Max Planck Institute for Astronomy

Heidelberg-Königstuhl

Annual Report 2024

Cover Picture

The image shows the Dorado Group of galaxies as seen by the Euclid Space Telescope. It is one of the richest galaxy groups in the southern hemisphere. Here, Euclid captures signs of galaxies evolving and merging 'in action', with beautiful tidal tails and shells visible as a result of ongoing interactions. As Dorado is a lot younger than other clusters, several of its constituent galaxies are still forming stars and remain in the stage of interacting with one another, while others show signs of having merged relatively recently. In size, it sits between larger galaxy clusters and smaller galaxy groups, making it a useful and fascinating object to study with Euclid.

This image was released as part of the Early Release Observations from ESA's Euclid space mission.

Credit: ESA/Euclid/Euclid Consortium/NASA, image processing by J.-C. Cuillandre (CEA Paris-Saclay), G. Anselmi

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Annual Report 2024

MAX PLANCK INSTITUTE FOR ASTRONOMY

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Credit: D. Elsässer

PREFACE

From the smallest particles to the largest cosmic structures, the Universe invites endless curiosity. It harbors an astonishing diversity of phenomena and conditions, giving rise to structures ranging from massive black holes to extrasolar planets. Year after year, astronomers continue to understand our universe better through thoughtful inquiry, diligent effort, and creative exploration, powered by innovative observational tools.

In this spirit, the Max Planck Institute for Astronomy pursues a wide range of research directions, including the formation of galaxies, stars, and planets and the analysis of the structure of exoplanets and their atmospheres. We develop and build instrumentation, observe and model data, and turn that information into insights through theory, numerical simulations, and laboratory experiments.

The year 2024 was remarkable for the sheer number of long-term projects that finally came to fruition: The James Webb Space Telescope continues to provide impressive new results at a rapid pace, including the first image of a cold, Jupiter-analog exoplanet and the discovery of massive black holes from the early universe. MPIA researchers also made the first discovery of a long-elusive intermediate mass black hole.

All of our science is driven by people. At MPIA, we aim to cultivate an ambitious, enthusiastic, and diverse community comprising excellent researchers, students, and engineers. A skilled outreach team makes its work public. The scientific and engineering staff receive support from efficient administration and technical services.

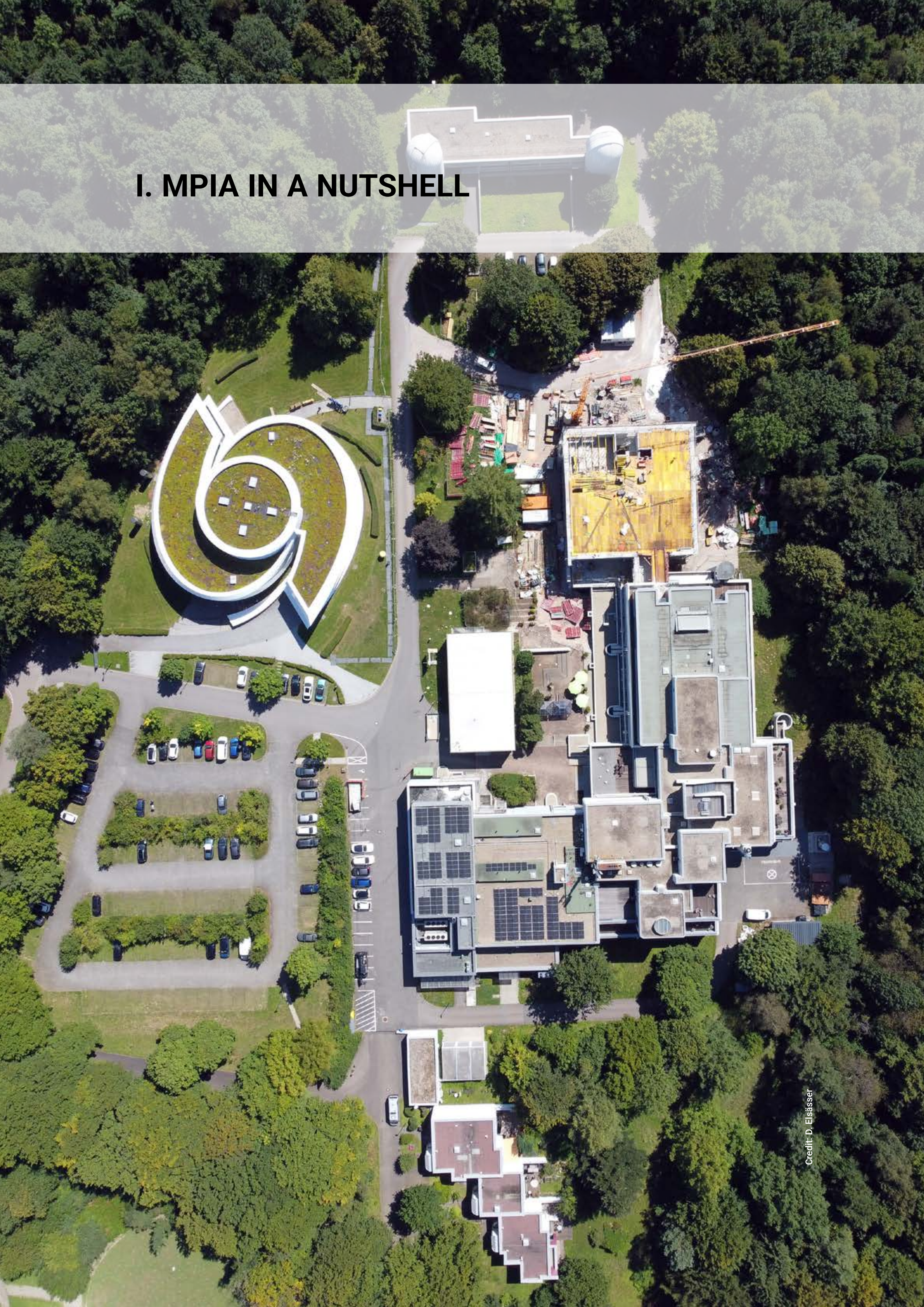
The year 2024 was also a time of transition and change. Thomas Henning, who had served as Director of the Planet and Star Formation Department since 2001, retired in May, passing the baton to Myriam Benisty. Meanwhile, MPIA's growing staff over the years created the need for an extension building to provide additional space for offices, laboratories, and a new canteen. The groundbreaking ceremony took place this year.

This report presents snapshots of our endeavors and discoveries in 2024, and of the many ways we seek to illuminate the physics and chemistry of our universe.

Myriam Benisty, Laura Kreidberg, and Hans-Walter Rix

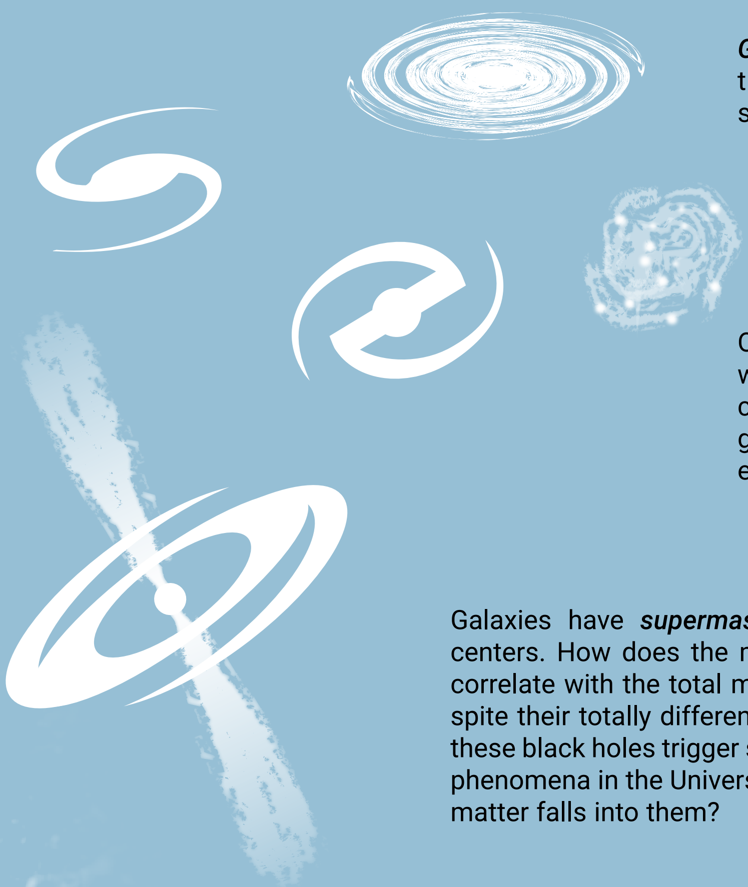
Heidelberg, January 2026

I. MPIA IN A NUTSHELL



Credit: D. Elsässer

OUR FIELDS OF RESEARCH: GALAXIES AND COSMOLOGY

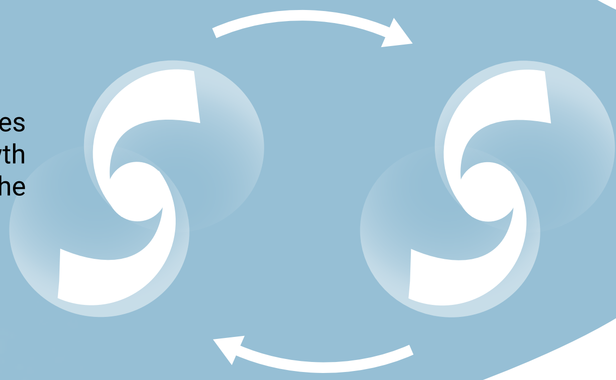


Galaxies come in many shapes and sizes. How do these differences arise? And what factors are responsible for how many stars a galaxy produces?

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?

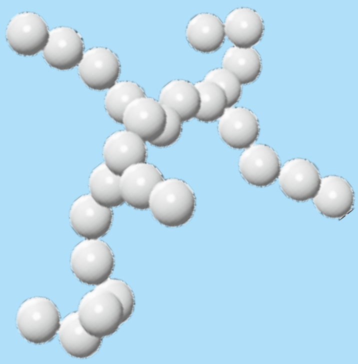
Galaxies grow as they merge with other galaxies or swallow smaller galaxies. How do these growth processes work in detail? How do they influence the properties of different types of galaxies?



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?

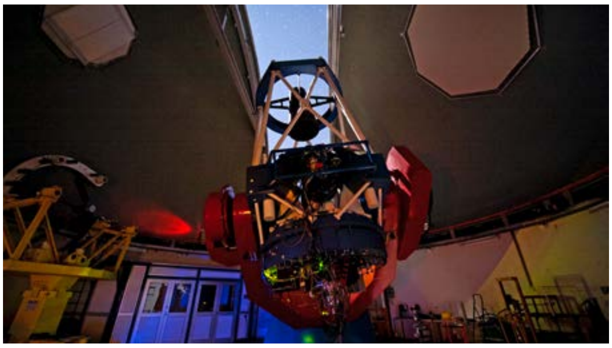


What are the ***stages of planet formation*** from the first colliding ***grains of dust*** to objects thousands of kilometers across? What can laboratory experiments tell us about the properties of cosmic dust and ways to detect these properties?

Since 1995, astronomers have discovered more than nearly 8000 ***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

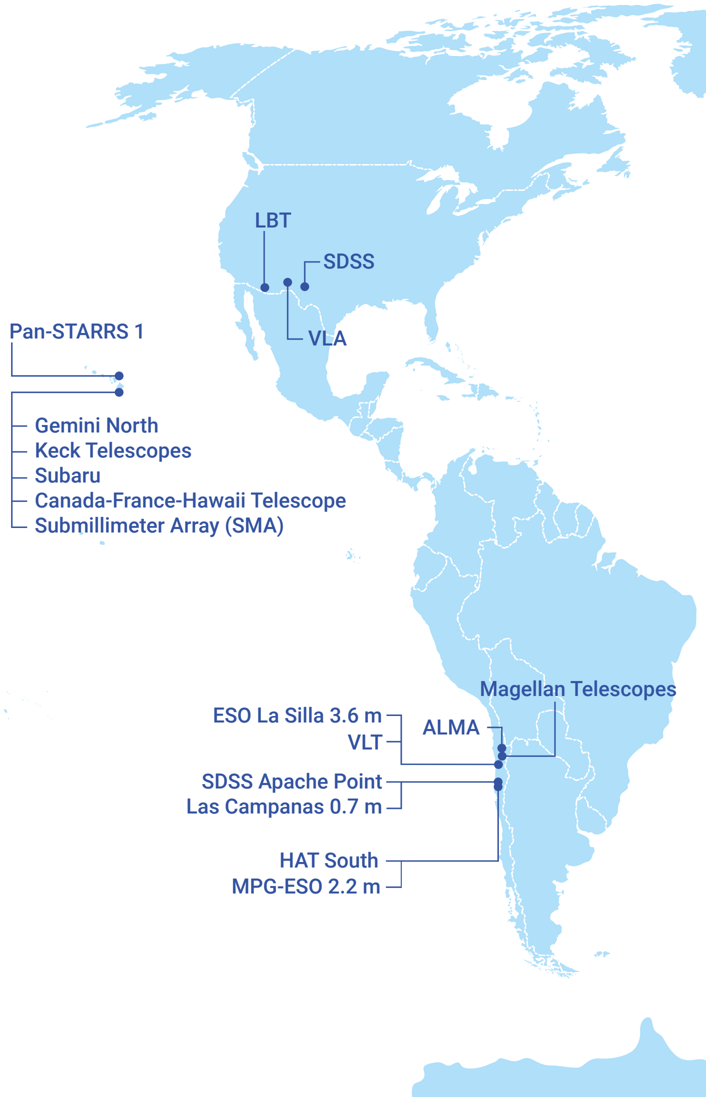


The MPG/ESO 2.2-meter telescope at La Silla observatory is owned by the Max Planck Society, and MPIA profits from guaranteed-time observations.

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 meters.

Credit: ESO



MPIA participates in the CARMENES program to search for exoplanets carried out at the Calar Alto observatory in Spain Furthermore, MPIA collaborated in developing, building, and upgrading the PANIC camera of the Calar Alto 2.2-meter telescope.

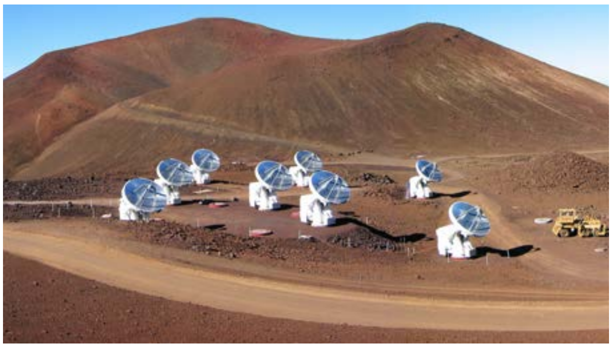
Credit: Eulalia Gallego Cano

The 100-meter 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

The ESO Very Large Telescope (VLT) is one of the major ground-based observatories MPIA scientists use in their research. MPIA is involved in various projects to develop and upgrade instruments for several ESO telescopes, including the VLTI.

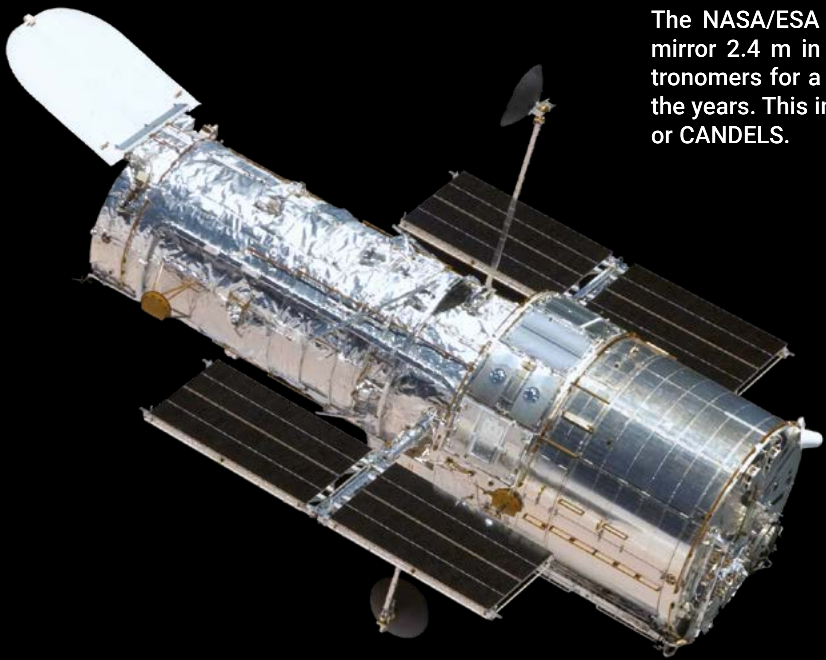
Credit: ESO / P. Horálek



The Submillimeter Array (SMA) is operated by the Smithsonian Astrophysical Observatory (USA) and the Academia Sinica Institute of Astronomy and Astrophysics (Taiwan) on Mauna Kea, Hawai'i.

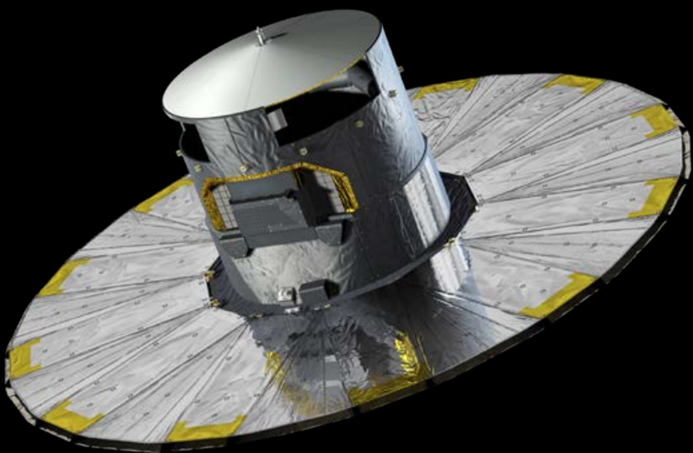
Credit: J. Weintroub

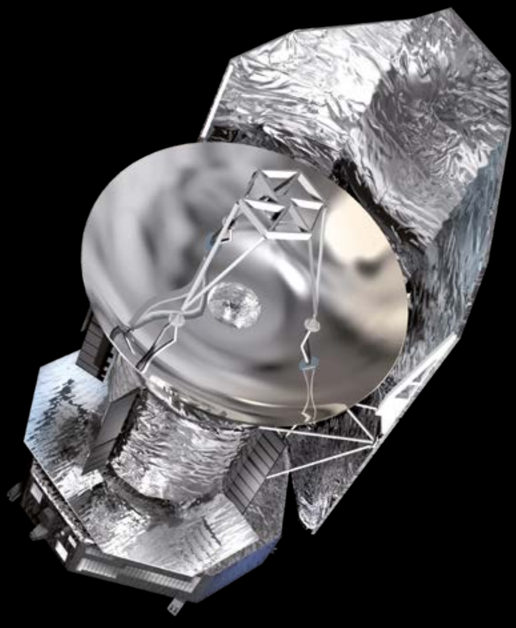
SPACE TELESCOPES



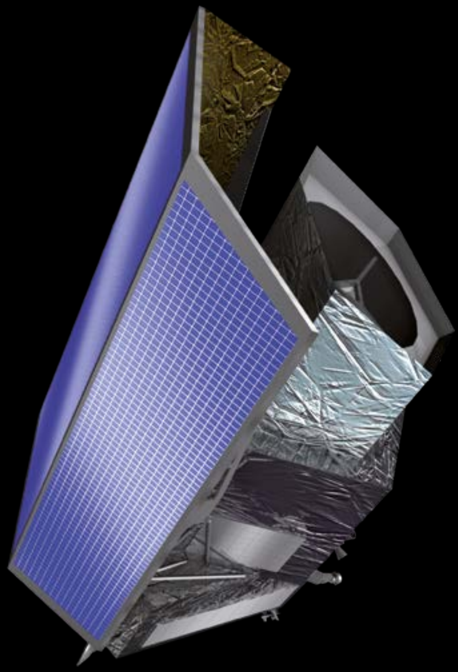
The NASA/ESA Hubble Space Telescope (with a main mirror 2.4 m in diameter) has been used by MPIA astronomers for a variety of successful observations over the years. This includes larger surveys such as COSMOS or CANDELS.

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 and played a key role in the data releases DR2 (April 2018), EDR3 (December 2020), and DR3 (June 2022).





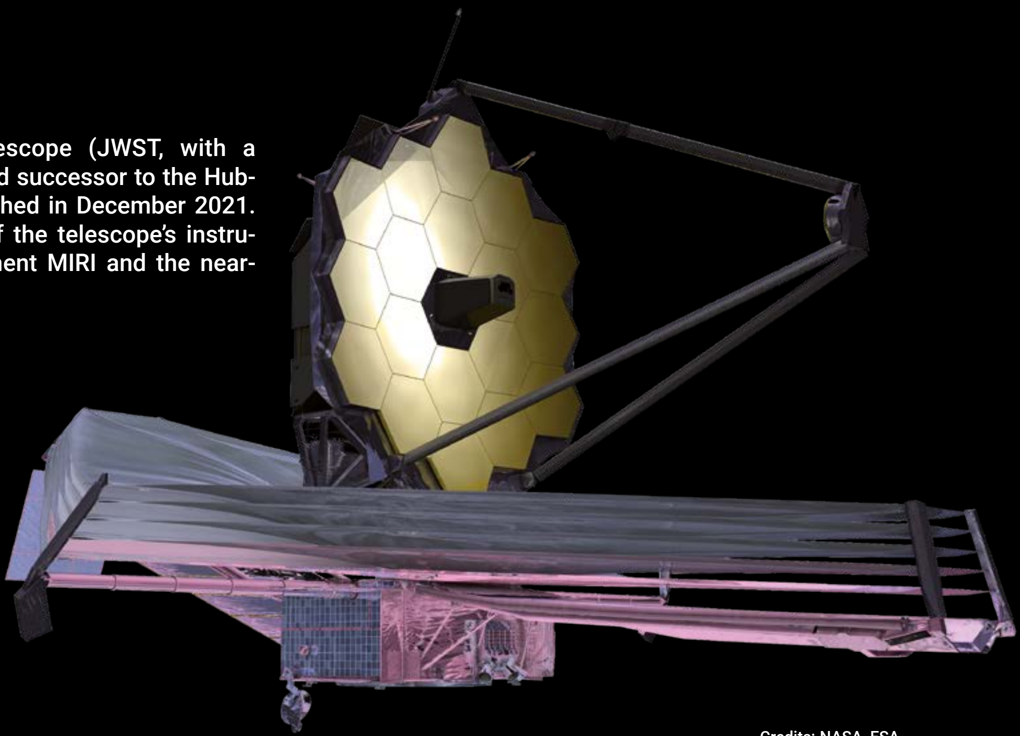
MPIA contributed to the construction of ESA's infrared observatory Herschel: We developed key components for the PACS instrument aboard the Herschel satellite, and were responsible for a number of observational programs undertaken with Herschel.



For ESA’s Euclid mission, which launched in July 2023, MPIA scientists have developed calibration strategies and contributed 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 Nancy Grace Roman Space Telescope is an optical-to-near-infrared 2.4 meter space telescope, slated to launch in 2027. Its objectives include searching for and studying extrasolar planets. The telescope will also probe the expansion history of the Universe and the growth of cosmic structure, with the goal of measuring the effects of dark energy. MPIA has developed precision mechanisms for certain optical elements of the Roman's CGI instrument. CGI is an ultra-high contrast coronagraphic camera that also includes a spectrometer.

The James Webb Space Telescope (JWST, with a 6.5-meter mirror), the designated successor to the Hubble Space Telescope, was 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

Credit: V. Krishnamurthy

Fig. I.1: Participants of the Meeting "Two HoRSEs: High-Resolution Exoplanet and Stellar Characterization Today and in the ELT Era."

Density Matters 2024: Uncovering the Formation, Interior Structure, and Evolution of Small Exoplanets
5 – 9 February
Ringberg Castle

Celebrating 30 Years of Protoplanetary Disk Chemistry: past, present, and future
19 – 23 February
Ringberg Castle

From Planet to Star Formation
4 – 8 March
Villa Vigoni, Menaggio, Italy

Fig. I.2: Participants of the conference "Early Phases of Star Formation (EPoS)."

Credit: H. Beuther / MPIA

Early Phases of Star Formation (EPoS)
12 – 17 May
Ringberg Castle

Exoplanets V
16 – 21 June
Leiden University, The Netherlands

Challenge Accepted: Linking Planet Formation with Present-Day Atmospheres
8 – 12 July
Haus der Astronomie

New Computational Methods in Milky Way Dynamics and Structure
12 – 17 July
Ringberg Castle

Two HoRSEs: High-Resolution Exoplanet and Stellar Characterization Today and in the ELT Era
15 – 19 July
Harnack House, Berlin

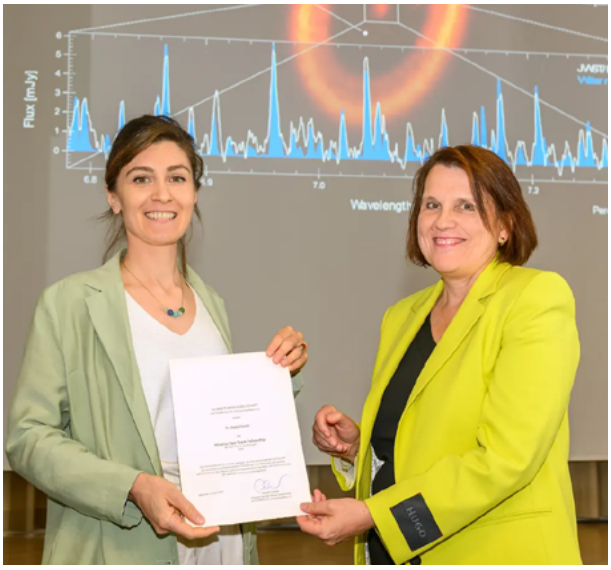
Physics of Star Formation: ISM dynamics and star formation: Linking (extra-)galactic scales to protoplanetary disks
3 – 6 December
Haus der Astronomie

Minor Bodies of the Solar System: Space Missions, Observations and Theory
16 – 20 December
Ringberg Castle

MAJOR GRANTS AND AWARDS

Credit: O. Völkel / MPIA

Fig. I.3: apl. Prof. Dr. Hubert Klahr.



Credit: D. Ausserhofer / MPG

Fig. I.4: Dr. Giulia Perotti *(left)*.

Hubert Klahr
was awarded an ERC Advanced Grant by the European Research Council. His project, "Turbulence, Pebbles, and Planetesimals: Origin of Minor Bodies in the Solar System (TiPPi)", will be funded with 2.49 million euros.

Giulia Perotti
received an MPG Minerva Fast-Track Fellowship.

Mario Flock
was awarded an ERC Consolidator Grant by the European Research Council. His project, "Revealing Accreting Planets Through Observations and Refined Simulations (RAPTOR)", will be funded with 2.13 million euros.

Patzer Prizes 2024

Maximilian Häberle, MPIA
for his publication "Fast-moving stars around an intermediate-mass black hole in Omega Centauri", 2024, Nature, 631, 285.

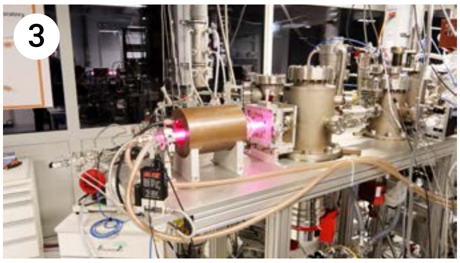
Jose Eduardo Mendez-Delgado, ARI/ZAH
for his publication "Gas-phase Fe/O and Fe/N abundances in Star-Forming Regions: Relations between nucleosynthesis, metallicity and dust", 2024, Astronomy & Astrophysics, 690, A248.

Brooke Polak, ITA/ZAH
for her publication "Massive star cluster formation II. Runaway stars as fossils of subcluster mergers", 2024, Astronomy & Astrophysics 690, A207.

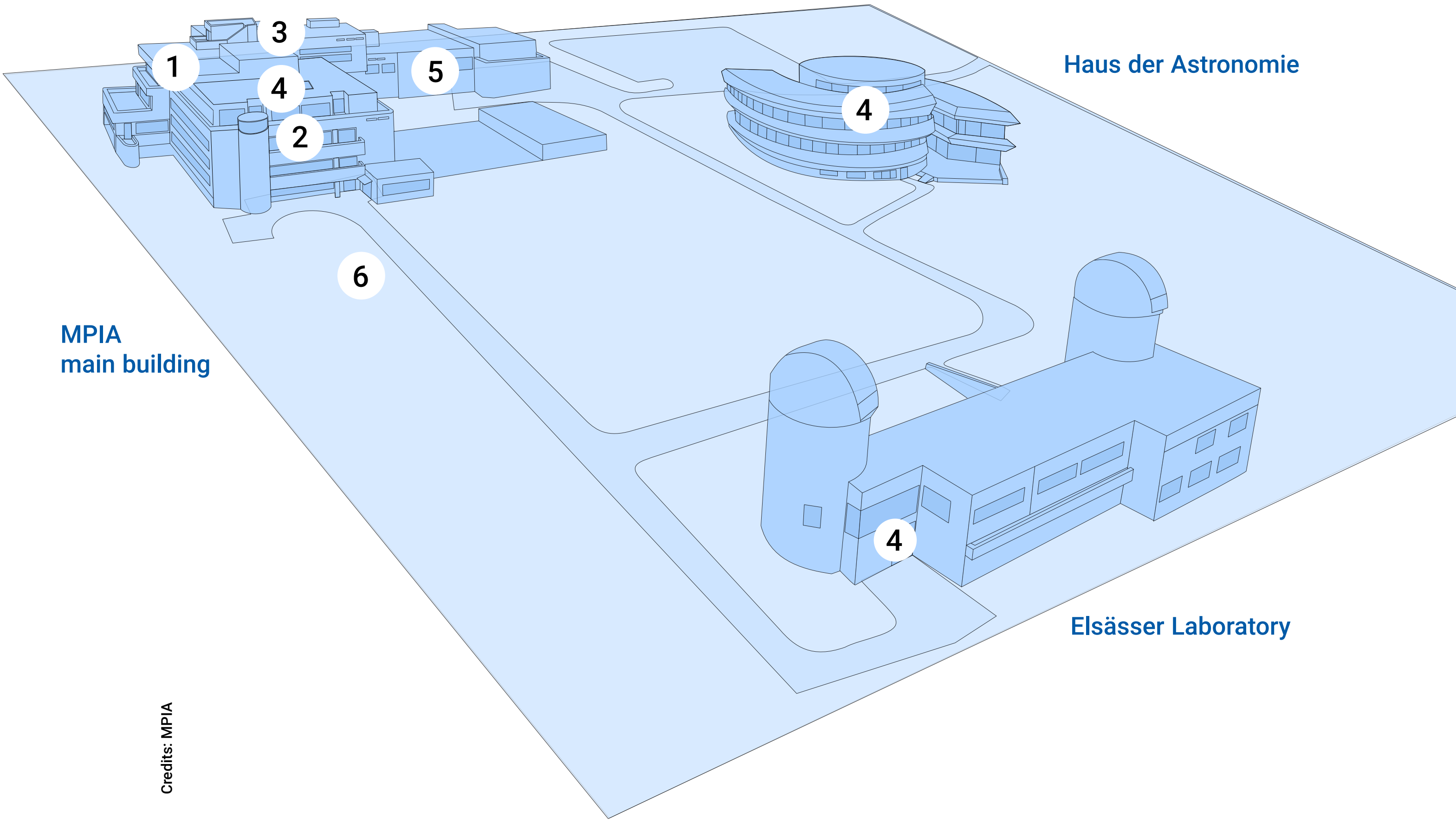
INFRASTRUCTURE

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 Origins of Life laboratory.



