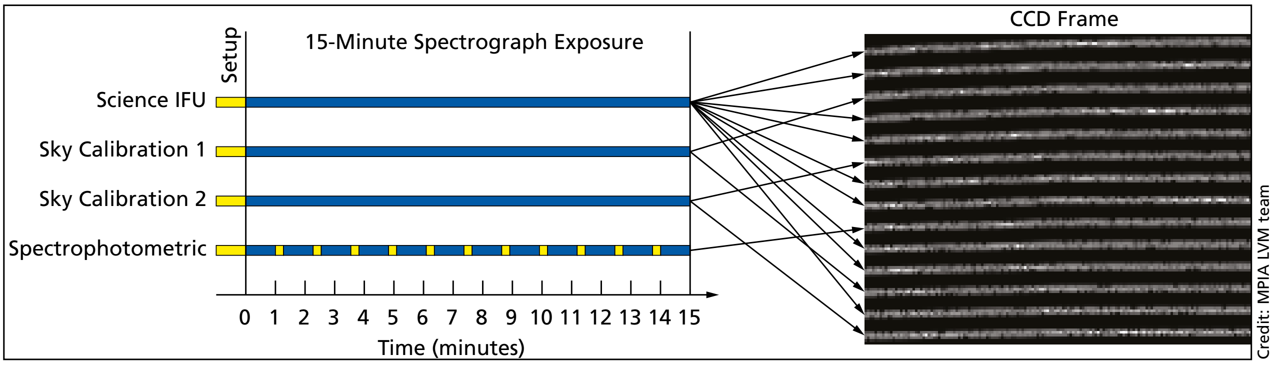


Fig. IV.2.2: Timeline and portion of a notional science exposure illustrating the LVM telescope operating principle of interspersing science, sky, and spectrophotometric observations.

The LVM instrument

Accurately mapping and calibrating a substantial portion of the sky in this way requires a unique type of instrument, and nowhere is this more true than with the design of the telescopes. Each of the four LVM telescopes consists of a two-mirror siderostat in alt-alt configuration – in essence, a configuration of movable flat mirrors that feed light into an optical breadboard protected by a dust-proof enclosure (Figure IV.2.1). This produces a fixed, stable focal plane for the Integral Field Units (IFU's), which are connected to optical fiber bundles that convey the light to the three spectrographs housed in an adjacent temperature-controlled chamber.

A custom-built enclosure with a roll-off roof protects the telescopes, IFU's, fiber bundles, and spectrographs. It also contains the necessary support infrastructure, including calibration lamps, network and power, and a small observing room. The LVM instrument is truly an international project, with contributions from five continents: North America, South America, Europe, Asia, and Australia.

How it works

The four LVM survey telescopes fall into three categories: the Science telescope hosts the primary science channel, while the two Sky telescopes and the Spectrophotometric telescope acquire simultaneous observations critical for proper survey calibration.

Light from the sky enters the Science telescope and is conveyed to the fixed, IFU fiber bundle in the focal plane. This bundle contains 1801 individual fibers in a hexagonal array of 25 concentric rings. To maximize throughput, a micro-lens array accomplishes the coupling between the telescope focal plane and the bundle, and at the other end of the fibers, a slit mechanism re-formats the focal plane on the entrance slits of the spectrographs. A typical survey exposure takes 15 minutes (Figure IV.2.2).

At the same time, two Sky Calibration telescopes make measurements of Earth's geocoronal emission near the science field. The geocorona is part of the outermost part of Earth's atmosphere, which is called the exosphere; it scatters sunlight towards Earth, which contaminates astronomical observations. Data from the Sky Calibration telescopes basically allows the SDSS astronomers to subtract that additional light. As with the Science telescope, microlens-coupling injects the light, this time into 119 fibers: 60 from one Sky Calibration telescope and 59 from the other. To reduce systematic errors and improve calibration, the spectrograph entrance slits intersperse the Science and Sky calibration fibers, resulting in about 40 sky measurements per spectrograph.

Finally, a single Spectrophotometric telescope points at 12 different bright calibration stars for approximately 1 minute each during the 15-minute exposure. The focal plane of this telescope hosts 12 fibers that are coupled and fed to the spectrographs in the same way. As with the sky calibration, the spectrophotometric measurements are interspersed with the Science and Sky fibers, leading to 4 spectrophotometric observations per spectrograph.

The LVM telescopes

MPIA has primary responsibility for designing and producing the unique and innovative telescope system for the Local Volume Mapper. Figure IV.2.3 shows the system architecture and components. Formally, the telescopes consist of all opto-mechanical elements between the sky and the micro-lenses on the fiber bundle. These elements include:

Subsystem	Components
Siderostat	Alt-Alt configuration Flat mirrors with mounts and sky baffles Pier with telescope platform interface
Optical Table	Optical breadboard Rigid support with adjustment
Opto-Mechanics	Objective lens with focus drive K-mirror field de-rotator Acquisition and Guide Hardware Fiber selector hardware IFU / fiber bundle interface

Note that the IFU and Sky calibration telescopes contain K-Mirror de-rotators as shown in Figure IV.2.3, while the fourth, the Spectrophotometric telescope, does not. It hosts a fiber selector shutter mechanism in its focal plane for isolating the flux of individual bright stars.

Siderostats

Physical motion of the IFU's and, in particular, the fiber bundles, can induce variations in optical quality and throughput that would degrade the global calibration of the LVM survey. And, needless to say, conveying light from a moving telescope, particularly one that is 16 cm in diameter, to a firm, fixed focal plane hosting a large, heavy, and delicate fiber bundle is far from straightforward. To address this, the MPIA team adopted the siderostat / optical table configuration shown in Figure IV.2.1.

To our knowledge, this is the first use of an alt-alt configuration telescope in astronomical research. Most modern observatories use an altitude-azimuth mount for reasons of mechanical simplicity when supporting large, heavy optical components. Of course, at 16 cm diameter, the LVM telescope optics are neither large nor heavy. Indeed, LVM is also unique among research facilities in having focal plane instrumentation that is considerably larger and heavier than the telescope optics. In such a situation, an alt-alt architecture offers numerous advantages, including very modest requirements on sky tracking rates and the natural ability to feed a stable, horizontal instrument platform – in other words, an optical table.

Objective lenses

Essentially all research telescopes are reflectors, that is, they use powered mirrors rather than lenses to concentrate the light. This is due to the impossibility of supporting lenses larger than about one meter in diameter without suffering from gravity-induced bending and loss of image quality. However, for smaller systems, such as the LVM telescopes, lenses have distinct advantages in producing wide, high quality fields of view. Nevertheless, LVM imposes some very demanding requirements on the powered optics: excellent image quality, extraordinarily broad wavelength coverage, and insensitivity to temperature change. This led to a challenging design exercise.

The LVM objective lenses are bonded triplets of N-BAK2 glass from Schott and monocrystalline CaF2 elements. A commercial company produced the individual lenses, while our collaborators at Carnegie Observatories bonded the elements into triplets and mounted them in precision aluminum barrels. A motorized focusing mechanism designed and built at MPIA provides the interface to the optical table.

K-Mirror de-rotators

Conveying light from the siderostats to a fixed, stable focal plane necessarily introduces image rotation that varies with time. We therefore must have an image de-rotator to both align the hexagonal footprint of the IFU correctly on the sky and to maintain that orientation during an exposure. To accomplish this, the LVM telescopes use custom K-Mirror de-rotators consisting of three flat mirrors mounted to a precision commercial motorized stage (Figure IV.2.4). Of course, adding three reflections