Two lecture halls and eight seminar/workshop rooms, here the Starbox meeting room.

Experimental and assembly facilities including clean rooms for instrumentation.

A computer-generated image of the MPIA's new extension building, which will adjoin the south end of the existing main building.

PEOPLE AT MPIA

426

employees
keep the institute running.
237 of these are scientists,
including 96 junior scientists
or long-term visitors,
and 74 PhD students

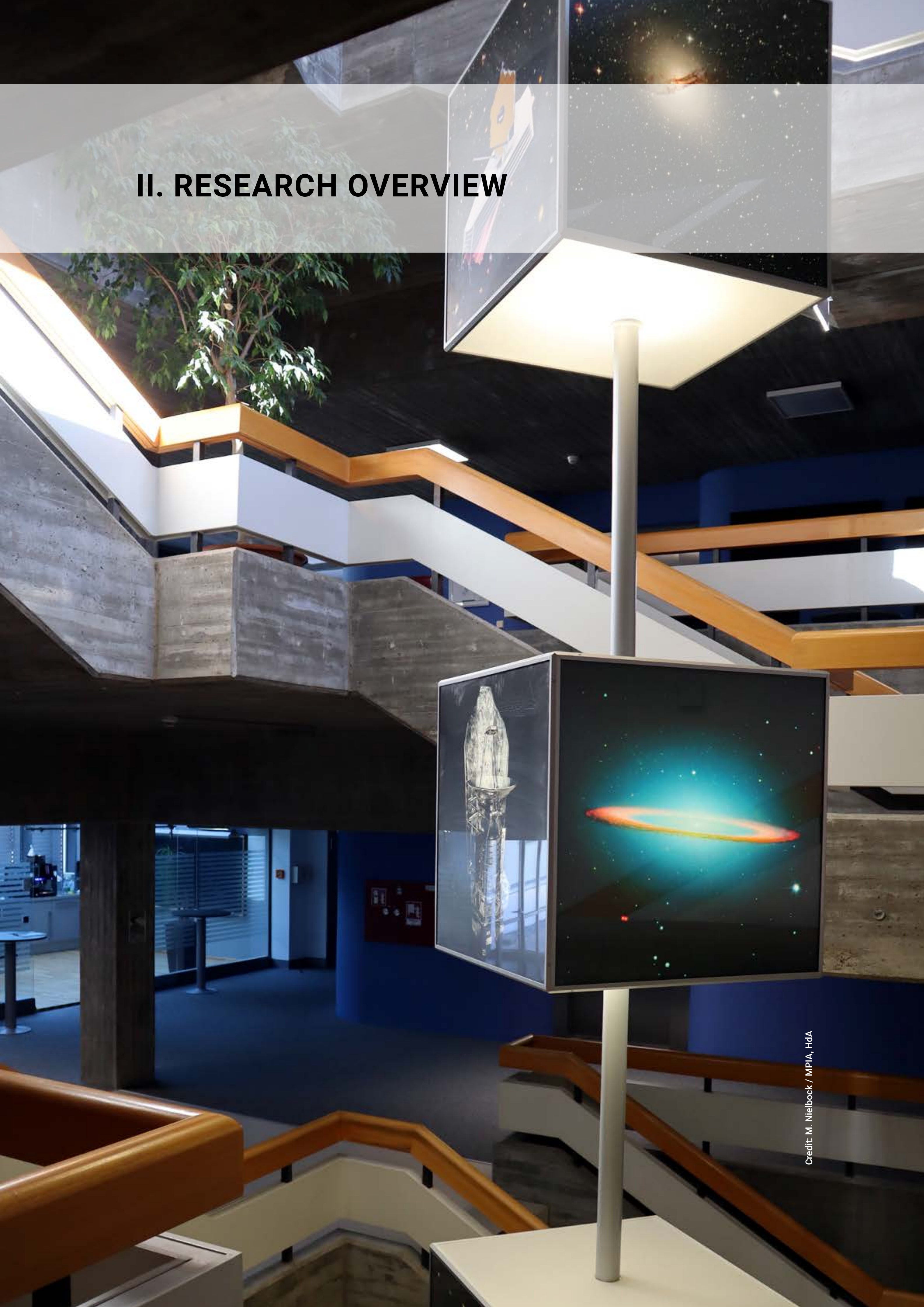
7

independent research groups
are part of our institute:
2 Lise Meitner Groups
2 Max Planck Research Groups
1 Sofia-Kovalevskaya group funded by the Alexander von Humboldt Foundation
2 European Research Council groups

Fig. I.5: A ground-breaking ceremony for MPIA's new extension building was held on November 13, 2024. The four-story building will extend the existing main building towards the South. Old and new buildings will be connected by covered skyways. Once completed, the extension will provide additional office space and laboratories, as well as a new canteen area. The inauguration is planned for 2026.

From left to right: Myriam Benisty (Director MPIA, PSF Department), Heike Kiko (Department of Research Buildings and Infrastructure of the Max Planck Society), Michael Wilkins (Architect, kreuger wilkins architekten Stuttgart), Laura Kreidberg (Managing Director MPIA, APEx Department), Eckart Würzner (Lord Mayor of the City of Heidelberg), Hans Walter Rix (Director MPIA, GC Department).

II. RESEARCH OVERVIEW



Credit: M. Nielbock / MPIA, HdA

II.1 RESEARCH OVERVIEW

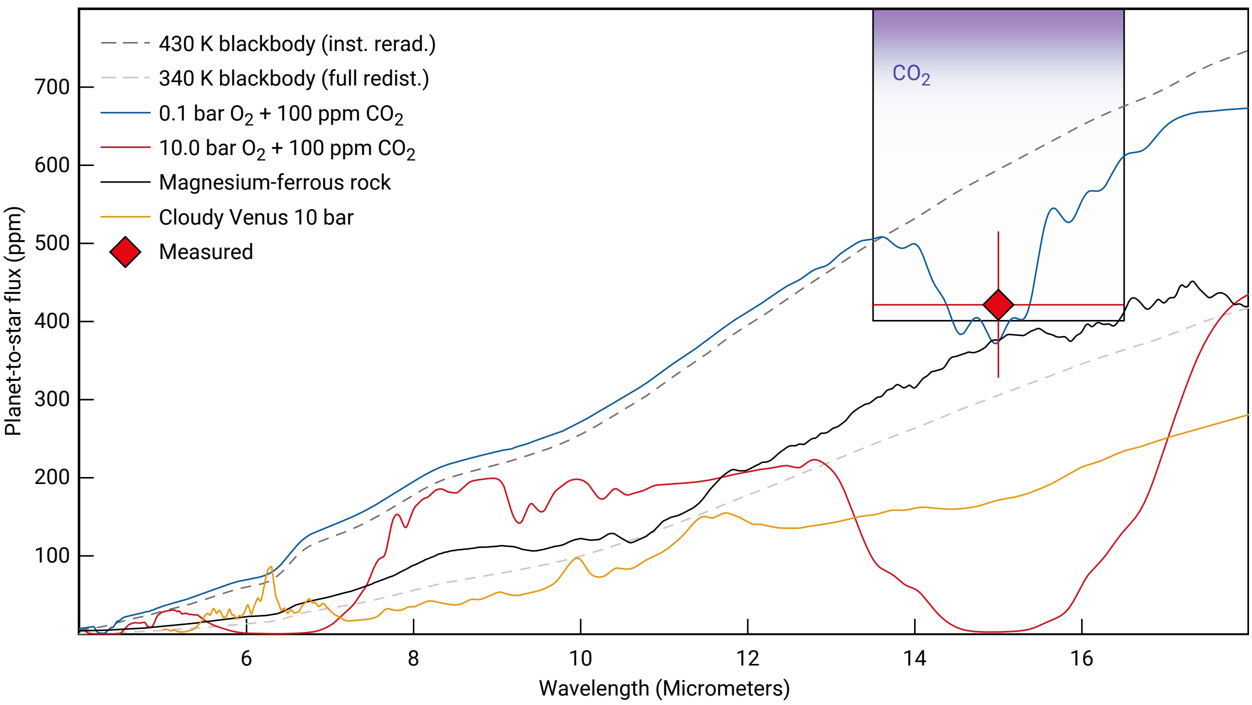
Atmospheric Physics of Exoplanets (APEx)
Director: Prof. Dr. Laura Kreidberg

Planets are ubiquitous in the Galaxy—most stars host at least one. Since the discovery of the first extrasolar planet 25 years ago, surveys have revealed that planets are very common indeed, and that extrasolar planets show a much greater diversity of properties than we see 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 a density as low as that of cotton candy (so-called super-puffs), and an abundant population of planets with radii intermediate between those of Earth and Neptune. Where this diversity comes from and how our own Solar System fits into this wider picture are two of the key science questions for exoplanets in the coming decade.

Characterizing diverse atmospheres

Now that this diverse population has been uncovered, the next step is to characterize planetary atmospheres in detail. Studying atmospheric physics and chemistry makes it possible to determine the planets' formation and evolutionary histories, their present-day climate, and even their habitability. With the foundation of the Atmospheric Physics of Exoplanets (APEx) department in 2020, headed by director Laura Kreidberg, MPIA expanded its efforts in this direction. APEx provides the opportunity to assemble a critical mass of exoplanet characterization experts in a single place. Exoplanet atmosphere characterization is challenging on multiple fronts. We push detectors beyond their design limits in order to search for the tiny signal of atmospheric absorption. Models of atmospheric physics and chemistry need to cover several orders of magnitude in time and distance. Tackling these challenges requires close collaboration between experts, and progress in the field will be significantly accelerated with an entire department devoted to these topics.

Fig. II.1.1: Simulated emission spectra compared with the measured eclipse depth of TRAPPIST-1c. The atmospheric CO_2 feature overlaps directly with the MIRI filter used for these observations. The two limiting cases for the atmospheric circulation for a zero-albedo planet (instant reradiation of incoming flux and global heat redistribution) are marked with dashed lines. Two cloud-free, O_2/CO_2 mixture atmospheres are shown with purple and red solid lines. They show decreased emission at 15micrometers owing to CO_2 absorption. The solid black line represents a bare-rock model assuming an unweathered planetary surface made of magmatic Magnesium-ferrous rock. The cloudy Venus model with a surface pressure of 10bar is shown with a solid yellow line.



Credit: S. Zieba et al. / MPIA

Building blocks of giant planets

The atmospheric chemical composition of gas giant planets provides an important piece of the puzzle. The largest exoplanets—similar in size to Jupiter—have thick, hydrogen-dominated atmospheres that were accreted during the early stages of their formation. The chemical enrichment of these atmospheres provides a record of the formation conditions in the disk, including the distance from the host star and the accretion rates of gas and solids.

New observing facilities have opened the door to a precise chemical census for gas giants. In particular, the recently launched James Webb Space Telescope (JWST) is a game changer for these measurements, thanks to its large mirror and broad wavelength coverage. Early science results have revealed many molecules in planetary atmospheres for the first time, including carbon dioxide and sulfur dioxide. Excitingly, the first precise transmission spectra of sub-Neptunes are now available, revealing metal-enriched atmospheres akin to the ice giants of our own Solar System (Chapter III.1). In combination with atmospheric retrieval frameworks, the wide range of upcoming data will provide a near-complete chemical inventory that can directly test predictions from planet formation models.

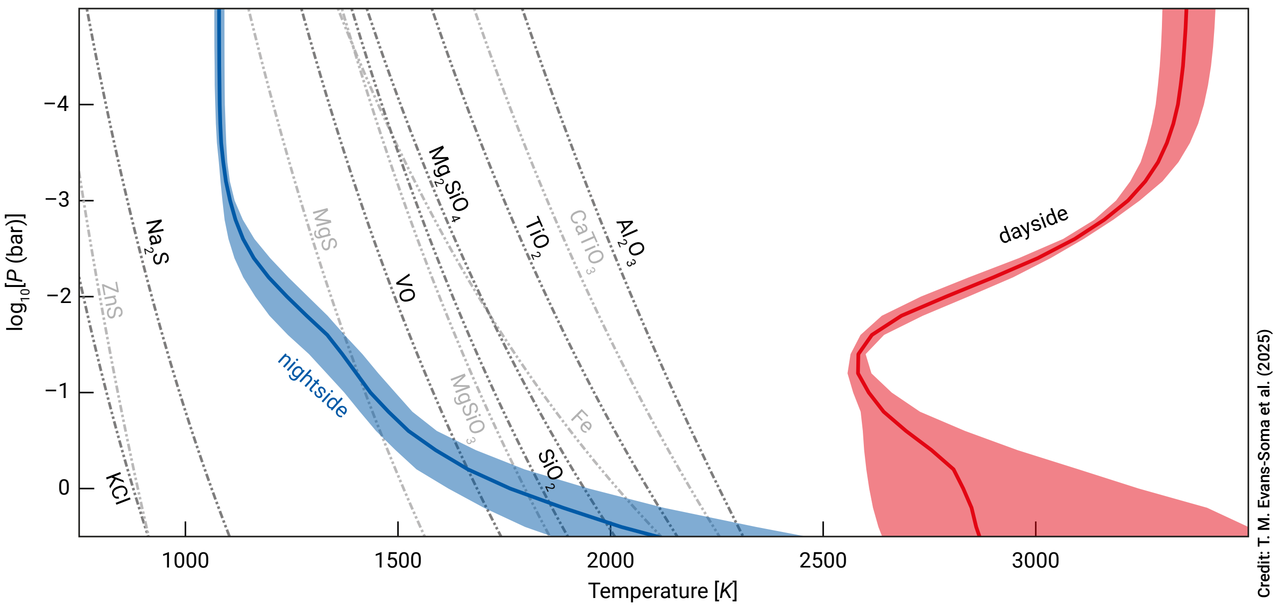
How's the weather up there?

In astronomy, the saying goes that everything can be approximated as a spherical cow in a vacuum. But for planetary atmospheres, that is definitely not true! From the example of our own Solar System, we know that the atmospheres are not homogeneous. Climate and chemistry vary dramatically across different regions of the atmosphere due to stellar irradiation, planet rotation, and orbital tilt. Climates are even more varied on exoplanets, particularly those with short-period orbits, where the planet may become tidally locked to its host star.

Observing and modeling exoplanet atmospheres in three dimensions is critical to measuring their underlying bulk composition. Some major open questions are: Where are molecules transported by vertical and horizontal mixing, and to what extent does the observable atmosphere represent the bulk? What types of clouds form, and where are they located? How does the temperature change as a function of latitude, longitude, and altitude? Recent JWST results have made the first steps in answering this question. For example, observations of the hot Jupiter WASP-43b revealed a surprisingly cold nightside, providing strong evidence for cloud formation on the permanently dark half of the planet (Chapter III.2).

Simple, one-dimensional models were largely sufficient to explain the previous generation of exoplanet atmosphere observations. With the influx of more precise data from new facilities, three-dimensional effects are front and center. A key area for future work is to map the global climate observationally, with phase curve

Fig. II.1.2: Pressure–temperature profiles of a hot Jupiter exoplanet atmosphere are shown for the dayside (thick red line) and nightside (thick blue line), assuming thermochemical equilibrium. These profiles indicate the vertical temperature distribution, with pressure serving as a proxy for altitude. Condensation curves for refractory chemical species are given as labeled dashed-dotted lines. The regions to the right of any pressure–temperature profile represent conditions where the corresponding species condense and form aerosols, potentially leading to cloud formation. In contrast, the regions to the left represent conditions where the species evaporate and remain in the gas phase. The shaded regions extending next to the pressure–temperature profiles indicate the associated 1σ uncertainties.



measurements and transit and eclipse mapping. 3D general circulation models help to interpret these measurements to determine the global climate, temperature structure, chemistry, and cloud properties.

Searching the skies of terrestrial worlds

It is now known that small exoplanets are very common around other stars. Most stars have at least one planet smaller than Neptune. Beyond the fact that these planets exist, however, little is known about them, even whether or not they have atmospheres. Planets around small M-dwarf stars are particularly vulnerable to atmospheric loss due to the large amounts of high-energy radiation emitted by the star in its early lifetime. Under what conditions can an atmosphere survive? Where is the boundary between rocky and gaseous planets? For planets with atmospheres, are they oxidizing or reducing? How typical is water on rocky worlds? These are some of the biggest open questions in exoplanet science.

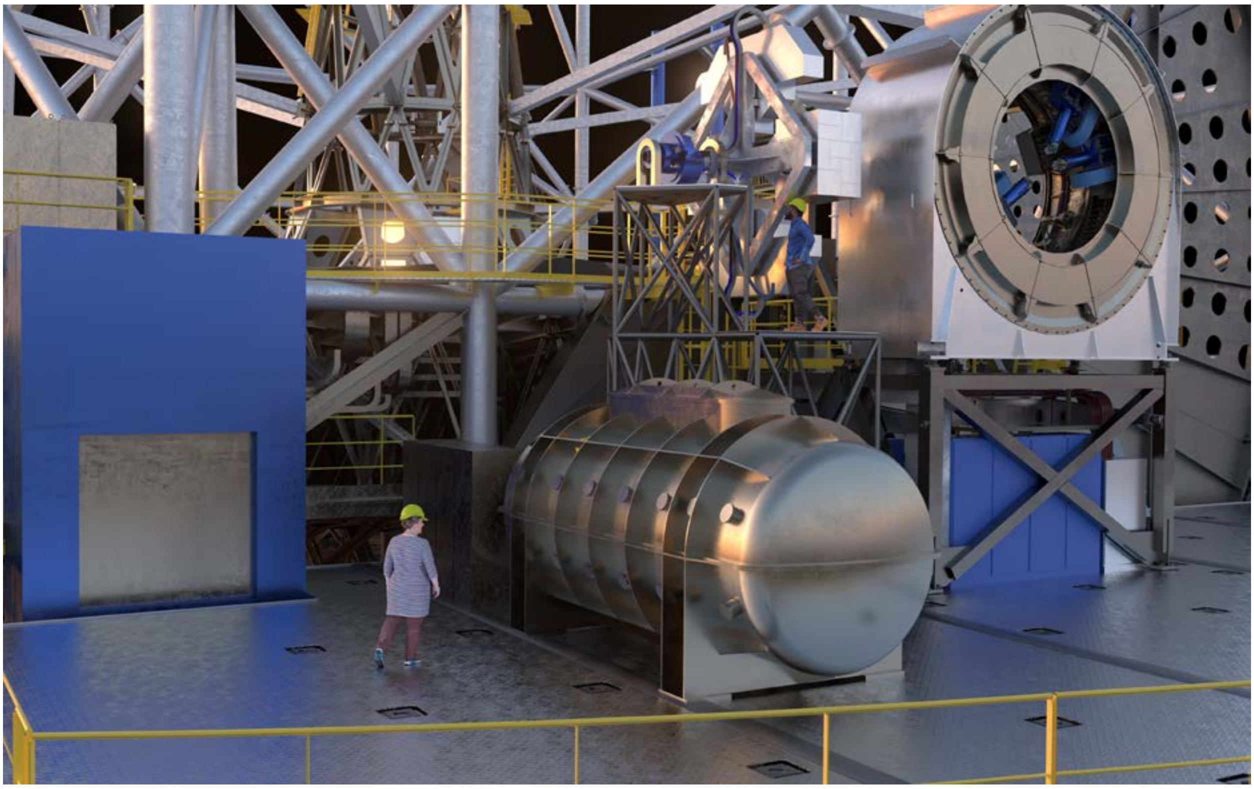
Excitingly, direct measurement of rocky planets' atmospheric properties is a frontier topic newly enabled by JWST and the ELT later in the decade. With thermal emission and transmission spectroscopy, these facilities can reveal the surface pressure and primary molecular constituents of rocky planet atmospheres. Such measurements will be the first milestone on the long path toward assessing the habitability of worlds beyond our Solar System.

Building an exoplanet atmosphere characterization toolkit

To address these questions, the growing APEx department is building up expertise in four key areas:

- **Observations of transiting and directly imaged planets.** APEx researchers are leading numerous observing programs with Hubble, JWST, and the VLT. The observational approach is comprehensive regarding what planets we study (gas giants, sub-Neptunes, and terrestrial worlds) and the techniques we use (transmission and emission spectroscopy, direct imaging, interferometry, and high-spectral resolution characterization).
- **Exoplanet atmosphere modeling in one and three dimensions.** We specialize in atmospheric parameter retrieval with fast 1D models, which

Fig. II.1.3: An artist's impression of the high-resolution ANDES spectrograph, a second-generation instrument for the ELT that was recently approved for construction. With a sufficiently high spectral resolving power to see individual absorption lines from exoplanets, ANDES will provide precise measurements of the chemical composition, wind patterns, and 3D structure of exoplanets. MPIA is a partner in the ANDES consortium and is responsible for the Calibration Unit electronics and a design study for a diffraction-limited *K*-band spectrograph module.



Credit: ESO

constrain the chemical composition and temperature structure based on observed planet spectra. We also develop general circulation models that predict the 3D atmospheric structure, chemistry, and clouds starting from first principles.

- **Open-source software tools.** We are the lead developers of several open-source packages for both atmospheric modeling and data reduction. These include the petitRADTRANS atmospheric retrieval code, the PACMAN tool for Hubble data reduction, and the GASTLI model for gas giant interior structures. We are also major contributors to the Eureka! Pipeline for JWST data.
- **Stellar characterization.** In the short history of the field of exoplanets, there is already one adage: "Know thy star; know thy planet." Precise measurements of host star temperatures, masses, and radii are crucial to interpreting the spectra of their planets. In order to measure stellar properties, we combine in-depth characterization of individual systems with statistical characterizations of large samples from the Gaia mission.

Instrumentation projects

Many of the advances in exoplanet characterization are the direct result of new instruments and observing capabilities. With this in mind, APEx is investing in several ground-based instrumentation projects that will provide unprecedented capability to study exoplanet atmospheres:

- **The METIS instrument, a first light instrument for ESO's upcoming Extremely Large Telescope (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 Very Large Telescope/GRAVITY upgrade.** 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 ELT/ANDES instrument**. ANDES is a second-generation ELT instrument capable of high-resolution optical and near-infrared spectroscopy. One of the major goals of the instrument is to study the atmospheres of Earth-size exoplanets and potentially even detect molecular oxygen in their atmospheres. APEx is leading a design study for a compact K-band spectrograph for the instrument (Fig. 3).
- **The Second Earth Spectrograph.** Second Earth is a planned extreme precision radial velocity spectrograph for the MPG/ESO 2.2-meter telescope on La Silla, jointly supported by the PSF and APEx departments. The instrument will monitor a sample of nearby stars with an approximately nightly cadence to tease out the tiny radial velocity signal from Earth analogs. These nearby Earths will be the targets of a future flagship space telescope capable of directly imaging the planets and searching for biosignatures in their atmospheres.

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 from the fiilamentary distribution of galaxies that is known as the cosmic web, 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 the cosmic large-scale structure appears to be driven by the ubiquitous self-clumping influence of gravity, mitigated mainly through cosmic expansion. In shaping individual galaxies, a plethora of other physical effects come into play, making these galaxy ecosystems so diverse and fascinating.

To understand quantitatively how such structures arose in an expanding Universe, however, models require an unusual extra ingredient: dark matter, which possesses mass and hence gravitational attraction but does not interact with electromagnetic radiation at all. The nature of this dark matter remains unknown. To make things "worse," the expansion of the Universe is observed to be accelerating, which forces us to postulate an even more exotic ingredient: dark energy, which acts as a form of repulsive force. There are places throughout the Universe where a dense concentration of dark matter arises from gravitational instability. Consequently, normal matter is concentrated, allowing stars to form from dense gas clouds. We call these places galaxies. They arguably form the centerpiece of the overall hierarchical structure of the Universe: they are the metropolises of the cosmos, where everything happens: stars are born, live, and die, producing the chemical elements of the cosmos; Black Holes live and grow there, and much more.

The formation of galaxies is difficult to understand, primarily 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 Milky Way, the only large galaxy 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 connections 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 challenging 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, their rate of producing new stars, the mass of the Black Holes at their very centers, and their sheer physical size. Nevertheless, as Edwin Hubble realized 80 years ago, these "island universes" are not as varied in appearance and structure as the laws of physics would allow. Observations, particularly those made over the last 15 years, have confirmed this in increasing detail: only a small fraction of the possible combinations of galaxies' characteristic quantities (stellar masses and ages, size, shape, and central black hole mass) actually exist in the Universe. Virtually all these physical properties are strongly correlated. 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 else it is possible that the initial conditions of the Universe only permitted the formation of the galaxies we see. Alternatively, 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 we currently observe. Current research suggests that all three aspects may contribute to this phenomenon.

Gas: the fuel for making the stars in galaxies

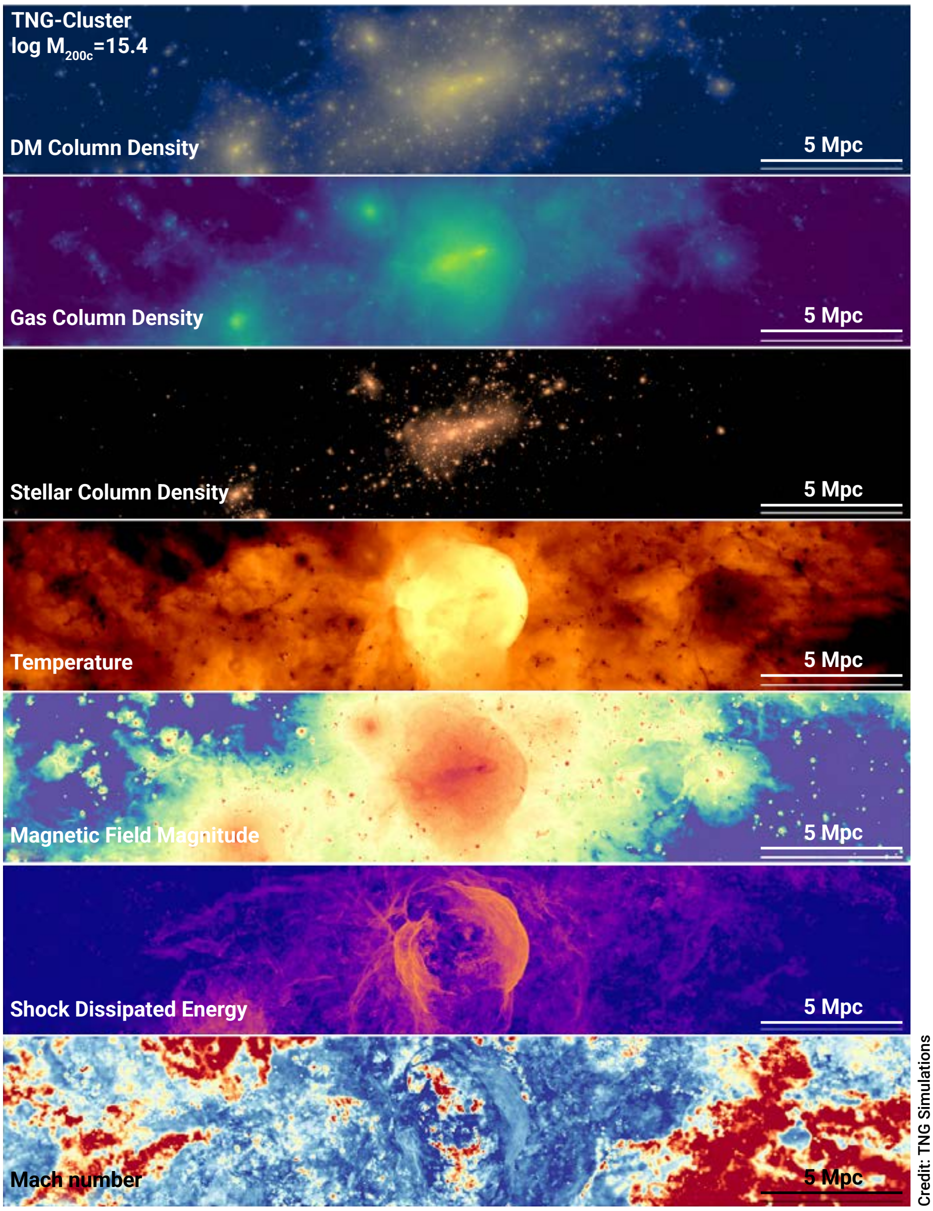
Stars, the most obvious, ubiquitous, and defining constituents of galaxies, are made from interstellar gas, particularly molecular gas—gas whose atoms are sufficiently cool to have bonded into molecules, notably hydrogen molecules H_2. However, most of the gas in the Universe is not part of any galaxy.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

In order to decipher galaxy formation, it is crucial to understand how gas cools and condenses at the centers of gravitational potential wells due to the presence of dark matter, transforms into molecular gas, and ultimately forms stars. Comprehending 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 circumgalactic gas cycle is far from understood. To improve our understanding, we need to develop methods for studying the various forms of gas, including dense molecular gas, neutral (atomic) gas, and ionized gas. We strive to achieve this goal by employing a diverse range of techniques, from submillimeter observations of molecular lines to studies of UV absorption lines resulting from hot gas. Facilities such as the IRAM NOEMA Interferometer, ALMA, and large optical telescopes are crucial tools for studying quasar absorption lines.

To understand how star-formation efficiency depends on position within a galaxy, the MPIA-led PHANGS project has drawn on spectacular new gas and dust maps from JWST and radio telescopes to show when new stars can form easily in a galaxy.

Fig. II.2.1: This image collage, extracted from the TNG Cluster simulation, shows the most massive galaxy clusters in the process of merging. The total halo mass is 1015.4 solar masses, and from top to bottom, the panels show: dark matter column density, gas column density, stellar column density, density-weighted temperature, mass-weighted magnetic field strength, shock dissipated energy, and the shock Mach number. Each image is 32 megaparsecs wide and six megaparsecs tall.



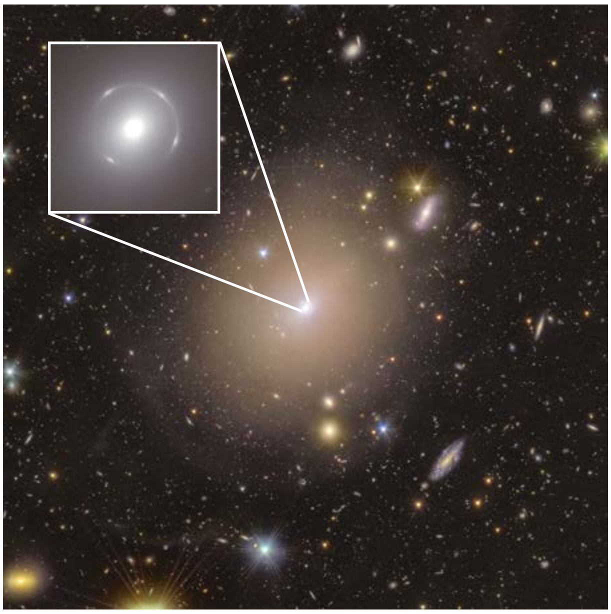
The Milky Way and its stars—a model organism for understanding galaxies

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

This progress in methodology 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 offer an unprecedented way to test 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 primary tools for diagnosing the physical properties of stars. The delightful deluge of survey data has shown that we do not 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 it. This circumstance has led to a renaissance of stellar spectroscopy as a cutting-edge research direction, with MPIA in a leading role.

Fig. II.2.2: After 15 years of preparation at MPIA and worldwide, the Euclid mission began its science survey in 2024. Even the early data show the power of imaging much of the sky with a high-resolution space telescope: one of the first galaxies imaged showed a rare "Einstein-Ring" around its center, the result of the galaxy's mass bending the light coming from behind it, mapping the same background galaxy 4 times (see inset). It is one of the best ways to measure mass in the Universe, simply by measuring the light-bending predicted by Einstein's General Relativity.



Credit: ESA / Euclid / Euclid Consortium / NASA, image processing by J.-C. Cuillandre, G. Anselmi, T. Li

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 is transforming fundamental questions into specific ones that can be addressed using current tools and methods.

Several 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? Moreover, when and where does gas turn from atomic to molecular species, 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 sizes?

The star formation process 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 galaxies' central Black Holes: Why is it possible to predict their properties from a galaxy's overall conditions? Furthermore, how did these Black Holes form and grow in the first place?

Most galaxies are so far away that we cannot individually study their stars, their central and defining ingredients. However, where possible, the chemical composition and orbits of individual stars provide clues to when and where they formed. Examining stars individually, primarily within our galaxy, can test our understanding of galaxy formation processes in entirely unique ways. Nevertheless, making the Milky Way a Rosetta Stone of galaxy formation remains a challenge. In particular, it requires learning all we can about the individual and population properties of stars, from their spectra and the ongoing Gaia space mission.

From observations to simulations

To tackle these questions, the GC Department follows a three-pronged approach.

- We study galaxies in the present-day Universe, including our Milky Way, capitalizing on the level of detail afforded by observations in our direct cosmic neighborhood.

- We study galaxies at earlier cosmic epochs by directly observing very distant objects, corresponding to high cosmological redshifts (z). After all, conducting astronomical research 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, providing us with a glimpse into the distant past.
- We develop physical models and progressively improve both them and our understanding of galaxy formation by testing their outcome against observations. The simulations developed and analyzed at MPIA follow the co-evolution of dark matter, stars, cosmic gas, and supermassive black holes starting from initial conditions shortly after the Big Bang and require computing investments of tens to hundreds of millions of computing hours using thousands of computers.

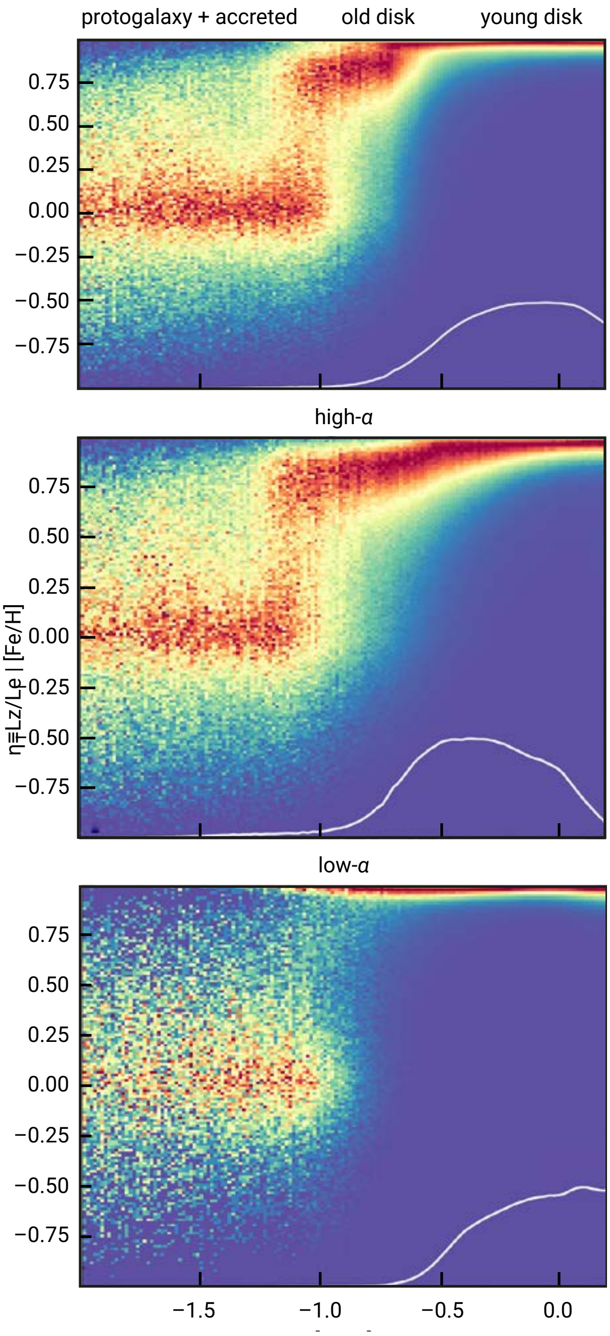
This strategy relies on a combination of different observational facilities, each serving a distinct purpose. We use wide-field survey telescopes to obtain large, statistically meaningful samples of cosmic objects. To investigate faint individual sources in detail, astronomers rely on the largest available telescopes with sufficient photon-collecting power. Finally, techniques such as adaptive optics and interferometry enable high spatial resolution, allowing researchers to reveal fine structural details.

Exciting progress in 2024

Progress in our field is driven primarily by increasingly accurate data and simulations. The most exciting data often comes from very large observatories, simulations, surveys, or space missions, which often take a decade or more to bring to fruition. Consequently, data sets that allow dramatic progress are few and far between. Yet, 2024 was another golden year for new data: we are learning how to conduct increasingly creative and ambitious observing programs with the James Webb Space Telescope, which reveals that galaxy formation at the earliest epochs was much more efficient than previously thought. It was the year in which the Euclid mission began its science mission, aiming to map a significant portion of the sky with nearly the same image quality as the Hubble telescope (see Figure 2). With Euclid, we are imaging more of the sky than Hubble did in its 30 years of operation. The Gaia mission continues to offer breakthroughs in stellar physics, with the discovery of the most massive stellar black hole yet.

Additionally, the SDSS-V survey, which MPIA co-initiated, has reached its full survey speed, becoming the first to map the entire sky with high-resolution spectroscopy (see also Figure 3). But all these new data need a cosmological context. However, 2024 again brought a new treasure: our cosmological simulation group released a new set of very large-scale simulations, known as TNG-Cluster simulations (Figure 1).

Fig. II.2.3: This Figure shows how the Gaia mission now allows us to grasp the whole formation history of our Milky Way in one view, as it allows us to map the orbits and the degree of nucleosynthetic pollution. This pollution, known as metallicity, indicates the number of generations of stars that have lived before the observed stars were born, thereby serving as a proxy for their age. In these plots, the color indicates the number of stars (red indicates a high number) with a given metallicity or age, and their proximity to simple circular orbits (vertical axis).



Credit: Vedant Chandra (2024)

II.3 RESEARCH OVERVIEW

Planet and Star Formation (PSF)
Directors: Prof. Dr. Thomas K. Henning and Dr. Myriam Benisty

The origin of stars and their planets

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

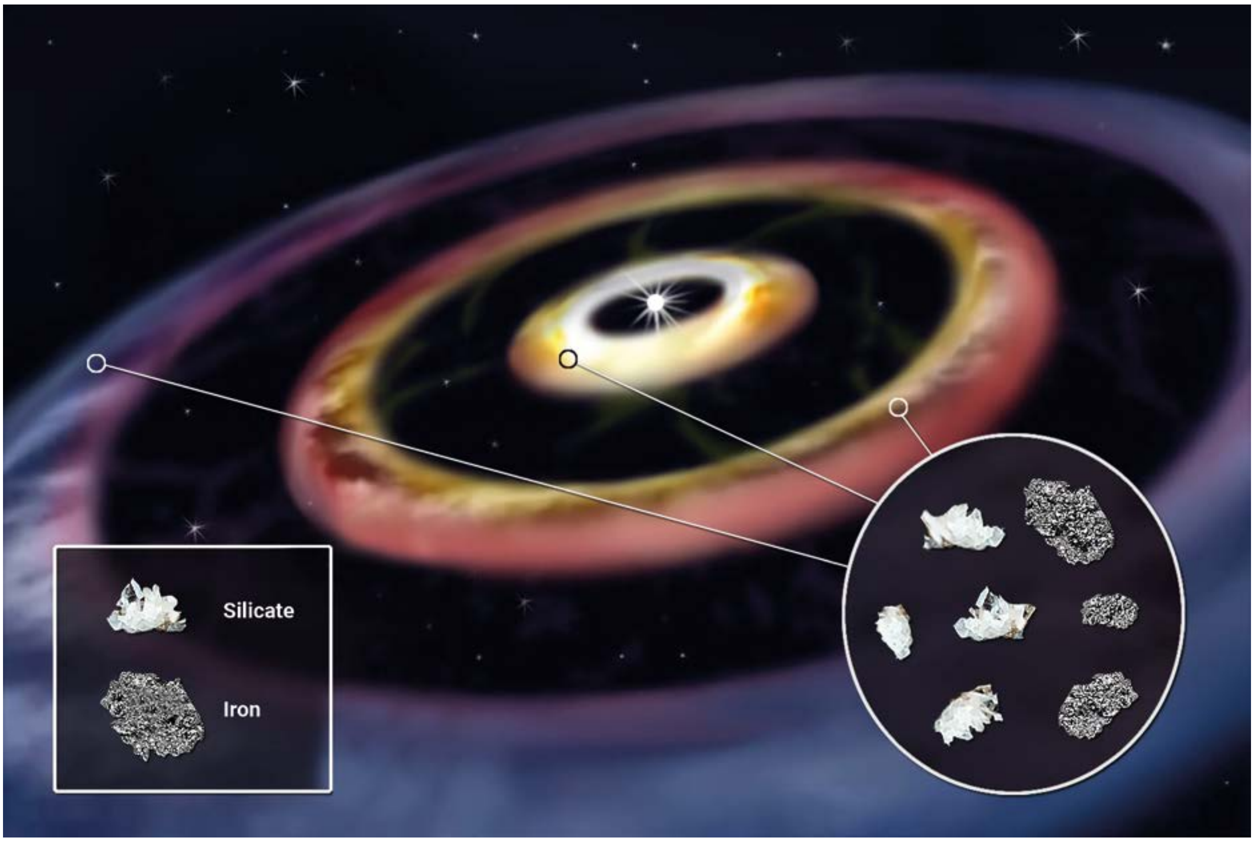
Stars are born in the densest and coldest parts of molecular clouds, with sizes ranging from Giant Molecular Clouds with masses up to a few million solar masses to tiny Bok globules with only a few solar masses. The dominant component of these clouds is molecular hydrogen, enriched with micron-sized dust particles and a large variety of other molecules, including complex organic species. The clouds often occur as filamentary structures, prone to fragmentation. With typical temperatures of about 10 Kelvin, these are the coldest structures in galaxies. As parts of these clouds collapse under their gravity, some compact regions within them 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 occurs in protoplanetary disks made of gas and dust, which surround 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 star and planet formation processes. In their quest for answers, they combine multi-wavelength observations with large-scale numerical simulations and custom-made 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

Fig. II.3.1: An artist's concept of the three-ringed structure in the planet-forming disk around HD 144432. Observations with the European Southern Observatory's (ESO) Very Large Telescope Interferometer (VLTI) found various silicate compounds and potentially iron, substances we also find in large amounts in the Solar System's rocky planets.



Credit: Jenry

wavelengths, from the optical to the infrared and radio domains, with a particular emphasis on high spatial and spectral resolution.

PSF researchers use a comprehensive set of telescopes and facilities for their work. In space, this includes the Hubble and James Webb Space Telescopes, while ground-based facilities include ESO's (European Southern Observatory) Very Large Telescope (VLT) and the Large Binocular Telescope (LBT) in Arizona. For observations at longer wavelengths, they turn to the IRAM (Institut de radioastronomie millimétrique) facilities, including the 30-meter Telescope and the NOrthern Extended Millimeter Array (NOEMA), as well as to the Atacama Large Millimeter/ Submillimeter Array (ALMA), and the Karl G. Jansky Very Large Array (VLA).

Scientists of the PSF Department are actively involved in open-time and guaranteed-time projects with the James Webb Space Telescope (JWST). Our data reveals a remarkable diversity of inner disk chemistry and powerful winds. After delivering all mechanisms for the coronagraph of the Roman Space Telescope, we are preparing the scientific exploitation. PSF scientists and engineers contribute significantly to the mid-infrared instrument METIS as part of the instrumentation program for ESO's Extremely Large Telescope (ELT), which is slated to commence science operations in 2029. METIS is now in the hardware phase, and the team is preparing the science program. Observations with present instrumentation and the coming new telescopes will 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 young 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 comparatively small throughout. 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 exceptionally high resolution. Or interferometry, which enables various 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.

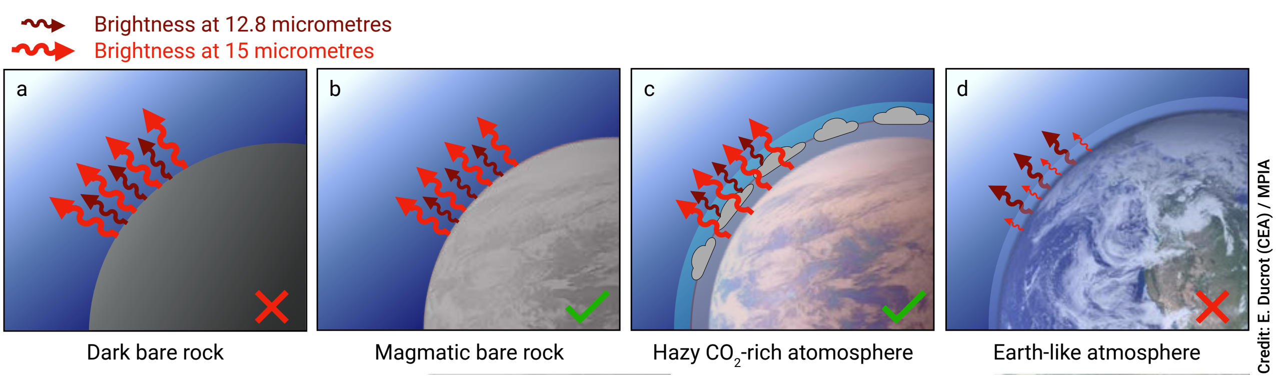
Understanding the origin of stars

One of the central questions of star formation aims to understand which cloud properties 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.

Individual collapsing cloud clumps will generally fragment to form binary stars or multiple systems. At the high end of the mass scale, massive stars form in clusters, making for exceedingly complex star formation environments and strong feedback processes, 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 build a stellar cluster? Do massive stars also use 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 questions under investigation by scientists of the PSF Department.

Fig. II.3.2: Representation of the infrared brightness emitted by Trappist-1 b at 12.8 and 15 micrometers for different scenarios involving bare rock and atmosphere. The four cases indicate which agree with the current data and which do not.



A peek behind the curtain

Enormous amounts of dust and gas obscure the earliest phases of star formation and can only be detected by sensitive far-infrared and (sub)millimeter observations. At later evolutionary stages, the objects emit radiation that 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 fundamental laws of fluid dynamics—notably 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 matter is ejected perpendicular to the disk via 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 disks all indicate a vigorous planet-forming process. Scientists of the PSF Department were the first to discover a young giant planet embedded in such a disk. In addition, we were able to demonstrate the impact of the exoplanet on its birth environment and discovered and characterized the first circumplanetary disk with ALMA observations.

Observing from the ground and space

One of the goals of the PSF Department is to understand the earliest development of stars, both at the low-mass end relevant to the formation of planetary systems and at higher masses, which is essential for galaxy evolution. The predominant tools for our research are space observatories such as Hubble and JWST, ground-based infrared, (sub)millimeter, and radio telescopes. The emerging results allow scientists of the PSF Department to detect and characterize star formation and study the subsequent evolution of young stars, covering the entire stellar mass range. To this end, scientists in this department have established large observing programs at internationally competitive astronomical facilities.

Presently, the department's work focuses heavily on conducting projects in star formation, protoplanetary disks, and exoplanets with the JWST, the designated successor of the Hubble Space Telescope. The JWST launched in December 2021. As a JWST mid-infrared instrument MIRI consortium member, we have direct access to guaranteed time for this instrument. We are leading and co-leading the large disk program, the protostellar program, and are heavily involved in exoplanet science. In addition, we succeeded in establishing several open-time programs.

In the fall of 2024, NASA selected the PRIMA (PRobe far-Infrared Mission for Astrophysics) project as one of two candidates for its new Probe Explorers mission class. PRIMA is designed as a space telescope that will observe in the far-infrared spectral range, allowing it to probe the mass budget and water content of protoplanetary disks. MPIA contributes opto-mechanical components, including control electronics, for the two scientific instruments. The conceptual design study phase, which will take about a year and a half, is now in progress.

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, astronomers managed to examine, compare, and contrast thousands of such systems instead of a single example of a planetary system—our Solar System.

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). With the Chilean-MPIA collaboration WINE, we are at the forefront of detecting and characterizing long-period giant planets from TESS and hunting for super-Earths. The project returned the highest number of detections of cold giant planets with the combination of transit and radial velocity techniques.

The CARMENES spectrograph at the Calar Alto Observatory is one of the most versatile instruments for the search for exoplanets around M-type stars. A multi-year survey is nearly complete to unravel the statistics of low-mass planets around these red stars. It has already returned a surge of exciting planet discoveries, including the discovery of rocky planets in their habitable zones. The collaboration continues to use CARMENES for TESS follow-up observations and exoplanet atmosphere spectroscopy.

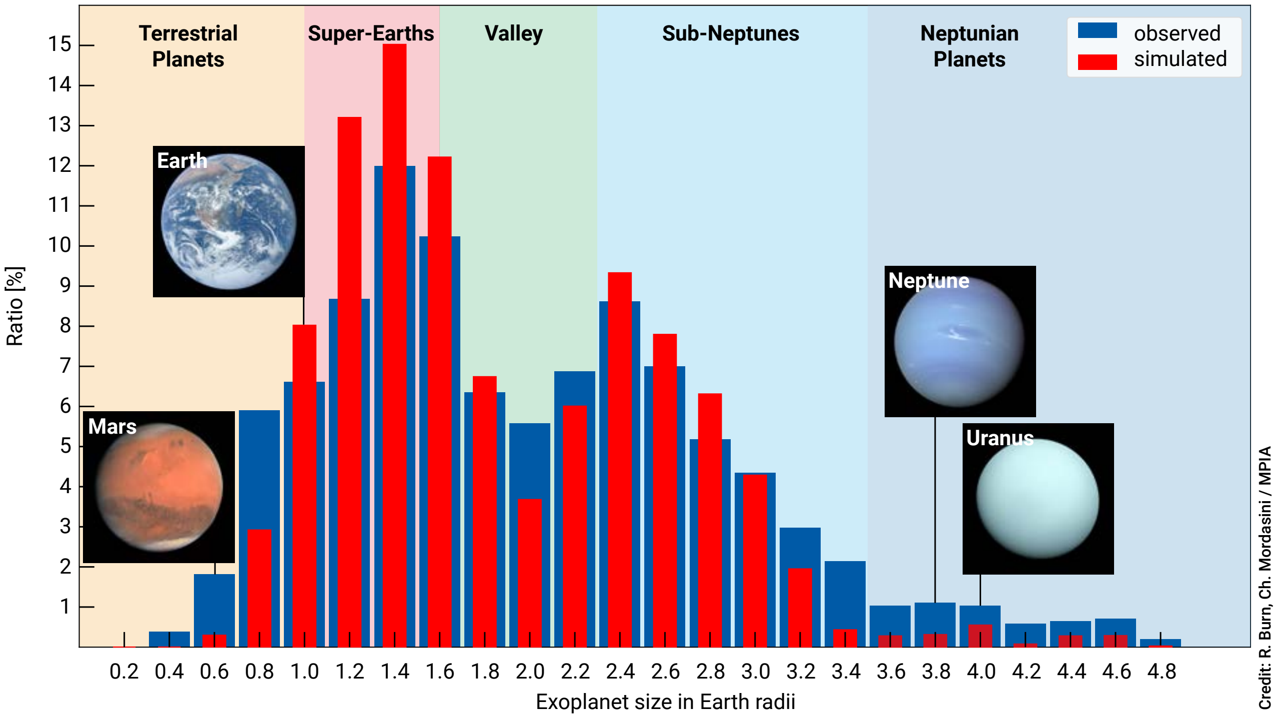
The consortium of the SPHERE planet finder instrument, in which MPIA is the Co-PI institute, conducted the largest direct imaging survey for exoplanets at a 10-meter class telescope. This investigation yielded the most stringent occurrence rates for giant planets at large orbits. In addition, this instrument reveals unprecedented details of planet-forming disks, from gaps and rings to spiral arms, which point to complex dynamics and planet-disk interactions. The "Second Earth Consortium," with MPIA as a member, commenced constructing a new instrument for the MPG 2.2-meter telescope at La Silla to search for Earth-like planets around Solar-type stars by measuring radial velocities with high precision.

Furthermore, two instruments for ESO's Very Large Telescope Interferometer (VLTI) that incorporate significant PSF Department contributions, namely GRAVITY and MATISSE, are delivering exciting results. GRAVITY has produced extraordinary scientific results in various fields, ranging from observations of the black hole in the Galactic Center to the spectroscopic characterization of exoplanets and planet-forming disks. MATISSE has detected a vortex-like structure in the inner regions of a disk and has revealed the structure of nearby AGNs. Both instruments allow us to study the cradles of planets—protoplanetary disks—and the accretion process with unprecedented spatial resolution, complementing our observations with the IRAM/NOEMA 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 emerges when astronomers connect observations to 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, 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 multidimensional radiative transfer codes that simulate how radiation travels through molecular clouds and their cores, protoplanetary disks, and the atmospheres of planets. These codes help interpret 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 will enable us to connect the conditions in planet-forming disks with the observed properties of planet populations. Another critical application is modeling planetary atmospheres, where these codes allow for computing transmission and emission spectra as telescopes would observe them on the ground or in space. High-resolution spectroscopy with CARMENES and measurements with the LBT supported the characterization of planetary atmospheres.

Fig. II.3.3: Size distribution of observed and simulated exoplanets with radii smaller than five Earth radii. The number of exoplanets decreases between 1.6 and 2.2, producing a pronounced valley in the distribution. Instead, more planets are present with sizes around 1.4 and 2.4 Earth radii. The latest simulations, which take realistic properties of water into account for the first time, indicate that icy planets that migrate into the interior of planetary systems form thick atmospheres of water vapor. It makes them appear larger than they would be at their place of origin. These produce the peak at around 2.4 Earth radii. At the same time, smaller rocky planets lose part of their original gas envelope over time, causing their measured radius to shrink and thus contributing to the accumulation at around 1.4 Earth radii.



We are conducting a versatile program to link planet formation with the properties of planets and their atmospheres. Our scientists develop radiative transfer codes, non-equilibrium chemistry models, cloud description, and retrieval techniques to reconstruct planet formation processes. The JWST/MIRI GTO program returns excellent science in the fields of protostars, protoplanetary disks, and exoplanets.

In addition, we have studied the formation of key prebiotic molecules such as HCN under early Earth conditions and have revealed how complex organic molecules form on asteroids.

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. The same holds for interpreting observational signatures in the spectra of these objects, which, in turn, can only be achieved by dedicated laboratory studies.

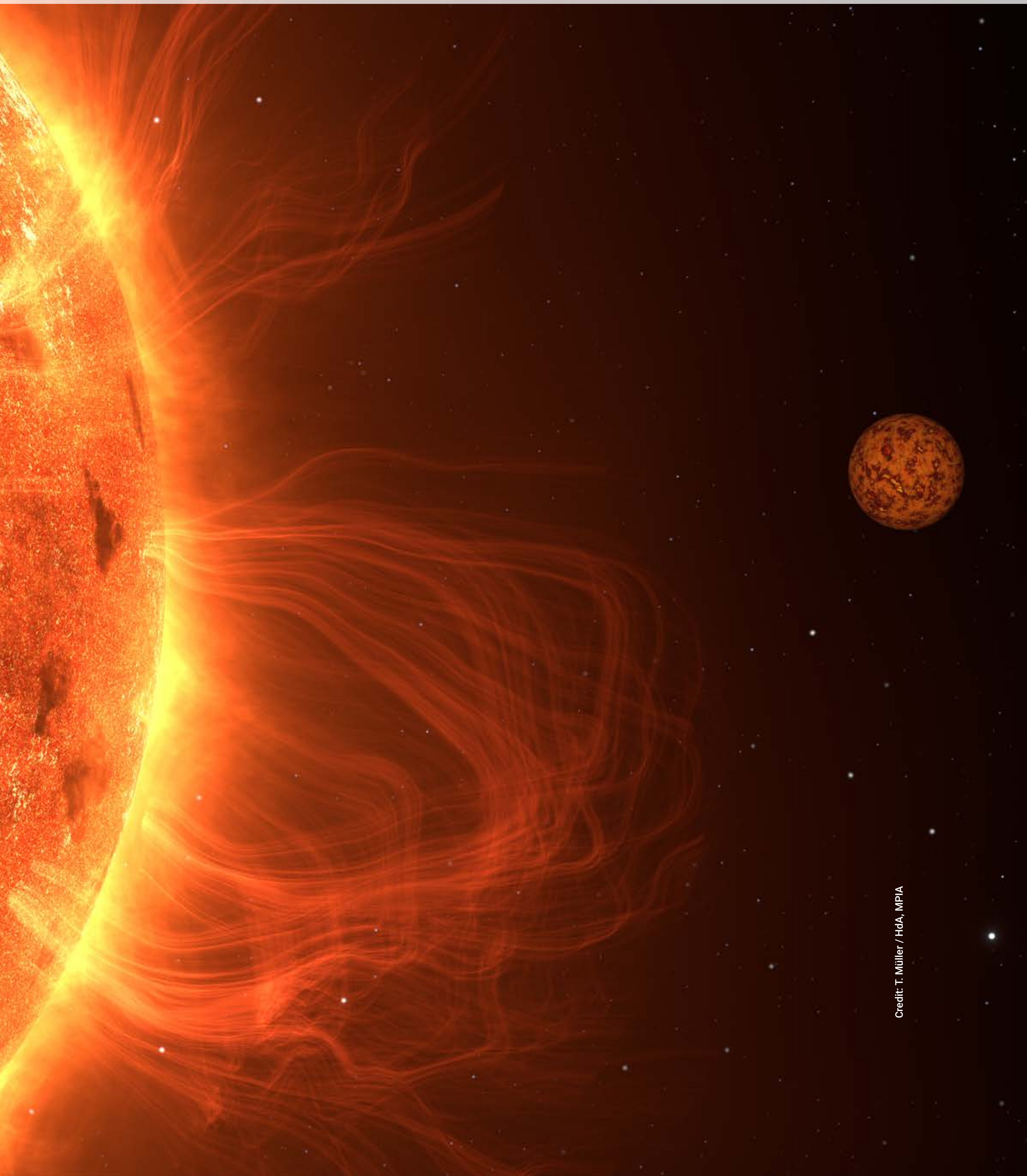
Such an astrophysics laboratory facility is part of the PSF Department based at the Institute for Solid-State Physics at the University of Jena. The Laboratory Astrophysics and Cluster Physics Group investigates the spectroscopic properties of nano- and micron-sized solid particles, as well as of complex 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. The group recently demonstrated that simple peptides can form under the conditions of the interstellar medium.

Linking the production of organic molecules with the origins of life is the aim of another collaboration: the Heidelberg Initiative for the Origins of Life (HIFOL), which the PSF Department established jointly with other scientific institutes in Heidelberg. This initiative aims to understand the fundamental physical, chemical, and biological processes involved in the origins of life and to connect them with the astrophysical conditions essential for its emergence. As part of this initiative, MPIA has established new Origins of Life laboratories to investigate the formation of prebiotic molecules under conditions typically found on comets and the parent bodies of meteorites. The experimental work detected a low-temperature phase transition of CO ice, potentially triggering complex organic chemistry.

A new director for the Planet & Star Formation Department

On September 1st, 2024, Myriam Benisty joined the MPIA as the new director for the PSF department, as Thomas Henning continued to lead a scientific emeritus group. Similar scientific interests ensure continuity in the MPIA research focus and departmental structure. Since 2022, Myriam Benisty has also led an ERC-funded project, PROTOPLANETS, that focuses on searching for embedded young planets and understanding their impact on their host environment. This ERC project fits perfectly in the PSF Department as it addresses key scientific objectives.

III. SCIENCE HIGHLIGHTS



Credit: T. Müller / HdA, MPIA

III.1 SCIENCE HIGHLIGHT

Hubble Finds Water Vapor in a Small Exoplanet's Atmosphere

Astronomers are intrigued when they find evidence of water vapor on exoplanets. Based on observations with the Hubble Space Telescope, a recent example is the planet GJ 9827d, which may have a water-rich atmosphere around it. Water is one of the most common molecules in the Universe, and all life on Earth requires it. It is a superior solvent and enables critical chemical reactions in biological cells. No bigger than twice Earth's diameter, GJ 9827d could be an example of potential water-rich worlds elsewhere in our galaxy. But don't plan on buying real estate there. The planet is as hot as Venus, which makes it a steamy world.

A team of astronomers, including MPIA's Laura Kreidberg and Thomas Evans-Soma, has identified water vapor in the atmosphere of the exoplanet GJ 9827d using the Hubble Space Telescope. Located 97 light-years away in the Pisces constellation, it is the smallest exoplanet with a confirmed atmospheric water signature. The detection marks a significant milestone in the search for habitable environments beyond the Solar System, as it demonstrates that even relatively small planets, perhaps even those mainly made of rock, can retain complex atmospheres containing water.

Water world or hydrogen-rich mini-Neptune?

Whether GJ 9827d hosts a puffy, hydrogen-rich atmosphere laced with traces of water, or whether its atmosphere consists predominantly of water vapor left over from a lost hydrogen-helium envelope, remains an open question. The observing campaign, which was specifically tailored to identify water vapor, supports both possibilities. In either case, the detection alone is a significant scientific achievement. The planet's advanced age—estimated at six billion years—and its close orbit around its host star suggest it has likely lost most of its primordial hydrogen through intense stellar radiation. Spectroscopic data so far have not revealed any hydrogen signatures, supporting the idea of a water-dominated atmosphere. GJ 9827d may occupy a transitional regime where small planets lose their lightweight gases and develop heavier, secondary atmospheres. Such transitions could yield planets more similar to Venus, which is dominated by carbon dioxide.