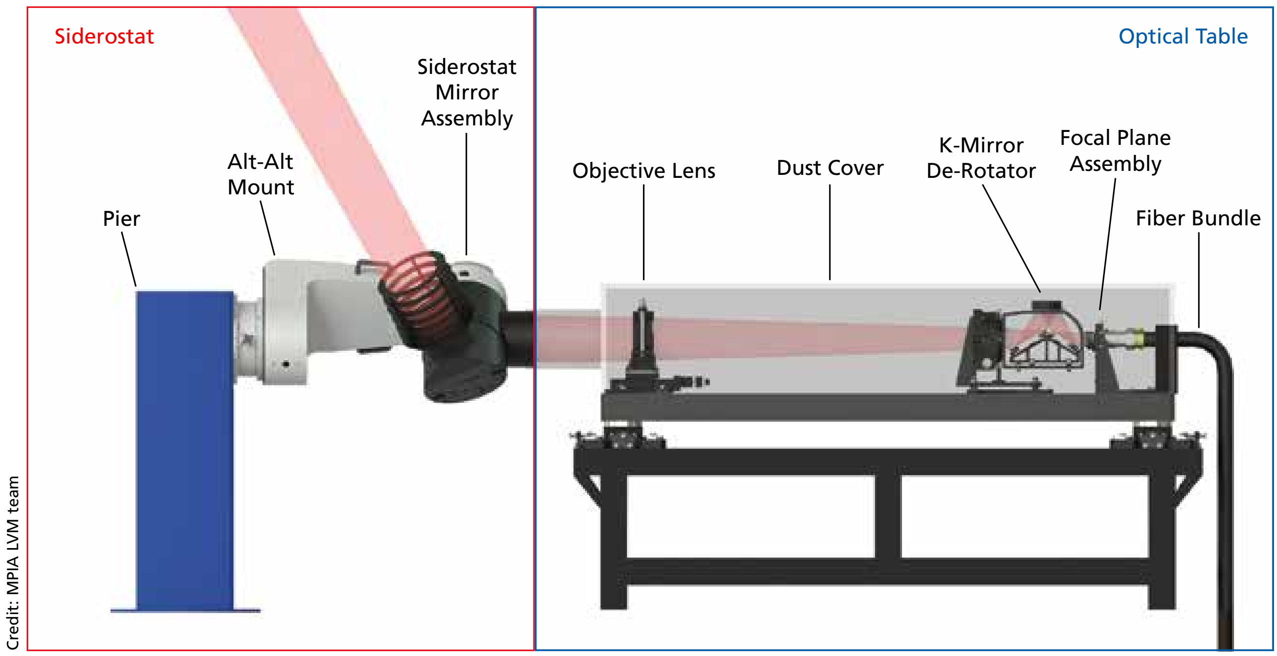


Fig. IV.2.3: System architecture of the LVM telescopes. See text for details.

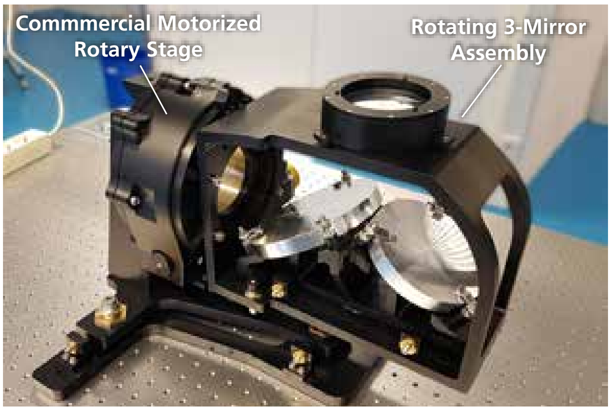


Fig. IV.2.4: The K-Mirror de-rotators combine three, high performance flat mirrors with a precision commercial rotary stage to cancel the field rotation induced by the combination of a moving telescope with a fixed focal plane. Note that this image shows the de-rotator with aluminum dummy mirrors used for preliminary assembly and functionality tests.

to the optical path can significantly impact throughput, particularly at near-UV wavelengths. To address this, the de-rotator mirrors have high performance dielectric coatings that deliver 99%-plus reflectivity across the full range of operating wavelengths.

The de-rotators can, in principle, sit at any location along the optical path, but in order to minimize the size of the mirrors themselves, we place the K-Mirror as close as possible to the focal plane in the converging beam. This arrangement has the added virtue that the image footprints on the mirrors from different sky locations are correspondingly reduced in size so close to focus. This relaxes somewhat the demand on surface quality, which can be important with thick, multi-layer coatings.

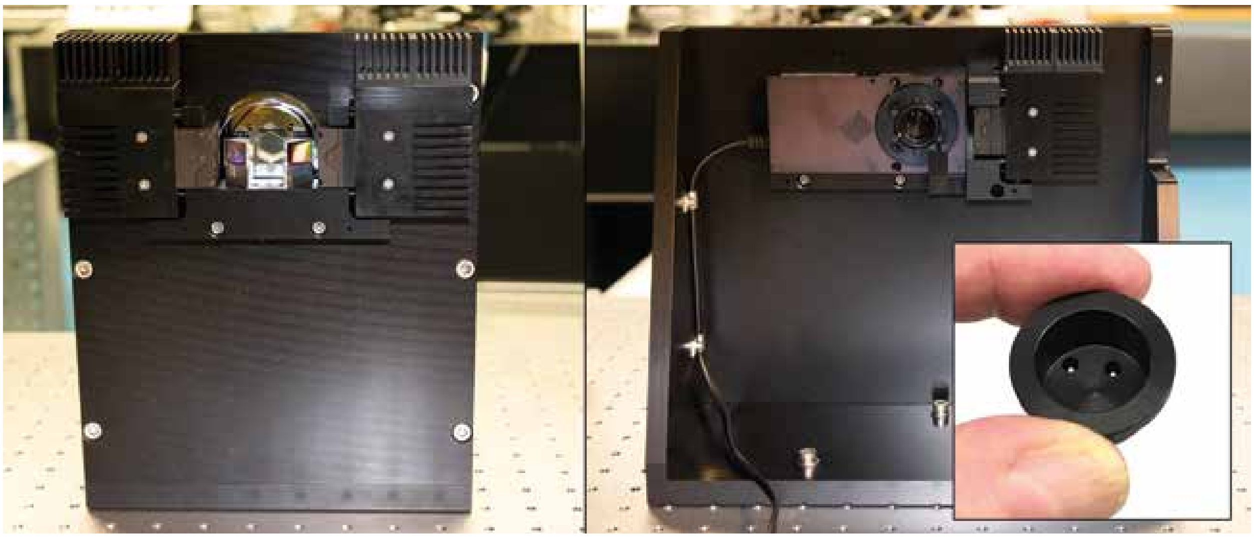
Note that, in principle, only the Science telescope requires a de-rotator for proper IFU tiling. In the case of the two sky telescopes, however, unwanted sky rotation could cause bright stars to drift in and out of the field of view during an exposure, complicating enormously the job of calibration. As a result, the two Sky calibration telescopes also have K-mirrors that are identical to the one in the science channel. As described above, the Spectrophotometric telescope makes a series of 1-minute pointings at very bright stars during the 15-minute spectrograph exposure. The light of these stars will dominate any additional sources in the field, and hence no de-rotation is necessary for this telescope.

Focal plane assemblies

Figure IV.2.5 below shows the two types of Focal plane assemblies (FPA) of the LVM telescopes. These mechanisms host the fixed IFU fiber bundles, as well as 45° mirrors and Acquisition and Guiding sensors. In all, we will use seven sensors: two each for the Science telescope and the two Sky telescopes, and one Acquisition-only sensor for the Spectrophotometric telescope. In the latter case, we are rapidly finding and centering on bright stars for short exposures, so guiding is unnecessary.

On the other hand, the spectrophotometric telescope makes 12 separate observations of bright stars during the 15-minute period of a single science exposure (see Figure IV.2.2). This means that, without additional hardware, each of the 12 active spectrophotometric fibers will receive unwanted light for 14 of the 15 minutes of an individual exposure. In order to prevent this excess background and contamination, we place a fiber selecting mask in the focal plane. This is a simple, rotating disk with two apertures that expose individual fiber tips to light one at a time (see inset of Figure IV.2.5). It must also block all fibers during telescope motion between acquisitions. A compact motorized rotary stage drives the selection mask.

Fig. IV.2.5: The Focal plane assemblies for the Sci/Sky telescopes *(left)*, and the Spec telescope *(right)*. The inset shows the rotating mask for the spectrophotometric fiber selector.



Motor control hardware and software

The LVM telescope system contains eight motorized mechanisms: four objective lens focusers, three K-Mirror de-rotators, and one fiber selector. Based on successful experience in the field and in-house heritage, we have elected to use standard MPIA motor controller units driven by our "Twice as Nice" interface software, a combination that has been deployed for several instruments at 2–8 m class telescopes.

A single MPIA motor unit can host up to three "MoCon" cards, which can each control up to eight motors. This means that a single Motor Unit has more than enough capacity to drive all of the mechanisms of the LVM telescopes. Nevertheless, we have produced two Motor Units to allow for spares.

Implementation plan and schedule

At the time of this writing (May 2022), the Milky Way Mapper and Black Hole Mapper surveys have already begun, using existing telescopes and spectrographs. Commissioning of the robotic components that will increase observing efficiency is well advanced.

The Local Volume Mapper represents a completely new hardware development, from the enclosure to the telescopes to the fiber IFUs to the CCD sensors of the spectrographs. Essentially all of this development work took place during the Covid-19 epidemic, and most of the collaborators on the geographically dispersed teams have never met face to face. Needless to say, this presents unique challenges, particularly when it comes to the assembly, integration, testing, and commissioning phases.