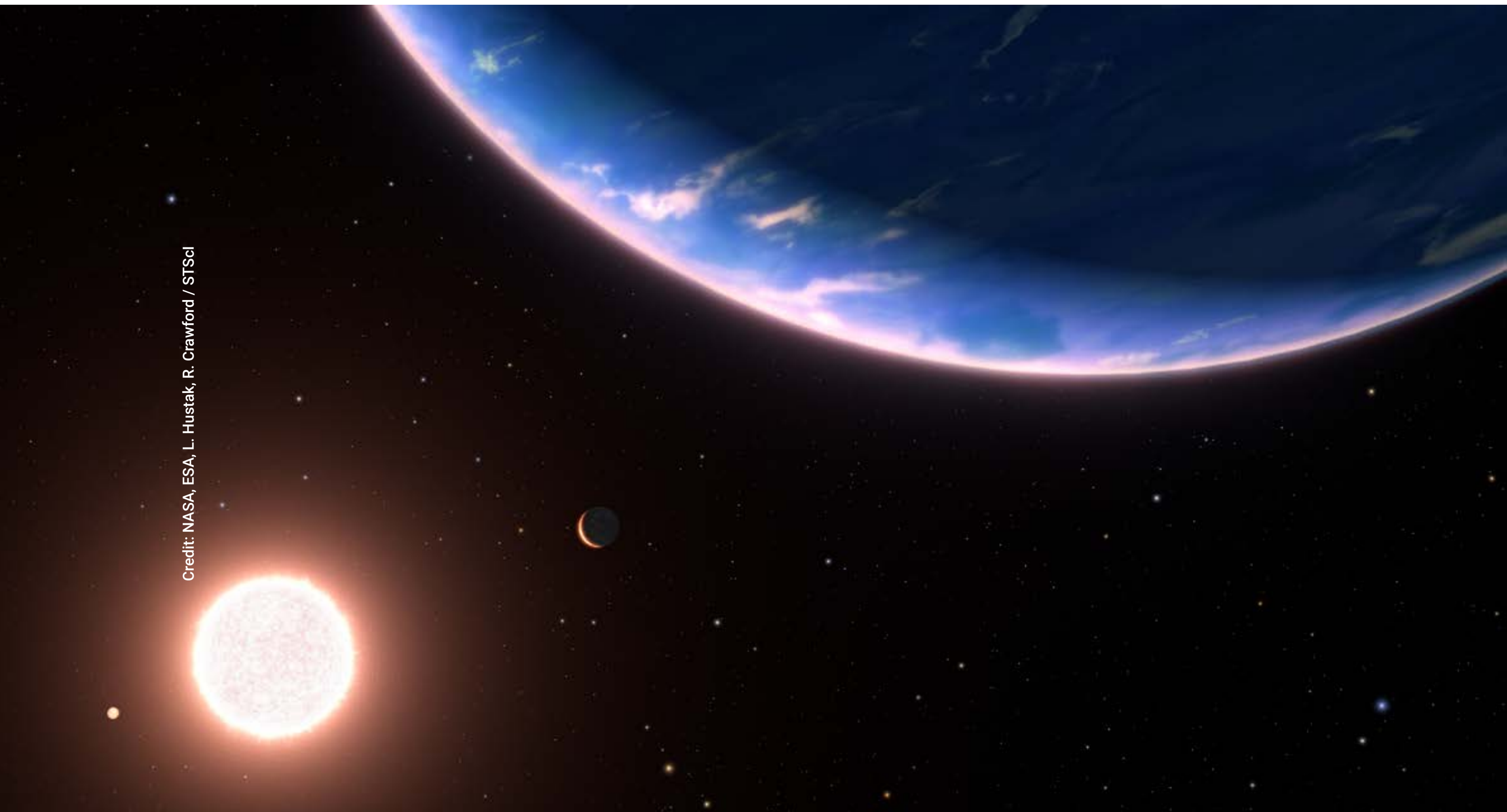


Fig. III.1.1: This illustration shows GJ 9827d, the smallest known exoplanet with a definitive detection of water vapor in its atmosphere. Orbiting the red dwarf star GJ 9827, the planet is about twice the size of Earth and may represent a class of water-rich worlds elsewhere in the galaxy. Two inner companion planets appear to the left. The background stars are shown as they would appear to the naked eye from GJ 9827's location, though the Sun is too faint to be visible. Notable stars include Regulus ***(top right)***, Denebola ***(center bottom)***, and Spica ***(bottom right)***. The constellations Leo ***(left)*** and Virgo ***(right)*** are recognizable, though slightly distorted from this vantage point, 97 light-years away.

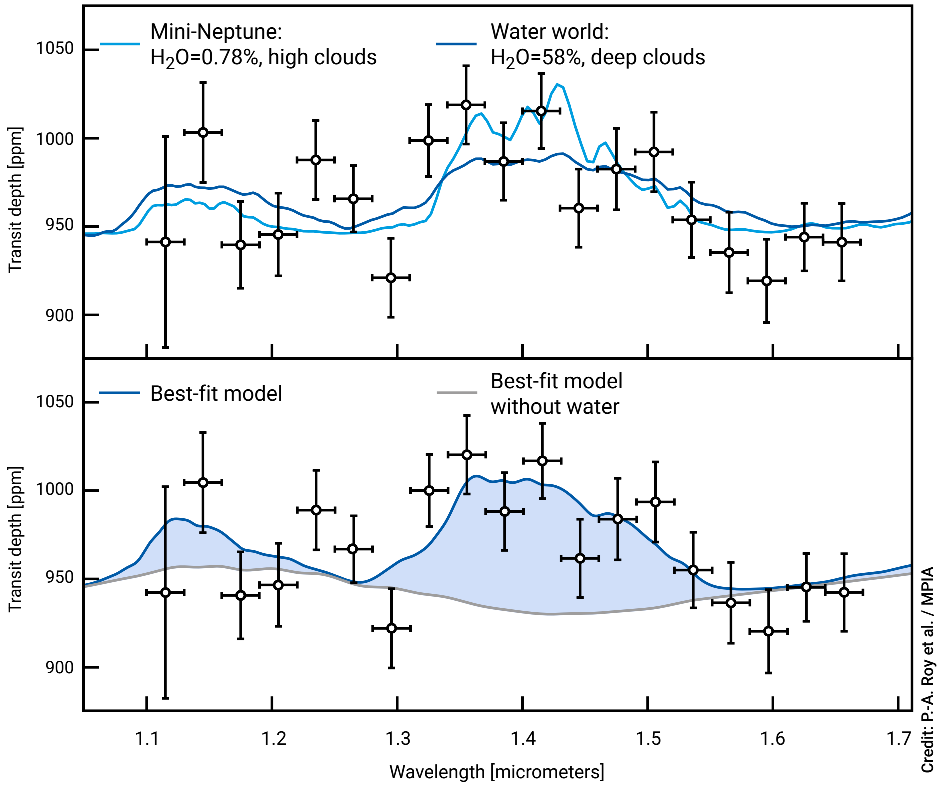


Fig. III.1.2: This figure shows how the atmosphere of the exoplanet GJ 9827d filters starlight during a transit, based on observations from the Hubble Space Telescope ***(black points)***. The colored lines represent different computer models of what the planet's atmosphere might be made of. In the top panel, two possible types of atmospheres are shown: one with mostly hydrogen and helium plus a small amount of water vapor ***(light blue)***, and another that is rich in water vapor ***(dark blue)***. In the bottom panel, we show the best-fitting model ***(light blue)*** and how it would look without any water vapor ***(gray)***, which helps show how much water contributes to the signal ***(blue shading)***. Features in the spectrum near 1.2 and 1.65 micrometers suggest that water vapor is likely present in the planet's atmosphere. The vertical axis shows how much starlight is blocked at each wavelength during the transit.

Formation history written in vapor

If GJ 9827d possesses a residual water-rich atmosphere, it may have formed farther out in its planetary system, where water could exist as ice. Over time, the planet could have migrated closer to its star, where the ice sublimated and the water was retained as vapor, while the lighter hydrogen gradually escaped into space. Another possibility is that the planet formed in its current position and contains only traces of water, remnants from its initial formation conditions. Surface temperatures on GJ 9827d are around 400 degrees Celsius, making it a hostile environment by terrestrial standards. Still, the presence of water vapor opens the door to studying such planets in greater detail. It could be a small Neptune-like world with a thin water presence, or perhaps a steamy version of Europa, with a composition roughly split between rock and water.

A target for the next generation of telescopes

The Hubble observations spanned 11 transits over three years, allowing researchers to detect the telltale spectral signature of water molecules as starlight filtered through the planet's atmosphere. Fortunately, any clouds present appear to sit low enough not to obscure the water vapor in the upper layers. This discovery lays the groundwork for follow-up studies. GJ 9827d has already been observed with the James Webb Space Telescope to probe the atmosphere more deeply. These new data may help answer a central question in exoplanetary science: Do true water worlds exist, and if so, how common are they?

Laura Kreidberg (Co-principal investigator) and Thomas M. Evans-Soma (also University of Newcastle, Australia)

in collaboration with

Pierre-Alexis Roy, Björn Benneke, Caroline Piaulet (all Université de Montréal, Montreal, Canada), and Ian J. M. Crossfield (Principal investigator, University of Kansas, Lawrence, USA)

Pierre-Alexis Roy et al., "Water Absorption in the Transmission Spectrum of the Water World Candidate GJ 9827 d" in The Astrophysical Journal Letters, Vol. 954, L52 (2023). DOI: 10.3847/2041- 8213/acebf0

III.2 SCIENCE HIGHLIGHT

Clouds Blanket the Night Side of the Hot Exoplanet WASP-43b

Using the James Webb Space Telescope (JWST), a team of astronomers, including scientists from MPIA, constructed a global temperature map of the hot, gas giant exoplanet WASP-43b. The nearby parent star perpetually illuminates one hemisphere, raising temperatures to a blistering 1250 degrees Celsius. Meanwhile, eternal night shrouds the opposite side. Violent winds transport the searing hot air to the nightside, where it cools to 600 degrees, allowing clouds to form and blanket the entire hemisphere. These tempests impair chemical reactions so much that methane can barely form, even though it should be abundant under calmer conditions.

Hot Jupiters are extreme gas giant exoplanets that circle their host stars in close orbits, leading to several exotic properties regarding temperature, density, composition, chemistry, and weather. With the advent of groundbreakingly sensitive telescopes, such as the James Webb Space Telescope (JWST), astronomers have begun to study their atmospheres in great detail.

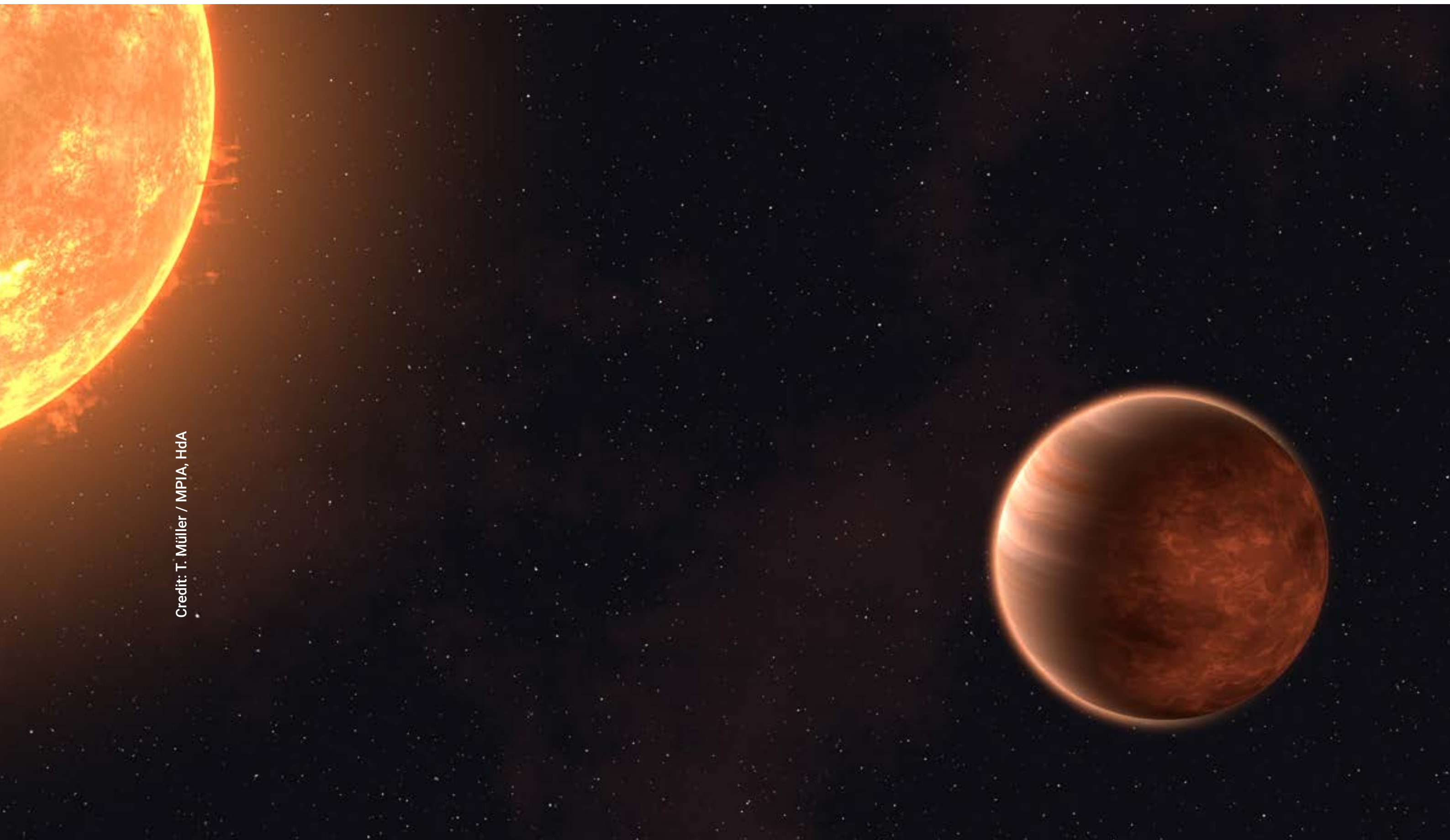
An international collaboration of astronomers, the JWST Transiting Exoplanet Early Release Science (JTEC-ERS) team, observed the hot Jupiter WASP-43b with JWST's Mid-Infrared Instrument (MIRI) to study its climate.

An extreme world unlike anything in the Solar System

The central outcome is a map outlining the global temperature distribution derived from the infrared light WASP-43b emits in response to the irradiation by its host star. By covering a spectral range sensitive to warm materials, MIRI works similarly to a non-contact thermometer used to measure body temperatures across large distances, amounting to 280 light-years for WASP-43b. In this map, the measured temperatures are between 600 and 1250 degrees Celsius. In contrast, using comparable observations, Jupiter, the gas giant in the Solar System, attains frosty -135 degrees.

Although similar in size and mass to Jupiter, it is a very different world. WASP-43b maintains an exceptionally tight orbit around its host star, WASP-43, travelling only two stellar diameters above the star's surface while

Fig. III.2.1: An artist's impression of the hot Jupiter WASP-43b closely orbiting its parent star. The planet's tight orbit resulted in its rotation period becoming synchronized with the orbital period, both amounting to 19.5 hours. As a result, WASP-43b always faces the star with the same side, permanently engulfed in daylight, with temperatures reaching 1250 degrees Celsius. The nightside pointing away from the star is covered by clouds of condensed mineral droplets at temperatures around 600 degrees.



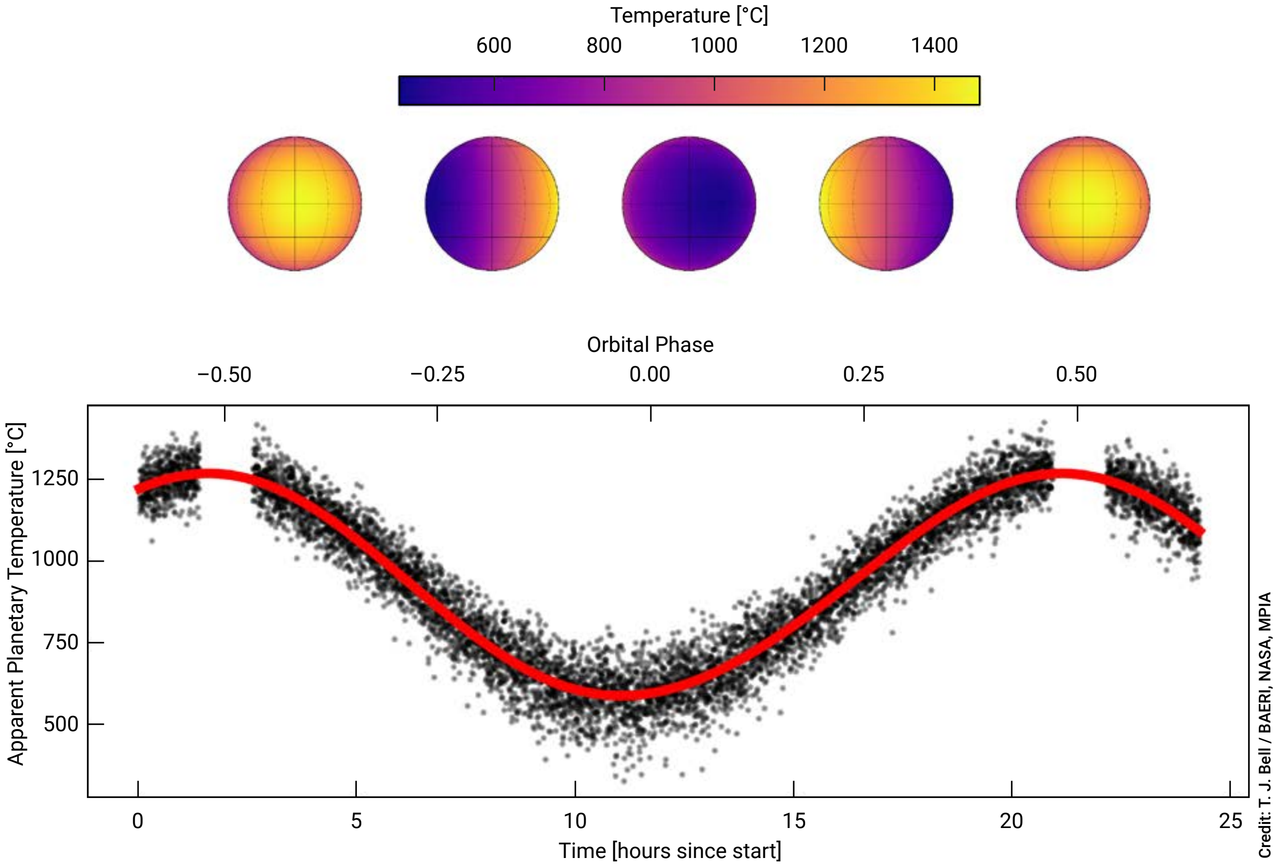


Fig. III.2.2: Using the James Webb Space Telescope (JWST), the JTEC-ERS team observed the WASP-43 system continuously for 27 hours to observe the entire orbit of the hot, Jupiter-sized exoplanet WASP-43b. As the planet orbits its host star, different faces of the planet are pointed towards the telescope (shown in the top panel). As a result, the astronomers measured different temperatures depending on the proportions of the hot dayside and the cold nightside that faced the observer. Using JWST's MIRI instrument, the team measured the temperature across the planet's surface by applying the phase curve observing method, with MIRI working like a gigantic contactless infrared thermometer. Because the planet orbits so closely to its host star, its dayside is a scorching 1250 degrees Celsius, and violent winds transport some of that heat to the relatively cool nightside, which is still a fiery 600 degrees.

completing its orbit in just 19.5 hours. The slight separation resulted in the day and year of the planet becoming synchronized. In other words, revolving around the star takes just so long as the planet needs to rotate around its axis. Consequently, the star always illuminates and heats the same side of the planet.

Winds carry the hot air to the opposite hemisphere, where it cools in eternal night. However, on WASP-43b, these winds are incredibly violent, with wind speeds reaching nearly 9000 kph, which is beyond anything we witness in the Solar System. In comparison, even Jupiter's strongest winds are but a mild breeze.

Water vapour, liquid-rock clouds, and a surprising lack of methane

Previous observations with the Hubble and Spitzer Space Telescopes have already identified water vapor on the dayside and have hinted at clouds on the nightside. However, to map the temperature, cloud cover, winds, and atmospheric composition in more detail across the planet, the team needed precision measurements that only JWST provides.

The JWST observations found the temperature contrast between the dayside and nightside to be stronger than expected for a cloud-free atmosphere. Model computations confirm that the planet's nightside is shrouded in a thick layer of clouds high up in the atmosphere, which blocks much of the infrared radiation from below the telescope would otherwise see. The exact type of clouds is still unknown. Clearly, they will not be water clouds like those on Earth, let alone ammonia clouds we see on Jupiter, as the planet is far too hot for water and ammonia to condense. Instead, clouds made of rocks and minerals are more likely to be present at these temperatures. Hence, we should expect clouds made of liquid rock droplets. In contrast, the hotter dayside of WASP-43b appears to be cloud-free.

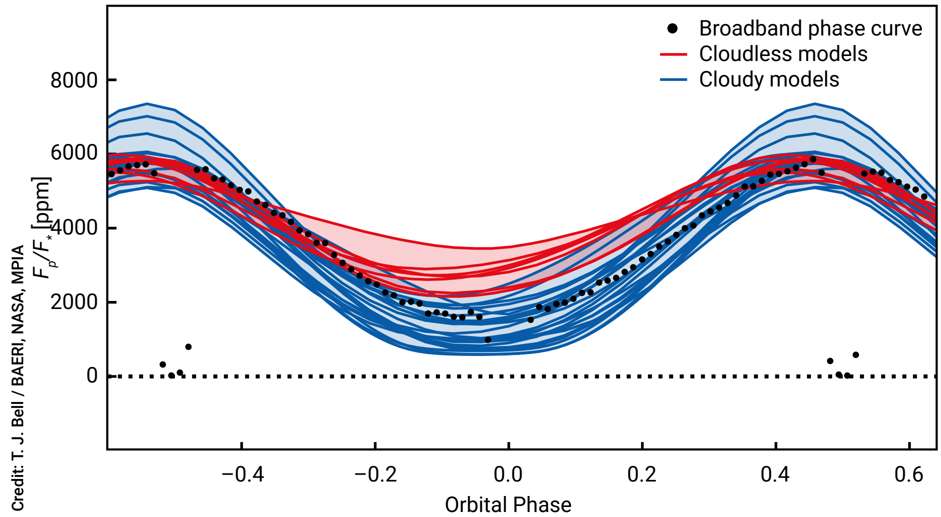


Fig. III.2.3: The phase curve of the hot Jupiter WASP-43b obtained with MIRI on board JWST displays the infrared brightness measured relative to the host star in parts per million (ppm) during an orbit. The orbital phase 0 is when the planet passes before the star and presents its nightside. Orbital phases -0.5 and 0.5 correspond to the configuration when the planet passes behind the star, and only the stellar signal remains. The planet's dayside is visible immediately before and after being covered by the star. The black points show the temporally binned data observed between five and 10.5 micrometers. The solid lines represent modelled phase curves derived from 31 model simulations separated into two groups based on the inclusion of clouds. The cloudless models (red lines) simulated completely cloud-free skies, whereas the cloudy models (blue lines) included at least some clouds on the nightside of the planet. The red and blue shaded areas span the range of all the cloudless and cloudy simulations, respectively, with the spread of values owing to differences in the various model assumptions and parameterizations. The cloudy models match the observed phase curve on the night side, while cloud-free models best represent the dayside.

To probe the atmospheric composition in more detail, the team produced spectra, i.e., they decomposed the received infrared light into tiny wavelength sections, similar to a rainbow that reveals the sunlight's color components. This method allowed them to identify the signatures of individual chemical compounds that radiate at specific wavelengths. As a result, the astronomers confirmed earlier water vapor measurements, but now over the entire planet. Hubble could only study the dayside, as the nightside was too dark to recognize molecules there. JWST, with its higher sensitivity, now completes the picture.

In addition, hot Jupiters typically host large amounts of molecular hydrogen and carbon monoxide, which could not be probed with the team's observations. However, when subjected to the cooler nightside, hydrogen and carbon monoxide participate in a set of reactions that would produce methane and water. However, JWST's MIRI didn't find any methane. The astronomers explain this surprise with the enormous wind speeds on WASP-43b. The reaction partners pass the cooler nightside so quickly that there is little time left for the expected chemical reactions to produce detectable amounts of methane. Any small fraction of methane becomes thoroughly mixed with the other gases. It quickly reaches the dayside again, where it is exposed to the destructive heat.

In summary, after a decade of observing attempts, JWST's unmatched ability to unveil the composition of planets like WASP-43b now allows astronomers to draw a picture of a complex, inhospitable world. With furious winds, massive temperature changes, and patchy clouds likely made of rock droplets, this planet presents itself as an uninviting place. WASP-43b is a reminder of the vast range of climates that may exist on exoplanets and the many ways in which Earth is special.

Observing a planetary carousel

WASP-43b was discovered in 2011 via the transit method. Whenever an exoplanet's orbit is oriented so that, from our perspective, it passes in front of its host star, the occultation blocks a small portion of the starlight. These periodic drops in stellar brightness are a tell-tale sign of an object revolving around the star. The exact shape permits computing the planet's size and orbital tilt.

Astronomers exploit a secondary effect to study the planet in detail. Consider Venus changing its illumination, resembling lunar phases, during its orbit around the Sun. Transiting exoplanets present varying phases of infrared emission in much the same way, depending on how the star heats the dayside. Observing the gradual change of proportions visible from the hot and cool hemispheres results in a characteristic pattern of how the planet's measured infrared brightness varies in time. Analyzing this minute signal, the so-called phase curve, the astronomers received from WASP-43b allowed them to construct a temperature map and localize the gases that make up the planet's atmosphere.

The future is infrared-bright

A follow-up study conducted by another team will look at WASP-43b with JWST's Near-Infrared Spectrometer (NIRSpec). These measurements will be sensitive to carbon monoxide gas, which should be prevalent throughout the atmosphere. In addition, the expanded wavelength coverage will improve the fidelity of the temperature map constructed from the MIRI data and help more precisely investigate the cloud distribution and composition.

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Sebastian Zieba (now at Center for Astrophysics,
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Patricio E. Cubillos (INAF – Osservatorio Astrofisico di Torino, Italy and Space Research Institute, Austrian Academy of Sciences, Graz, Austria)

Taylor J. Bell, Nicolas Crouzet, Patricio E. Cubillos, Laura Kreidberg et al., "Nightside clouds and disequilibrium chemistry on the hot Jupiter WASP-43b" in Nature Astronomy, Vol. 8, 824 (2024). DOI: 10.1038/s41550-024-02230-x

III.3 SCIENCE HIGHLIGHT

Webb Finds Differences between the Eternal Morning and Evening Skies on a Distant World

Researchers, including astronomers from the Max Planck Institute for Astronomy (MPIA), have finally confirmed what models have previously predicted: that an exoplanet has variations between its morning and evening atmosphere, exhibiting different temperatures and cloud coverages. The results follow from infrared observations of the giant gas planet WASP-39b using the James Webb Space Telescope (JWST). The planet is tidally locked to its parent star, leading to a constant dayside and nightside. One hemisphere of the planet is constantly exposed to its star, while the other is shrouded in darkness.

Using JWST's NIRSpec (Near-Infrared Spectrograph), astronomers confirmed a temperature difference between the morning and evening, with the evening appearing hotter by roughly 200 degrees Celsius. They also found clues that the morning could be cloudier than the evening. The results help understand the climates of exoplanets.

The variation of the signals the telescope received from both regions is minute. Resolving this slight difference is only possible due to JWST's and NIRSpec's sensitivity across near-infrared wavelengths and the instrument's extremely stable sensors. Any tiny movement in the instrument or with the observatory while collecting data would have severely compromised the measurement.

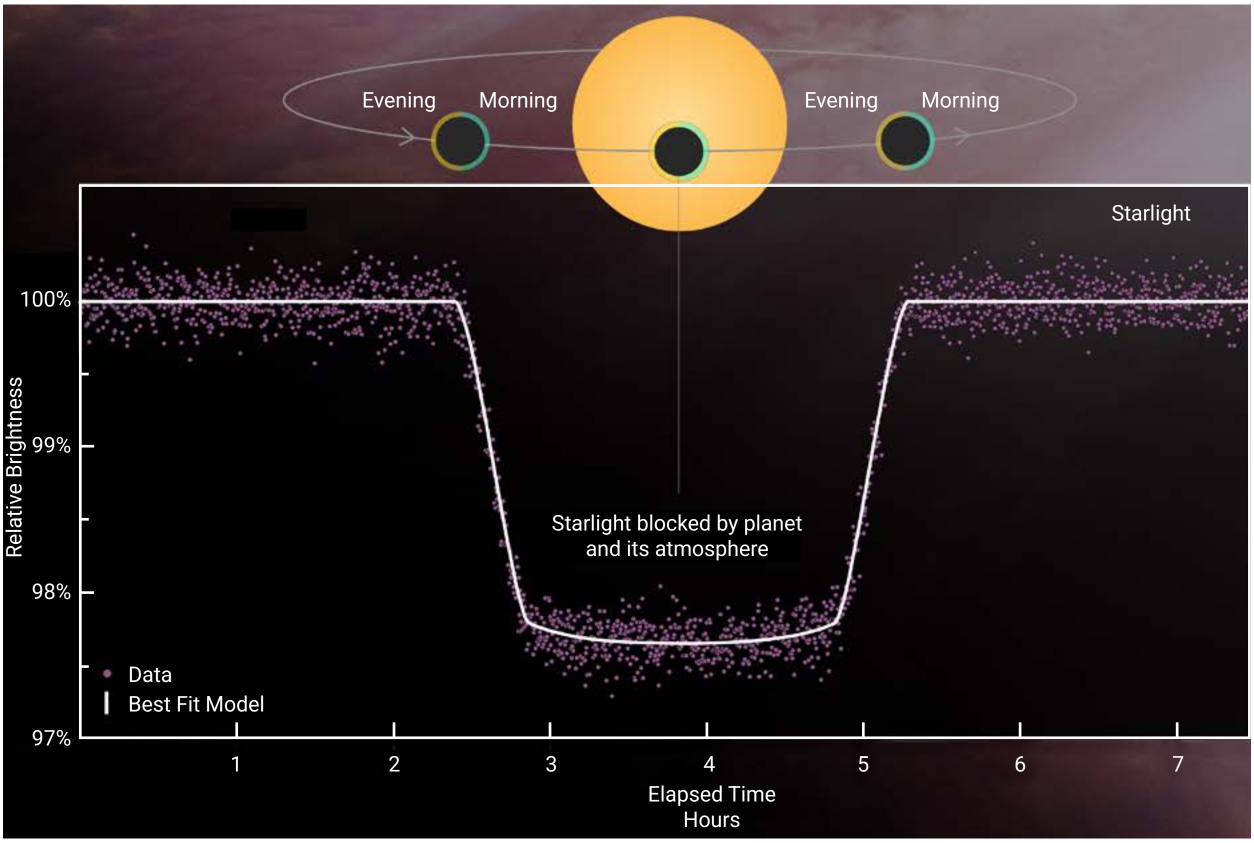
There have been similar attempts to observe morning and evening terminators with ground-based telescopes, but interference from the Earth's atmosphere invalidates most of the spectral information.

Earlier results couldn't distinguish morning from evening

Previously published data of WASP-39b's atmosphere obtained with the JWST revealed the presence of carbon dioxide, sulfur dioxide, water vapor, and sodium across the entire day-to-night boundary. There was no detailed attempt to differentiate between one side and the other. The ability to detect such rich chemistry was already ground-breaking in its own right.

These conclusions were based on analyzing what astronomers call a transition spectrum. Whenever an exoplanet's orbit is oriented so that, from our perspective, it passes in front of its host star, the occultation blocks a small portion of the starlight. At the same time,

Fig. III.3.1: This artist's concept shows what the exoplanet WASP-39b could look like based on indirect transit observations from JWST and other space- and ground-based telescopes. Data collected by its NIRSpec (Near-Infrared Spectrograph) shows variations between the morning and evening atmosphere of the planet.



Credit: NASA, ESA, CSA, R. Crawford (STScI)

Fig. III.3.2: A light curve from JWST's NIRSpec (Near-Infrared Spectrograph) shows the star's brightness change over time as the planet WASP-39b transits the star. This observation measured the brightness at range of wavelengths of light at set time intervals that capture the planet's atmospheric morning and evening limbs.

starlight shining through the atmospheric limb changes its spectral composition. The gaseous components filter out specific colors that are missing in the light entering the telescope. Spectrographs decompose this light into tiny wavelength sections, generating a spectrum that contains the gaps the atmosphere causes.