The current plan is to ship much of the hardware to Chile by the late summer of 2022. Since the telescopes are almost identical, we plan to retain one optical table / siderostat pair at MPIA for ongoing testing and software development, while the remainder get installed at Las Campanas. The Heidelberg campaign includes on-sky measurements from the Königstuhl in August-September 2022.

All hardware should be in place at the observatory by December, allowing a focused commissioning period before science operations begin early in 2023. An initial Science Verification (SV) phase will demonstrate that the LVM instrument meets specifications. The survey itself begins concurrently with SV. Initially, all measurements will be controlled and monitored by remote observers, but we plan to migrate to increasingly robotic operations as the survey proceeds.

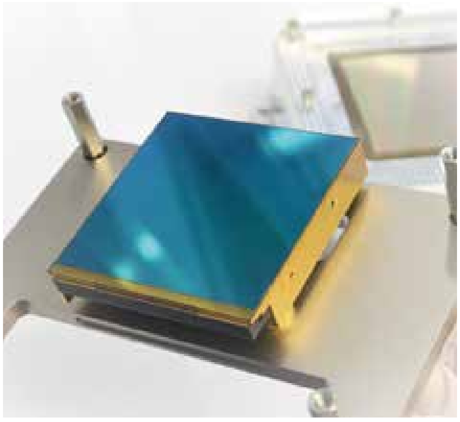
Finally, a map of the Local Volume cannot be entirely complete without coverage from the northern hemisphere. A sister facility, including a 1-meter telescope to map nearby galaxies, is under development for the Apache Point Observatory in New Mexico, the site of the northern components of the Milky Way and Black Hole Mappers.

Tom Herbst
SDSS-V Local Volume Mapper Telescope Lead

IV.3 Instrumentation at MPIA

Overview of current projects

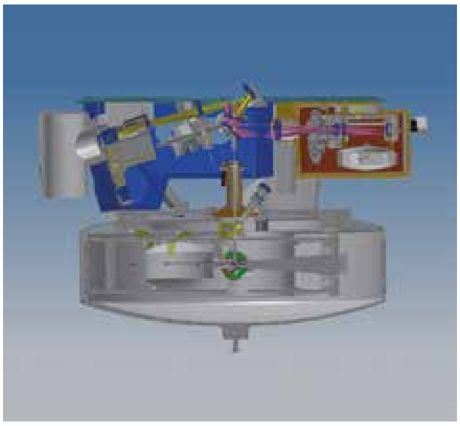
Astronomical instruments have different strengths and specializations. Here, we list **ongoing MPIA instrumentation projects for the year 2020**. Almost all of the instruments are cameras for producing astronomical images, spectrographs for analyzing the color components of light, or combinations thereof.



PANIC-4K

4×4 K detector for the Panoramic Near-Infrared Camera

Telescope	2.2-meter Telescope, Calar Alto, Spain
Wavelength range	Near-infrared, 0.9 – 2.15 µm
Targets	Multipurpose wide-field survey imager
Resolution	Seeing limited
Special features	Large field-of-view – size of the full Moon
MPIA contribution	Purchase, integration, and testing of novel 4×4 K near-infrared detector
Status	Tests and verification ongoing at MPIA



NTE

Nordic Optical Telescope Transient Explorer

Telescope	2.5-meter Nordic Optical Telescope, La Palma, Canary Islands
Wavelength range	UV, visible, near-infrared, 334 – 2200 nm (imaging and spectroscopy)
Targets	Transient phenomena, gamma-ray bursts, gravitational wave sources, kilo- and supernovae
Resolution	Imaging: 0.18″/pixel, field-of-view 6′; spectroscopy: R~5000; 20″ long slit
Special features	Rapid resonse mode (< 2 minutes) under development
MPIA contribution	Read-out systems for the NIR cameras, characterization of the NIR detectors
Status	Working toward FDR

LINC-NIRVANA

LBT INterferometric Camera –
Near-InfraRed Visual Adaptive interferometer for Astronomy

Telescope	Large Binocular Telescope, Mt. Graham, Arizona
Wavelength range	Near-infrared, 1.1 – 2.4 µm
Targets	Star clusters, black holes, protoplanetary disks
Resolution	30 – 90 mas (wavelength-dependent) as adaptive optics imager
Special features	Particularly wide-field adaptive optics
MPIA contribution	PI institute, project lead, optics, cryogenics, electronics, software
Status	Advanced commissioning phase

METIS

Mid-infrared ELT Imager and Spectrograph

Telescope	Extremely Large Telescope
Wavelength range	Mid-infrared (2.9 – 13.5 µm = L/M, N bands)
Targets	Disks, exoplanets, supermassive black holes, high-*z* galaxies
Resolution	16 – 72 mas depending on wavelength
Special features	Can do coronagraphy and polarimetry
MPIA contribution	Imager and single-conjugate adaptive optics
Status	Preliminary design review passed, entered the final design review phase

MICADO

Multi-AO Imaging Camera for Deep Observations

Telescope	Extremely Large Telescope
Wavelength range	Near-infrared, 1.1 – 2.5 µm
Targets	Stellar motions in galaxies, dwarf galaxies, first supernovae
Resolution	6 – 13 mas depending on wavelength
Special features	High sensitivity, precise astrometry
MPIA contribution	Relay optics, astrometric calibration
Status	Working toward final design review

4MOST

4-meter Multi-Object Spectroscopic Telescope

Telescope	VISTA Telescope, Paranal, Chile
Wavelength range	420 – 900 nm
Targets	Milky Way and galaxies, structure of the cosmos
Resolution	Spectral resolving power of 5000 – 20 000 (spatial resolution n/a)
Special features	2400 fibres over a field-of-view of 4 square degrees
MPIA contribution	Instrument control electronics, carbon fibre housing for metrology camera
Status	Part 2 of final design review passed, MPIA electronics delivered

Specific instruments have characteristic **special features** or properties. A particularly wide field of view, for instance, allowing for survey images of larger regions of the sky. Adaptive optics counteracts atmospheric disturbances. Other examples are the ability to determine the orientation in which an electromagnetic wave is oscillating (polarimetry), or to block out light from part of the field of view (coronagraphy), or the use of interferometry to combine the light from several telescopes, allowing them a level of detail otherwise accessible only to a much larger telescope.

Each instrument is designed with specific astronomical **targets** in mind. For MPIA researchers, these targets focus on our central research themes of planet and star formation on the one hand, galaxies and cosmology on the other. That is why typical targets are star formation regions, which are hidden behind clouds of dust that can be pierced using infrared radiation, or very distant galaxies, whose light has been shifted by cosmic expansion, again necessitating infrared observations.

LVM TELESCOPES

Telescope	Array of four, 16-cm telescopes, Las Campanas Observatory, Chile
Wavelength range	360 – 1000 nm
Targets	Complete survey of southern Milky Way and Magellanic clouds to resolve the scale of stellar feedback – ISM interactions
Resolution	Spatial resolution 37″ /spaxel, spectral resolution R~4000
Special features	One IFU with 1801 fibres, three spectrographs
MPIA contribution	Telescopes design and manufacture
Status	Procurement and manufacturing ongoing

CORONAGRAPH INSTRUMENT (CGI)

Telescope	Nancy Grace Roman Space Telescope (formerly WFIRST)
Wavelength range	Near-infrared, large region imaging
Targets	Exoplanet detection and dark energy research
Resolution	Wide field near-infrared imaging with an angular resolution of ~ 0.2 arcsec
Special features	Field-of-view 100 times that of the HST; coronagraphs
MPIA contribution	Mechanical components, related ground support equipment
Status	PDR passed

Each camera or spectrograph has a characteristic **wavelength range**, describing the kind of electromagnetic radiation it can receive. Most MPIA instruments work in visible light, with radiation we can see with our own eyes, or in the infrared regions of the spectrum: in the near-infrared (adjacent to the region of visible light, able to see through clouds of dust), the mid-infrared (where dust heated by stars radiates, as in protoplanetary disks) or the far-infrared (radiated by the coldest known objects in the cosmos, or the most distant).

Astronomical objects are extremely distant, making it difficult to discern any details. The **resolution** is a measure of the level of detail that can be achieved using a particular instrument. Resolution is given as an angle on the sky: a resolution of 0.1 arcseconds means that, say, an astronomical camera can distinguish two small objects that are 0.1 arcseconds (less than 0.00003 of a degree) apart on the sky. Resolution is typically given in arcseconds (1 arcsecond = 1/3 600 of a degree) or even milli-arcseconds, mas (1 mas = 1/1000 arcsecond).

For each instrument, we also list its current **status**. The design and construction of an instrument encompasses several phases. In the beginning, there are several phases of intensive planning, namely conceptual design (phase A), preliminary design (phase B), and final design phases (phase C), which all are concluded with a review. This often includes verification tests of the necessary technology using prototypes. The construction phase is followed by integration, in which the separate components are combined to form the instrument as a whole; the verification phase, in which the as-built hardware is tested; the commissioning phase, which commences once the instrument has been installed at the telescope; first light as the first images / spectra are taken; science verification as the new instrument is tested on various astronomical targets; and finally an operations phase for scientific operations.

IV.4 Highlight Technical Departments

Recent developments in detector read-out software – sub-modes for HAWAII detectors

For modern telescopes, optics is just the beginning – when the light has been focussed, or else spread out into a spectrum, its arrival needs to be documented by an electronic detector that, these days, is more-or-less distant kin to the camera chips you can find in mobile phones or digital cameras. What the detector has documented then needs to be read out and converted into a digital signal suitable for scientific analysis. MPIA has long been involved in contributing to this particular aspect of astronomical instrument-building.

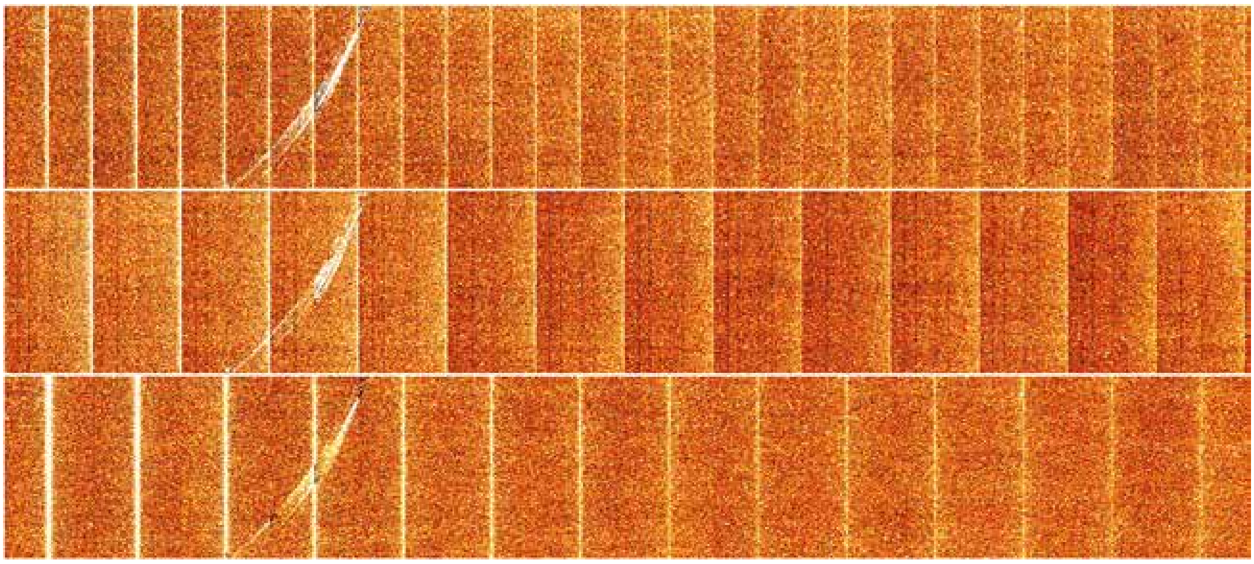
MPIA-developed read-out electronics for HAWAII infrared detectors, a common type of infrared detector in astronomy, is in use as part of a variety of astronomical instruments: Omega-2000 (Calar Alto Observatory) since 2004 with one HAWAII-2 detector, LUCI-1 and LUCI-2 (Large Binocular Telescope) since 2013 with one HAWAII-2RG each, CARMENES (Calar Alto Observatory) since 2015 with two butted HAWAII-2RG, a lab demonstrator for PAWS (Astrophysikalisches Institut Potsdam) since 2018 with four butted HAWAII-2RG, and LINC-NIRVANA (Large Binocular Telescope) in commissioning since 2016 with one HAWAII-2. It is also built and tested for NTE (Nordic Optical Telescope), a spectrograph and imager with two individual HAWAII-2RG and, last but not least, a PANIC (Calar Alto Observatory) detector upgrade to one of the novel HAWAII-4RG devices.

The associated software, originally developed by former MPIA software engineer Clemens Storz, has been continuously updated over the past 25 years. Recent developments noticeable to the observer are the replacement of the C/X11 graphical user interface to Java, covering Ubuntu as another Linux operating system, and the support of Teledyne's new HAWAII-4RG HgCdTe detector.

The read-out electronics has always been fully equipped with one pre-amplifier analog-to-digital converter chain for each channel of the respective detector chip. This translates to full-frame read-out times of 1.3 seconds for the four megapixels of a HAWAII-2RG with 32 channels, and 2.6 seconds for the 16 megapixels of a HAWAII-4RG with 64 channels at 100 kHz pixel clock. Twice these times are the minimum integration times for a standard correlated double-read. A drop-out of some channels in the LUCI detectors led to the aim of supporting flexible read-out schemes with 4 instead of 32 channels for the HAWAII-2RG and 4, 16 or 32 instead of 64 channels for the HAWAII-4RG.

If misfitting channels are not one of the remaining subset, the entire pixel set can still be read out. The

Fig. IV.4.1: A 1800 × 270 pixels subsection of the PANIC HAWAII-4RG frame recorded in March 2022. From *top to botton* with arrows indicating the read-out directions: 64 channels→→, 32 channels→→, and 64 channels→← (alternating directions).



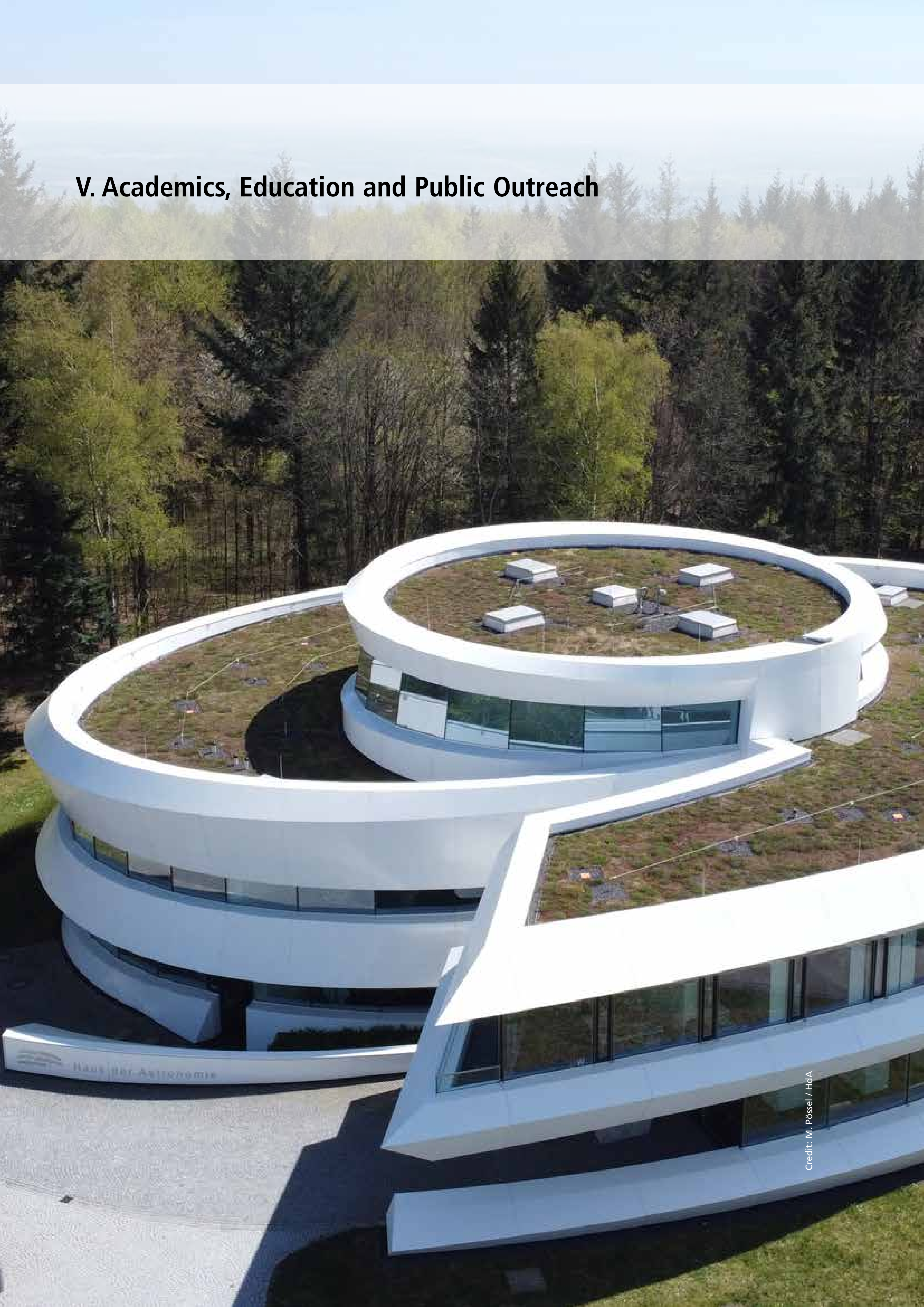
Credit: MPIA

fact that the minimum integration time rises inversely proportional to the number of active channels is a disadvantage, but at least for spectrographs, this is not of great concern as such instruments are typically integrating for minutes or tens of minutes in any case.