Therefore, such observations are particularly sensitive to the conditions along the terminators—the boundary that separates the daysides and nightsides—of tidally locked planets such as WASP-39b. When analyzing WASP-39b in this way, researchers obtained information about the temperature, composition, and other properties of the planet's atmosphere. Furthermore, WASP-39b's inflated, puffy atmosphere helps the starlight interact efficiently with atoms and molecules, producing a strong filtered signal.

New analysis finds slight differences between morning and evening skies

The analysis of the new data takes the next step. It yields two different spectra from the terminator region, essentially splitting the day-to-night boundary into two semicircles, one from the evening and the other from the morning. Data reveals the evening as significantly hotter, a searing 800 degrees Celsius, than the morning, boiling at a relatively cooler 600 degrees Celsius.

Extensive data modelling also allows researchers to investigate the structure of WASP-39b's atmosphere and its cloud cover, and provides hints as to why the evening is hotter. While future work will explore how the cloud cover may affect the temperature and vice versa, astronomers confirmed gas circulation around the planet as the main culprit of the temperature difference on WASP-39b.

Strong winds can explain the variations

On a highly irradiated exoplanet like WASP-39b that orbits relatively close to its star, researchers generally expect the gas to be moving as the planet rotates around its star: hotter gas from the dayside should move through the evening to the nightside via a powerful equatorial jet stream. Since the temperature difference is so extreme, the air pressure difference would also be significant, which in turn would cause high wind speeds.

Using General Circulation Models, three-dimensional computational models similar to the ones used to predict weather patterns on Earth, researchers indeed found that on WASP-39b, the prevailing winds are moving from the nightside across the morning terminator, around the dayside, across the evening terminator, and then around the nightside again. More precisely, MPIA's Maria Steinrück calculated wind speeds exceeding 10,000 kph, four times faster than those on Neptune, the windiest planet in our Solar System. These violent winds circulate hot air from the dayside to the nightside and blow clouds from the nightside to the dayside.

This new analysis also revealed unprecedented 3D information on the planet's geometry. The hotter evening edge must be a little puffier. There should be a slight swell at the terminator approaching the planet's nightside.

Maria Steinrück (now University of Chicago, USA), Laura Kreidberg, Duncan Christie, Eva-Maria Ahrer, and David Hägele (also Heidelberg University, Germany)

in collaboration with

Néstor Espinoza (Space Telescope Science Institute and Johns Hopkins University, Baltimore, USA), Ryan MacDonald (University of Michigan, Ann Arbor, USA), James Kirk (Imperial College London, London and University of Warwick, Coventry, UK), as well as Arjun Savel, Kenneth Arnold, and Eliza Kempton (all University of Maryland, College Park, USA)

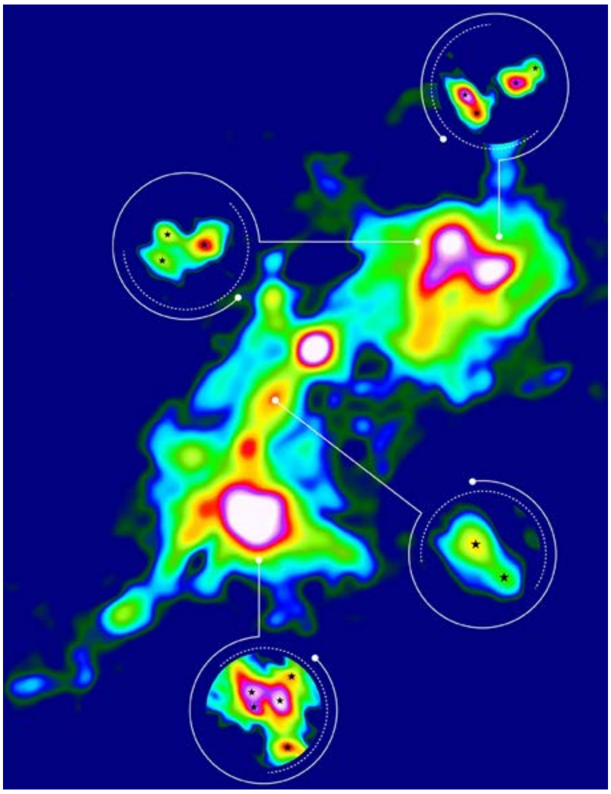
Néstor Espinoza, Maria E. Steinrueck, et al., "Inhomogeneous terminators on the exoplanet WASP-39 b" in Nature, Vol. 632, 1017 (2024). DOI: 10.1038/s41586-024-07768-4

III.4 SCIENCE HIGHLIGHT

Twins, Triplets, Quadruplets, and More: Observations Show Massive Stars Are Indeed Born as Multiples

Massive stars have long been thought to be born as twins, triplets, or higher multiples. But so far, there was little observational evidence confirming the multiplicity of massive star births. This has changed with the observations presented here: a detailed study using the ALMA radio observatory that found four binary protostars, one triple, one quadruple, and one quintuple system in one massive star cluster. The new results confirm our current understanding of the formation of massive stars: such stars are indeed born as multiples.

In human newborns, multiples are rare. Typically, less than 2% of all births involve multiples, mostly twins. On the other hand, multiple birth has long been thought to be the norm for massive stars. That was shown by simulations which traced the collapse of giant clouds of gas and dust from the beginnings to the formation of separate stars within: a hierarchical process in which larger cloud portions contract to form denser cores, and where smaller regions within those "parent cores" collapse to form the separate stars: massive stars, but also numerous less massive stars. In fact, our Sun formed as a low-mass proto-star in such a massive star cluster.



Credit: S. Li / MPIA, Data: ALMA Observatory

Massive stars, which have more than about eight times the mass of our Sun, are of particular interest to astronomers: These are the stars that form neutron stars and black holes, including the black holes that merge and emit copious amounts of gravitational waves. Also, massive stars are very bright, up to a million times as bright as our Sun, so we see these stars in other galaxies.

Until now, although there was a good theoretical understanding of star formation under those circumstances, key evidence was missing: It is very difficult to observe star formation regions in sufficient detail. Observations had, up to that point, been able to show only a few candidates for isolated multiples in massive star clusters, but nothing like the teeming crowd of multiples predicted by the simulations.

Pointing ALMA at a massive star cluster

In order to confirm or rule out the current models of massive star formation, it was clear that more detailed observations were needed. This became possible once the ALMA observatory in Chile became operational. In its present form, ALMA combines up to 66 radio antennae to act as a single gigantic radio telescope, allowing radio observations that show exquisitely small details. Led by Patricio Sanhueza of the Japanese National Observatory (NAOJ) and the Graduate University for Advanced Studies in Tokyo, and including several researchers from the Max Planck Institute for Astronomy (MPIA), a group of astronomers set out to observe 30 promising massive star-formation regions with ALMA between 2016 and 2019.

Analyzing the data proved a considerable challenge and took several years. Each separate observation yields around 800 GB of data, and reconstructing images from the contributions of all the different antennae is a complex process. The result is based on the analysis of one of the star-formation regions, which has the catalogue number G333.23–0.06. MPIA's Shanghuo Li led the analysis. The resulting reconstructed images are remarkable: They show details down to about two hundred astronomical units (200 times the Earth-Sun distance) for a large region around 200,000 astronomical units across.

Fig. III.4.1: False-color image of the massive star formation region G333.23–0.06 from data obtained with the ALMA radio observatory. The insets show areas in which Li et al. managed to detect multiple systems of protostars. The star symbols indicate the location of each newly forming star. The image covers a region 0.62 by 0.78 light-years in size (which on the sky covers a mere 7.5 times 9.5 arc seconds).

Multiples on display

The results are excellent news for the current picture of massive star formation. In G333.23–0.06, Li and his colleagues found four binary proto-stars, one triple, one quadruple, and one quintuple system, consistent with the expectations.

In fact, the observations of the environments bolster a particular scenario for high-mass star formation: They provide evidence for hierarchical star formation, where the gas cloud first fragments into "cores" of increased gas density, and where each core then fragments into a multiple proto-star system.

The observations also seem to indicate that when the cloud collapses, the multiples form very early on. Investigating additional star formation regions, some of them younger than G333.23–0.06, should confirm this trend. Specifically, the astronomers are working on a similar analysis for the additional 29 massive star formation regions they had observed. They will soon be joined by 20 more, with new ALMA observations led by Li. That should permit farther-reaching statistics on the properties of such regions, and insight into the evolution of the multiples. But even with the present results, the role of multiples in massive star formation is now firmly anchored in observation.

Shanghuo Li (now at Nanjing University, China),
Henrik Beuther, and Thomas Henning

in collaboration with

Patricio Sanhueza (National Astronomical Observatory of Japan and School of Physical Science, SOKENDAI (The Graduate University for Advanced Studies), Tokyo, Japan), Huei-Ru Vivien Chen (National Tsing Hua University, Hsinchu, Taiwan), and Rolf Kuiper (University of Duisburg-Essen, Duisburg, Germany)

Shanghuo Li, Patricio Sanhueza, Henrik Beuther, et al., "Observations of high-order multiplicity in a high-mass stellar proto-cluster" in Nature Astronomy, Vol. 8, 472 (2024). DOI: 10.1038/s41550-023-02181-9

III.5 SCIENCE HIGHLIGHT

Planet-Forming Disks around Very Low-Mass Stars Are Different

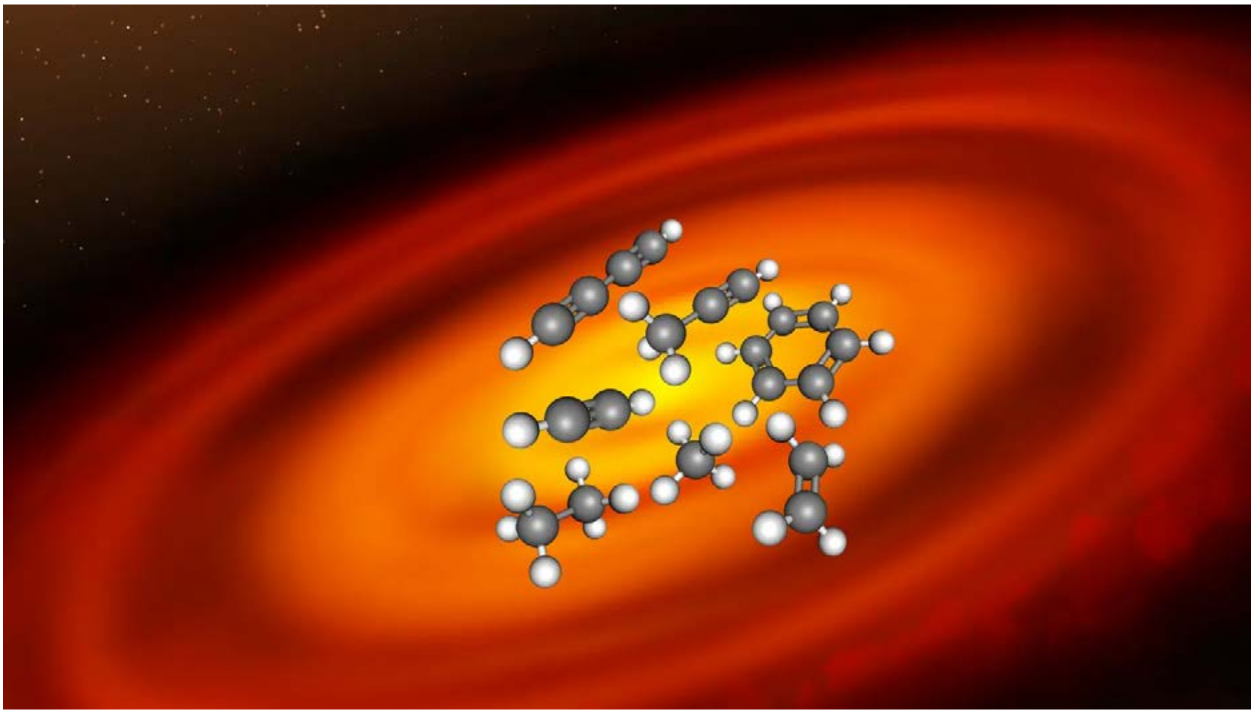
A team of astronomers, including MPIA scientists, has used the James Webb Space Telescope (JWST) to investigate a planet-forming disk surrounding the young, very low-mass star ISO-Chal 147. This study reveals an exceptionally rich hydrocarbon chemistry in the disk—unlike anything previously observed in similar environments. Among the outstanding discoveries are the first detections beyond our Solar System of ethane and other hydrocarbons, along with a notable scarcity of oxygen-bearing molecules. This finding confirms a trend of disks around very low-mass stars to be chemically distinct from those around more massive stars like the Sun, influencing the atmospheres of planets forming there.

Planetary systems form within disks of gas and dust orbiting young stars. The MIRI Mid-INfrared Disk Survey (MINDS), coordinated by MPIA's Thomas Henning, aims to build a representative sample of such disks. By analyzing the physical and chemical properties of these disks with JWST's Mid-Infrared Instrument (MIRI), the program links observed disk characteristics to the types of planets that may form within them. In this particular case, the focus was on a star known as ISO-Chal 147 with only 0.11 times the mass of the Sun.

JWST opens a new window to the chemistry of planet-forming disks

The observational data, made possible through JWST's sensitivity and spectral resolution, revealed gas temperatures of around 300 Kelvin (approximately 30 degrees Celsius). The disk's chemical makeup was found to be dominated by carbon-rich molecules, with oxygen-bearing species appearing in much lower abundance. This composition contrasts starkly with that of disks around stars similar in mass to the Sun, which typically exhibit high levels of water vapor and carbon dioxide.
Previous observations, such as those from the disk around the star PDS 70, have shown that oxygen-rich environments are common around solar-type stars. The findings from ISO-Chal 147, when considered together with earlier studies, reinforce the idea that planet-forming disks around very low-mass stars evolve along different

Fig. III.5.1: Artist's impression of a protoplanetary disk around a very low-mass star. It depicts a selection of hydrocarbon molecules (Methane, CH4; Ethane, C2H6; Ethylene, C2H2; Diacetylene, C4H2; Propyne, C3H4; Benzene, C6H6) detected in the disk around ISO-Chal 147.



Credit: ALMA (ESO/NAOJ/NRAO) / MPIA

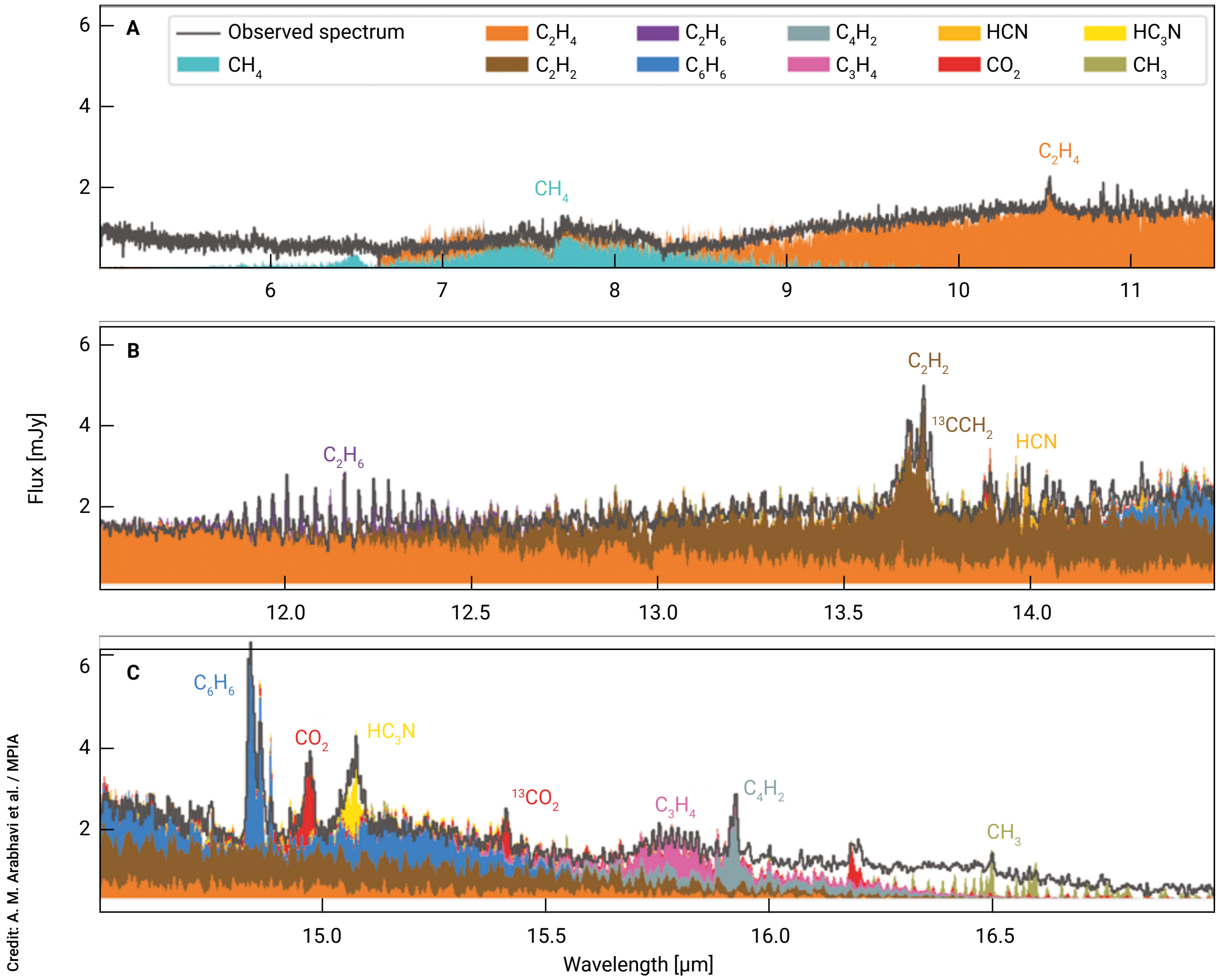


Fig. III.5.2: Mid-infrared spectrum of ISO-Chal 147. The black line shows the continuum-subtracted MIRI spectrum; the panels display different wavelength regions. Colored areas indicate the modeled contributions from various molecules (labeled; see color key), which are stacked. The infrared radiative flux density is given in millijanskys (mJy).

chemical pathways. These variations in composition directly impact the potential atmospheres of emerging planets, suggesting that while rocky planets may still form, their chemical environments may differ significantly from Earth's.

What does it mean for rocky planets orbiting very low-mass stars?

The material content and spatial distribution within such disks place natural limits on the size and number of planets they can produce. Data indicate that Earth-sized rocky planets form more efficiently in disks around very low-mass stars compared to Jupiter-like gas giants. Since these stars are the most common in the universe, they likely host the majority of terrestrial planets.

The study suggests that many of these rocky planets may develop primary atmospheres dominated by hydrocarbon compounds rather than water vapor or carbon dioxide. Earlier analyses have shown that carbon-bearing gases in such disks are transported more rapidly and effectively into the inner disk regions—where rocky planets typically form—than in the disks of more massive stars.

Although the prevalence of carbon relative to oxygen is clear, the underlying cause of this imbalance remains uncertain. It may result from either an enrichment of carbon or a depletion of oxygen. If the cause is carbon enrichment, it likely stems from solid particles within the disk releasing vaporized carbon into the gas phase. These grains, having lost their carbon, later become the building blocks of rocky planets, which would thus be carbon-poor in their solid composition—similar to Earth—but surrounded by carbon-rich atmospheres. Therefore, very low-mass stars may not offer the best environments for finding planets akin to Earth.

JWST discovers a wealth of organic molecules

To characterize the gaseous components in the disk, the research team used MIRI's spectrograph to break down the incoming infrared light into fine spectral features, similar to dispersing sunlight into a rainbow. This approach revealed a diverse set of molecular signatures.

Altogether, the disk around ISO-ChaI 147 displays the richest hydrocarbon chemistry ever recorded in a protoplanetary environment. Thirteen carbon-based molecules were identified, including benzene (C6H6). For the first time in an extrasolar disk, the presence of ethane (C2H6)—the largest fully saturated hydrocarbon detected outside the Solar System—was confirmed. Other newly detected species included ethylene (C2H4), propyne (C3H4), and the methyl radical (CH3). Water and carbon monoxide, on the other hand, were absent from the spectral data.

Sharpening the view of disks around very low-mass stars

The MINDS team plans to expand their observations to a larger population of very low-mass star systems to assess how widespread this kind of carbon-rich chemistry is in planet-forming regions. A broader sample will also aid in understanding the molecular formation mechanisms at play. Some features in the spectral data remain unidentified and will require additional observations to interpret fully.

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A. M. Arabhavi, I. Kamp, Th. Henning, E. F. van Dishoeck, V. Christiaens, et al. "Abundant hydrocarbons in the disk around a very-low-mass star" in Science, Vol. 384, 1086 (2024). DOI: 10.1126/science.adi8147

III.6 SCIENCE HIGHLIGHT

Webb Images Nearest Super-Jupiter, Opening a New Window on Exoplanet Research

Using the James Webb Space Telescope (JWST), an MPIA-led team of astronomers imaged a newly confirmed exoplanet that orbits a star in the nearby triple star system Epsilon Indi. The planet is a cold super-Jupiter exhibiting a temperature of around 0 degrees Celsius and a wide orbit, comparable to that of Neptune around the Sun. This measurement was only possible thanks to JWST's unprecedented imaging capabilities in the thermal infrared. It exemplifies the potential of finding many more such planets similar to Jupiter in mass, temperature, and orbit. Studying them will improve our knowledge of how gas giants form and evolve in time.

Initial analyses revealed a bright source in the JWST MIRI images that deviated from prior predictions. Earlier radial velocity studies had correctly flagged a planet in this system, but significantly underestimated its mass and orbital separation. With JWST data, astronomers, including MPIA's Elisabeth Matthews, were able to revise these key parameters, clarifying the planet's true nature.

Fig. III.6.1: This artist's concept shows what the exoplanet WASP-39b could look like based on indirect transit observations from JWST and other space- and ground-based telescopes. Data collected by its NIRSpec (Near-Infrared Spectrograph) shows variations between the morning and evening atmosphere of the planet.

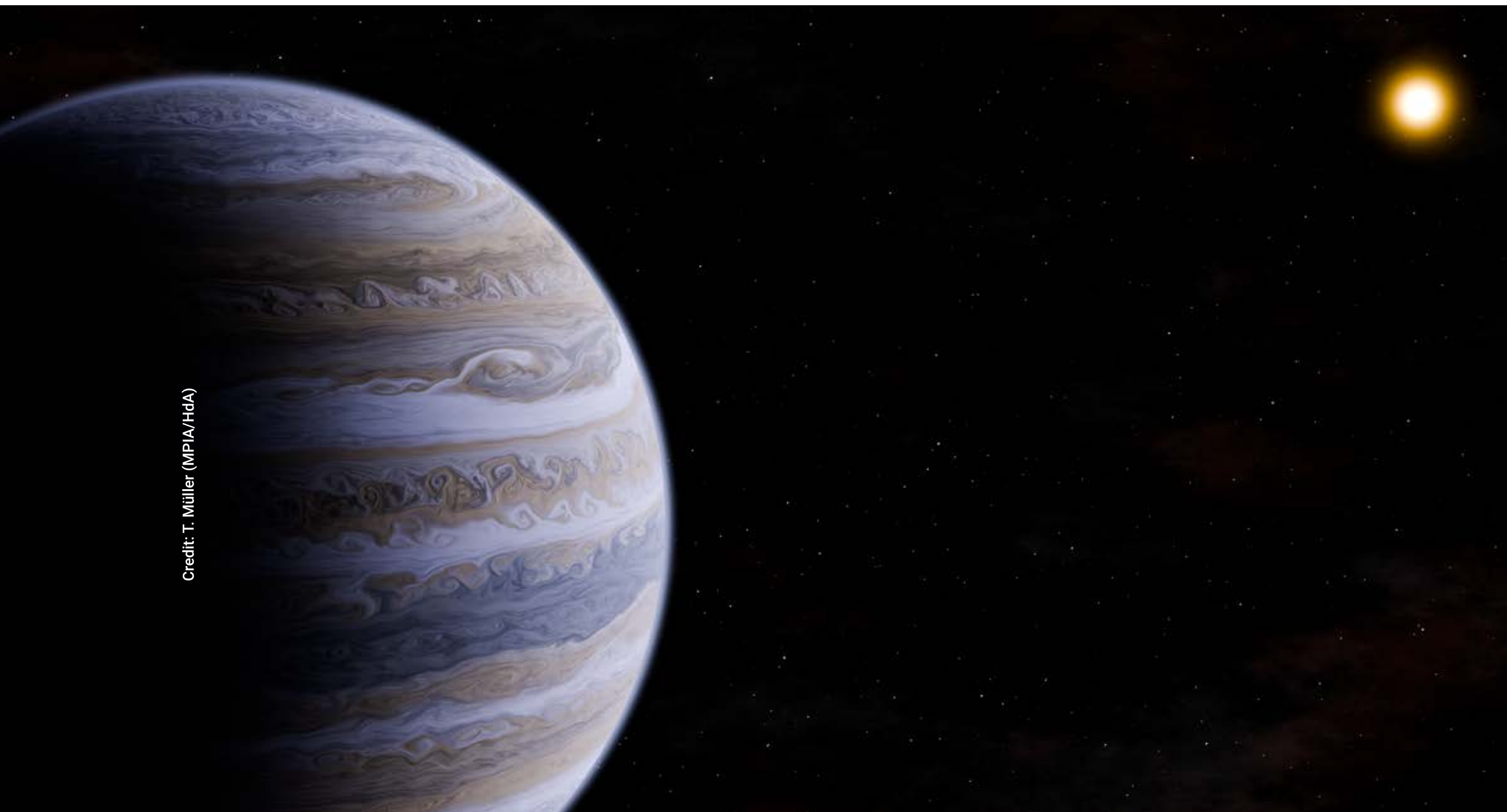
This detection is quite unusual in several aspects. It shows the first exoplanet imaged with JWST that had not already been imaged from the ground, and is much colder than the gas planets JWST has studied so far. Unlike indirect detection methods like transits or radial velocities, direct imaging captures the planet as a distinct point of light, providing direct visual evidence of its existence.

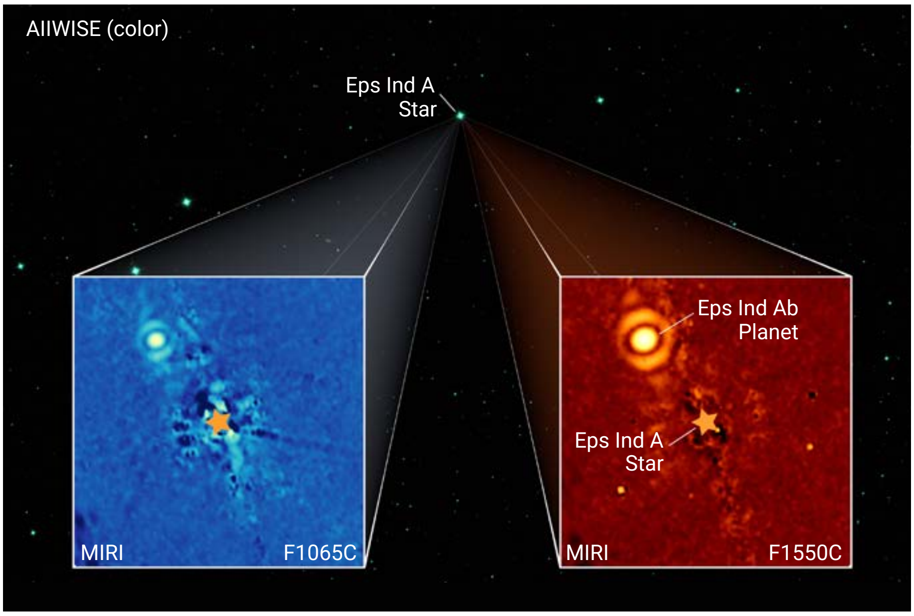
JWST observations update previous measurements

The planet revolves around the main component of the nearby triple star system Epsilon Indi, or Eps Ind for short. Astronomical labelling conventions assign the label Eps Ind A to that primary star, a red dwarf star a little smaller and cooler than the sun. To construct the planet's name, a "b" is appended, resulting in the designation Eps Ind Ab.

Eps Ind Ab orbits Eps Ind A, the primary component of the Epsilon Indi system, which lies only 12 light-years from Earth. Eps Ind A is a red dwarf star, slightly smaller and cooler than the Sun. The planet's designation follows astronomical naming conventions, with "b" appended to the host star's name.

The new JWST data are consistent with a super-Jupiter having a mass six times that of Jupiter in the Solar System. Eps Ind Ab orbits its host star on an eccentric,





Credit: T. Müller (MPIA/HdA), E. Matthews (MPIA)

Fig. III.6.2: The image summarizes the observations with JWST/MIRI that led to the rediscovery of Eps Ind Ab. The inserts show cropped versions of the MIRI images obtained at mid-infrared wavelengths 10.65 ***(left)*** and 15.55 micrometers ***(right)***, which depict the area around the star Eps Ind A, whose position is indicated by star symbols. A coronagraph blocks the light from the star that would outshine both images. Instead, a new object becomes visible to the top left. This source is the exoplanet Eps Ind Ab. The background was obtained from the AllWISE sky survey.

elliptical orbit whose farthest separation from Eps Ind A ranges between 20 and 40 astronomical units. One astronomical unit (au) equals the average Earth–Sun distance, approximately 150 million kilometers. The new values differ considerably from earlier studies, which is why the team chose to call this a "new" planet.

Cool planets, hot science

Only a few cold gas-giant planets orbiting solar-age stars are known to date, and these have all been inferred indirectly from radial velocity measurements.

Imaging such objects, and ideally acquiring spectra, enables researchers to probe their atmospheric composition and better understand how these planets evolve. The comparison between observational data and theoretical models of planetary formation can help refine assumptions about the later stages of planetary system development.

The detection of Eps Ind Ab paves the way for a broader search for similar cold gas giants. Identifying and characterizing these objects allows scientists to explore an entirely new category of exoplanets and place them in the context of the Solar System's gas giants.

How to detect cold gas planets

However, these planets are hard to find using conventional detection methods. Planets far from their host stars are typically very cold, unlike the hot Jupiters that circle their stars at separations of only a few stellar radii. Wide orbits are highly unlikely to be aligned along the line of sight to produce a transit signal. In addition, measuring their signals with the radial-velocity method is challenging when only a small section of the orbit can be monitored.

Earlier studies attempted to investigate a giant planet orbiting Eps Ind A using radial velocity measurements. However, extrapolating a small part of the orbit led to incorrect conclusions about the planet's properties. After all, Eps Ind Ab needs around 200 years to orbit its star. Observations carried out over a few years are insufficient to determine the orbit with high precision.

Therefore, the team devised a different approach. They wanted to take a picture of the known planet using a method commonly known as direct imaging. Since exoplanet host stars are immensely bright, they outshine any other nearby object. Regular cameras would be overwhelmed by the blinding starlight.

For this reason, the team employed JWST's MIRI (Mid-Infrared Instrument) camera equipped with a coronagraph. This light-blocking mask covers the star like an artificial eclipse. Another advantage is Eps Ind's proximity to Earth, which is only 12 light-years. The smaller the distance to the star, the larger the separation between two objects that appear in an image, providing a better chance of mitigating the host star's interference. MIRI was the perfect choice because it observes in the thermal or mid-infrared regimes, where cold objects shine brightly.

What do we know about Eps Ind Ab?

The data revealed a planetary signal that diverged from previous orbital predictions. After confirming that the source was unlikely to be a background object, such as a distant galaxy, the team examined archived data from the VISIR instrument at the European Southern Observatory's (ESO) Very Large Telescope (VLT), dating back to 2019. A re-analysis of these images showed a faint object exactly where it would be expected if it were gravitationally bound to Eps Ind A, strengthening the identification of the planet.

The scientists also attempted to understand the exoplanet atmosphere based on the available images of the planet in three colors: two from JWST/MIRI and one from VLT/VISIR. Eps Ind Ab is fainter than expected at short wavelengths. This could indicate substantial amounts of heavy elements, particularly carbon, which builds molecules such as methane, carbon dioxide, and carbon monoxide, commonly found in gas-giant planets. Alternatively, it might indicate that the planet has a cloudy atmosphere. However, more work is needed to reach a conclusion.

Plans and prospects

This initial discovery marks only the beginning of efforts to characterize Eps Ind Ab. Future observations aim to obtain spectra revealing detailed information about the planet's atmospheric chemistry and climate. By analyzing its molecular fingerprint, scientists hope to better understand how such planets form and what conditions shape their atmospheres.

Looking ahead, the team plans to extend this approach to other nearby planetary systems. A systematic survey for cold gas giants would fill a critical gap in exoplanetary research and contribute to a deeper understanding of giant planet formation across different stellar environments.

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E. C. Matthews et al. "A temperate super-Jupiter imaged with JWST mid-infrared imaging" in Nature, Vol. 633, 789 (2024). DOI: 10.1038/s41586-024-07837-8

III.7 SCIENCE HIGHLIGHT

JWST Peers Into the Heart of a Starburst Galaxy

Using the James Webb Space Telescope's (JWST) supreme infrared sensitivity, astronomers have investigated the environment of exceptionally intense star formation in the center of the starburst galaxy Messier 82 (M82). They used large organic molecules to map the massive galactic wind expelling vast amounts of gas caused by star formation and supernova explosions in unprecedented detail and trace its origin back to the dense stellar clusters in the galaxy's disk. The study represents a significant step towards a deeper understanding of how M82 forms stars and how such intense activity affects the galaxy as a whole.

Starbursts are phases of rapid and efficient star formation. Most galaxies experienced such active periods more than 10 billion years ago, in the early universe. However, observing these conditions remains challenging due to their considerable distance. Fortunately, some starburst galaxies are relatively close, offering a rare opportunity to investigate these extreme environments in detail.

A galactic laboratory

One of the closest examples is Messier 82 (M82), situated 12 million light-years away in the constellation Ursa Major. Despite its relatively compact size, M82 undergoes vigorous star formation, producing new stars at a rate roughly ten times higher than the Milky Way today. About 10 million years ago, that rate peaked at nearly 80 times the current Milky Way star formation rate.

As a prototypical starburst galaxy, M82 provides an ideal environment for studying intense star formation and the associated large-scale outflows, commonly referred to as galactic winds. These phenomena play a critical role in the life cycles of galaxies, yet are challenging to observe in more distant, early-universe systems. For many years, researchers have studied M82's galactic wind to gain a deeper understanding of these processes.

Leveraging JWST's powerful NIRCam (Near-Infrared Camera) instrument, astronomers obtained a detailed view of the central region where new stars are forming. The observations revealed the physical conditions responsible for driving the galactic wind with greater clarity than ever before. Prior to these results, both cold and hot ionized gas had been detected within the wind. Now, the latest JWST data offer a new, high-resolution perspective on these complex and seemingly contradictory conditions.

Fig. III.7.1: To the left is the starburst galaxy M 82, observed by the Hubble Space Telescope in 2006. The small box at the galaxy's core corresponds to the area captured by the NIRCam (Near-Infrared Camera) instrument on the JWST. The resulting image features red filaments illuminated by polycyclic aromatic hydrocarbon (PAH) emission, which reveals the origin and shape of the galactic wind. In the Hubble image, the light at 0.814 microns is colored red, 0.658 microns is red-orange, 0.555 microns is green, and 0.435 microns is blue (filters F814W, F658N, F555W, and F435W, respectively). In the NIRCam image, the light at 3.35 microns is colored red, 2.50 microns is green, and 1.64 microns is blue (filters F335M, F250M, and F164N, respectively).

Credit: NASA, ESA, CSA, STScI, A. Bolatto (University of Maryland)

Credit: NASA, ESA, CSA, STScI, A. Bolatto (University of Maryland)

Fig. III.7.2: This image from JWST's NIRCam (Near-Infrared Camera) instrument highlights emission from sooty chemicals known as polycyclic aromatic hydrocarbons (PAH), which trace the shape of M 82's galactic wind. The red filaments of PAH emission extend away from the central region, the heart of the star formation activity. Unexpectedly, the structure is similar to that of hot, ionized gas, suggesting PAHs may be replenished by continued ionization of molecular gas. In this image, the light at 3.35 microns is coloured red, 2.50 microns is green, and 1.64 microns is blue (filters F335M, F250M, and F164N, respectively).

Credit: NASA, ESA, CSA, STScI, A. Bolatto (University of Maryland)

Fig. III.7.3: This image from JWST's NIRCam (Near-Infrared Camera) instrument shows the starburst region in the galaxy M 82. The galaxy's core glows brightly with dark brown tendrils of dust threaded throughout. Small red patches signify localized areas where a nearby young star's radiation is lighting up molecular hydrogen. At the same time, green specks mark concentrated regions of iron, most of which are supernova remnants. In this image, the light at 2.12 microns is coloured red, 1.64 microns is green, and 1.40 microns is blue (filters F212N, 164N, and F140M, respectively).

A vibrant community of stars

Studying star formation remains challenging because the process is shrouded by curtains of dust and gas, obscuring these processes from view. Fortunately, JWST's ability to peer into the infrared is a valuable asset in mitigating these unfavorable conditions. Additionally, these NIRCam images of M82's starburst core were obtained using an observing mode designed to prevent the bright source from overwhelming the detectors.

While dark brown tendrils of heavy dust pervade M82's glowing white core even in this infrared view, JWST's NIRCam revealed a level of detail that has historically been obscured. Looking closer towards the center, small red patches signify regions where molecular hydrogen lights up under the radiative influence of nearby young stars. Green specks trace concentrated regions of iron, largely associated with supernova remnants.

Massive stars end their short lifetimes in supernova explosions. As star formation intensifies during a starburst, these explosions become more frequent, injecting energy into the surrounding environment. The resulting supernovae contribute significantly to the galactic wind that pushes gas and dust away from the disk and into the galaxy's halo. Observations at specific wavelengths reveal material rising above and below the plane of the galaxy, providing a glimpse into this dynamic feedback process.

Finding structure in lively conditions

One of the primary goals of this research was to investigate how the galactic wind, caused by the rapid rate of star formation and subsequent supernovae, is launched and influences its surrounding environment. By resolving a central section of M82, scientists examined the launch site of the wind and gained insight into how hot and cold components interact.

The NIRCam instrument is well-suited to trace the structure of the galactic wind using the emission from molecules known as polycyclic aromatic hydrocarbons (PAHs). PAHs are considered tiny grains at the border between large molecules and sooty dust particles that survive in cooler temperatures but disintegrate under intense heat.

The new observations revealed intricate filamentary structures of PAH emission, highlighted as red filaments extending outward from the central star-forming region. These features provide the most detailed view to date of the galactic wind's structure. Unexpectedly, the PAH emission closely resembles the distribution of hot, ionized gas observed in previous studies. This similarity suggests that PAHs may be replenished over time, possibly through ongoing processes that release fresh molecular material into the wind. The results challenge previous assumptions and demonstrate the need for further investigation into the physical conditions within these extreme environments.

The remarkable detail revealed in the PAH structures illustrates JWST's unprecedented capability to resolve complex features in starburst galaxies. These observations offer critical new information about how galactic winds are launched and how they interact with the surrounding material.

Lighting a path forward

The near-infrared observations of M82 raise new questions about star formation processes that the team plans to explore with additional JWST data. Upcoming spectroscopic observations will provide precise age estimates for stellar clusters, helping to determine the timescales of different star formation phases within the galaxy. In addition, large-scale imaging will allow astronomers to map the full extent of M82's galactic wind.

Studying galaxies like M82 not only advances our understanding of nearby starbursts but also provides valuable insights into the early universe. JWST's ability to observe galaxies across vast distances, combined with its capacity to examine nearby targets in detail, creates an essential bridge between local star-forming environments and the conditions that shaped galaxies billions of years ago.

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A. D. Bolatto et al., "JWST Observations of Starbursts: Polycyclic Aromatic Hydrocarbon Emission at the Base of the M82 Galactic Wind" in The Astrophysical Journal, Vol. 967, 63 (2024). DOI: 10.3847/1538-4357/ad33c8

III.8 SCIENCE HIGHLIGHT

Astronomers Find the Nearest Massive Black Hole, a Missing Link in Massive Black Hole Formation

Newly identified fast-moving stars in the star cluster Omega Centauri provide solid evidence for a central black hole in the cluster. With at least 8200 solar masses, it is the best candidate for a class of black holes astronomers have long believed to exist: intermediate-mass black holes, formed in the early stages of galaxy evolution. The discovery bolsters the case for Omega Centauri as the core region of a galaxy that was swallowed by the Milky Way billions of years ago. Stripped of its outer stars, that galaxy nucleus has remained "frozen in time" since then.

Omega Centauri is a spectacular collection of about ten million stars, visible as a smudge in the night sky from Southern latitudes. Through a small telescope, it looks no different from other so-called globular clusters: a spherical collection of stars, so dense towards the center that it becomes impossible to distinguish individual stars. The new results confirm what astronomers had been suspecting for some time: Omega Centauri contains a central black hole. The black hole appears to be the "missing link" between its stellar and supermassive kin: Stuck in an intermediate stage of evolution, it is considerably less massive than typical black holes in the centers of galaxies. Omega Centauri seems to be the core of a small, separate galaxy whose evolution was cut short when the Milky Way swallowed it.

A range of black hole masses

In astronomy, black holes come in different mass ranges. Stellar black holes, between one and a few dozen solar masses, are well known, as are the supermassive black holes with masses of millions or even billions of Suns. Our current picture of galaxy evolution posits that the earliest galaxies should have had intermediate-sized central black holes, which would have grown over time as those galaxies evolved, gobbling up smaller galaxies (as our Milky Way has done) or merging with larger galaxies.

Such medium-sized black holes are notoriously hard to find. Galaxies like our own Milky Way have long outgrown that intermediate phase and now contain much larger central black holes. Galaxies that have remained small ("dwarf galaxies") are generally difficult to observe. With the currently available technology, observations of their central regions that could detect the central black hole are extremely challenging. Although there are promising candidates, there has been no definite detection of such an intermediate-mass black hole—until now.

A galaxy (core) frozen in time

This is where Omega Centauri is special. If it was once the core of a separate galaxy, which then merged with the Milky Way and lost all but its central batch of stars in the process, the remaining galactic core and its central black hole would be "frozen in time": There would be no further mergers, and no way for the central black hole to grow. The black hole would be preserved at the size it had when Omega Centauri was swallowed up by the Milky

Fig. III.8.1: From left to right: The globular star cluster Omega Centauri as a whole, a zoomed-in version of the central area, and the region in the very center with the location of the mid-size black hole that was identified in the present study marked.

Credit: ESA / Hubble & NASA, M. Häberle / MPIA

Way, providing a glimpse of the missing link between early low-mass black holes and the later supermassive black holes.

To test this hypothesis, it is necessary to actually detect a central black hole in Omega Centauri, and a definite detection had eluded astronomers until now. While there was evidence from large-scale models of the motion of stars in the cluster, that evidence left room for doubt: Maybe there was no central black hole at all.

Needle in an archival haystack

When in MPIA Research Group Leader Nadine Neumayer and Anil Seth of the University of Utah designed a research project aimed at an improved understanding of the formation history of Omega Centauri in 2019, they realized that here was an opportunity to settle the question of the cluster's central black hole once and for all: If they were able to identify the expected fast-moving stars around a black hole in the center of Omega Centauri, that would be the proverbial smoking gun, as well as a way of measuring the black hole's mass.

The arduous search became the task of PhD student Maximilian Häberle. He led the work of creating an enormous catalogue for the motions of stars in Omega Centauri, measuring the velocities of 1.4 million stars by studying over 500 Hubble images of the cluster. Most of these images had been produced for the purpose of calibrating Hubble's instruments rather than for scientific use. But with their ever-repeating views of Omega Centauri, they turned out to be the ideal data set for the team's research efforts.

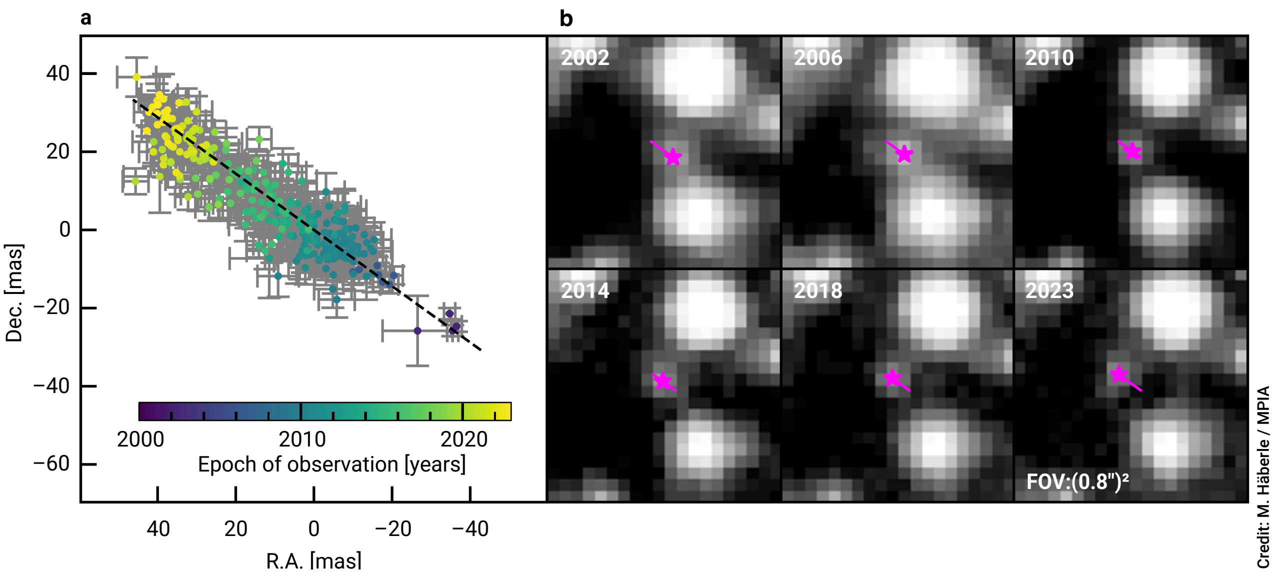
The process of identifying high-speed stars and tracking their motion proved to be extremely difficult and time-consuming. Nevertheless, the investigation not only produced the most complete catalogue of the motion of stars in Omega Centauri yet, but also resulted in a list of seven fast-moving stars in a small region at the center of Omega Centauri.

Uncovering a black hole

Those fast-moving stars are fast because of the presence of a concentrated nearby mass. For a single star, it would be impossible to tell whether it is fast because the central mass is large or because the star is very close to the central mass—or if the star is merely flying straight, with no mass in sight. But seven such stars, with different speeds and directions of motion, allowed Häberle and his colleagues to separate the different effects and to determine that there is a central mass in Omega Centauri, with a mass of at least 8,200 suns. The images do not indicate any visible object at the inferred location of that central mass, as one would expect for a black hole.

The broader analysis not only enabled Häberle to pinpoint the speeds of his seven high-speed stars. It also narrowed down the location of just where the central region, three light-months in diameter (on images, three arc seconds), is located within Omega Centauri. In addition, the analysis provided statistical reassurance: A single high-speed star in the image might not even belong to Omega Centauri. It could be a star outside the cluster

Fig. III.8.2: These diagrams depict the measured positions of the fastest and centermost of the seven fast-moving stars discovered in the heart of ω Cen. (a) The individual sky positions with 1σ error bars indicate a gradual shift of approximately 100 arcseconds within 21 years of observations. (b) Multi-epoch imaging shows the movement relative to the surrounding stars. The traced star is indicated with a pink marker on the images.



that passes right behind or in front of Omega Centauri's center by chance. The observations of seven such stars, on the other hand, cannot be pure coincidence and leave no room for explanations other than a black hole.

An intermediate-mass black hole at last

Earlier studies had prompted critical questions about the absence of observed high-speed stars. With the new data, that gap is now closed, and the presence of an intermediate-mass black hole in Omega Centauri is confirmed. At a distance of about 18,000 light-years, this makes it the closest known example of a massive black hole. For comparison, the supermassive black hole at the center of the Milky Way lies around 27,000 light-years away. This detection not only promises to resolve the decade-long debate about an intermediate-mass black hole in Omega Centauri. It also provides the best candidate so far for the detection of an intermediate-mass black hole in general.

Given their findings, Neumayer, Häberle, and their colleagues now plan to examine the center of Omega Centauri in even more detail. They already have approval for measuring the high-speed star's movement towards or away from Earth (line-of-sight velocity) using the James Webb Space Telescope, and there are future instruments (GRAVITY+ at ESO's VLT, MICADO at the Extremely Large Telescope) that could pinpoint stellar positions even more accurately than Hubble. The long-term goal is to determine how the stars accelerate: how their orbits curve. Following those stars once around their whole orbit, as in the Nobel-prize-winning observations near the black hole in the center of the Milky Way, is a project for future generations of astronomers, though. The smaller black hole mass for Omega Centauri means ten times larger time scales than for the Milky Way: orbital periods of more than a hundred years.

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Maximilian Häberle et al., "Fast-moving stars around an intermediate-mass black hole in ω Centauri" in Nature, Vol. 631, 285 (2024). DOI: 10.1038/s41586-024-07511-z

Maximilian Häberle et al., "oMEGACat. II. Photometry and Proper Motions for 1.4 Million Stars in Omega Centauri and Its Rotation in the Plane of the Sky" in The Astrophysical Journal, Vol. 970, 192 (2024). DOI: 10.3847/1538-4357/ad47f5

III.9 SCIENCE HIGHLIGHT

Record Blazar Discovery Hints at How Black Holes Grew So Fast in Early Universe

Astronomers have discovered an important piece of the puzzle of how supermassive black holes were able to grow so quickly in the early universe. The key lies in the discovery of the most distant blazar – a special type of active galaxy whose light has traveled more than 12.9 billion years to reach us. This distant blazar serves as more than just a record-breaker. Its very existence implies the presence of a large but hidden population of similar objects, all of which should emit powerful particle jets. This is where the discovery becomes important for cosmic evolution: black holes with jets are thought to be able to grow considerably more quickly than without jets.

Active galactic nuclei (AGN) are extremely bright centers of galaxies. The "engines" driving their enormous energy output are supermassive black holes. Matter falling onto such black holes ("accretion") is the most efficient mechanism known to physics when it comes to setting free enormous amounts of energy. That unmatched efficiency is why AGN are able to produce more light than all the stars in hundreds, thousands, or even more galaxies put together and in a volume of space smaller than our own solar system.

Fig. III.9.1: Artist's impression of the bright, very early active galactic nucleus, which has fundamental implications for black hole growth in the earliest billion or so years of cosmic history.

At least ten percent of all AGN are thought to emit focused high-energy beams of particles, known as jets. These jets shoot out from the direct vicinity of the black hole in two opposite directions, sustained and guided by magnetic fields in the "accretion disk" of material: the disk formed by gas swirling around, and falling into, the black hole. For us to see an AGN as a blazar, something very improbable needs to happen: Earth, our base of observations, needs to be in just the right location for the AGN jet to point directly toward us. The result is the astronomical analog of someone shining the beam of a really bright flashlight directly into your eyes: a particularly bright object in the sky. Characteristically for a blazar, we also see quick changes in brightness on time scales of days, hours, or even less than that—a consequence of random changes in the swirling accretion disk at the base of the jet and of instabilities in the jet's interplay between magnetic fields and charged particles.

Finding active galactic nuclei in the very early universe

The new discovery was the result of a systematic search for active galactic nuclei in the early universe conducted by Eduardo Bañados, a group leader at the Max Planck Institute for Astronomy who specializes in the first billion

years of cosmic history, and an international team of astronomers. Since light takes time to reach us, we see distant objects as they were millions or even billions of years ago. For the more distant objects, the so-called cosmological redshift, due to cosmic expansion, shifts their light to far longer wavelengths than the wavelengths at which the light was emitted. Bañados and his team exploited this fact, searching systematically for objects that were redshifted so far that they did not even show up in the usual visible light (of the Dark Energy Legacy Survey, in this case) but that were bright sources in a radio survey (the 3 GHz VLASS survey).

Among 20 candidates that met both criteria, only one designated J0410–0139 met the additional criterion of showing significant brightness fluctuations in the radio regime—raising the possibility that this was a blazar. The researchers then dug deeper, employing an unusually large battery of telescopes, including near-infrared observations with ESO's New Technology Telescope (NTT), a spectrum with ESO's Very Large Telescope (VLT), additional near-infrared spectra with the LBT, one of the Keck telescopes and the Magellan telescope, X-ray images from both ESA's XMM-Newton and NASA's Chandra space telescopes, millimeter wave observations with the ALMA and NOEMA arrays, and more detailed radio observations with the US National Radio Astronomy Observatory's VLA telescopes to confirm the object's status as an AGN, and specifically a blazar. The observations also yielded the distance of the AGN (via the redshift) and even found traces of the host galaxy in which the AGN is embedded. Light from that active galactic nucleus has taken 12.9 billion years to reach us (z = 6.9964), carrying information about the universe as it was 12.9 billion years ago.

Where there is one, there's one hundred more.

The identification of J0410–0139 as a blazar, with its jet pointing directly at Earth, has direct statistical implications. Winning $100 million in a lottery may serve as a real-life analogy. Given how rare such a win is, a reasonable conclusion is that there must have been many more people who participated in that lottery but have not won such an exorbitant amount. Similarly, finding one AGN with a jet pointing directly toward us implies that at that time, there must have been many AGN in that period of cosmic history with jets that do not point at us.

Light from the previous record-holder for the most distant blazar has taken about 100 million years less to reach us (z = 6.1). The extra 100 million years might seem short in light of the fact we are looking back more than 12 billion years, but they make a crucial difference. This is a time when the universe is changing rapidly. In those 100 million years, a supermassive black hole can increase its mass by an order of magnitude. Based on current models, the number of AGN should have increased by a factor of five to ten during those 100 million years. Finding that there was such a blazar 12.8 billion years ago would not be unexpected. Finding that there was such a blazar 12.9 billion years ago, as in this case, is a different matter altogether.

Helping black holes grow since 12.9 billion years before the present

The presence of a whole population of AGN with jets at that particular early time has significant implications for cosmic history and the growth of supermassive black

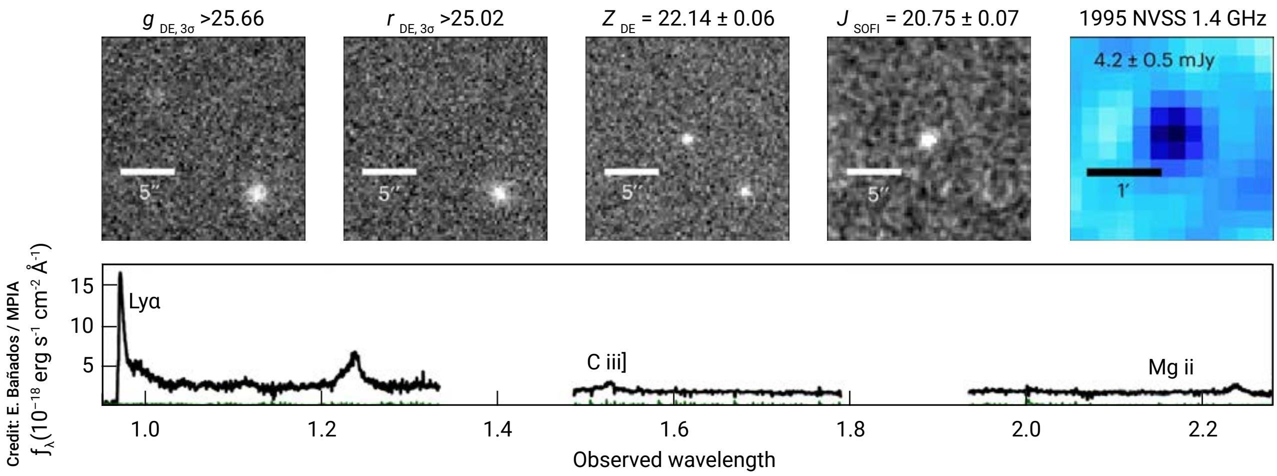


Fig. III.9.2: Multi-wavelength observations leading to the identification of a blazar at z=7. The optical/near-infrared images ***(top left, greyscale)*** show that the source is a dropout in optical bands but detected in the Z-band. Comparing radio observations ***(top panel in blue tones)*** shows dramatic variability at 1.4 gigahertz between 1995 and 2021, a key indicator of a blazar-like behaviour. The radio maps show an unresolved, compact source in all epochs. The near-infrared spectrum ***(bottom)*** reveals prominent emission lines, which confirm the redshift and the quasar nature of the source. Multi-wavelength and multi-epoch observations presented in the paper enabled the discovery of the most distant blazar currently known.

holes in the centers of galaxies in general. Black holes whose AGN have jets can potentially gain mass faster than black holes without jets. Contrary to popular belief, it is difficult for gas to fall into a black hole. The natural thing for gas to do is to orbit the black hole, similar to the way a planet orbits the Sun, with increased speed as the gas gets closer to the black hole ("angular momentum conservation"). In order to fall in, the gas needs to slow down and lose energy. The magnetic fields associated with the particle jet, which interact with the swirling disk of gas, can provide such a "braking mechanism" and help the gas to fall in.

This means the consequences of the new discovery are likely to become a building block of any future model of black-hole growth in the early universe: they imply the existence of an abundance of active galactic nuclei 12.9 billion years ago that had jets, and thus had the associated magnetic fields that can help black holes grow at considerable speed.

Eduardo Bañados, Silvia Belladitta (also at INAF Bologna), Fabian Walter, Zhang-Liang Xie, Yana Khusanova, and Sofía Rojas-Ruiz (also at UCLA),

in collaboration with

Emmanuel Momjian (National Radio Astronomy Observatory, USA), Thomas Connor (Harvard-Smithsonian Center for Astrophysics), Roberto Decarli (INAF Bologna), and Chiara Mazzucchelli (Universidad Diego Portales, Chile)

E. Bañados et al., "A blazar in the epoch of reionization" in Nature Astronomy, Vol. 9, 293 (2025). DOI: 10.1038/s41550-024-02431-4

E. Bañados et al., "[CII] properties and Far-Infrared variability of a z = 7 blazar" in The Astrophysical Journal Letters, Vol. 977, L46 (2024). DOI: 10.3847/2041-8213/ad823b

IV. INSTRUMENTATION AND TECHNOLOGY

Credit: ESO / Apical

IV.1 OVERVIEW

Instrumentation for Ground-Based Astronomy

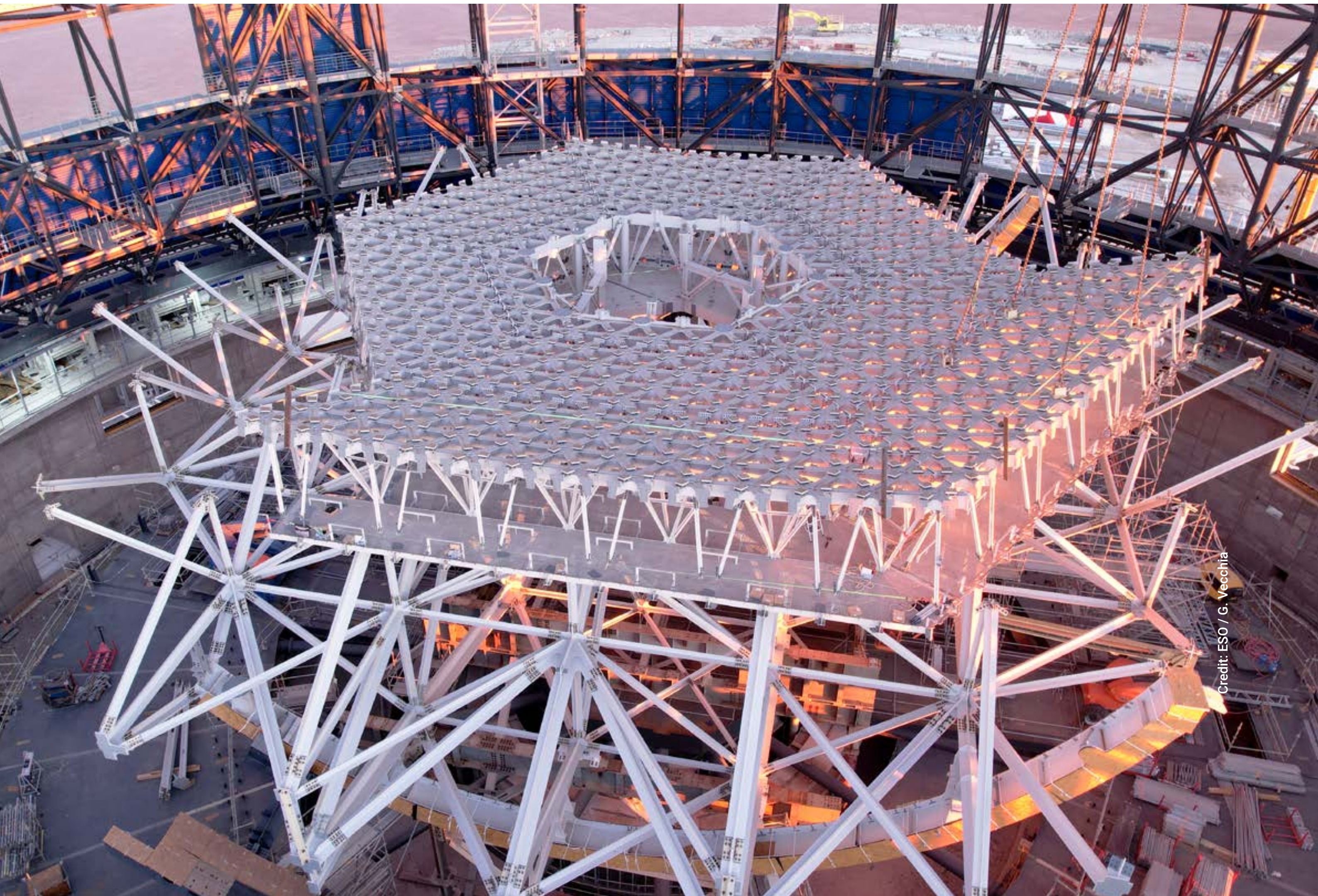
MPIA's Technical Departments play a vital role in designing and constructing instrumentation for several ground-based observatories and telescopes. In 2024, our primary focus was the European Southern Observatory's (ESO's) Extremely Large Telescope (ELT)—the upcoming flagship facility for European optical and infrared ground-based astronomy. MPIA is a member of three large international consortia building instruments for this "world's biggest eye on the sky." In addition to the work on ELT instrumentation, the Technical Departments took part in several smaller projects, further showcasing our varied expertise.