The figure shows results from a lab experiment and illustrates the effect of reading our HAWAII-4RG detector with only 32 channels instead the full 64, plus the effect of either reading all channels in left-to-right pixel order or switching to right-to-left order in each second channel (correlated double-read with 10.4 seconds integration time at 95 Kelvin). To check that the serialized 16-bit pixel data are correctly ungarbled by the software after routing through a fiber pair to the computer, a region around some plume feature of the chip is shown at left.

Richard Mathar
for the MPIA instrumentation software department

V. Academics, Education and Public Outreach



Credit: M. Pössel / HdA

V.1 Academics, Education and Public Outreach

Academics

As a research institute, MPIA takes its responsibility for fostering future generations of scientists seriously. A key academic contribution of MPIA, and at the same time a central part of the institute's research structure, is the training of doctoral students. This is done in the framework of the International Max Planck Research School for Astronomy & Cosmic Physics at the University of Heidelberg (IMPRS-HD) that involves not only MPIA, but also the other astronomy-related institutes in Heidelberg. The IMPRS-HD organizes the application and selection process for the new students, fosters interaction between the students during IMPRS seminars and retreats, and offers help with everyday administrative problems. It also offers a social network, in particular for foreign students who may arrive in Heidelberg from far-away destinations.

For the IMPRS-HD, 2020 was in the 16th year of activity, with the arrival of the so-called "16th generation" of IMPRS students. The new generation was somewhat smaller in number, but, with 20 students, is still strong. Just as in 2019, almost half of the new students (i.e. 9) are members of MPIA. The new MPIA IMPRS students are Verena Fürnkranz, Maximilan Häberle, Evert Nasedkin, Selina Nitschai, Eric Rohr, Tjoa Jesper, Nico Winkel and Xie Zhang-Liang. Sebastian Zieba is an IMPRS guest student at MPIA, who is enrolled at Leiden University. The single IMPRS fellowship 2020 was awarded to Brooke Polak, who is doing her PhD at the Institute for Theoretical Astrophysics under the supervison of Ralf Klessen.

The year 2020 was severely impacted by the Covid pandemic, and this included the IMPRS and its students. An unusually high number of five students abandoned their thesis projects during 2020. These were mainly students from the generation which had started their PhD work before the pandemic, and was thus most strongly affected by the pandemic-related changes in circumstances.

In 2020 the IMPRS received a total 262 of new applications for the upcoming 17th generation of IMPRS students who will begin their PhD in 2021. Of those 262, 33% were applications from female students, while of the shortlisted applications, 32% were from female students. Note, however, that in the strongest applicant group, namely the applications internally ranked as "A+" (23 in total), there were 35% female students, and thus a higher proportion compared to the totality of applications. Numerous applications arrived from India (49), China (17), the Netherlands (15), the UK (14), Italy (12), and the US (12). From Germany, we received 39 applications.

Fig. V.1.1: Participants of the IMPRS-HD Summer School 2020 – due to the pandemic, the event was conducted entirely online.

Credit: C. Fendt, MPIA

Note that these numbers consider the origin of the application (that is, the location of the institution of the MSc/BSc student at the time of application) and not the citizenship of the applicant.

Thirty IMPRS students completed their doctoral degree in 2020. The MPIA students among them are listed in Table V.1.1.

The 2020 IMPRS-HD summer school was on the topic of “Planet Formation in Protoplanetary Disks”. The scientific program was organized by a group of MPIA junior research group leaders, namely Bertram Bitsch, Mario Flock, and Paola Pinilla. Invited lecturers were Pablo Benítez Llambay (Niels Bohr Institute, University of Copenhagen), Cornelis P. Dullemond (ITA, University of Heidelberg), Michiel Lambrechts (Lund Observatory), Yamila Miguel (Leiden Observatory), and Catherine Walsh (Leeds University). Due to the Covid pandemic, the school was held as an online event. This had the advantage that we were able to accommodate 110 participants – more than ever before. While the online event was a new experience, and needed extra thought and preparation from the organizational point of view, the school went very well, including many vivid discussions and highly successful exercises.

While training doctoral students is undoubtedly the most important field of academic involvement for MPIA, the institute’s contributions begin at the undergraduate level. Our directors and research group leaders are involved in teaching at Heidelberg University. For instance, this year MPIA scientists were involved in teaching the Cosmology Block Course (Annalisa Pillepich) and the lecture on Star Formation (Henrik Beuther and Thomas Henning), while Coryn Bailer-Jones offered a lecture on The Physics of Interstellar Travel.

MPIA also offers bachelor and masters students from Heidelberg University or from other universities the opportunity to conduct research for their theses at the institute. For students who want to gain research experience, the institute offers a successful international summer internship program (coordinated by Bertram Bitsch).

Christian Fendt

Table V.1.1: PhDs completed by MPIA students in 2020.

Name	Defense Date	Title	Supervisor
Aida Ahmadi	10.01.20	In search of disks in high-mass star formation	Beuther
Christos Vourellis	22.01.20	GRMHD Launching of Resistive and Dynamo Active Disks	Fendt
Karan Molaverdikhani	05.02.20	Characterization of Planetary Atmospheres	Henning
Xudong Gao	06.02.20	Low-mass Stellar Evolution Traced with Non-LTE Abundances	Lind
Johannes Esser	27.04.20	Physical properties of the circumnuclear cloud distribution in Active Galactic Nuclei	Pott
Nico Krieger	28.05.20	Zooming into the Blast Furnace – A close Look into the Molecular Gas in the NGC253 Starburst with ALMA	Walter
Paula Sarkis	12.07.20	Transiting Exoplanets: Linking Observations and Theory	Henning
Ivana Barišić	19.06.20	Dust Attenuation and Maintenance Mode Feedback in the 6 Gyr old Universe and Now	van der Wel
Asmita Bhandare	19.06.20	Numerical simulations of star and disc formation	Henning
Manuel Riener	10.07.20	The detailed velocity structure and distribution of 13CO emission in the Galactic plane	Kainulainen
Arianna Musso Barcucci	23.07.20	The relation between discs and young companions – observational studies	Henning
Christian Lenz	28.07.20	Semi-analytical Modeling of Planetesimal Formation. Implications for Planet Formation and the Solar Nebula	Klahr
Johanna Coronado	29.07.20	Small scale structure of the Milky Way's stellar orbit distribution	Rix
Neige Frankel	14.10.20	Forward Modeling the Secular Evolution of the Milky Way Disk	Rix
Miriam Keppler	11.11.20	Giant Planet Formation in Disks: An Observational Perspective	Henning

V.2 Academics, Education and Public Outreach

Public Outreach

As in all areas of institute activity, 2020 was radically different. When the institute went into pandemic mode in March, the usual face-to-face activities for the public ceased as well. This was true both for MPIA activities, including the Girls' Day as well as for public on-site events after mid-March, and for the numerous education and outreach activities carried out at Haus der Astronomie (HdA), our center for astronomy education and outreach on our Königstuhl campus, operated by the Max Planck Society and administered by MPIA. A detailed description of HdA activities can be found in section IV.3.

Given the restrictions imposed by the pandemic, we adapted the focus of our activities. For one, it was clear that with the absence of in-person conferences, it would be more difficult for MPIA postdoctoral researchers to network, and to get their work noticed in the wider academic world – which would likely put them at a disadvantage when it came to applying for their next positions. To help mitigate this effect, we decided to up our publication rate for press releases presenting scientific results, given that press releases are an alternative way of making results known beyond the small community of those working directly in the same sub-field. All in all, we published 17 science releases this year, an increase of 30% compared to 2019.