Fig. IV.1.1: This picture shows the support structure of the ELT's primary mirror under construction. Weighing 200 metric tons, it will be the largest segmented mirror ever built for a telescope. When in operation, it will need to move constantly and very smoothly during observations while keeping its optical shape. Therefore, it will rest on this assembly that is both lightweight and sturdy. Altogether, 798 hexagonal segments will work together as a single 39-meter mirror, staying aligned as the telescope moves, even under varying gravity loads, wind conditions, vibrations, or temperature fluctuations.

Instrumentation for the future – ELT

By the end of this decade, the ELT will open a new era of astronomy with its 39-meter mirror and groundbreaking instruments. It will allow us to investigate the earliest galaxies, trace the buildup of mass in the Universe, study the formation of planets in the habitable zone, and analyze the chemical composition of their atmospheres. MPIA plays a key role in three instrument projects for the ELT: two first-light instruments, METIS and MICADO, and a second-phase instrument, ANDES. METIS and MICADO officially passed their final design reviews in 2024, and ANDES is currently working towards the preliminary design review.

METIS (Mid-infrared ELT Imager and Spectrograph) is an imaging camera and spectrograph operating at mid-infrared wavelengths, covering the 3-13 micrometers range. It matches the region of the electromagnetic spectrum where objects at room temperature radiate strongest. Therefore, the entire instrument must be cooled to low temperatures to prevent disturbing artificial ambient radiation and ensure optimal performance.



METIS features a single-conjugate adaptive optics unit, enabling the instrument to achieve diffraction-limited observations and achieve an impressive spatial resolution by leveraging the telescope's enormous aperture. As the second-largest partner in the METIS consortium, MPIA is building the imager and single-conjugate adaptive optics module. The METIS science cases include 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 the luminous centers of nearby galaxies, high-redshift active galactic nuclei, and high-redshift gamma-ray bursts.

MICADO (Multi-AO Imaging Camera for Deep Observations) is a near-infrared imaging camera that, combined with a multi-conjugated adaptive optics system, will provide spatial resolution exceeding that of the James Webb Space Telescope (JWST) by a factor of approximately six. The camera will be sufficiently sensitive to observe stars as faint as 29th magnitude in the near-infrared. In visible light, such a brightness limit would include stars more than a billion times fainter than are visible to the naked eye. MPIA is building MICADO's warm relay optics and its calibration assembly. The science cases for MICADO include, among others, fully resolving stellar chemical and kinematic properties in the centers of galaxies, star clusters, and stellar populations in the Local Group (the group of galaxies to which our galaxy, the Milky Way, belongs), detailed morphological studies of galaxies at high redshift, searching for intermediate-mass black holes, and high-contrast imaging of extrasolar planets.

The second-phase ELT instrument ANDES (ArmazoNes high Dispersion Echelle Spectrograph) is a high-resolution spectrograph with broad wavelength coverage from the ultraviolet to the near infrared. The instrument will consist of four fiber-fed Echelle spectrographs with a spectral resolution of approximately 100,000. MPIA is designing and building the control electronics for the ANDES calibration unit and vacuum control electronics for the spectrographs. In addition, MPIA is developing the K-band spectrograph concept for ANDES, the fourth spectrograph currently pursued as a goal and not part of the baseline design. In November 2024, the K-band spectrograph very successfully completed the preliminary design review for this sub-system. The science cases for ANDES include characterizing exoplanet atmospheres, identifying the first stars in the Universe, testing physical constants, and measuring the acceleration of cosmic expansion. The first science case, exoplanet atmospheres, drives MPIA's development of the K-band spectrograph.

Fig. IV.1.2: MICADO's carbon fiber optical bench, manufactured by CarbonVision, that will hold its relay optics. The picture shows parts of the CarbonVision and MPIA teams at the acceptance of the bench in the CarbonVision facilities.

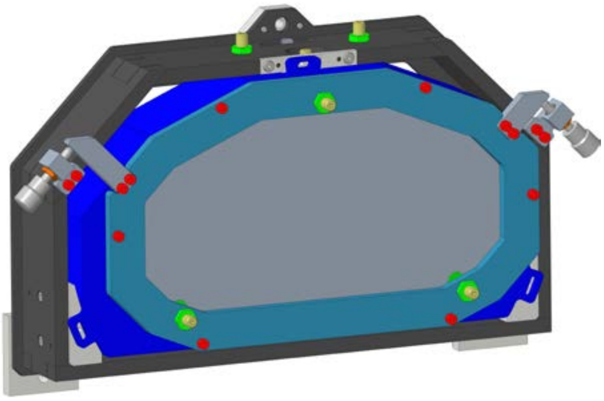


Fig. IV.1.3: Mechanical design of the Second Earth Spectrograph collimator mirror mount. The mount is seen from the back side in this illustration.

Instrumentation for ESO's VISTA telescope

MPIA joined the 4MOST (4-meter Multi-Object Spectrograph Telescope) consortium in 2014. This instrument is a multi-object spectrograph for the 4.1-meter infrared survey telescope VISTA at ESO's Paranal Observatory. The instrument will study the origin of the Milky Way and its chemical and kinematic substructure, as well as the evolution of other galaxies. It will utilize 2400 fibers covering a field of view of 4 square degrees, enabling the simultaneous spectroscopy of up to 2400 objects.

MPIA is responsible for the instrument control electronics of 4MOST. In 2023, MPIA verified the control electronics and helped with the entire instrument assembly, integration, and testing (AIT). Several sub-systems of 4MOST were shipped to Paranal in 2024, and the MPIA team participated in the instrument's on-site commissioning. The spectrographs proper will be shipped to Paranal in 2025, and commissioning of the complete instrument will follow.

Other instrumentation projects

In addition to the aforementioned projects, MPIA's Technical Departments are participating in the development of several other instruments. Two main additional projects were undertaken in 2024: PANIC-4k and 2ES.

The Panoramic Near-Infrared Camera (PANIC) is a wide-field general-purpose instrument for the 2.2-meter telescope at the Calar Alto Observatory in Spain. PANIC is a joint development of MPIA and the Instituto de Astrofísica de Andalucía and was in use at Calar Alto between 2015 and 2018. Initially, the instrument contained four HAWAII-2-RG infrared detectors, providing a field of view of 30 × 30 arcminutes (corresponding to the apparent size of the full moon in the sky), which is perfect for wide-field surveys of astronomical sources. The instrument was returned to MPIA in August 2018 for refurbishment of its detector system and to equip it with a higher-quality single HAWAII-4-RG detector, replacing the four original detectors. This upgraded instrument, PANIC-4k, will cover a slightly reduced field of view of about 25 × 25 arcminutes. Reinstallation at Calar Alto occurred in December 2022, which was delayed due to the global pandemic. In 2024, the MPIA team participated in the recommissioning of the upgraded instrument.

The Second Earth Spectrograph (2ES) is a next-generation high-precision radial velocity spectrograph for the ESO/MPG 2.2-meter telescope at ESO's La Silla Observatory. The instrument will run a survey lasting at least 5 years with the goal of discovering temperate terrestrial Earth-mass planets in the habitable zone around the brightest solar-type stars in the sky. The international consortium building the instrument is led by the Technical University of Denmark, with partners in Germany, the USA, and Chile. MPIA's main contribution to 2ES is the allocation of telescope observing time. Additionally, our engineering design department has been involved in designing several of the mechanical components required for the spectrograph.

Heidi Korhonen for the MPIA Technical Departments

IV.2 OVERVIEW

Instrumentation for Space-Based Astronomy

Nancy Grace Roman Space Telescope

The Nancy Grace Roman Space Telescope (formerly WFIRST) has been in development for about a decade under the leadership of NASA. The diameter of the primary mirror is 2.4 meters in diameter and is a replica of the Hubble Space Telescope's primary mirror. MPIA built the crucial optomechanical parts for one of its two scientific instruments, the Coronagraph Instrument (CGI). CGI is a technology demonstration that tests a new measurement method for directly imaging exoplanets. If it successfully images gas giants like Jupiter near their host stars as a point of light, as expected, this technique could later be used to detect and study rocky planets like Earth with future space telescopes.

MPIA's contribution to CGI

MPIA designed and manufactured six flight models and an additional six engineering models of the Precision Alignment Mechanisms (PAM). These mechanisms, which adjust and stabilize optical components such as mirrors and filters of the CGI during observations, were meticulously crafted and rigorously tested in MPIA's workshops and laboratories.

Fig. IV.2.1: Roman Spacecraft Integrated Payload Assembly in the cleanroom at NASA's Goddard Space Flight Center in December 2024. The telescope is mounted on top of the instrument carrier with both the CGI and WFI instruments.

Fig. IV.2.2: PRIMA spacecraft.

As a direct partner of NASA and the Jet Propulsion Laboratory (JPL) at the California Institute of Technology (CalTech) in the CGI project, MPIA has been gradually delivering these CGI core elements to JPL since spring 2022. The PAM flight models were installed in the CGI hardware and extensively tested during an instrument test campaign at JPL in the spring of 2024. These ground tests with a star simulator provided the primary set of calibration data prior to Roman's launch into space. After these instrument-level tests, CGI was shipped to NASA's Goddard Space Flight Center in May 2024, where the instrument will be mounted to the telescope and integrated into the Roman spacecraft and subjected to further extensive functional and stress tests.

A camera design for the search for a second Earth

CGI combines two common observation techniques, coronagraphy and adaptive optics, for use in space for the first time. Astronomers use coronagraphs to block out bright objects with dedicated masks, making fainter celestial bodies in their vicinity visible. This method already allows the detection of exoplanets by direct imaging. However, the masks often cause considerable image artifacts around the blocked-out stars. Thus, any potential exoplanet reflecting the light of its parent star can only be reliably detected at relatively large separations. Therefore, astronomers use this method almost exclusively to find giant gas planets similar to Jupiter on wide orbits around their host stars.

Reducing these artifacts is crucial for detecting smaller planets with narrower orbits. Therefore, CGI also has an adaptive optics system that enables a higher brightness contrast between the star and the planet. This technology usually helps to reduce disturbances in images taken with ground-based telescopes caused by the Earth's turbulent atmosphere.

For CGI, this technology mitigates the distorting effects of the telescope's optical system. However, the computing power required for this is a novel challenge for space cameras. With both techniques working in tandem, scientists should be able to detect exoplanets as close to their bright parent stars as ever before, visible as a bright point of light in the image. CGI is designed to identify a planet whose nearby parent star is a billion times brighter, roughly equivalent to the contrast between Jupiter and the Sun. Compared to today's capabilities, this corresponds to an improvement of up to a thousand times. A built-in spectrograph will then facilitate research into the composition of the atmosphere of these planets.

Technology with the highest precision and sophisticated data reduction algorithms

To achieve this, the PAMs manufactured by MPIA must guarantee an extremely high level of accuracy and stability in positioning the optical elements, such as filters, coronagraphs, and mirrors, over several hours. During operation, the PAMs are not allowed to tilt by more than 40 milliarcseconds over an eight-hour period.

These requirements and CGI's complexity make it the most elaborate and expensive scientific instrument ever to be stationed in space. In addition to the CGI hardware, the CGI data processing algorithms and software also play a crucial role in the exoplanet detection and characterization chain. As part of the CGI Community Participation Program (CPP), MPIA contributes in key areas to the software development, instrument calibration, and observation planning.

A blueprint for future generations

If the CGI mission succeeds, optimizing the technique may qualify it for future space telescopes such as the Habitable Worlds Observatory. The direct imaging of a second Earth would then be within reach.

The Roman Space Telescope, initially called WFIRST (Wide-Field Infrared Survey Telescope), is named after the astronomer Nancy Grace Roman, who led NASA's astronomical research programs for decades. Among other things, she was responsible for the scientific planning of the Hubble Space Telescope. The launch of the Roman telescope is currently scheduled for September 2026.

PRIMA - Probe Far-Infrared Mission for Astrophysics

The cold infrared space telescope PRIMA (Probe Far-Infrared Mission for Astrophysics) is one of two mission proposals selected in October 2024 for phase A studies for NASA's next major astrophysics mission, the Astrophysics Probe Explorer. It is scheduled for launch in 2032. The cost cap for this mission, including launch and operations, is US$1.5 billion.

PRIMA will enable groundbreaking observations with unprecedented sensitivity in the wavelength range from 24 to 261 micrometers, extending the observing window of the James Webb Space Telescope to longer wavelengths. Following the retirement of the NASA/DLR SOFIA telescope, PRIMA is the only mission capable of observing in this fundamental astrophysical domain in the foreseeable future. Its -269°C cold and 1.8 meters large primary mirror, as well as new detectors, make PRIMA about 100 times more sensitive than the former far-infrared space telescope HERSCHEL. PRIMA's instruments PRIMAger & FIRESS enable different measurement methods (direct imaging, spectroscopy, and polarimetry) to solve open questions in astrophysics, ranging from the evolution of galaxies in the early universe to the formation of stars and planetary systems in our Milky Way.

MPIA's contribution to PRIMA

MPIA serves as a Co-Investigator (Co-I) institute in the PRIMA collaboration, contributing to planning the science program, preparing the instrument operation, and developing the data center. The primary German hardware contribution will consist of two cryogenic beam steering mirror mechanisms with control electronics. These mechanisms modulate IR radiation to the instruments and are vital for highly sensitive operations such as mapping, calibration, and differential signal chopping. In collaboration with space industry partners, a reference design, including Phase A documentation and TRL assessment, is currently being established for the beam steering mechanisms and control electronics. The space suitability of critical components will be demonstrated in the laboratory, and a prototype mechanism will be developed.

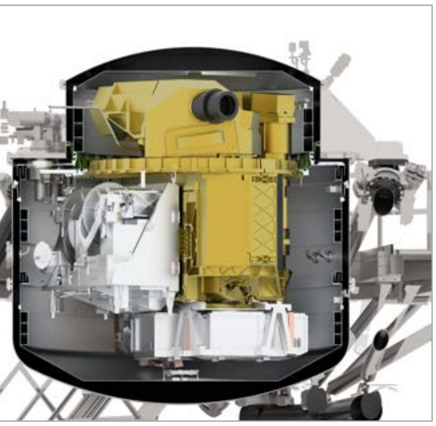
The goal is to have this prototype hardware ready by the end of 2025, when the phase A study report is due. The selection of the NASA Astrophysics probe is expected around mid-2026.

Oliver Krause

IV.3 INSTRUMENTATION AT MPIA

Overview of current projects

Astronomical instruments have their strengths and specializations. Here, we list **ongoing MPIA instrumentation projects for the year 2024**. Almost all the instruments are cameras for producing astronomical images and spectrographs for analyzing the color components of light or combinations thereof.

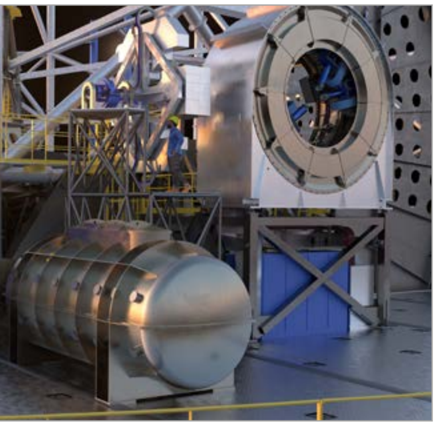


METIS
Mid-infrared ELT Imager and Spectrograph

Telescope	Extremely Large Telescope, Armazones, Chile
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	Coronagraphy and polarimetry
MPIA contribution	Imager and single-conjugate adaptive optics
Status	In the manufacturing, assembly, integration, and testing phase

MICADO
Multi-AO Imaging Camera for Deep Observations

Telescope	Extremely Large Telescope, Armazones, Chile
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, calibration assembly
Status	In the manufacturing, assembly, integration, and testing phase



ANDES
ArmazoNes high Dispersion Echelle Spectrograph

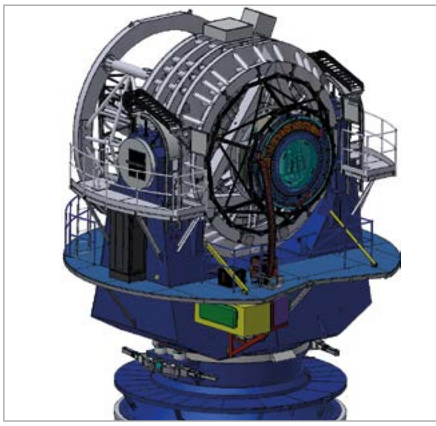
Telescope	Extremely Large Telescope, Armazones, Chile
Wavelength range	Ultraviolet (0.35 µm) to *K*-band (2.4 µm), *U* and *K*-bands as goals
Targets	Exoplanet atmosphere characterization, first stars, constants of physics, measure the acceleration of the universal expansion
Resolution	Spectral resolving power of ~100,000
Special features	Four fiber-fed spectrograph units
MPIA contribution	Electronics for the calibration unit and spectrograph vacuum control; potentially *K*-band spectrograph
Status	*K*-band spectrograph passed sub-system preliminary design review

Each camera or spectrograph has a characteristic **wavelength range** describing the kind of electromagnetic radiation it can detect. Most MPIA instruments work in visible light, with radiation we can see with our eyes, or in the infrared regions of the spectrum: in the near-infrared (slightly longer wavelengths than 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 (emitted by the coldest known objects in the cosmos, or the most distant).

4MOST

4-meter Multi-Object Spectroscopic Telescope

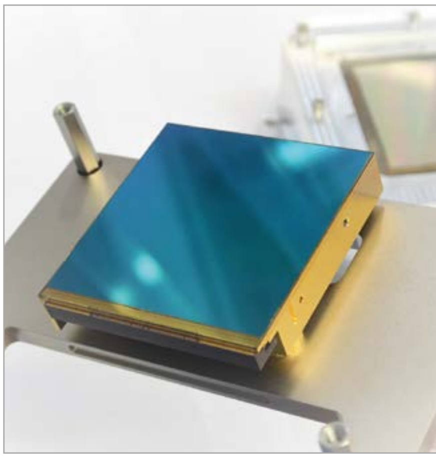
Telescope	VISTA, Paranal, Chile
Wavelength range	420–900 nm
Targets	Milky Way and galaxies, structure of the cosmos
Resolution	Spectral resolving power of 5000–20,000 (spatial resolution n/a)
Special features	2400 fibers over a field-of-view of 4 square degrees
MPIA contribution	Instrument control electronics, carbon fiber housing for metrology camera
Status	Moving to commissioning phase



PANIC-4K

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

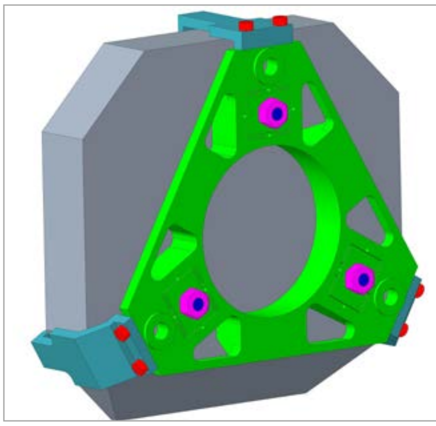
Telescope	2.2-meter Telescope, Calar Alto Observatory, Spain
Wavelength range	Near-infrared, 0.9–2.15 µm
Targets	Multipurpose wide-field survey imager
Resolution	Seeing-limited
Special features	Large field-of-view of 25' × 25'
MPIA contribution	Purchase, integration, and testing of novel 4 K × 4 K near-infrared detector
Status	PANIC reinstalled at the Calar Alto 2.2-meter telescope in 2022, and some commissioning activities took place in 2024



2ES

Second Earth Initiative Spectrograph

Telescope	2.2 m ESO/MPG telescope, La Silla Observatory, Chile
Wavelength range	Visible, 370–850 nm
Targets	~ 5-year survey of bright solar-type stars
Resolution	High spectral resolution of 120,000
Special features	Ultra-high instrumental radial-velocity precision
MPIA contribution	Mechanical design of several spectrograph components and observing time at the ESO/MPG 2.2m telescope
Status	Design phase



CGI

Coronagraph Instrument

Telescope	Nancy Grace Roman Space Telescope (formerly WFIRST)
Wavelength range	545–865 nm
Targets	Exoplanet detection and characterization
Resolution	20 mas
Special features	First adaptive-optics coronagraph (contrast ratio 10^7–10^9) in space
MPIA contribution	Precision Alignment Mechanisms, related ground support equipment
Status	MPIA's mechanisms delivered to JPL

PRIMA

PRobe far-Infrared Mission for Astrophysics

Telescope	Cryogenic 1.8m space telescope
Wavelength range	24–261 µm
Targets	High-redshift galaxies; protoplanetary disks; general astrophysics
Resolution	6 arcsec at 40 µm
Special features	Ultra-sensitive MKID detectors for spectroscopy and (polarimetric) imaging with 10^3 – 10^5 gain in mapping speed over previous missions
MPIA contribution	Beam steering mirrors and control electronics
Status	Phase A

Astronomical objects are extremely distant, making it difficult to discern their structural details. The **resolution** is a measure of the level of detail that can be achieved using a particular instrument. There are two types of resolution: spatial and spectral. In an imaging camera, spatial 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; this kind of resolution is typically given in arcseconds (1 arcsecond = 1/3 600 of a degree) or even milliarcseconds, mas (1 mas = 1/1000 arcsecond). In spectrographs, spectral resolution, or resolving power, measures the wavelength separation between two spectral features that can be distinguished.

Specific instruments have characteristic **special features** or properties. For instance, a particularly wide field of view allows surveying images of large regions of the sky. Adaptive optics assists observations to counteract the disturbances caused by Earth's atmosphere. Other examples include determining the orientation of an electromagnetic wave's oscillation (polarimetry) or blocking light from part of the field of view (coronagraphy).

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, exoplanet atmospheres, galaxies, and cosmology. That is why typical targets are star-forming regions, hidden behind dust clouds that infrared radiation penetrates, or very distant galaxies, whose light has been shifted by cosmic expansion, both of which again require infrared observations. Also, exoplanet atmospheres exhibit many interesting spectral features in the infrared.

We also list the current status of each instrument. The design and construction of an instrument encompasses several phases. In the beginning, there are several phases of intensive planning: conceptual design (phase A), preliminary design (phase B), and final design (phase C), all of which are concluded in a review. These steps often include verification tests of the necessary technology using prototypes. The construction phase is followed by integration, in which the separate components are assembled to form the complete instrument; 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.

Heidi Korhonen, Martin Kürster, Oliver Krause

IV.4 HIGHLIGHT: GROUND-BASED INSTRUMENTATION

The ANDES K-Band Spectrograph – Taking Exoplanet Observations to the Next Level

Project overview and science cases

ANDES is a second-generation instrument for the European Southern Observatory's (ESO) Extremely Large Telescope (ELT), currently in the design phase. It is being developed by a large international consortium led by the Istituto Nazionale di Astrofisica (INAF) in Italy. This high-resolution spectrograph, with a resolving power of 100,000, is designed to cover a broad spectral range within the infrared part of the spectrum, from 0.35 to 2.4 micrometers. The outer ends of this range—the U-band (0.35–0.41 micrometers) and the K-band (1.8–2.4 micrometers)—are currently considered goals rather than part of the baseline design.

ANDES will achieve its extended wavelength coverage through four distinct spectrographs, each optimized for a specific part of the spectrum. MPIA is a member of the consortium, contributing to the instrument's electronics. Moreover, MPIA has a strong scientific interest in extending ANDES into the near-infrared K-band and has conducted a comprehensive feasibility study for this purpose.

The primary science objectives of ANDES include searching for biosignatures in exoplanet atmospheres and studying potential variations in fundamental physical constants. In addition to these, the instrument supports a wide range of scientific investigations. K-band exoplanet transmission and reflection spectroscopy, in particular, is considered a flagship science case, with the potential to dramatically advance our understanding of giant exoplanet atmospheres. This spectral region is well-suited to detecting strong CO molecular features, making the K-band spectrograph a vital enhancement to the ELT's capabilities.

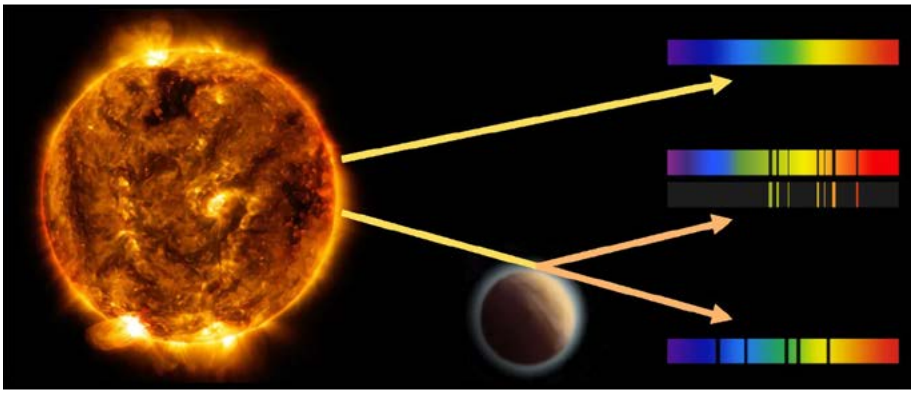
Expanding spectral coverage into the near-infrared will increase the number of observable targets from a handful (with current 8-meter-class telescopes and the James Webb Space Telescope) to more than 50 with the ELT. It will also enable detailed studies of wind patterns in the atmospheres of giant exoplanets and facilitate the characterization of smaller planets. Furthermore, the K-band spectrograph will enable unprecedented investigations of protoplanetary disks. As both exoplanetary atmospheres and disk science are key priorities at MPIA, enhancing ANDES with K-band capability is of strategic importance to the institute.

In 2024, several ANDES subsystems underwent preliminary design reviews (PDRs). The MPIA-led K-band spectrograph successfully passed its PDR in November.

Technical requirements

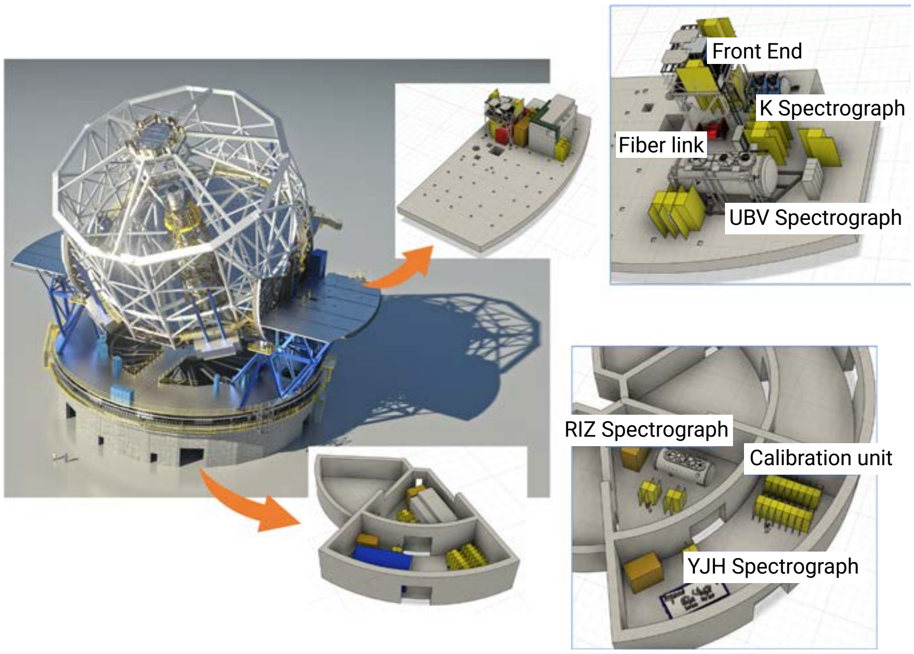
The K-band spectrograph science cases place less stringent requirements on performance than the overall ANDES objectives. This allows for more flexibility in the design to accommodate technical constraints. At the same time, we aim to keep the design approach as simple and straightforward as possible before implementing more complex optical or mechanical elements.

K-band wavelengths require optical fibers made of different materials than those used in the YJH-band range (0.95–1.9 µm). As a result, the K-band spectrograph must be built as a separate unit and cannot share components with the spectrographs designed for YJH wavelengths.



Credit: W. Gaessler / MPIA , NASA / SDO

Fig. IV.4.1: Transmission and reflected/emitted light spectroscopy probing exoplanet atmospheres. As starlight passes through the atmosphere of an exoplanet, absorption or stimulated emission processes leave a characteristic imprint in the forms of lines or bands. Those lines or bands distinguish the light that has passed through the atmosphere from light emitted by the planet and observed directly.



Credit: ANDES Consortium

Fig. IV.4.2: Schematic view of the ANDES instrument at ELT, with K-band spectrograph placed on the Nasmyth platform.

At the same time, ELT instruments are mounted on one of two 27-meter-high Nasmyth platforms, each of which hosts multiple heavy instruments, typically weighing between 10 and 20 metric tons. Given the limited space and high load, designs must be both compact and lightweight.

The K-band spectrograph will consist of a mechanical structure housing the cryogenic vessel and all internal optical and mechanical components. The concept is based on the proven cryo-mechanical design of the SPIrou spectrograph at the Canada-France-Hawai'i Telescope. The subsystem also includes the software and hardware for temperature and vacuum control, as well as the detector system. The design presented at the November 2024 PDR features nine fibers: six for the integral field unit (IFU), two for the seeing-limited arm, and one for the calibration unit.

Fig. IV.4.3: ANDES K-band spectrograph cryostat design presented in the subsystem review in November 2024.

Credit: ANDES Consortium

Outlook

What are the next steps following the successful PDR of the MPIA-led K-band spectrograph? Once all individual ANDES subsystems pass their respective PDRs—expected in 2025—the instrument will undergo a system-level PDR. A successful review will pave the way for the final design phase, followed by manufacturing, assembly, integration, and testing (MAIT). The instrument will then undergo preliminary acceptance in Europe before being shipped to Chile for final integration and commissioning on-site at the ELT. Projects of this complexity and scale require many years to complete, and the earliest realistic timeframe for ANDES to become operational is in the mid-2030s.

Wolfgang Gässler, Wolfgang Brandner, Paul Mollière, Monica Ebert, Ralf-Rainer Rohloff, Santiago Barboza, Michael Lehmitz, Werner Laun, and Heidi Korhonen

IV.5 HIGHLIGHT: TECHNICAL DEPARTMENTS

Testing Astronomical Instrumentation at Ultra-Low Temperatures

Project overview

MPIA plays a key role in the development of METIS (Mid-Infrared ELT Imager and Spectrograph), one of the first-light instruments for the Extremely Large Telescope (ELT). The METIS consortium, responsible for constructing the instrument, consists of twelve institutions from ten countries, as well as ESO itself, and is led by NOVA (the Netherlands Research School for Astronomy). MPIA is the second-largest partner in the consortium and leads the development of two key subsystems: the imager and the adaptive optics unit.

METIS operates in the mid-infrared wavelength range of 3-13 microns, a range where objects at room temperature, including the human body, emit most of their thermal radiation. This natural background emission can easily outshine the faint signals from astronomical targets. To enable meaningful observations at these wavelengths, the entire instrument must be cooled to very low temperatures.

Testing METIS components under these extreme conditions is essential in order to ensure reliable operations. Designing, procuring, and installing the specialized test equipment required close coordination and dedicated effort from all MPIA technical departments. Designing the vacuum cryostat and super insulation was particularly challenging due to the container's large size and the resulting air pressure load. To address the stringent thermal requirements, the system mimics the cryo-cooling approach used in the METIS cryostat, utilizing an identical cooler. PLC-based control electronics, including an interlock arrangement, ensure safe and reliable operation.

Test setup for METIS subsystems at MPIA

The MPIA technical departments have established an extensive test setup for METIS in the Assembly Hall. This setup, which is fully integrated within a cleanroom environment, enables thorough testing of the sensitive equipment for both the METIS imager and the adaptive optics

Fig. IV.5.1: MPIA Assembly Hall with the METIS test cryostats. The open adaptive optics unit test cryostat is visible in the center of the picture. The imager test cryostat is located at the back of the room, on the right side, and the imager itself is currently positioned in the front part of the room, also on the right side.

unit. Tests are performed at ultra-low temperatures, down to as low as 40 Kelvin. The test setup can reach temperatures as low as 20 Kelvin, which is approximately 160 degrees Celsius below the coldest naturally recorded temperature on Earth and even frostier than Pluto during local winter.

The MPIA test setup consists of two large test cryostats: one optimized specifically for verifying the METIS adaptive optics unit, and the other for testing the imager. While these cryostats are tailored to METIS requirements, they have been designed as a part of a broader, long-term infrastructure investment, enabling their future use as general-purpose cryogenic test facilities. Each cryostat features dedicated mechanical and optical interfaces for the METIS subsystems, as well as general-purpose interface plates to support a broader range of experiments.

The cryostats provide two distinct temperature regimes: one at 70 Kelvin and another reaching down to 40 Kelvin—a low temperature rarely supported for testing such large volumes. These two cryostats enable thorough testing of MPIA-developed METIS hardware under actual operating conditions. Both are equipped with closed-cycle coolers for efficient, automated thermal control and are managed by MPIA-developed PLC-based electronics. In addition, each cryostat features Calcium Fluoride interface ports, enabling detailed optical measurements of the components inside.

Fig. IV.5.2: METIS adaptive optics unit test setup being assembled at MPIA.

Future outlook

The assembly of the test equipment, including the first cool-downs of the test cryostats, was completed in 2024. We will advance to the main testing phase in 2025.

MPIA will carry out a series of critical verification and validation activities under cryogenic conditions. These include high-precision interferometric measurements to verify the optical performance of components under operating conditions. Alignment checks will also be performed at cryogenic temperatures to ensure all optical elements remain correctly positioned when cooled to their final working temperature. At the unit level, we will conduct detailed functional tests to validate the performance and stability of each component. Finally, we will perform end-to-end verification of the complete subsystems, adaptive optics module, and imager, ensuring that all components work seamlessly together.

After integration and testing, the METIS adaptive optics unit and imager will be officially delivered to the PI institute, NOVA, in Leiden, the Netherlands. There, the MPIA-built components will be integrated with the other METIS subsystems in a dedicated large integration hall, and the entire instrument will be tested as a whole. The complete instrument is ultimately scheduled to be shipped to Chile in late 2029, where it will be installed at the ELT on Cerro Armazones in northern Chile.

Peter Bizenberger, Werner Laun, Thomas Bertram, Harald Baumeister, Armin Huber, Lars Mohr, Matthias Alter, Armin Böhm, and Heidi Korhonen

V. ACADEMICS, EDUCATION AND PUBLIC OUTREACH

Credit: D. Elsässer

V.1 ACADEMICS, EDUCATION AND PUBLIC OUTREACH

Academics

As a research institute, MPIA takes its responsibility seriously to foster future generations of scientists. Our primary focus in this area is on training doctoral students. The International Max Planck Research School for Astronomy & Cosmic Physics at Heidelberg University (IMPRS-HD) plays a central role at MPIA and other astronomy-related institutes in Heidelberg. The IMPRS-HD organizes the application and selection process for new students, fosters interaction between students during IMPRS seminars and retreats, offers assistance with everyday administrative tasks, and provides a social network, particularly for international students who may arrive from distant destinations. Heidelberg University makes a significant contribution to the success of IMPRS: four of the six astronomical institutes in Heidelberg involved in the IMPRS are university institutes, which provide and fund half of the IMPRS students. The IMPRS is also an independent part of the Heidelberg Graduate School of Fundamental Physics (HGSFP), which has provided administrative and financial support to the PhD students since 2007. The rectorate of Heidelberg University has agreed to fund two doctoral fellowships between 2023 and 2028.

In 2024, the 20th generation of students arrived, comprising 21 new IMPRS students. Of those, nine work at MPIA, while one is on a project with shared supervision between MPIA and the Institute for Theoretical Astrophysics (ITA) at Heidelberg University. The new MPIA IMPRS students are Stefan Adelbert, Rogelio Albarracin, Cade Bürgy, Ben Pennell, Jorge Perez Gonzalez, Bipradeep Saha, Peter Smith, Anastasia Tzouvanou, Macarena Vega Pallauta, and Antonia v. Stauffenberg.

Elected student representatives for this generation are Kristian Vitovski (Heidelberg Institute for Theoretical Studies, HITS) and Ben Pennell (MPIA). This generation's fraction of female students is 43% (precisely at last year's level). Non-German students are 17 of the 21. The IMPRS-funded IMPRS fellowship 2024 was awarded to Shuyu Tan (supervised by Ralf Klessen, ITA), while Veronica Agaeva (supervised by Friedrich Roepke, HITS) received the university-funded IMPRS fellowship.

Considering new applications — these students are supposed to arrive in 2025 — the IMPRS has received a total of 440 in 2024, again more than ever before. Of those 440, 35% were applications from female students. The list of promising candidates comprised 195 applicants, thus a long shortlist. Of the female applicants, 38% advanced to the shortlist, while the percentage for male applicants was 58%. In addition to the 440 applications collected by the IMPRS application system, another 37 were received by the HGSFP (approximately a 60% overlap with IMPRS applications).

In the strongest applicant group, namely those ranked as A+ (a total of 35), 37% of students were female, and in the subsequent class, A (with a total of 79 applicants), the percentage was 38%. Again, numerous applications arrived from India (135), China (39), Italy (20), and Chile (22). We received 48 applications from Germany, a relatively low number. Note that these numbers consider the application's origin (the localization of the M.Sc. or B.Sc. student) and not the applicant's citizenship.

Fig. V.1.1: The participants of the IMPRS Summer School 2024 on the topic "New Opportunities to Test Cosmology."

Twenty IMPRS students completed their doctoral degrees in 2024.

The IMPRS-HD summer school 2024, the 19th since the beginning, was on "New Opportunities to Test Cosmology". Hans-Walter Rix (MPIA), Björn-Malte Schäfer (ARI), and Luca Amendola (Institute for Theoretical Physics) organized the scientific program. Invited speakers for the lecture program were Camille Bonvin (Geneva), Shirley Ho (New York), Benjamin Joachimi (London), and Alessandra Silvestri (Leiden). The number of participants was 69 from all over the world, including 18 local students.

The IMPRS seminar retreat 2024 was held at the "Bildungshaus Neckarelz" near Heidelberg, with the 18th generation of students in attendance. Invited speakers were IMPRS alumna Diana Kossakowski (Körber Digital), talking about leaving academia, and Giovanna Pugliese (U. of Amsterdam), who offered a hands-on workshop on post-PhD careers. Rainer Spurzem (Astronomisches Recheninstitut, ARI, Heidelberg University) and Andreas Quirrenbach (Landessternwarte, LSW, Heidelberg University) served as tutors for the retreat seminar.

An exceptional activity was the student-organized "IMPRS Astro Hackathon" from May 21 to 24, 2024, at the Haus der Astronomie (HdA) in Heidelberg, jointly with students from the IMPRS for Astrophysics in Garching. The aim was to bring astronomy students together while working on common projects, learning new skills, and building connections and collaborations. The idea surfaced during a visit by Heidelberg students in Garching on their way to their 1st year retreat.

While training graduate students is the focus of MPIA's academic involvement, our activities begin much earlier at the undergraduate level. Two of our directors and numerous research group leaders are involved in teaching at Heidelberg University. For example, this year, MPIA scientists were engaged in teaching the "Physics and populations of stars" (Maria Bergemann), accompanied by a seminar series, and in a lecture on "Protostars and planets" (Henrik Beuther). At the same time, Hubert Klahr taught the "Physics of planet formation" via a lecture and a seminar. Star formation was the topic of two lectures by Thomas Henning and Henrik Beuther. Dmitry Semenov lectured on molecular astrophysics, while Annalisa Pillepich held a course on cosmology.

MPIA also offers bachelor's and master's students from Heidelberg University or other universities the opportunity to conduct research for their theses at the institute. There is a successful international summer internship program for students who want to gain research experience (coordinated by Ivelina Momcheva).

Christian Fendt, Markus Nielbock

Table V.1.1: PhDs graduations completed by MPIA students in 2024.

Name	Defense Date	Title	Supervisor
Maria-Selina Nitschai	2 July	Dynamics of the Milky Way Disk and Spectroscopic Analysis of ω Centauri	Neumayer
Lukas Eisert	18 July	Inferring the assembly and merger histories of galaxies with the IllustrisTNG simulations and machine learning	Pillepich
Diego Sotillo Ramos	19 July	Milky Way and M31 analogues: insights from the cosmological simulation TNG50	Pillepich
Evert Nasedkin	24 July	Atmospheric Characterisation of Directly Imaged Exoplanets	Kreidberg, Mollière
Verena Fürnkranz	21 October	The Small-Scale Structure of the Milky Way's Orbit Distribution	Rix
Nico Winkel	21 October	Pathways to Supermassive Black Hole Growth – Resolving Gas Flows and Black Hole Mass Scaling Relations in AGN Host Galaxies	Huesemann, Jahnke
Eric Rohr	28 November	Jellyfish Galaxies and the Multiphase Nature of Gas Around Galaxies	Pillepich

V.2 ACADEMICS, EDUCATION AND PUBLIC OUTREACH

Public Outreach

MPIA has a long tradition of science outreach in different forms and shapes. As in past years, many of these outreach activities were carried out at or in collaboration with Haus der Astronomie (HdA), the center for astronomy education and outreach on the MPIA campus, which is operated by the Max Planck Society and administered by MPIA. A description of separate HdA activities can be found in section V.3.

The institute regularly communicates its scientific results, as well as more general news items, to the public, both via its website and by informing the news media with the help of press releases. The science highlights in chapter III of this report all started out as institute press releases, and a number of them led to significant media coverage. For press releases or on other occasions, our scientists also give interviews to the news media or take part in TV broadcasts.

This year, the science release that generated the most attention was the one on the intermediate-mass black hole in the globular cluster, or better: the remnant satellite galaxy core Omega Centauri, discovered by Maximilian Häberle as part of his PhD research at MPIA, in the Lise Meitner Group of Nadine Neumayer (cf. section III.8). Altogether, more than 300 domestic news media outlets covered this story, including more than 80 printed newspaper articles.

Scientists and engineers from MPIA accounted for a significant fraction of the public talks at Haus der Astronomie this year, with contributions ranging from the dark side of the universe (Wolfgang Gässler) or the search for siblings of our home planet (Markus Feldt) to a presentation of the METIS instrument MPIA is helping to build for ESO's Extremely Large Telescope in Chile (Silvia Scheithauer). We were also pleased to see MPIA graduate students participate, with talks on the hidden center of the Milky Way (Franziska Bruckmann), the intermediate black hole in Omega Centauri (Maximilian Häberle), and our closest black hole neighbor (Rhys Seeburger).

The basic astronomy exhibition "Astronomie für Alle" ("Astronomy for everybody"), co-organized by MPIA and HdA with support from the Klaus Tschira Foundation, was in its sixth year of operations this year, and began the year in the small Baden-Württemberg city of Leonberg, where it had opened in October 2023. In September 2024, the exhibition finally arrived in Heidelberg, specifically at the Carl Bosch Museum. The exhibition itself

Fig. V.2.1: The "Astronomie für Alle" exhibition at the Carl Bosch Museum in Heidelberg.

Credit: F. Seitz / HdA

Fig. V.2.2: Participants of the 2024 MPIA/HdA Girls' Day proudly present printed and framed versions of the galaxy images they created from authentic observational data.

features hands-on exhibits that allow visitors to learn about the basics of astronomy: from the night sky and the Solar system to the basics of cutting-edge research, notably on exoplanets and the Milky Way. The exhibition will remain on display at Carl Bosch Museum until the end of April 2025.

For members of the general public, guided tours of the Königstuhl Campus provide a chance to learn about astronomical research at MPIA first-hand. Many of the tours are guided by the MPIA Outreach Fellows, who are MPIA PhD students who spend some of their time gaining experience in public outreach. Guided tours routinely make use of the digital planetarium in HdA, and are offered in cooperation with the neighbouring Landessternwarte (the former state observatory, now part of Heidelberg University).

In cooperation with HdA, MPIA is a regular participant in Germany's nationwide "Girls' Day." This is an annual one-day program that is meant to introduce female pupils aged 13 to 18 to professions in which women are underrepresented. All in all, 20 young women visited MPIA/HdA on April 25 to learn about astronomy-related professions. Sixteen of them went to HdA to work with authentic astronomical data, using galaxy observations obtained with the LCO robotic telescopes; they also heard a talk by MPIA PhD student Selina Nitschai on what it means to work as an astronomer. Four participants learned about the instruments necessary for doing astronomy, from aiming a laser with the help of a tip-tilt mirror to exploring work at cryogenic temperatures.

Markus Pössel, Markus Nielbock and Klaus Jäger

V.3 ACADEMICS, EDUCATION AND PUBLIC OUTREACH

Haus der Astronomie – Center for Astronomy Education and Outreach

Haus der Astronomie (HdA; literally "House of Astronomy") is the Center for Astronomy Education and Outreach on the MPIA Campus. Its mission is to communicate the fascination of astronomy to the public, support astronomy education, and foster knowledge exchange between scientists. Here, an active team of twenty astronomers and astronomy educators dedicates its time to developing and producing materials and resources for the public, as well as for use in schools, organizing events, and networking.

Virtual spaceflight in a down-to-earth galaxy

In 2024, a total of 6290 members of the general public visited the galaxy-shaped HdA building for talks, presentations, and guided tours. Among our most thought-after events were the regular "Reise[n] ins Universum" ("Voyage[s] into the Universe"), each an hour-long virtual trip from planet Earth to the edge of the observable universe. Virtual journeys like this are made possible by the digital planetarium in our central Klaus Tschira Auditorium, and the projectors recreate a spectacular view similar to what one might see when travelling the cosmos in an unrealistically fast spaceship.

In addition to monthly journeys into the universe for a general audience, we also offered four extra events, each with a journey particularly suitable for children six years and older. Another one of those "family events" was our Christmas special: "Hitchhiking through the Galaxy," featuring our home galaxy, the Milky Way, and its distant cousins.

Special events for visitors of all ages have been offered in conjunction with "International Observe the Moon Night" and Germany's National Astronomy Day, which coincided with the "Lange Nacht der Astronomie."

Touring exhibitions

Accompanying the stay of our travelling exhibition "Astronomie für Alle" ("Astronomy for Everybody", cf. section V.2) at the Carl Bosch Museum in Heidelberg from August 2024 onwards, the museum organized several events, from "astronomical movies" at Karlstorkino (featuring movies as diverse as WALL·E and Interstellar) to a lecture series and a guided tour to Heidelberg's astronomical sites. Our contributions included several workshops for schoolchildren of different ages, as well as a scavenger hunt for children visiting the exhibition.

The JWST exhibition we had developed for the German science year 2023 also continued to travel, spending January and February in the ESO Supernova in Garching near Munich, two weeks in April/May hosted by Physikalischer Verein in Frankfurt, one week in May/June at IHK Osttühringen in Gera, July to September in Nuremberg, and two weeks in September/October hosted by MINT Werra-Meißner Kreis e.V. in Witzenhausen in northeastern Hesse.

Fig. V.3.1: Posters for events in and around Haus der Astronomie.

Credit: Design: Daniela Leitner; production: MPIA graphics department

Credit: M. Pössel / HdA

Fig. V.3.2: *Left:* Hubert Klahr explaining the water-rotation-and-ice toy model to young visitors. Klahr and his group had originally created this exhibit for MPIA's Open Day 2023. ***Right:*** Details of turbulent streams inside the water, made visible with the help of drops of food coloring.

HdA on Tour

While many of our activities take place in our galaxy-shaped home on the Königstuhl mountain, there are occasions when you can find HdA "on location." A regular example is "Explore Science," the open-air science event organized each year in Mannheim (and, more recently, at other locations) by the Klaus Tschira Foundation—one of the partners behind HdA. The event took place in Mannheim's Herzogenriedpark, and this year's overarching theme was "Climate and the environment."

At the HdA tent for younger pupils, the focus was on the search for a second Earth. Older pupils could play with our "exoplanet wheel of fortune" as an illustration of just how rare habitable exoplanets are, and learn about spectroscopy of exoplanet atmospheres. We also featured a toy model in the form of a rotating cylindrical pool. In the center of the pool, a tin containing ice created a cooler area; in the water itself, drops of liquid food coloring served to highlight the turbulent streams that emerged in the rotating water. This setup can serve as a model of Earth's atmosphere and the prevailing large-scale winds, while also illustrating the turbulence in the disks of gas and dust surrounding young stars, where turbulent flow plays a crucial role in planet formation.

Closer to home, we supported Deutsch-Amerikanisches Institut (DAI) Heidelberg on the occasion of their Science Day, part of the International Children's Book Festival 2024: When journalist Lucy Hawking presented the book "Unlocking the Universe", a collection of essays she had compiled together with her father, Stephen Hawking, Natalie Fischer provided a live translation for the German-speaking children in the audience.

In autumn, HdA managing scientist Markus Pössel, together with Roman Gold from Heidelberg University's Interdisciplinary Center for Scientific Computing (IWR), gave the lecture "Astronomy for the curious: Black holes and gravitational waves". The lecture is part of a series aimed at students at Heidelberg University who are not physics students but are interested in astronomical topics.

Reaching online audiences

Haus der Astronomie, through the tireless efforts of Carolin Liefke, is active on social media, specifically on Instagram (2007 followers), Facebook (4026 followers), Mastodon (1948 followers), and Bluesky (5969 followers), where we inform about HdA's activities and events as well as general astronomical topics. Following the platform's steep decline over the last two years, we put our Twitter/X presence on hold, with 6,526 followers at the end of the year.

At the beginning of 2024, we switched to a new online streaming format: "Astro & Co" is broadcast on YouTube and on Facebook, every Monday at 7 pm. Each broadcast features a brief introduction to the evening's topic, followed by ample time for discussion, typically between Carolin Liefke and Markus Pössel as moderators and a scientist guest. The audience participates by writing questions in the chat, which are then discussed on stage.

Topics ranged from recent astronomical events and current research to the 30th anniversary of the Shoemaker-Levy collision with Jupiter, during which key observations were made from the Calar Alto observatory, which MPIA operated at the time. A number of broadcasts provided basic information, e.g., on gravitational lensing or the properties of galaxies. At the end of 2024, our YouTube channel had 15.216 subscribers.

Astronomy for pupils of all ages

Teachers are our natural allies when it comes to bringing astronomy to at least a particular section of the public, namely, their pupils. Astronomy is fascinating to many students and can serve as a gateway to physics, more generally to the sciences, and, given the role it has played in human cultures, as a bridge to selected topics in the humanities as well.

Our most immediate contact with school classes or kindergarten groups occurs when they visit our galaxy-shaped building. In 2024, 128 groups with a total of 2,375 pupils visited us for interactive workshops with topics as diverse as the Moon or constellations for younger children, or spectroscopy, exoplanets, and infrared observations for high school groups. A typical workshop includes a topical presentation in our digital planetarium, and some workshops feature a visit to one of the telescopes on campus or at the neighboring Landessternwarte, or a stroll along our scale model of the solar system.

Some pupils want to know more than can be learned in a half-day workshop. This is where HdA's internship opportunities come into play. Our flagship program is the International Summer Internship for High School Students, a compact three-week program where participants work with authentic astronomical data, writing their own Python scripts to analyze the data and derive interesting astronomical results. This year, eight interns from Germany, Greece, Italy, Peru, Poland, Spain and the US participated in this program.

In addition, we ran three shorter German-speaking internship programs with a total of 31 participants. These one or two-week programs are often attended by pupils participating in BOGY/BORS, a school-mandated internship in Baden-Württemberg whose focus is on exploring different professions and fields of work, or their equivalent in other federal states. HdA joined forces with MPIA for the nationwide Girls' Day (cf. section V.2) and once again organized a Boys' Day event, which focuses on the challenges faced by kindergarten educators in bringing astronomy to their charges.

HdA's Carolin Liefke mentored several students enrolled in regional projects, such as the Hector Seminar or the astrophysics working group of the Heidelberg Life Science Lab, and supported groups participating in science contests like Jugend Forscht.

Carolin Liefke also continued her collaboration with the International Astronomical Search Collaboration (IASC), supervising three asteroid search campaigns for high-school students with groups from Germany, and supported German groups interested in remote observations with the Faulkes telescopes at Las Cumbres Global Observatory.

Teaching the teachers

When it comes to reaching school-age children and adolescents, school teachers provide an opportunity for a highly efficient multiplication effect: teach the teachers, and they can bring astronomy into their own classrooms!

Here, we start early: All pre-service physics teachers at Heidelberg University attend the block course "Introduction to Astronomy for Teachers" (abbreviated as PASTRO in their curriculum) at Haus der Astronomie. That is how, from February 26 to March 22, our building was transformed into a learning environment for future physics teachers, making full use of our in-house planetarium, our pool of small teaching telescopes, and our various demonstration experiments for astronomical concepts and phenomena. PASTRO covers all the basics of astronomy, from celestial coordinates and the daily and annual rhythms of observations to exoplanets, galaxies, and cosmology.

We also provide astronomy for pre-service elementary, special education, and secondary school teachers at Heidelberg's University of Education (Pädagogische Hochschule). Specifically, the target group's annual block seminar, "Basic Astronomy in School," was held at Haus der Astronomie. In the kindergarten sector, as in previous

Fig. V.3.3: Six of the 52 "Astro & Co" talks from 2024.

Credit: HdA

Fig. V.3.4: Participants of the 12th WE Heraeus Nationwide Teacher Training on Astronomy in November 2024.

years, four one-day training courses were held in cooperation with local seminar providers, showing prospective kindergarten teachers how easy it is to incorporate astronomical topics into kindergarten activities.

These offerings are complemented by in-service training, again for the full spectrum of the German kindergarten and school system. In cooperation with Forscherstation, Klaus Tschira Kompetenzzentrum für frühe naturwissenschaftliche Bildung, Natalie Fischer conducted two five-part training events for kindergarten and elementary school teachers.

For high school teachers, our main event is the yearly WE Heraeus Nationwide Astronomy Teacher Training, which is traditionally held in November. This event again provided three astronomy-packed, intensive days of training for 120 secondary school teachers. The mornings were filled with teacher-accessible lectures covering topics ranging from the first scientific results of JWST (Oliver Krause) to space law (Katja Grünfeld), quantum physics in the universe (Harald Lesch), and the Extremely Large Telescope and its instrumentation (Bruno Leibundgut, Heidi Korhonen). The afternoon sessions were centered around the teachers themselves sharing resources and best-practice examples, as well as hands-on workshops. Afternoon session topics included radio astronomy and ham radio, quantum physics, and micrometeorites. Thursday afternoon also saw the annual in-person meeting of the HdA's network of particularly active teachers.

Beyond our in-house teacher training, Carolin Liefke again conducted her “Telescope Driver's License” at Umweltbildungsstätte Oberelsbach and Landesschulzentrum für Umweltbildung.

Abroad, our German-Italian summer school “Astronomy from Four Perspectives,” which brings together participants from Heidelberg, Padova, Jena, and Milano (formerly Florence), rotating between those venues, circled back to Jena this year. In this eleventh edition of the school, we explored the astrophysics of compact objects, from tests of general relativity using the massive black hole in the galactic center (Stefan Gillessen) or simple curved spacetime diagrams near the black hole horizon (Ute Kraus) to gravity experiments with radio pulsars (Norbert Wex), with hands-on/minds-on tutorials to complement the course of lectures. We continued our collaboration with Dominik Elsässer at the Technical University of Dortmund by including some of the teacher students in the “Heidelberg contingent” attending this summer school.

Creating astronomy resources

In addition to training teachers in astronomy, we also provide them with astronomy-themed educational resources. In this area, our flagship is “Wissenschaft in die Schulen!” (literally “Science into Schools!”, WIS), which has provided such resources even since before the establishment of HdA: exercises suitable for the classroom, with a tie-in to modern research that references current articles in the popular magazine Sterne und Weltraum (“stars and space”), whose editorial team has their offices in our building. In 2024, the WIS team of volunteer authors produced their usual twelve articles, one per month, providing classroom inspiration as varied as celestial spectroscopy, dealing with long astronomical time scales, and the beginning and possible end of the cosmos as a whole. Among the contributions by HdA staff, Natalie Fischer described how a primary school built a Planet Trail, a scale model of the Solar System,

Credit: F. Eberhardt.

Fig. V.3.5: Simon Kraus joined Haus der Astronomie in October 2024, as the successor of Olaf Fischer.

in a forest, and Olaf Fischer contributed articles on the diversity of exoplanets and on the practicalities of building a Moon village.

For Haus der Astronomie in general, and WIS in particular, 2024 marked a turning point: Olaf Fischer retired, after nearly 20 years of editing WIS, and nearly 15 years as an HdA staff member. We consider ourselves very lucky to have found a worthy successor in Simon Kraus, who joined our staff in October 2024. Previously a staff member in the physics education group at the University of Siegen, Kraus has taken over from Fischer both WIS and the organization of the nationwide WE Heraeus teacher training.

Additional astronomy resources for elementary and secondary schools were developed and tested for Explore Science (see above).

Conferences and scientific events

Part of HdA's mission is the support of scientific exchange. For conferences with up to about a hundred participants, our building offers an attractive venue: the central auditorium for plenary sessions, our seminar rooms for breakout sessions, and our foyer as a location venue for catered meals during the conference.

In 2024, Haus der Astronomie hosted seven scientific conferences and meetings, attracting a total of 295 participants. A particular highlight at the beginning of December was the 10th edition of the annual Heidelberg–Harvard Meeting on Star Formation (HHFS), which alternates yearly between Harvard University and Haus der Astronomie. Over the course of four days, 75 participants, predominantly from Germany and the US, tackled questions related to the physics of star formation and the dynamics of the interstellar medium, with the ambitious goal of spanning the range from galactic (or even extragalactic!) scales down to the scales of the protoplanetary disks that surround young stars.

The year's MPIA Summer Conference, held at HdA, was organized by the APEx Department. Titled "Challenge accepted: Linking Planet Formation with Present-Day Atmospheres," the workshop brought together more than fifty researchers to discuss the link between the formation history of gaseous exoplanets and their present-day atmospheres—a timely topic, at a time when JWST had just provided the first observations of disks as well as atmospheric spectra.

August 6–15, organized by Carolin Liefke, HdA became one of the "Remote Viewing Centers" of the International Astronomical Union's General Assembly (cf. below). During that time, Heidelberg scientists could gather at HdA for live viewings of the various symposia and sessions of the event.

Our international scope: the IAU Office of Astronomy for Education

Since 2019, Haus der Astronomie hosts the International Astronomical Union's Office of Astronomy for Education (IAU OAE), which has become the focal point of our international impact. Our work of the IAU OAE is supported by grants from the Klaus Tschira Foundation and the Carl Zeiss Foundation, as well as by eight independently-funded branch offices: the OAE Center Italy, the OAE Center Cyprus, the OAE Node Nepal, the OAE Center India, the OAE Center China Nanjing, the OAE Center Egypt, the OAE Node Republic of Korea, and the OAE Node France at CY Cergy Paris University. Our liaisons into the various parts of the world were (end-of-year numbers for 2024) 323 volunteers representing 111 countries and territories: our National Astronomy Education Coordinators (NAECs).

Similar to HdA itself, IAU OAE is active in networking, providing teaching resources, and helping teachers and also astronomers with in-service training. Our main networking and training event is a large-scale online conference every November. This year's edition, the "6th Shaw-IAU Workshop on Astronomy for Education," brought together almost 740 participants from nearly 90 countries for a diverse program that ranged from astronomical science (special science topic: the first years of JWST) to sharing educational practices, astronomy education, and teaching methods. One particular focus this year was the question of how to evaluate astronomy education activities.

With funds allocated by the Shaw Prize Foundation for the years 2023–2025, we also organized two regional Shaw-IAU Workshops, aimed at bringing astronomy education stakeholders in a particular region, including our NAECs, for an in-person meeting with the possibility of intensive interactions. The Mediterranean Regional Shaw-IAU Workshop on Astronomy for Education (MASTED) brought together 32 participants from 16 countries in Istanbul, Turkey, from October 16 to 20, 2024. Two months later, the regional Shaw-IAU Workshop in Kathmandu, Nepal, brought together stakeholders from India, Bangladesh, Bhutan, and Nepal, organized by the OAE Node Nepal and the Nepal Astronomical Society.

The International Astronomical Union in Cape Town

For the OAE staff at Haus der Astronomie, the most memorable event of the year was our participation in the XXXII General Assembly of the International Astronomical Union in South Africa. From August 6 to 15, we joined more than 2,600 other participants at the Cape Town Convention Center for lectures, discussions, and networking. Many of our interactions took place at the central IAU booth in the exhibition hall, which featured an OAE section. Numerous attendees visited us during their stay at the General Assembly, not least to obtain a pair of the "spectral glasses" we had produced as an OAE give-away. Those fascinated by the spectra produced by those glasses included the South African Deputy Minister for Science, Ms Nomalungelo Gina. OAE also organized three sessions as part of the General Assembly program: An introduction to the OAE and its networks, a session on astronomy education curricula and evaluation, and a community discussion of our draft teacher training transparency standards.

Teacher training workshops, resources, and networking

The OAE team was also busily at work expanding the fundamental teaching resources for astronomy that OAE aims to offer. Different teams with native-speaker volunteer members worked on translating the basic astronomy glossary into Italian, Arabic, French, German, Hindi, Marathi, Bengali, Spanish, Chinese (in simplified characters, with automatic transliteration to traditional characters), Persian, and two localizations of Portuguese

Fig. V.3.6: Participants of the Mediterranean Regional Shaw-IAU Workshop in front of the Hagia Sophia Grand Mosque in Istanbul.

Credit: IAU GA 2024

Fig. V.3.7: The OAE team at our booth, part of the wider IAU presence in the Exhibition Hall at the General Assembly 2024. Left to right: Sophie Bartlett, Eduardo Penteado, Samantha Brown, Markus Pössel, Tshiamiso Makwela, Gwen Sanderson.

(Iberian and Brazilian). With the help of funding from the Klaus Tschira Foundation, the OAE completed a first version of its basic astronomy teaching illustrations collection, designed by professional illustrators in close consultation with practitioners. This year also saw the completion of the OAE Review on Evaluation, written by Sophie Bartlett (Cardiff University and OAE), as well as 12 new peer-reviewed activities published by astroEDU.

The 2024 edition of our Teacher Training Program (TTP), a small-grant program designed to stimulate new and/or innovative teacher training workshops within our community, funded 21 workshops, with funds from the IAU, the OAE Center Italy, and the African Astronomical Society.

Networking activities for our National Astronomy Education Coordinators (NAECs) this year centered on the re-certification of the NAECs, which occurs every three years, in sync with the IAU general assemblies' cadence. We also offered training opportunities for our NAECs, notably a Wikipedia workshop organized by Samantha Brown in coordination with the Wikimedia Foundation UK.

In terms of wider partnerships, 2024 marked the beginning of the Astro-Journeys Erasmus+ project, led by the OAE Node France at Cergy Paris University, in which we are a participant. The project is built around the Big Ideas in Astronomy, a community-consensus definition of astronomy literacy that is hosted by the OAE, and centered on the notion of utilizing artificial intelligence to help teachers select appropriate teaching resources in astronomy.

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