The year's most successful science release was that on the anomalous dimming of Betelgeuze, based on work by Thavisha Dharmawardena, with more than 40 articles in regional and national newspapers in Germany, Austria and Switzerland. But in addition, a number of releases received more moderate coverage, in media as diverse as Neues Deutschland, Greenpeace Magazine, Focus Online, Hamburger Abendblatt or Der Standard. The effort of MPIA astronomer Knud Jahnke and colleagues to both document and improve the sustainability of their science, including a documentation of MPIA's carbon emissions for the year 2018, was featured in both Frankfurter Allgemeine Zeitung and Deutschlandfunk.

Fig. V.2.1: Announcement tiles for talks held by MPIA staff as part of the "Faszination Astronomie Online" lecture series.

MPIA scientists also prominently took part in the public online talk series “Faszination Astronomie Online” organised by Haus der Astronomie. Among others, Gesa Bertrang took viewers on a journey of discovery as she traced the evolutionary path from dust grains to planets; Ludmila Carone gave a weather report from extrasolar planets; MPIA scientific coordinator Klaus Jäger explained how astronomers found out about the physical nature of quasars; Melanie Kaasinen presented the history and future of star formation, while Fabian Walter explored what information about distant galaxies we can decode from the light we receive from those distant star systems.

A key feature of that online talk series is that it brings together German-speaking astronomers from all over the world, with no geographical restrictions. But for those in the know, the roster of speakers shows a clear connection with MPIA – in addition to MPIA staff, the talks feature numerous MPIA alumni, as well as members of the institute's Scientific Advisory Board and Board of Trustees.

Markus Pössel, Markus Nielbock,
Klaus Jäger and Axel M. Quetz

V.3 Academics, Education and Public Outreach

Haus der Astronomie
Center for Astronomy Education and Outreach

Haus der Astronomie (HdA; literally "House of Astrono my") is the Center for Astronomy Education and Outreach on MPIA Campus. Its mission: to communicate the fascination of astronomy to the general public, to support astronomy education, and to foster the exchange of knowledge between scientists.

Haus der Astronomie is an unusual institution at the interface between science and the public. Its custom-built, galaxy-shaped building hosts an active team of astronomers and astronomy educators dedicated to developing and producing materials and resources for the public or for use in schools.

Just as for most of the rest of the world, the year 2020 started in the usual way: In January, February and March we welcomed visitors to each month's instalment of our public talk series "Faszination Astronomie". We wowed visitor groups with virtual journeys into the depths of space in our planetarium, including the groups that took part in a total of 27 guided tours. We linked cinematography and science in our series "Science meets fiction", this time with a movie about Alexei Leonov and the first-ever spacewalk. We welcomed more than 400 pupils and kindergarteners for interactive workshops. We taught students from Pädagogische Hochschule Heidelberg and conducted six workshops for future Kindergarten teachers. At the end of February, Olaf Fischer and Markus Nielbock interacted with particularly interested students at a Juniorakademie course about stars, while our "Mobile Teacher Training" financed by the Reiff-Stiftung was hosted this year at our partner school, Gymnasium Marne-Europaschule, in the far North of Germany at the beginning of March. We were also active abroad, with Olaf Fischer organising three two-day teacher training workshops for more than 150 participants in Chile in January. Then, mid-March rolled around, and everything changed.

HdA goes into pandemic mode

As soon as it became clear that the Covid pandemic had not only reached Germany but was spreading, and even before the official restrictions came into force, we decided that HdA would, if anything, err on the side of caution. We initially cancelled all upcoming in-person

Fig. V.3.1: Broadcasting the PASTRO astronomy course live from Haus der Astronomie.

Credit: M. Pössel / HdA

events, only very gradually allowing for in-person interaction, beginning with the tutoring of individual students – a number of Staatsexamens or bachelor thesis projects were finished, and a number of new ones begun, this year.

The most immediate effect was on our PASTRO course, which is an obligatory introduction to astronomy and astrophysics for all students at Heidelberg University who are training to be physics teachers for high schools. PASTRO is a three-week block course, and in 2020 took place from March 2 to March 19. When Baden-Württemberg's science ministry ordered the immediate stop of in-person teaching at universities for March 12, we immediately moved the course online, broadcasting from HdA via Zoom. When the MPIA campus followed suit in implementing a safe work-from-home mode, we taught the last course week broadcasting from our homes.

Our key advantage was that HdA does have excellent video equipment – part of which we had used in a project funded by the Carl Zeiss Foundation to transform PASTRO into an "inverted classroom" format, with video lectures available to students before each lesson, while the lesson itself concentrates on interactive exercises. With that advantage, we were able to move our teaching online quickly and effectively – and we were even able to assist and advise Heidelberg's physics faculty as a whole, as they planned for online teaching in the upcoming Summer semester.

"Faszination Astronomie Online" – our new online public talk series

When we cancelled public talks in Haus der Astronomie, beginning with the April edition of "Faszination Astronomie", it was clear that universities, planetaria, and science centers all throughout Germany were doing the same. Carolin Liefke immediately came up with the idea of an online talk series, and "Faszination Astronomie Online" premiered on March 17 – and has continued steadily twice a week, every Tuesday and every Thursday, since then. While we of course contacted local speakers as well, the online format meant that our range for inviting speakers was suddenly much wider. Instead of being restricted to speakers who would take it upon themselves to travel to Heidelberg, we could include speakers almost worldwide – with some limitations since getting up at an ungodly hour to give a talk at 19:00 German time is not something one can expect from speakers in, say, New Zealand.

"Faszination Astronomie Online" talks are nominally 30 minutes, and it typically takes an additional 30 minutes to answer the audience's questions. Our topics cover the whole range of astronomy. While most talks are indeed about topics in astrophysics and modern astronomical research we also had talks about the future of space travel, science fiction (by Sterne-und-Weltraum-editor-in-chief Andreas Müller), astrophotography for beginners, the history of the constellations, and also a talk near the end of the year on what to do if there was a telescope among your Christmas presents. Our traditional christmas-time family event also took place in virtual form, with Natalie Fischer taking viewers on "A stroll under the night sky".

#FasziAstroOnline: topics, speakers, numbers

Our roster of speakers was as diverse as the spread of topics: professors, post-doctoral and doctoral researchers, amateur astronomers, a high-school student, but e.g. also ESA Science Director Günther Hasinger talking about ESA's science missions. Two of our speakers were astronauts: Reinhold Ewald, who is also on the Board of Trustees of the Max Planck Institute for Astronomy, talked about the construction and operation of the International Space Station, while Claude Nicollier told the audience about his missions fixing the Hubble Space Telescope.

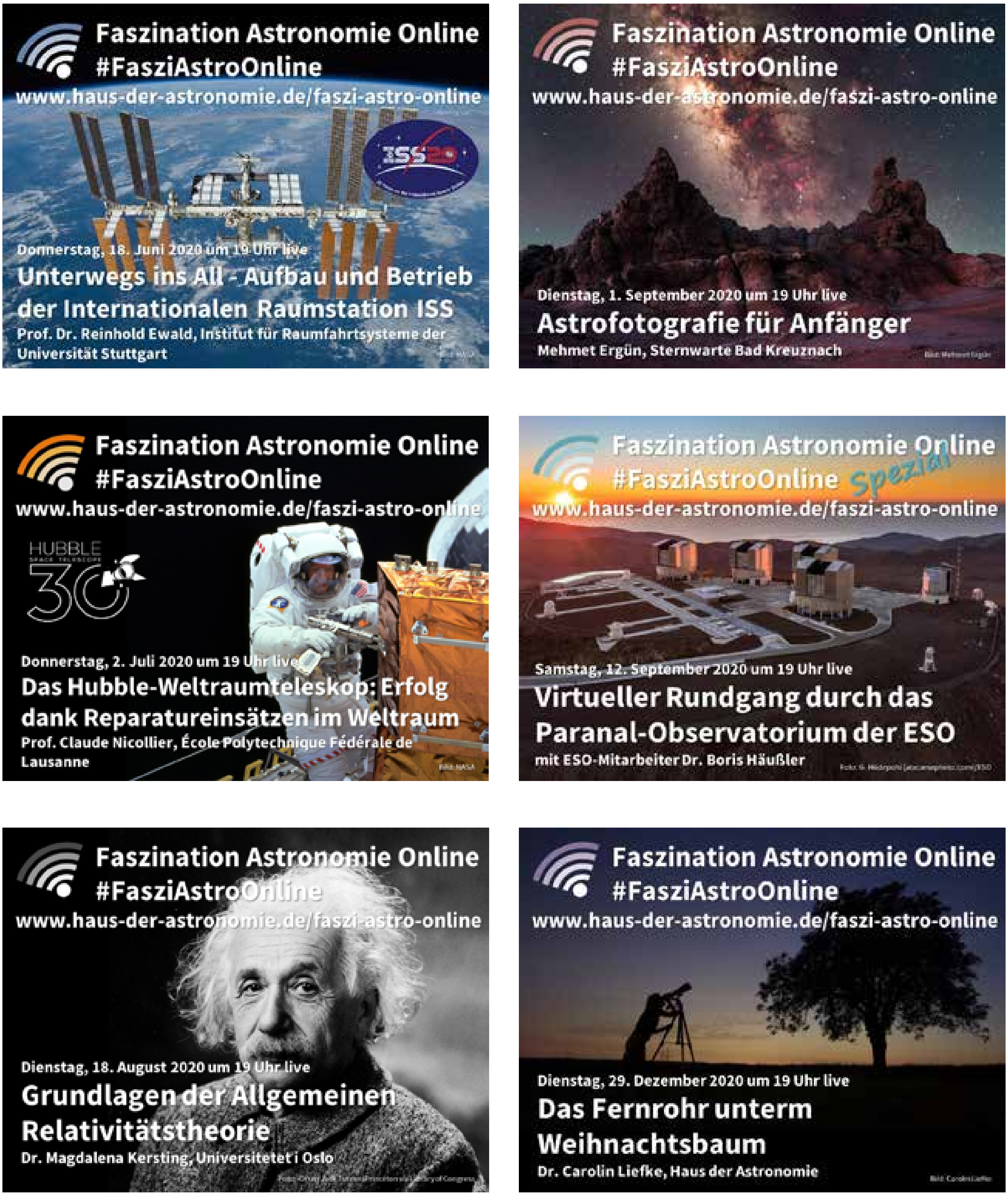


Fig. V.3.2: Examples of announcement tiles created by Carolin Liefke for talks given as part of the "Faszination Astronomie Online" lecture series.

Exactly one-third of our 2020 roster of speakers were women – thanks in large part to the #astrophysikerinnen list compiled by the astronomer Victoria Grinberg, a long-term Twitter thread listing women who make good (German-language) speakers on astrophysical topics. Thanks almost exclusively to the online public talk series, over the year, the Haus der Astronomie YouTube channel gained 3100 subscribers, growing from 1400 to 4500. All in all, in 2020, we had 86 online talks, with an average of 2300 views per video.

Browser-based Astro Apps and other resources

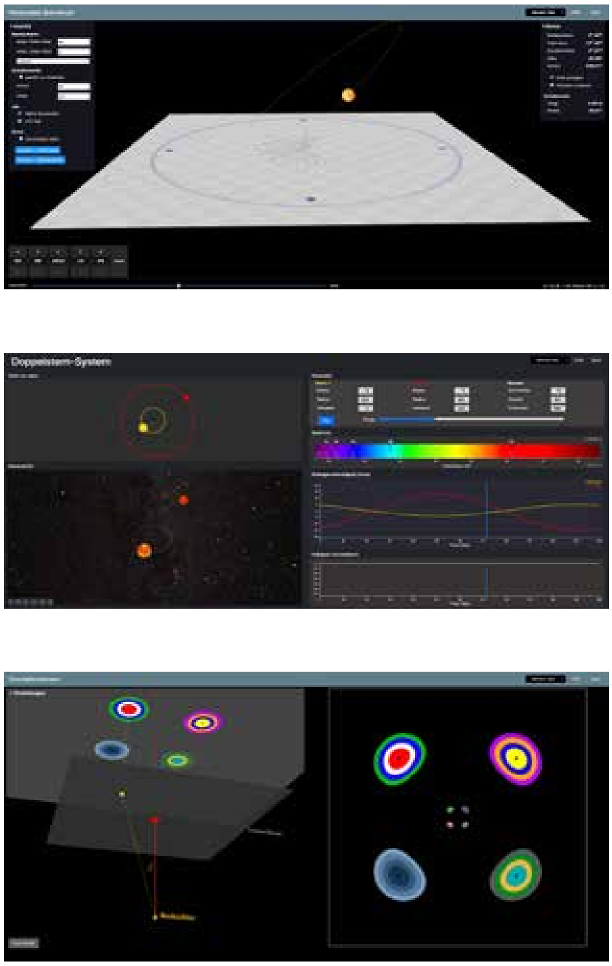
A major reason why our situation was less difficult than for other institutions is that in-person events are only a part of what we do. Another major area of activity, that of creating resources for education and public outreach, was largely unaffected by pandemic restrictions. "Wissenschaft in die Schulen!", coordinated by Olaf Fischer, produced 16 contributions this year, each linking classroom teaching to a current topic of astronomical research. Thanks to the help of two Hungarian students, who visited us in February, there are now also Hungarian translations for seven selected WIS articles, which have been made into a booklet for distribution at 500 schools in Hungary. Natalie Fischer, on the other hand, not only developed new resources for astronomy workshops for younger children, but also published an astronomy book for children: "Entdecke das Weltall," literally "Discover outer space" (Verlag Natur und Tier 2020).

By spring 2020, when it had become clear that pandemic mode was going to be more than a fleeting interruption, we decided that we would deliberately invest the time that would ordinarily have been taken up by in-person events in a joint project: the creation of browser-based astronomy applications, which would help users to explore interactively basic concepts of astronomy.

At this point, it was crucial that the skills of Thomas Müller, our in-house visualization specialist, extend to programming Javascript interactive apps that can be run in most modern browsers without the need for additional software to be installed – in fact, the interactive touch-table exhibits about the Solar System, nuclear fusion and the Milky Way created for our exhibition "Astronomie für Alle" were programmed in this way.

For the conceptual development, the whole HdA team participated, each staff member bringing their personal experience and skills to bear. At the time of the writing of this report (in Spring 2022), our collection has grown to 20 custom-made apps that let users explore diverse aspects of astronomy, from star trails and the geometry of solar eclipses via the most common methods of detecting exoplanets to the distortion caused by gravitational lenses, an easy way to reconstruct a Hubble diagram from authentic data from the NED database of redshift-independent distances, and reconstructing the appearance of a black hole with an accretion disk – allowing users to reconstruct the basics of the optical appearance of the famous first image of the shadow of a black hole, published by the Event Horizon Telescope Collaboration in 2019.

Some of the apps are now also integrated into the Leifi Physik-Portal, probably Germany's largest website for physics teachers, thanks to a cooperation with the Joachim Herz Foundation. For other apps, there are matching articles in our Wissenschaft in die Schulen! resources portal.



Credit: T. Müller / HdA

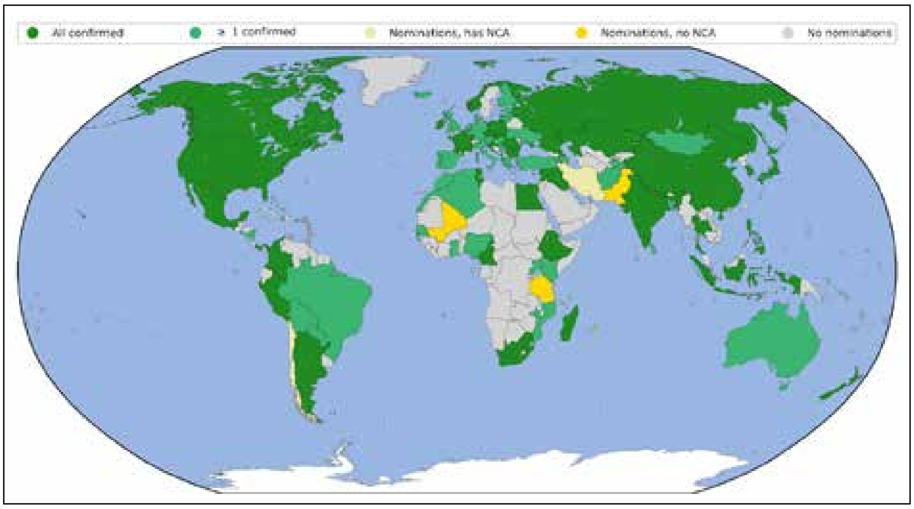
Fig. V.3.3: Screenshots from three of the AstroApps created by HdA staff, implemented by Thomas Müller. *Top to bottom:* Sundial simulator, observational data from a binary star, and gravitational lensing simulator.

Thomas Müller also programmed a "virtual tour" of Haus der Astronomie, allowing users to look around the various public areas of our galaxy-shaped building. The giant planisphere in our foyer can even be used interactively, in app form! The virtual tour is accessible under [haus-der-astronomie.de/virtualtour].

In parallel, our social media activities, coordinated and implemented by Carolin Liefke, continued to grow and expand on YouTube, Twitter, Facebook and Instagram. We also continued our support of the outreach work of the European Southern Observatory ESO, as part of the ESO Science Outreach Network (ESON), with the support of volunteer translators: making ESO press releases, announcements and picture releases available in German.

Additional events online (and, cautiously, offline)

Similar to how the rest of society coped, we took a number of additional activities online – gaining considerable experience in the process, which we hope to make use of even after the pandemic is over.



Credit: Niall Deacon / OAE

Fig. V.3.4: World map showing countries with and without National Astronomy Education Coordinator Teams (NAEC teams) as of the end of 2020. Green are countries with NAECs (dark green if there is more than one), in yellow are countries for which there are NAEC nominations, but they are not yet confirmed (light yellow are countries with a National Committee for Astronomy [NCA] which, where it exists, is responsible for confirming NAEC nominations).

Instead of our usual on-site WE Heraeus Teacher Training in November, we had a one-day online training event, combining the usual talks by the year's winners of the Reiff Prizes for Amateur and School Astronomy with a talk by spaceflight expert Eugen Reichl about the ongoing efforts to return to the Moon, followed by a public discussion meeting of HdA's partner teachers.

In non-pandemic times, HdA staff is frequently on tour to give public talks at more or less distant locations, visiting planetaria, amateur or professional observatories or science centers. This year, our staff travelled virtually to give talks about astronomical topics, but also about Haus der Astronomie itself, and about the new Office of Astronomy for Education we are hosting – throughout Germany, but also to Switzerland and South Africa. The "Public Outreach in Astronomy" meeting of the German Astronomical Society, co-organized in the framework of the society's annual meeting by MPIA's Klaus Jäger and HdA's Markus Pössel and Carolin Liefke also went fully virtual.

In addition to our public talks in German – and using the same technology – we supported the international infrared astronomy workshop IR2020 by hosting public online talks on infrared astronomy in Hungarian, Spanish, English, Hindi, Portuguese, German and Farsi, in mid-October.

Our BOGY internship for high-school students, which we had needed to cancel in spring, was also revived in an online format, with 7 participants (including one joining us from Turkey) joining us in late October. For our support of the IASC Asteroid Search programme for school students, the online format proved quite suitable – it even allowed high-school groups to join us at three search events during a time when German schools had gone fully virtual, and were teaching their pupils remotely.

In the winter semester 2020/2021, teaching at Heidelberg University was still almost exclusively online, and Markus Pössel's lecture on "From the Big Bang to Black Holes: Einstein's astrophysics for non-physicists" was held as a fully online lecture, with pre-recorded videos, interactive quizzes on the university Moodle, and live sessions for questions.

Natalie Fischer, on the other hand, cautiously returned offline for workshops for Kindergarten and elementary school teachers between October and December, with the workshops taking place in the Forscherstation in Heidelberg, our cooperation partner for the workshops. And Olaf Fischer took part in an in-person teacher training workshop in September at Sonneberg Observatory. Olaf Fischer on the other hand participated in the teacher training workshop at Sternwarte Sonneberg in Thuringia, which was cautiously held in an in-person format at the end of September.

IAU Office of Astronomy for Education

This year was also the first year of operations for the newly founded IAU Office of Astronomy for Education (OAE), for which HdA had submitted the winning proposal in an international competition for hosting this IAU office. The aim of the OAE is to foster the use of astronomy for education worldwide, in particular in STEM subjects (science, technology, engineering, and mathematics). This involves supporting the professionalization of work in astronomy education, the creation of infrastructure and the curation and creation of basic resources for teaching about astronomical topics. In our proposal, we were supported by the Klaus Tschira Foundation and the Carl Zeiss Foundation, which contribute substantial funding to the OAE.

An ambitious undertaking like the OAE is only possible with a network of supporters. By the end of 2020, we had built a network of 300 volunteer National Astronomy Education Coordinators, covering 82 countries and territories, to serve as liaisons between the OAE and the various countries' STEM education communities.

We brought together the NAECs and other astronomy education stakeholders online in the 2nd Shaw-IAU Workshop on Astronomy for Education, a format that the Shaw Prize Foundation funds as a collaboration with the IAU. With 347 participants from 82 countries, we had sessions on making astronomy education equitable, diverse and inclusive, astronomy education in low-tech environments, overviews of resources and relevant activities within the IAU, and presentations of particularly useful resources.

During this workshop, we pioneered a format that has continued to serve us really well in later online events: All talks were pre-recorded, with the speakers in attendance during the session, ready to interact with participants in the event platform's chat. Almost all sessions were offered more than once, for the convenience of participants from different time zones. In addition, all talks were subtitled, with live closed captioning of all discussion sessions, to ensure accessibility not only for those with hearing disabilities but more generally to support those participants for whom English is not their first language.

The opening event of the workshop doubled as the formal opening of the Office of Astronomy for Education, featuring addresses by IAU President Ewine van Dishoeck, IAU General Secretary Teresa Lago, and representatives from the foundations that fund the OAE: Theresia Bauer, MdL, Chair of the Carl Zeiss Foundation Administration and Minister for Science, Research and Art of the State of Baden-Württemberg; Beate Spiegel, Managing Director of the Klaus Tschira Foundation; and Kenneth Young, Chairman of the Shaw Prize Council and Vice Chair of its Board of Adjudicators, from the Shaw Prize Foundation.

The opening event also featured a keynote talk by Svein Sjøberg, Professor in Science Education, Department of Teacher Education and School Research, University of Oslo, Norway. Sjøberg is responsible for the groundbreaking ROSE study of pupils' interest in various subject areas of science for forty different countries. He talked on the subject of "Astronomy and Space Science: On top of Children's interest. Selected results from the ROSE-project."

In the course of 2020, we also began building additional infrastructure in support of our mission: In October, the "Big Ideas in Astronomy" project, which aims to define astronomical literacy around 11 central ideas, became part of the OAE via a Memorandum of Understanding. The Big Ideas had been created within Commission C1 of the IAU, with the University of Leiden taking the lead.

Fig. V.3.5: This image of the comet C/2020 F3 (NEOWISE), called "Neowise's metamorphosis", by Tomáš Slovinský and Petr Horálek from Slovakia, placed first in the category "Comets" of the first OAE Astrophotography Contest.

The central importance of creating astronomy resources in various languages has been pointed out to us by numerous of our NAECs; this is, of course, particularly important in countries that do not have a professional astronomical community. Our first building block is a peer-reviewed multilingual glossary, which is meant to contain a few hundred key astronomical terms, in as many different languages as we can manage. That glossary is then meant to serve as the basis of faithful translations. We began in 2020 with a draft version of key terms, in English.

One key resource that we began to create was astronomical imagery that is freely available under Creative Commons licenses. For some areas, there is already plenty of good material around; e.g. for galaxies, the freely licensed images by NASA, ESA and ESO in particular provide everything an educator could hope for. In December 2020, we kicked off a first OAE Astrophotography Contest, aimed at creating images for areas that were not covered by professional observatories – wide-field images, lunar eclipses, halo phenomena, to name a few. Additional visualizations were created for the OAE by our visualization specialist Stefan Payne-Wardenaar.

This year also saw the commencement of the EU-funded Erasmus+ project "TASTE – Good Practices for Teaching Astronomy at Educational Level," which will foster student education about elementary astronomical topics involving time and space, such as time measurement, the seasons, and the apparent motion of celestial objects in the day and night sky.

Last but not least, we began supporting astroEDU, the portal for peer-reviewed astronomy education activities created by Edward Gomez and Pedro Russo, again in the context of IAU Commission C1. With the help of OAE organizational assistant Gwen Sanderson, we managed to clear most of the sizeable backlog of astroEDU submissions by the end of 2020. (In 2021, astroEDU would formally become part of the OAE with a Memorandum of Understanding.)

Markus Pössel, Sigrid Brümmer, Carmen Müllerthann, Gwen Sanderson, Niall Deacon, Natalie Fischer, Olaf Fischer, Renate Hubele, Esther Kolar, Carolin Liefke, Thomas Müller, Juan Carlos Muñoz, Markus Nielbock, Matthias Penselin, Florian Seitz, Martin Wetz, Saeed Salimpour and Jakob Staude